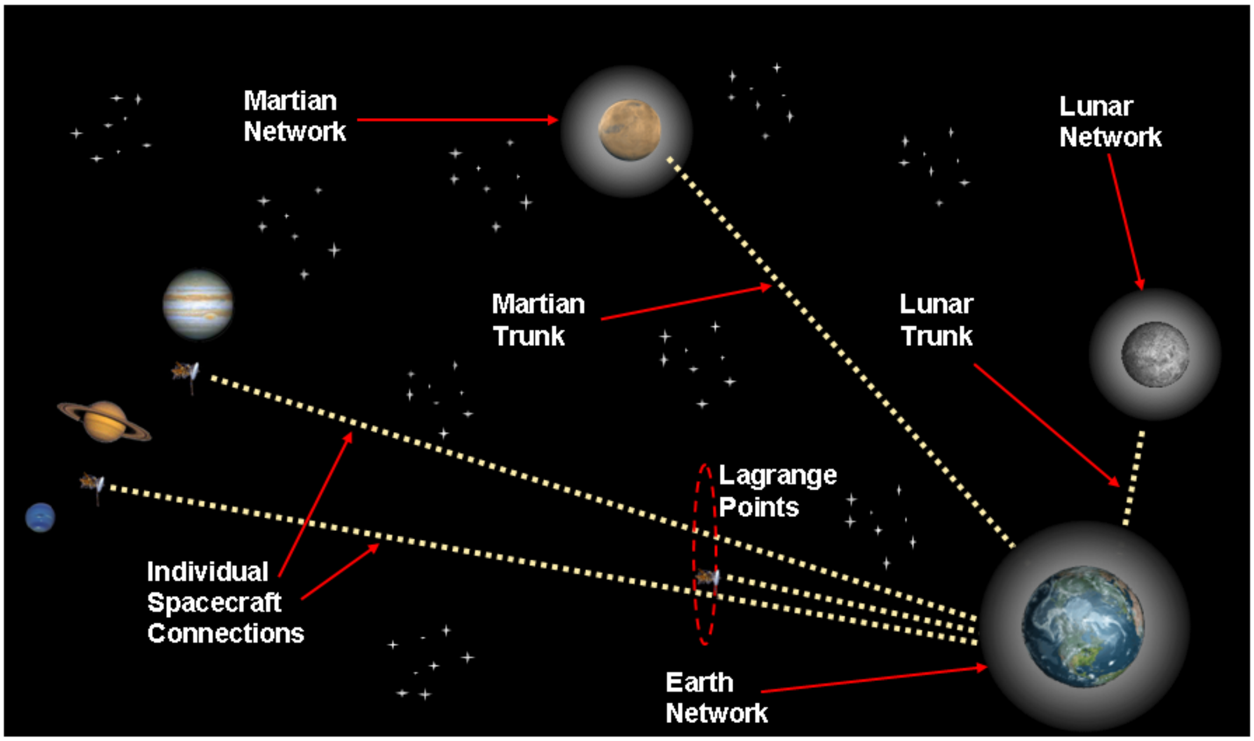
Space Communication Architecture Working Group (SCAWG)

NASA Space Communication and Navigation Architecture Recommendations for 2005-2030



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Final Report

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Executive Summary

The Space Communication Architecture (SCA) developed by the Space Communication Architecture Working Group (SCAWG) and described in this document is designed to provide the necessary Communication and Navigation (C&N) services for NASA space Exploration and Science missions out to the 2030 time frame. The architecture is composed of four physical elements with overlaying network, security, radio frequency (RF) spectrum, and navigation architectures as shown in Figure 1.

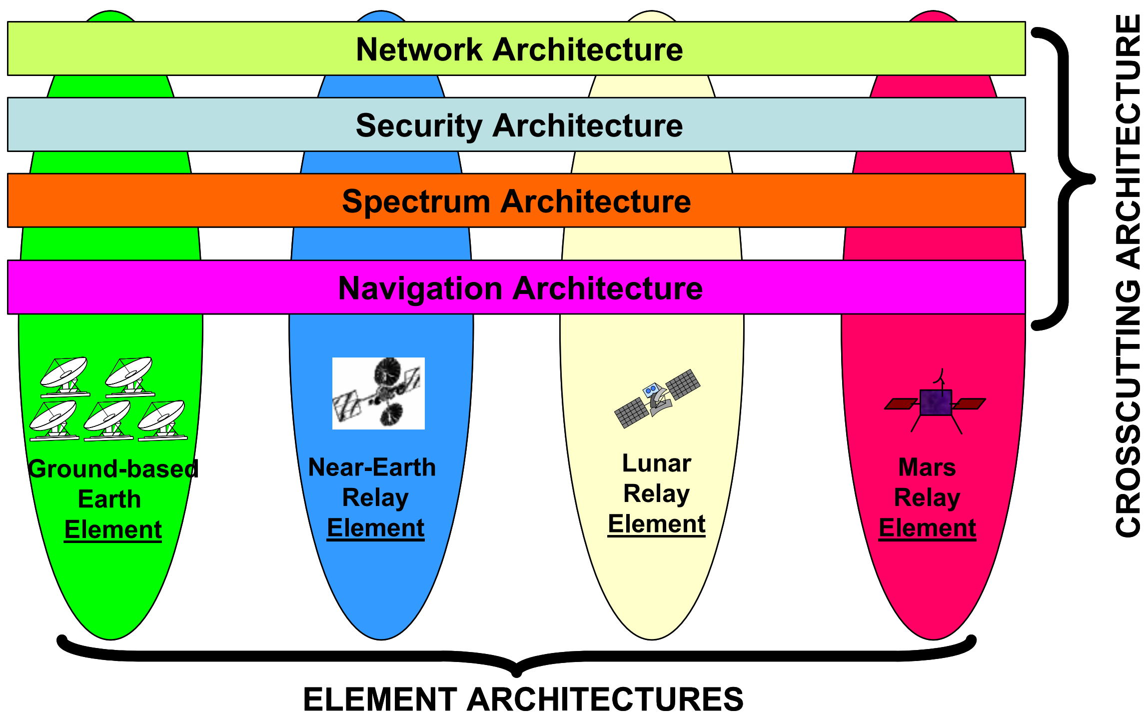

Figure 1. C&N Architecture Consists of Element & Cross-cutting Architectures

This architecture supports the provision of communication services to space missions operating anywhere in the Solar System and beyond, featuring clustered networking services at the Earth, Moon, and Mars that are connected to Earth via long-haul links. The architecture also provides radiometric tracking services available to all spacecraft.

Today's systems evolve into the elements of the future architecture: The Ground-based Earth Element (GEE), the Near-Earth Relay (NER) Element, the Lunar Relay (LR) Element, and the Mars Relay (MR) Element. They are tied together via an integrated networking architecture that leverages modern communication networking techniques used today on Earth and extends them throughout the solar system providing seamless transition for users going from one element's services to another. A spectrum architecture is defined that enables the elements to provide interoperable C&N services throughout the solar system. Spectrum is allocated so that two communication channels may be made available to each user spacecraft: one for robust, low data rate communications designed for critical Tracking, Telemetry, and Command (TT&C) and voice services, and a second, high data rate channel designed for transporting mission data. The security architecture provides a set of selectable options that provide missions with the flexibility to meet their communication security requirements with minimal overhead. The key points of the element and crosscutting architectures are described in the following paragraphs.

Networking Architecture

The networking architecture is organized as a set of standardized layered data communications services that support end-to-end user applications. "On-ramps" are defined in the layered structure such that legacy systems, new services or diverse service providers can be easily integrated into the network. Extensive use of programmable communication devices throughout the network is assumed, allowing reconfiguration and upgrade as technology and mission requirements evolve. NASA's network infrastructure is governed by a unified policy that features a One NASA approach towards management of the network services, including the selection and specification of evolving data communications and network management standards.

Security Architecture

The security architecture provides selectable data protection services for those users needing them, including both confidentiality and authentication. Missions may select security options provided by the infrastructure or may develop their own.

Spectrum Architecture

The spectrum architecture for solar system-wide operations uses spectrum bands that are approved by international agreement. The architecture implements spectrum bands for Earth-based operations that are in agreement with ITU allocations for space C&N services, including proposed strengthening of some allocations for space users. The coordination of local spectrum use with other international agencies potentially operating in the Lunar and Martian vicinities will enable future interoperability with other organizations without requiring any immediate commitments.

Navigation Architecture

The navigation architecture supports conventional radiometric tracking services for all user spacecraft, utilizing the same links as are used for operational communications. In addition, the navigation architecture relies on Global Positioning System (GPS) capabilities for those user missions in Low Earth Orbit (LEO) to Geostationary Earth Orbit (GEO) needing high precision orbit determination or low cost continuous autonomous position determination. The architecture also supports time distribution that is related to a common time reference.

Ground-based Earth Element (GEE

The GEE evolves out of the current Deep Space Network (DSN) and Ground Network (GN) and implements a concept of small aperture, arrayed antennas to receive mission communications from missions beyond GEO. This is a scalable, highly efficient architecture that allows "virtual antennas" to be formed that match or exceed the current capability of the DSN large aperture antennas. By being scalable, performance of the element evolves in small, affordable increments. The architecture also allows for the use of monolithic antennas where unique capabilities are required. Launch head antennas primarily support launch vehicles. High latitude antennas primarily support polar missions.

Near-Earth Relay (NER) Element

The NER evolves from the current Space Network (SN) and Tracking and Data Relay Satellite System (TDRSS) but remains a GEO constellation of “bent-pipe” relay satellites that provide global connectivity for satellite users in S and Ka-band. The S-band services are provided on both Multiple Access (MA) phased array antennas and on Single Access (SA) high gain steerable antennas. The Element includes two ground stations to provide global coverage and leverages the terrestrial internet for its ground communications capabilities.

Lunar Relay Element

The Lunar Relay (LR) Element architecture begins with the Robotic Lunar Exploration Program (RLEP) and evolves to either a two satellite constellation that supports the Lunar Outpost at the Moon’s South Pole or a larger constellation to support “go anywhere” missions. All RLEP Lunar Relay satellites are developed according to a planned approach that evolves towards a flexible Lunar Relay architecture meeting Constellation Program requirements by the first human sortie mission. The Lunar Relay architecture includes small satellite concepts that allow the Constellation Program to benefit from multiple deployment options, including launching as a secondary payload or stacking on a dedicated launch vehicle. The Lunar Relay satellites supporting the Constellation Program are equipped with onboard network routing that meet the requirements of the Constellation Command, Control, Communications, and Information (C3I) Interoperability Specification.

Mars Relay Element

The Mars Relay (MR) Element provides an early communication capability by “piggybacking” relay communications payloads on Science orbiters and implementing a store-and-forward capability for communication with surface and orbital users. The longer term architecture uses dedicated relay satellites with technology and system capabilities evolved from the early Mars Relay and Lunar Relay Element designs. The Mars Relay Element uses software defined radio technology for flexible and upgradeable communications.

Technologies Supporting the SCA

Technology development to enable the future SCA needs includes transformational as well as evolutionary products. The SCAWG recommends strategic investments in the following six technology areas to provide opportunities that will enable more capable C&N: Uplink arraying, Optical communications, Spacecraft RF technology, X-ray navigation, Network technology, and Programmable communications systems (Software Defined Radio). Of these six, X-ray navigation represents a truly original capability for autonomous onboard navigation throughout the solar system. Network technology extends terrestrial networking capabilities into space. The other areas enhance the performance of traditional communications technologies.

1. Top Level Architecture

The top level NASA space C&N architecture presented in this document has been developed by the SCAWG to address all known NASA Exploration, Science and Operations space mission needs through the 2030 time period. The SCAWG was chartered by the NASA Space Communications Coordination and Integration Board (SCCIB) as an agency-wide forum of space communication users and providers and was charged with the responsibility of determining the best value architecture that will enable NASA's future space missions to be provided with two of the most basic services required for space flight: communications and navigation.

> *Architecture* is defined as the elements of a system, the interactions among them, and the guidelines and principles that should be used to govern their development and evolution to provide a particular capability.
>
> DOD Integrated Architecture Panel, 1995,
> based on IEEE STD 610.12, 1990

The C&N architecture presents the recommended long-term target architecture that should evolve from the current capability. Although evolution from the present architecture to the goal architecture presented in this document has been a consideration during its development, a more detailed evolution plan, in five year increments, will be developed by the SCAWG once Agency-level approval of the architecture has been obtained.

As the emerging NASA exploration and science program visions mature it is clear that the present space communication infrastructure will not be adequate to meet future needs. Some of the critical considerations that need to be addressed as new architecture concepts are developed are:

- Projections of remaining spacecraft life for TDRSS indicate that replenishment satellites are needed in the 2015 timeframe.
- The large aperture antennas of the DSN are aging, becoming costly to maintain and will need replacement beginning in the 2015 timeframe.
- If the lunar exploration program includes operations in areas of the moon that are not in line of site of Earth-based antennas, there is no lunar relay capability today to handle lunar communications.

Therefore, the architecture described in this report includes correcting these deficiencies while continuing to serve the needs of NASA's diverse set of missions.

1.1. Overview of the Top Level Architecture

The architecture encompasses all systems that contribute to providing NASA space C&N services. NASA's space Exploration, Science and Operations missions anticipated over the next 25 years will operate throughout the solar system with concentrated activity in Earth orbit, the lunar vicinity, and the Martian vicinity. A basic Mission Model for this time period was developed and is described in Appendix E.

The top level space C&N architecture (depicted in Figure 2) will be composed of elements that will provide the necessary end-to-end data C&N services to user spacecraft operating in the regions of concentrated activity as well as individual missions operating anywhere in the solar system. The physical elements of the space C&N infrastructure that support science and exploration user spacecraft in the various regions are:

- Earth vicinity:
  - Ground-based Earth Element
  - Near-Earth Relay Element
- Lunar vicinity:
  - Lunar Relay Element
  - Ground-based Earth Element
- Mars vicinity:
  - Mars Relay Element
  - Ground-based Earth Element
- Spacecraft operations throughout the solar system (but not in the Earth, Moon, or Mars vicinity)
  - Ground-based Earth Element

The elements are connected in a network of networks that provide seamless C&N services to missions.

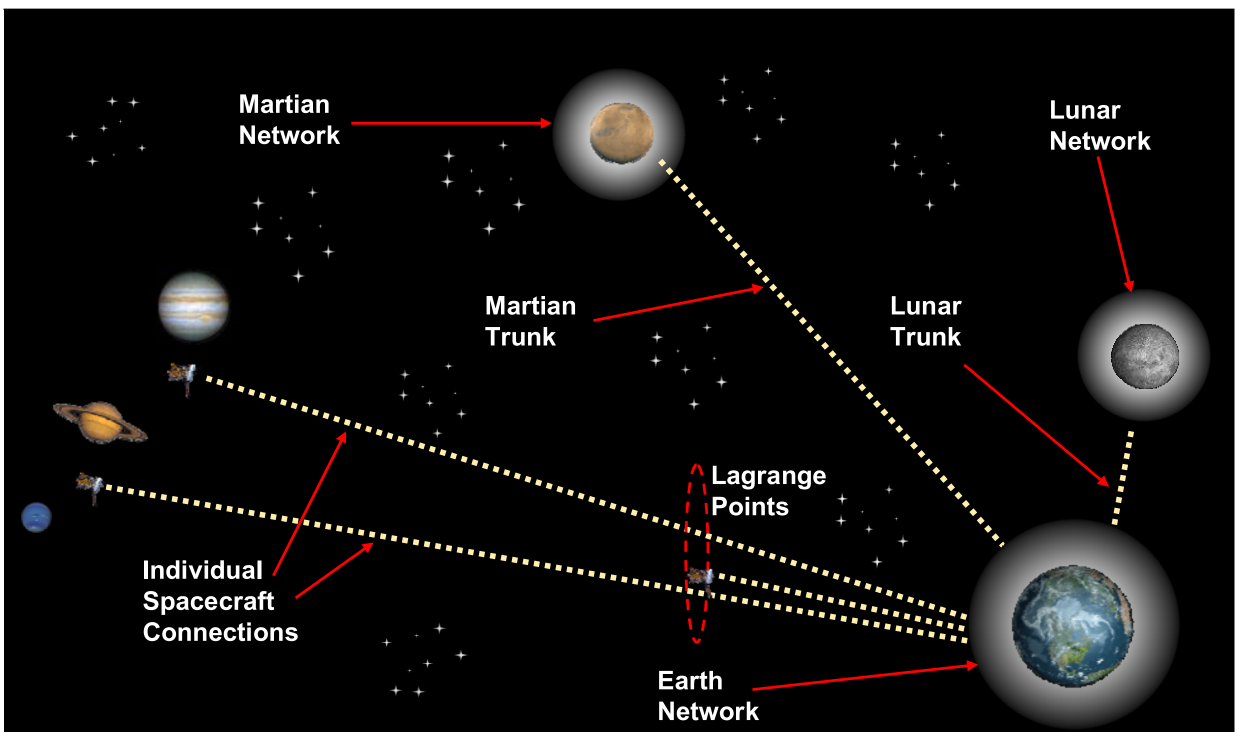

Figure 2. Space Communications Architecture ~2030: A Network of Networks

1.1.1. Earth Vicinity C&N

Exploration and Science missions between GEO and the Earth's surface are supported by a combination of the GEE and NER Elements. The NER element provides C&N services for users from the surface of the Earth up to GEO altitudes. It provides the means for global continuous connectivity for those users needing such services. GEE antennas are configured to provide C&N services for users operating in specific regions such as beyond GEO, Earth polar orbits, or near launch pads. For spacecraft departing the Earth vicinity NER satellites provide communication and radiometric tracking services up to ~30,000 km. Above that altitude GEE antennas provide continuous communication and tracking services as shown in Figure 3.

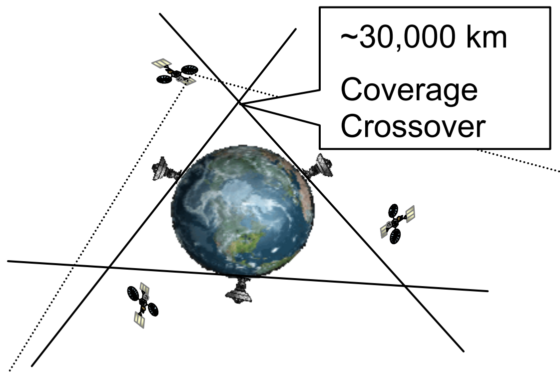

Figure 3. Earth Vicinity Communications Coverage

1.1.2. Lunar Vicinity C&N

Exploration and Science missions operating in the lunar vicinity receive C&N services from a combination of the GEE and the LR Elements. The GEE antennas provide services to spacecraft operating in Lunar orbit when they are visible from Earth and to lunar surface Exploration and Science spacecraft operating on the lunar surface on the Earth-facing side of the Moon and in line of sight of the antenna. Spacecraft operating on the lunar surface or in lunar orbit on the far side of the Moon, or in any region of the Moon not visible from Earth, are supported by the LR Element. The LR Element also supplements the GEE in support of operations conducted in the lunar vicinity and visible from Earth as an option available to mission operators.

1.1.3. Mars Vicinity C&N

Exploration and Science spacecraft operating in the Martian vicinity receive C&N services from the MR Element, providing user spacecraft with significant advantages over Direct-To-Earth (DTE) communications, in terms of performance and required user telecom system mass and power. The MR satellites can be supplemented with support from the GEE in some cases. The MR operates in a store and forward mode and provides communication relay services for Mars surface operations and orbiting users.

1.1.4. C&N for the Solar System and Beyond

Exploration and Science missions to locations in the solar system other than Earth, Moon, and Mars are supported as individual missions using the C&N support provided by the GEE.

1.2. Top Level Requirements

Table 1 contains a summary of the key requirements that drive NASA's architecture for space C&N.

Table 1. Top Level Architecture Driving Requirements

Architecture Driving Requirement	Source	Associated Milestone
Provide C&N services to all NASA Exploration and Science missions	Enabling capability to fly any space mission	Current to 2030
Support Earth-orbiting Exploration and Science spacecraft	Earth orbiters in future NASA Mission Model	Current Science & Human Space Flight 2012: Begin CEV Earth Orbit Checkout
Support Lunar-orbiting and surface Exploration and Science spacecraft	Lunar missions in future NASA Mission Model	~2018: Human lunar missions begin
Support Martian-orbiting and surface Exploration and Science spacecraft	Martian missions in future NASA Mission Model	Current to 2030 ~2030: First Human Exploration at Mars
Support missions to elsewhere in the solar system and beyond	Deep space missions in the Mission Model	Current to 2030

1.3. Functional Description

The space C&N architecture is designed to support two basic functions required for space flight: communications and navigation.

1.3.1. Communications Function

The architecture provides each user spacecraft, no matter where in the solar system it is operating, with a set of flexible end-to-end data communications services that support a full spectrum of user communications needs, including command and control, high and low rate data return, integrated audio and video, and emergency operations.

The C&N service channels are provided in specific RF spectrum areas that are defined as an RF spectrum framework for the architecture. This allows for two communications channels to be available to missions: a robust channel designed to provide assured TT&C services and a high rate mission data channel. Each mission may select whether and how it utilizes the two available channels. A user anywhere in the solar system has access to both the robust band for providing assured low rate communications and the high rate data transfer band.

A networking architecture that is composed of well defined layered services provides an open, flexible, and evolvable networked data communications services across all elements. This architecture enables mission selectable end-to-end communication options in accordance with established and evolving network policies that also govern the set of communication standards in use at any given time.

The use of programmable communication devices throughout the architecture is a key consideration in providing flexible and upgradeable network services. However, current technology constraints limit the use of these devices such that further technology development is necessary to extend their use.

The architecture provides a means for missions that determine there is a need to protect their data exchange with security provisions for authentication and confidentiality. This determination is made by the mission and can be applied at the spacecraft and associated control center ends of the communication links.

1.3.2. Navigation Function

All elements of the architecture provide radiometric tracking services to users. The GPS may also be employed to support Earth-orbiting users needing either high precision or autonomous orbit determination up to GEO. In addition, under the Space-Based Range (SBR) concept being jointly developed by NASA and DOD, GPS will be used by Launch Vehicles for real-time position determination.

For spacecraft operating beyond GEO, radiometric tracking is provided by the GEE. The LR and MR satellites also provide radiometric navigation aids to spacecraft operating in orbit or on the surface in their respective environments.

1.4. Architecture Options Considered

Numerous architecture alternatives have been considered in developing the space C&N architecture presented in this document. The architecture alternatives considered for each of the element and crosscutting architectures (spectrum, network, security, and navigation) are addressed in the sections of this document that describe those architectures. However, at the top level some basic alternatives were considered and are listed below for each of the areas of concentrated mission activity:

1.4.1. Earth Missions

Earth-orbiting user missions operate in all inclinations and eccentricities with some requiring continuous communication links, such as spacecraft carrying humans. The following alternatives were considered:

- Coverage of all Earth orbit missions with GEE antennas
- Supplement GEE antennas with NER satellites

1.4.2. Lunar Missions

User spacecraft traveling to the Moon operate in lunar orbit and on the lunar surface. Since some spacecraft operate out of line of sight of GEE antennas, spacecraft communication is relayed back to the Earth via the LR and GEE elements.

1.4.3. Mars Missions

Robotic and human exploration spacecraft operate in Mars orbit as well as on the Martian surface. The following architecture alternatives were considered:

- Provide coverage to all Mars users spacecraft from GEE antennas
- Supplement GEE antennas with MR satellites

1.5. Top Level Operations Concept

The SCA supports all phases of space flight for NASA's future Exploration and Science missions. The top level Concept of Operations (CONOPS) described below addresses how the elements of the architecture work together to support the various phases of space missions as a homogeneous C&N service network.

NASA's space flight missions fall into four general categories: Earth orbiting robotic and human missions; lunar robotic and human missions; Mars robotic and human missions; and robotic science missions to destinations in the solar system other than Earth, the Moon, and Mars. Spacecraft of each of these generic mission types are provided C&N services that support their flight phases of operation as well as their planning and development phases.

1.5.1. Mission Operational Flight Phases

The tables below depict the various flight phases that must be supported by the C&N architecture. Each mission type is treated separately: Earth orbit missions (Table 2), Lunar missions (Table 3), Mars missions (Table 4), and solar system science missions (

Table 5). GPS is included since it is a critical part of the navigation architecture, even though it is not considered part of the NASA infrastructure. All flight phases may not occur in a given mission; for example, a deep space mission may remain at its destination or may return to Earth as in a sample return mission.

The pre-launch phase consists largely of service management activities and coordination/verification of assets that will be used to support launch and early orbit activities. Post-flight activities may include such things as supporting the Crew Exploration Vehicle (CEV) at its landing site until recovery crews arrive.

In the tables below, there are numerous flight phases that require handover of the user from one C&N element to another. A critical feature of the network architecture is that the handover occurs in a seamless manner.

Table 2. C&N Support during Earth Orbit Mission Flight Phases

Earth Orbit Mission Flight Phases			Elements Providing C&N Functions				External Elements
Earth Vicinity	Transit	Destination Vicinity	GEE	NER	MR	LR	GPS
1) Pre Launch			X	X			
2) Launch			X	X			X
3) Early Orbit			X	X			X
4) Rendezvous				X			X
5) Earth Orbit Operations			X	X			X
6) Earth Re-entry				X			
7) Post Flight				X			X

Table 3. C&N Support during Lunar Mission Flight Phases

Lunar Mission Flight Phases			Elements Providing C&N Functions				External Elements
Earth Vicinity	Transit	Destination Vicinity	GEE	NER	MR	LR	GPS
1) Pre Launch			X	X			
2) Launch			X	X			X
3) Early Orbit			X	X			X
4) Rendezvous			X	X			X
	5) Trans-lunar Cruise		X				
		6) Orbit Insertion	X			X	
		7) Lunar Orbit	X			X	
		8) Lunar Descent & Landing	X			X	
		9) Surface Operations	X			X	
		10) Lunar Ascent & Rendezvous	X			X	
	11) Trans-Earth Cruise		X				
12) Earth Capture			X	X			X

Lunar Mission Flight Phases			Elements Providing C&N Functions				External Elements
13) Earth Re-entry				X			X
14) Post Flight				X			X

Table 4. C&N Support during Mars Mission Flight Phases

Mars Mission Flight Phases			Elements Providing C&N Functions				External Elements
Earth Vicinity	Transit	Destination Vicinity	GEE	NER	MR	LR	GPS
1) Pre-Launch			X	X			
2) Launch			X	X			X
3) Early Orbit			X	X			X
4) Rendezvous			X	X			X
	5) Trans-Mars Cruise		X				
		6) Orbit Insertion/ Aerobraking	X		X		
		7) Mars Orbit	X		X		
		8) Mars Descent & Landing	X		X		
		9) Surface Operations	X		X		
		10) Mars Ascent & Rendezvous	X		X		
	11) Trans-Earth Cruise		X				
12) Earth Capture			X	X			X
13) Earth Re-entry				X			X
14) Post Flight				X			X

Table 5. C&N Support during Solar System Science Mission Flight Phases

Solar System Science Mission Flight Phases			Elements Providing C&N Functions				External Elements
Earth Vicinity	Transit	Destination Vicinity	GEE	NER	MR	LR	GPS
1) Pre-Launch							
2) Launch			X	X			X
3) Early Orbit			X				
	4) Cruise		X				
		5) Science Observation	X				
	6) Trans-Earth Cruise		X				
7) Earth Capture			X				
8) Earth Return			X				
9) Post Flight							

1.6. Summary – Key Points of Top Level Architecture

The key points of the top level Space Communication Architecture are summarized here.

- The Architecture is composed of four physical elements:
  - Ground-based Earth Element (GEE);
  - Near-Earth Relay (NER) Element;
  - Lunar Relay (LR) Element; and,
  - Mars Relay (MR) Element.
- Crosscutting architectures overlay the element architectures.
  - The Spectrum Architecture allocates specific RF bands.
    - Two communication channels are provided to all NASA science and exploration users: a robust channel designed for TT&C and Voice, and a high rate communication channel designed for mission data.
  - The layered Networking Architecture is governed by a unified set of policies that:
    - Control a set of standards-based communication protocols, and
    - Govern the management of network operations.
  - The Security Architecture supports user-determined needs for communication protection including:
    - Confidentiality, and
    - Authentication.
  - The Navigation Architecture provides navigation services to users including:
    - Radiometric tracking for all NASA missions;

- GPS for Earth-based users below GEO that need precise location; and,
- A time distribution process for operations throughout the solar system.

- The architecture Concept of Operations covers all phases of flight for future NASA science and exploration missions and requires handoffs of user spacecraft from one element to another while providing interoperability among the elements to minimize the user's burden.

1.7. Future Studies

While the SCAWG completed a large number of studies over two years, much work remains to be done, both in addressing aspects of the architecture that have not yet been studied in detail and in extending the architecture to resolve issues uncovered during the analyses. Further studies are expected to be performed under the direction of the SCCIB. The key candidate studies that need to be addressed include the following:

- Integrated Planning and Scheduling: Since the SCAWG focused on primary cost drivers such as the quantity and complexity of space assets while working to define emerging requirements, a comprehensive concept of operations was not attempted. One opportunity for further simplification of NASA's architecture is the development of a unified approach for providing user missions with both long term planning support and near term/real-time operations scheduling support. Currently, NASA's space networks employ multiple tools in labor-intensive procedures that are costly and sub-optimize utilization of assets. The Constellation Program is already working with the Exploration C&N System (ECANS) to define a single interface to all networks as a means of simplifying the Constellation architecture. This topic is partially addressed in the sections on the GEE and NER architecture. This study would identify candidate architectures for unifying the set of network planning and scheduling mechanisms and analyze their costs and benefits leading to a recommended architecture and implementation approach.
- Network Services and Protocols Selection and Governance: Having defined the layers of the network architecture, specific services and the standards to implement them need to be selected forming the basis of a large study. In addition, the policies and mechanisms for governing these services and standards across the networks need to be defined. The governance process would need to provide the ability to work from current architectures and assess transition impacts in defining implementation options that meet mission requirements within budgets.
- Time Architecture: The SCAWG and SCCIB concluded that Time is a more fundamental and widely used function than the navigation-related focus in this report suggests. Consequently, Time would be promoted to a separate function equal to the Navigation and Communication functions. This would enable other timing requirements to be addressed including operations and mission-unique needs. Alternate means of maintaining and disseminating time would be studied including low cost/low accuracy and high cost/high accuracy options.

- Security Architecture Refinement: Aspects of the Security Architecture not addressed in this report would be studied in more depth including Key Management Infrastructure, details of implementing encryption standards, and mitigating threats other than the information and communication security threats studied to date.
- Precision Landing and Surface Navigation: For lunar missions out of Line Of Sight (LOS) of the Earth, Apollo-style navigation will be inadequate. Additional investigation would be performed on tradeoffs between autonomous vehicles, pre-positioned surface aids, and orbiting one-way and two-way aids for tracking and position determination.
- Space-Based Range: If decisions are made to pursue range modernization either to reduce Operations and Maintenance (O&M) costs or to achieve the Operationally Responsive Space (ORS) capability specified in National Security Presidential Directive (NSPD) 40, U.S. Space Transportation Policy, then there are likely to be significant impacts to the requirements and design of the GEE and NER elements. SBR requirements are still poorly understood both within NASA and the Air Force. This study would pursue additional definition of SBR requirements, architecture and implementation options, and the allocation of responsibilities between NASA and the Air Force.
- Lunar Communication for RLEP: As a result of a Lunar Robotic Architecture Study (LRAS) performed by ESMD in parallel with SCAWG studies, the RLEP strategy is being reassessed to identify better ways of using RLEP to reduce costs and mitigate risks of the Constellation Program. Lunar communication infrastructure plays a role in this; hence, a new lunar communication study would analyze alternate lunar relay configurations and options including technology risk reduction, space qualification of components, and pre-positioning infrastructure for Constellation missions.
- Array Antenna Refinement: SCAWG studies to date have focused on validating the antenna array concept, assumed requirements, and the relative cost of various array options. This study would perform additional analyses to assess impacts on implementation among the networks and recommend guidelines for determining where to use arrays vice monolithic antennas and recommend transition approach(es) to mitigate implementation risks.

1.8. SCAWG Study Methodology

The SCAWG defined a standard approach to performing architecture studies. Every study followed this basic approach with tailoring to meet specific needs of the individual study. The basic approach is described in this section. Modifications adopted for each study are described in the crosscutting and element architecture sections.

The SCAWG's objectives in defining a standard approach are to:

- Establish a process for producing high quality results that are sufficient to justify SCCIB decisions & document results for future reference;

- Establish a process that forces objective evaluation and prevents bias, e.g., omitting unpopular options, over-emphasizing pet options, subjective scoring, etc.; and,
- Establish a repeatable process that all SCAWG members can follow and the team can gain proficiency in execution.

The study methodology is broken into two components: the management approach and the technical approach.

1.8.1. Management Approach

The management approach discusses the elements of planning and managing execution of SCAWG studies.

A written study plan approved by the SCAWG is required for all studies. The purpose is to define a plan for evaluating candidate architectures and their performance constrained by explicit assumptions and requirements resulting in SCAWG recommendations supported by well documented results. The basic steps required for a study team leader to develop a study plan are:

- Work with management to define the study scope, deadline, ground rules and assumptions;
- Develop a draft plan following this standard study process;
- Identify resources needed and coordinate with appropriate Centers & managers to obtain them;
- Define a detailed schedule based on study approach and resource commitments;
- Execute the study according to the plan; and
- Present the plan to the SCAWG for approval. If necessary, present the plan to the SCCIB for approval.

As part of defining the scope and objectives of the study, identify all ground rules and assumptions imposed to constrain the breadth, depth and resources required for the study. At the discretion of the study team leader, determine whether to perform sensitivity analyses on any rules or assumptions to test the robustness of the results.

Staffing SCAWG studies is challenging for several reasons. Study team leaders are not allocated a study budget nor are they able to draw on the expertise of personnel from a typical line or matrix home organization. Also, organizations outside of NASA may be involved requiring additional coordination. The SCAWG budget is allocated to Centers as part of planning for the Program Operating Plan (POP) at which time details of which studies will be needed are not known. Consequently, as studies are identified, personnel with appropriate expertise must be identified and recruited from all stakeholder organizations. Several principles are established to ensure that the right type and level of participation is focused on the task:

- Identify all stakeholders who need to participate in study including: (a) NASA Directorates, Centers, Offices, Programs; (b) Partner agencies, academia, and industry.

- Solicit and/or negotiate for the best people in the relevant fields. Use the excitement & challenge of NASA's programs to stimulate contributions.
- Identify special skills and knowledge needed, e.g., specific information on Apollo or new technologies.
- Estimate resources required to meet objectives and schedule. Use SCAWG leverage to obtain resource commitments.

During the study, progress is periodically reported to the SCAWG to engage the stakeholders, keep the larger working group informed, resolve issues, confirm proposed direction, and track progress against the schedule. The SCAWG review is informal and consensus driven but it has proven to be effective in controlling quality and integrating results.

Study teams must integrate the final results into a written report for the SCAWG consistent with direction from the NASA Chief Engineer. Intermediate presentations to the SCAWG must be integrated into a comprehensive final report. The final report is briefed to the SCAWG as a minimum to get approval for study closure. Depending on the nature of the study and degree of interest by the SCCIB, some studies may be briefed to the SCCIB and require this higher level of approval. Study results are archived on the SCAWG web site.

1.8.2. Technical Approach

The technical approach discusses the technical elements necessary to perform high quality studies. The technical approach discusses the process for evaluating candidate architectures and designs constrained by assumptions and requirements. The result is a technical recommendation or a set of recommendations.

The following steps help define the technical approach:

1. Define requirements and concepts of operation. Requirements define the parameters that candidate architectures and design options must meet to be evaluated. The requirements may specify threshold (minimum acceptable) and objective (maximum desirable) performance levels. The CONOPS describes a future capability that envisions where, what, how and how much communications will be needed to serve all potential users and uses. CONOPS are essential to identify the most important factors or dimensions that bound the analysis space. Define scenarios as needed to describe more specific operational sequences at a lower level of detail.
2. Tailor Figures of Merit (FOM) for the study. Each study develops an appropriate set of FOMs based on the general SCAWG FOMs. The FOM set captures characteristics that can be used to measure the relative effectiveness of alternatives with criteria such as user burden, robustness, evolvability, complexity, failure tolerance, and capacity. A metric or assessment method is developed for every FOM and each FOM is then applied to all of the selected alternatives to generate a matrix of scores versus alternatives. As part of the FOM development, the team identifies the extent to which risks are addressed as part of the FOMs.
3. Define architecture classes and/or candidate design options. The selection of alternatives to be studied and evaluated should be broad enough to span the trade

space but limited enough in number to keep the study from becoming unmanageable. Design and technical risks should be identified for each option and outside input (industry, academia, etc.) should be solicited where necessary to increase the realism and confidence in the approach.

4. Develop performance models to generate raw FOM scores. Where possible, analytical models should be created for the architecture alternatives that assist in generating quantitative FOM scores. An example might be a Satellite Tool Kit scenario developed for each lunar relay orbit constellation alternative from which the FOM for surface coverage can be calculated. When FOMs are defined in qualitative or semi-quantitative terms, an assessment procedure is defined in lieu of a model.
5. Develop cost models using Continuous Cost Risk Methodology (CCRM). Coordinate with the Headquarters (HQ) cost team to ensure that the study's cost approach is consistent with other studies. Determine whether models are to be based on full or partial Work Breakdown Structures (WBS) and if they cover full or partial system life cycle. Partial models are considered suitable for comparing alternatives, whereas full models can be used for budgeting. Costing tools such as ACEIT and NAFCOM are used for standardized Cost Estimating Relationships (CER) based on historical data. Risks are incorporated where possible and cost estimates are normalized to the 70% risk confidence level.
6. Normalize FOM scores, weight results and compare with cost. The results of the performance models should be integrated into a set of raw FOM scores which can then be normalized into a standardized range, typically a 0-100 point scale. For each architecture alternative, a composite score is calculated and used with cost to create a cost-benefit diagram.
7. Develop study conclusions based on results of the FOM scores and cost-benefit results. The conclusions should be facts based directly on study analyses.
8. Develop study recommendations based on the conclusions and the expertise of the team in context with other SCAWG C&N architecture recommendations.

2. Element and User Relationships in the Architecture

This section describes those aspects of the SCA that are common to all of the physical elements whether on or near Earth, around the Moon or Mars, or extending across the solar system. These portions of the architecture are shared across the layers of the communication network of networks. Since the extension of terrestrial networking concepts into space is central to the recommended architecture, the Networking Architecture is discussed first. In terms of the layers of network protocols, this is starting in the middle of the protocol stack. From the middle, the discussion drives down to the underlying but integral Security Architecture followed by the Spectrum Architecture at the physical layer. Finally, this section discusses the Navigation Architecture in terms of the navigation, tracking, and time dissemination capabilities common to all elements.

2.1. Networking Architecture

The Networking Architecture presents a long term (25-40 year) vision and strategy for the evolution of NASA's space communications systems, conceptually towards eventual provision of ubiquitous end-to-end user connectivity across the entire solar system. To accomplish this, the Network Architecture absorbs evolving terrestrial Internet technologies within its ground segment and extends them into and across space. In common with the terrestrial Internet, the underpinning of the Networking Architecture is a set of standard, low cost, layered data communications services.

2.1.1. Overview of the Networking Architecture

The progressive and evolutionary build-up of standard infrastructure is a fundamental architectural tenet: It recommends that NASA progressively invest in ground and flight data handling system designs that are engineered to be re-usable and that, over time, accrete into an "Interplanetary Internet" which spans the solar system in support of our missions of Science and Exploration.

The Networking Architecture supports the full lifecycle of a space mission. It benefits mission planning by stimulating opportunities for interoperability with different organizations and by being easily scalable (up and down) to meet variable mission loading. It benefits the development, test and launch phases by reducing costs via re-use of common hardware and software infrastructure. It benefits the mission operations phase by enabling increased automation and security, by fostering the use of standard commercial products, and by reducing the need for unnecessary redundancy and labor-intensive planning. It benefits its operational users by providing access to familiar network-based applications using robust and reliable communications services (even when intermediate nodes are not available).

The Networking Architecture is built upon the Space Communications Architecture's Security (Section 2.2) and Spectrum Architecture (Section 2.3). The Spectrum Architecture establishes the spectrum bands that will be used when implementing individual point to point data communication "hops" between space systems. Such *hops* are components of the end to end space data communications network – spanning both

Earth and space assets – that interconnects space mission user applications. The Networking Architecture also defines how the overall network containing those hops is structured in the context of the Security Architecture which establishes how the information transiting that network is to be protected. Security services can be implemented at multiple points in the Networking Architecture.

2.1.2. Driving Requirements on the Networking Architecture

The Networking Architecture is driven by a set of top-level requirements either taken from existing requirements documents or assumed as a result of analysis of the integrated mission set. The key requirements driving the networking architecture are:

- Provide multi-mission data communication services for:
  - Legacy missions
  - New Science missions
  - New Exploration missions
- Support IP routing and internet applications for space and ground elements
- Provide data communication service "on-ramps" for future government and, potentially, commercial service providers
- Accommodate both scheduled and unscheduled communications
- Accommodate both continuous and intermittent connectivity
- Provide service over space data links characterized by:
  - Both large and small signal propagation latencies
  - Both uni-directionality and bi-directionality
  - Both low and high bit error rates
- Support data flows that:
  - Originate at arbitrary user locations on Earth and in space
  - Terminate at arbitrary user locations or sets of user locations (i.e., multi-point delivery) on Earth and in space
  - Traverse N-hop transmission paths where N $\geq$ 1
- Support transmission of the following types of data:
  - Command
  - Telemetry
  - Files (including web pages)
  - Messages (e.g., electronic mail)
  - Voice
  - Video
  - Range safety
- Provide the following qualities of data communication service (not necessarily in all combinations):
  - Isochrony
  - Reliability
  - Transmission order preservation
  - Timeliness
  - Priority

- Provide data communication performance metrics and accountability

2.1.3. Scope of the Space Communications Network

NASA's Space Communications Network logically interconnects end users via a series of physical layer "hops" or transmissions, as shown in Figure 4.

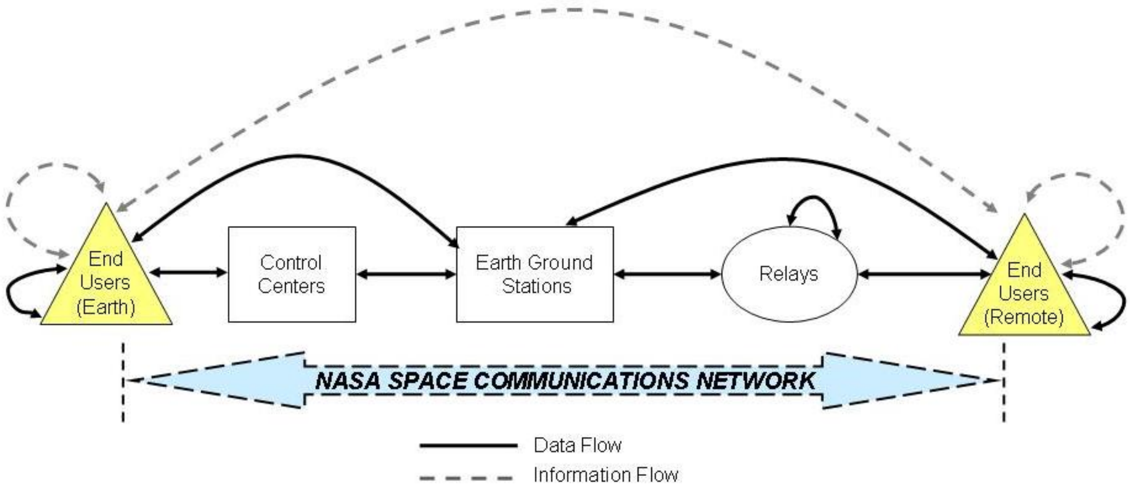

Figure 4. Network Connects End Users via Physical Layer "Hops"

The individual hops connect adjacent elements of the architecture and feature:

- Terrestrial links connecting users to control centers, users to ground stations, or control centers to ground stations.
- In-space links connecting ground stations to remote user vehicles, ground stations to relays, relays to relays, relays to remote user vehicles, remote vehicles to remote vehicles, or interconnecting end systems within remote vehicles.

Information exchange between users flows logically (dashed lines) from source to destination independent of the underlying network structure. This flow is either wholly on Earth, between Earth and space, or wholly in-space. Although most transfers are between a single source and a single destination, the architecture supports point-to-multipoint (single source, multiple destinations) delivery where required.

2.1.4. Layered Service Architecture

In accordance with modern practices, user information exchange within the Networking Architecture is achieved by drawing upon a stack of "layered" services (Figure 5). Within a layered architecture, peer functions that exchange information across a data communications path are organized so that they provide a standard service to the layer above and draw upon standard service(s) from the layer below. As long as the service interfaces are preserved, an individual layer can be easily replaced as technology and mission requirements evolve.

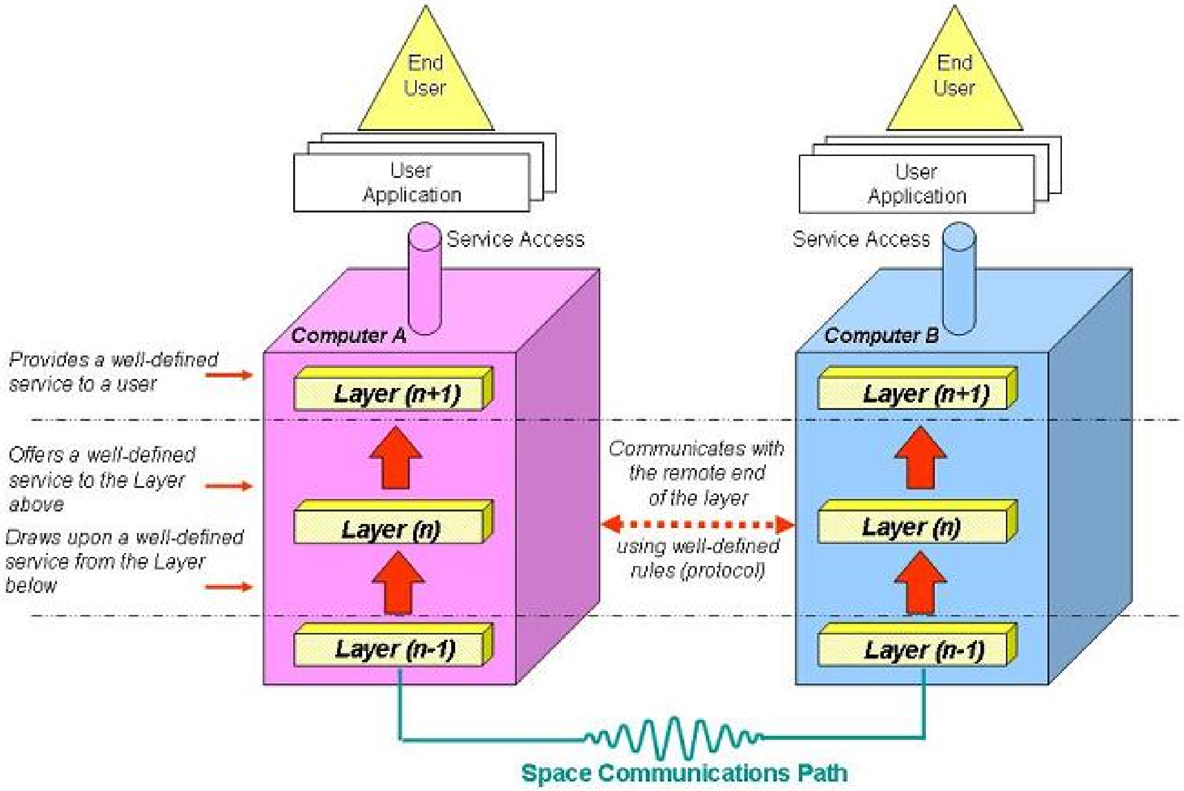

Figure 5. Networking Architecture: A Stack of Layered Services

Peer functions at the sending and receiving ends of a layer exchange information across the network using a standardized dialog known as a data communications protocol. The protocol is represented by the "bits on the wire" and it is the standardized mechanism by which senders and receivers in different organizations achieve interoperability.

> *Interoperability* is defined as the ability of two or more systems or components to exchange information and to use the information that has been exchanged.[1]

Some of the service layers may reside in the user end systems and some may reside in the supporting mission-independent communications systems. The Networking Architecture encompasses all layers independent of the implementing organization.

2.1.5. Exposed Services

The service layers within the Networking Architecture are constructed as a "staircase" (Figure 6), with multiple service access points exposed that allow users to "reach down" to lower layers if higher layers are not needed.

[1] Institute of Electrical and Electronics Engineers. IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries. New York, NY: 1990.

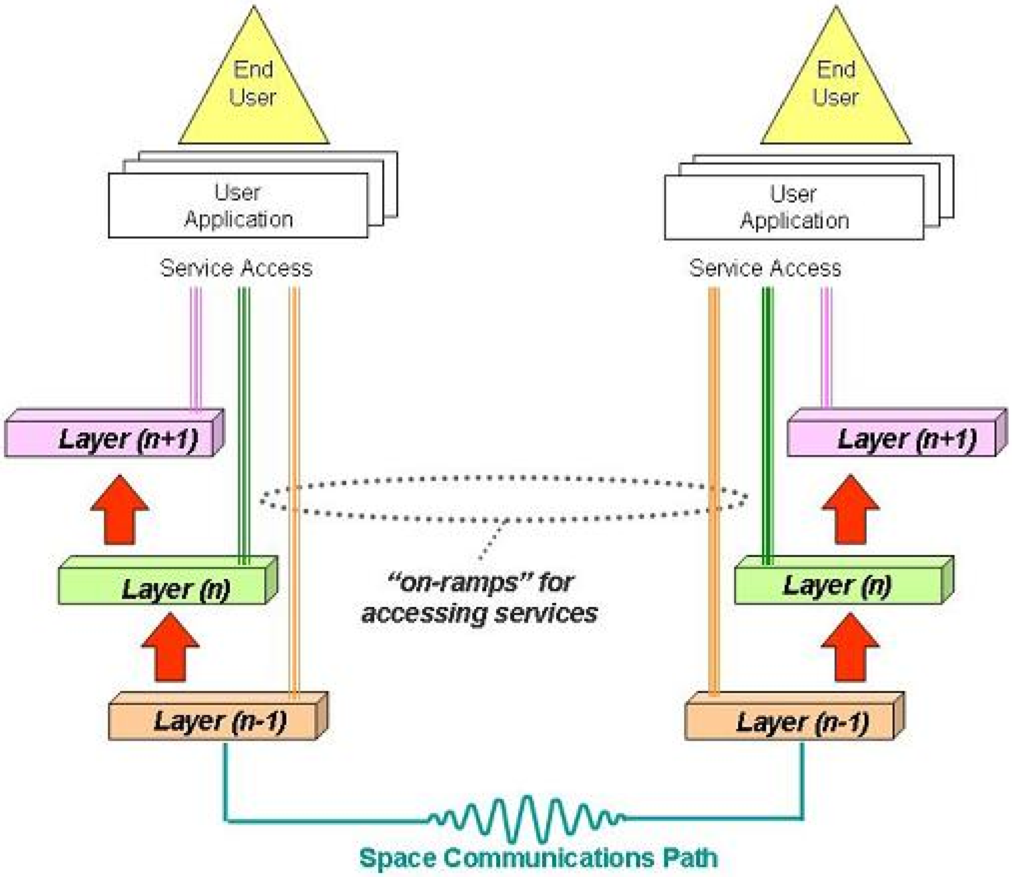

Figure 6. Service Access Points in the Network

"On-ramps" are provided so that users can reach-down as needed to access the services of lower layers if they don't need the service of a higher layer. This enables several key capabilities:

- Basic emergency commanding can be done by bypassing all but the most rudimentary communications services;
- Legacy systems, which do not necessarily conform to all the standard service layers, may be accommodated; and,
- Different organizations (e.g., future commercial providers) may "drop in" their services as a confederated contribution to the overall end-to-end network.

2.1.6. Definition of Networking Layers

The Networking Architecture follows international standard service layering conventions as embodied in the well-known Open Systems Interconnection (OSI) model, including its terrestrial Internet derivative which reduces the OSI model to five layers:

- *Application Services* reside in the *Application* layer and provide common utilities in support of familiar user applications (File Transfer, Messaging, Web browsing, audio and video formatting, etc.). The Application Services (which are part of the infrastructure) sit directly below the user applications (which are provided by missions).

- *Transport* layer services support user-selectable levels of end-to-end data transfer reliability.
- *Network* layer services automatically route data between user applications.
- *Link* layer services support structured data transfer through a single point-to-point hop.
- *Physical* layer services support unstructured symbol transfer through a single point-to-point hop.

The relationship between these layers when two end systems are separated by a single space link hop is shown in Figure 7.

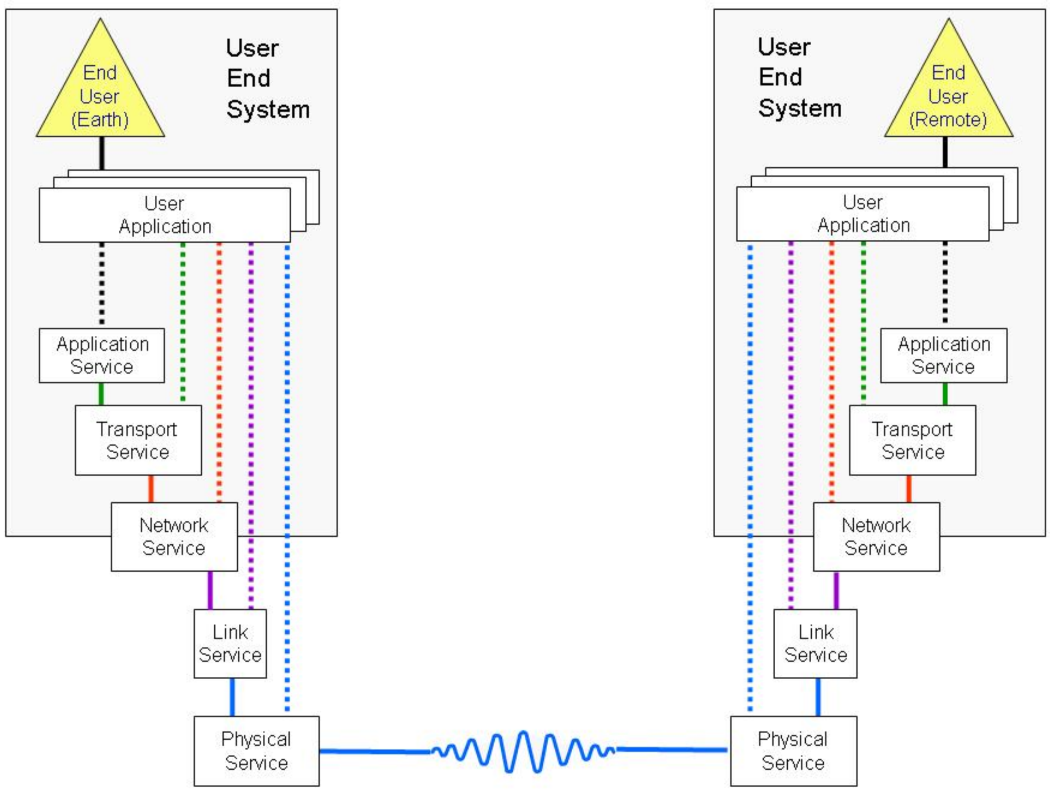

Figure 7. Definition of Networking Services

The network comprises all of the devices that may participate in the transmission of data between two users of NASA's end-to-end data communications infrastructure. The *Application service* and *Transport service* are hosted within the user end systems, yet they are still part of the end-to-end Networking Architecture. These are *network utilities* that are provided to users. The *Networking Architecture* therefore embraces the spacecraft and the supporting ground networks, including control centers. The Network, Link and Physical services are implemented as part of an underlying *"core"* of multi-mission service infrastructure. How these abstract networking services are allocated to physical mission elements varies. One example is shown in Figure 8.

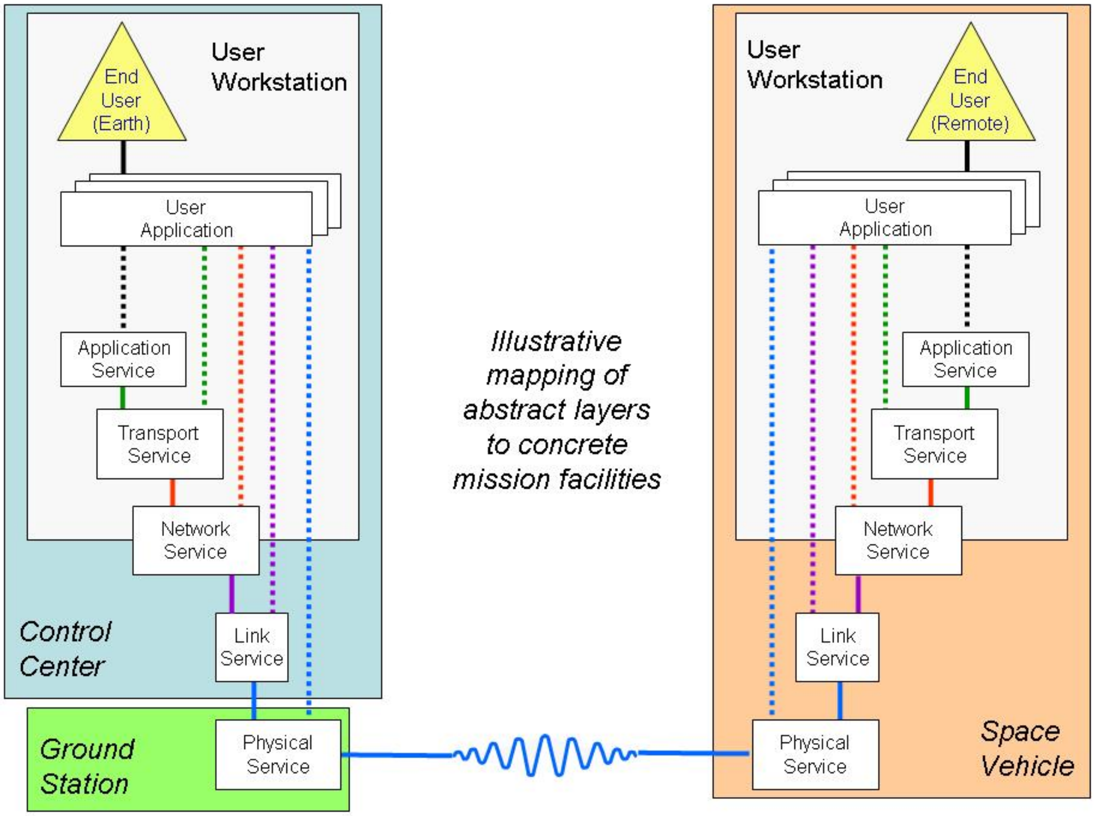

Figure 8. Example of Networking Services Allocated to Physical Elements

In some current and many future mission configurations, end-to-end data transfer may involve multiple hops, with core services embedded within in-space relays. Figure 9 shows how layered services may be configured in a simple two-hop intermediate space relay data flow.

The Physical and Link services can only be provided across a single hop. If it is desired to bridge either of them across the inbound and outbound sides of a relay so that they tunnel transparently through the relay, then a relay application must be provided for this purpose. This application may operate either in real-time or in a store-and-forward mode. Unless all inbound and outbound links are engineered to be homogeneous, this relay application may be complex.

The Network service, by its layering, is inherently independent of the underlying heterogeneous Link and Physical layers. It is relatively easy to standardize and as such it may be readily located at key hops in the end-to-end path, such as in-space relays.

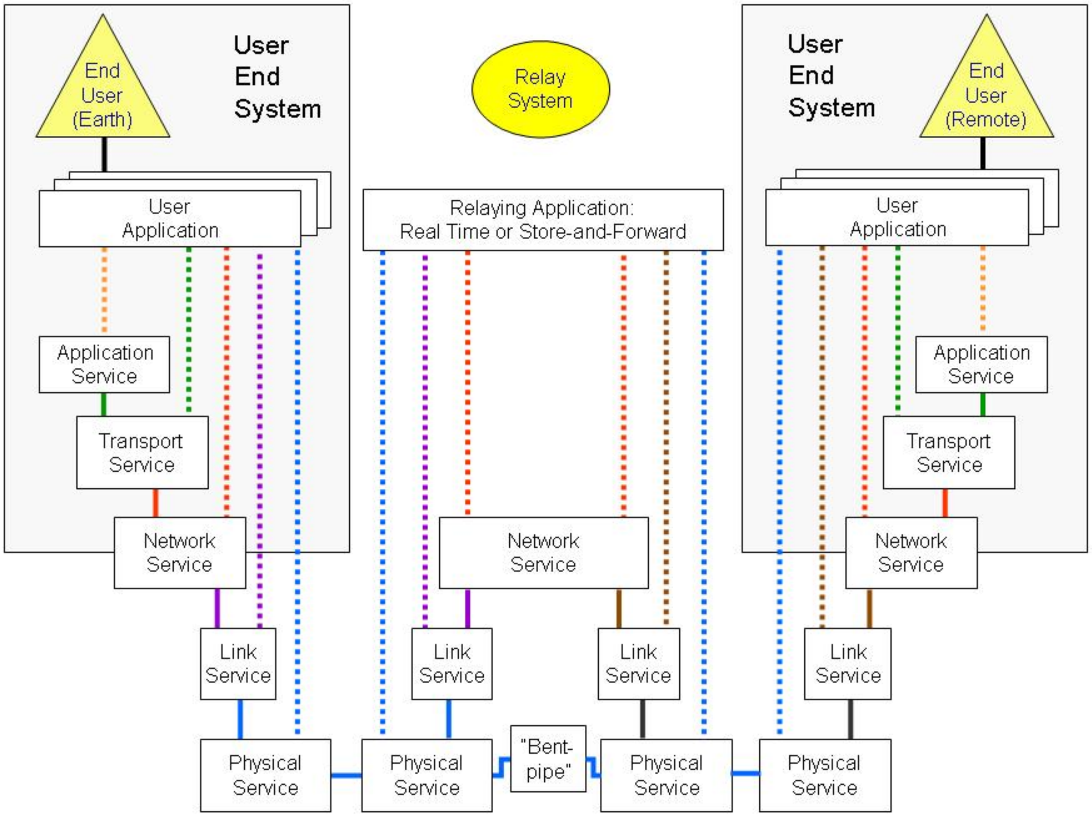

Figure 9. Layered Services in a Two-Hop Intermediate Space Relay Data Flow

In such a relay architecture, data protection via "bulk encryption" of the channel is usually only feasible if the in-space relay simply transponds (via a "bent-pipe") the physical symbol stream in real time between its input and output sides. Such a scheme is currently implemented by legacy systems such as Space Shuttle and the ISS, which use the TDRSS in pure bent-pipe mode. To implement a Link or Network relay using such a data protection scheme, the Physical layer encryption(s) must be locally terminated. The Security Architecture allows bulk encryption of the channel for future systems, however, this is operationally complex.

2.1.7. Service Management

The collective activities of communication service *users* and *providers* to identify, negotiate, reserve, configure, monitor, control, and account for the use of those communication services is called Service Management (SM). The SM Architecture presents all elements of the network infrastructure to users in terms of standard communication services and allows management of those services in a standard way. Figure 10 shows a simple example that illustrates the exercise of SM for a spaceflight mission that is responsible for configuring the local area network in the mission control center as well as the entire onboard local area network and the spacecraft's communications terminal. In the example, a Mission Management entity interacts with Domain-Internal SM in both the control center and the spacecraft and also with a Space

Communications SM entity, which uses its own Domain-Internal SM function to configure the intermediate provision of communications across the space link.

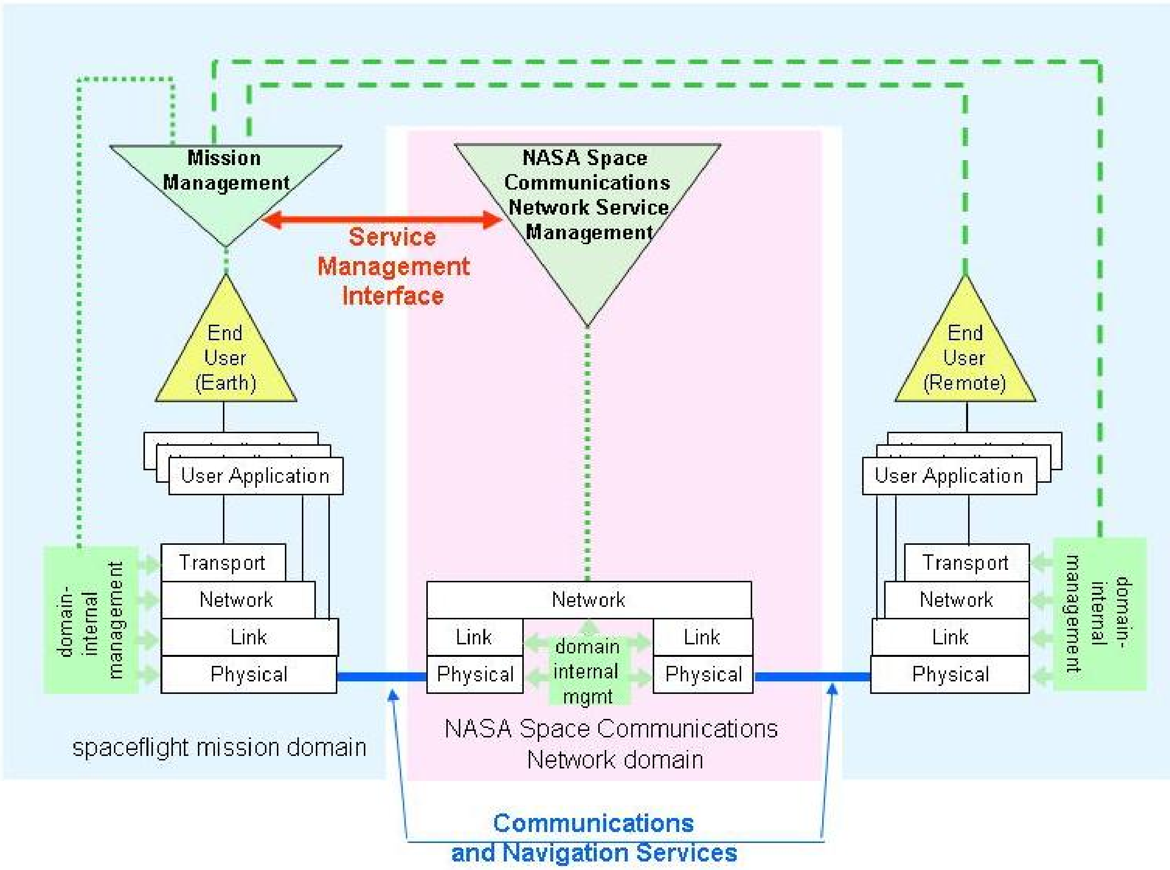

Figure 10. Service Management Interactions

SM manages various combinations of communication service layers, rather than a single monolithic "stack" of services. This feature accommodates the various combinations of network *administrative domains* envisioned in the future. For example, some administrative domains may represent networks that offer only Physical layer services; some may represent networks that offer Physical layer through Network layer services; and some may represent value-added entities that overlay network services on links acquired from other domains. The SM framework supports such combinations in a uniform and consistent way. It also follows international standards to facilitate automation and interoperability with networks across the world space community.

2.1.8. Network Interoperability and Standardization Policy

Only rarely does a particular mission "own" the entire end-to-end data flow. More typically, multiple organizations may confederate their individual services to support the mission and these organizations may be housed in different NASA Centers, different US partner agencies, different international partner agencies, or in private commercial organizations.

Standards enable interoperability among different organizations, and support interoperable standardized security in such configurations. For each layer of service within the Networking Architecture where interoperability is required across organizational boundaries, a standard (or a related family of standards) are specified. Therefore, policies are established in association with the Networking Architecture to select standards according to the desired level of secure interoperability. Those policies reflect that standards are not static. As requirements and technology change, the selected standards (and the standardized space communications infrastructure that uses them) evolves as a controlled end-to-end architecture.

Standards can be classified into three types:

- Voluntary consensus standards require that owners of relevant intellectual property have agreed to make that intellectual property available on a non-discriminatory, royalty-free or reasonable royalty basis to all interested parties (OMB Circular A-119).
- Government unique standards usually do not have intellectual property restrictions but are not formulated by a voluntary consensus body, and thus may not have widespread acceptance.
- Proprietary standards usually require license agreements or royalty payments and therefore may inhibit open procurement.

Standards may be agreed upon privately, domestically (e.g., nationally), or internationally. In accordance with the Vision for Space Exploration to "promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests", international voluntary consensus standards are recommended over national standards (where possible) to enable international interoperability. In accordance with NASA Policy Directive 8070.6B, standards for the Networking Architecture are selected according to the following order of preference:

1. International voluntary consensus standards;
2. Domestic voluntary consensus standards;
3. NASA or other US Government standards;
4. Program-specific or proprietary standards.

NASA investment is provided to develop flight and ground tools that make it easy for a mission to interface with and use the standard service. A mission that wishes to utilize a particular service must demonstrate conformance to the relevant published interface standard or seek a waiver from the policy organization that steers the provider of that service.

2.1.9. Network Architecture Alternatives

The Networking Architecture considered five different options for where best to standardize the service infrastructure:

1. At the Physical Layer (Bit/Symbol stream services only).
2. Up to the Link Layer, with access to a standard Physical layer.
3. Up to the Network Layer, with access to standard Link and Physical layers.

4. Up to the Transport Layer, with access to standard Network, Link and Physical layers.
5. Up to the Application Layer, with access to standard Transport, Network, Link and Physical layers.

In conjunction with the alternatives for network layer standardization, a set of options were evaluated for service management interfaces. These alternatives are termed Service Management Interface Options (SMIOs):

1. Status quo (SMIO1): The "Status Quo" SMIO is based on maintaining the current state of SM interfaces within the NASA C&N domains.
2. Standard SM interfaces for new C&N services only (SMIO2): The "Standard SM for New C&N Services Only" SMIO is based on only upgrading to a standard SM interface for the new services while maintaining the current SM approach for all legacy services. Specifically, this option posits that a standard management interface be adopted for new C&N services provided across multiple constituent providers of the NASA Space Communications Network, but that providers offer custom SM interfaces to manage those services not included in the new standard service set. Thus, each user/provider pair interacts via a pair of SM interfaces.
3. Legacy users are grandfathered (SMIO3): The "Legacy Users Grandfathered" SMIO is based on upgrading to a common standard approach for all new users and providers while maintaining the legacy services for existing missions. Specifically, this option posits that a standard management interface covering all C&N services provided by the constituent providers of the NASA Space Communications Network be adopted, but that existing providers continue to offer their custom SM interfaces to existing users.
4. Globally-standard SM interfaces (SMIO4): The "Globally-Standard SM Interface" SMIO is based on transitioning to a new common SM approach. This option posits that a standard management interface covering all C&N services provided by the constituent providers of the NASA Space Communications Network be adopted, and that this standard interface replaces all existing custom SM interfaces of the constituent providers of the NASA Space Communications Network.

2.1.10. FOM Definition, Analysis, and Conclusions

The networking architecture was analyzed in two segments: standardizing at different layers and service management interfaces. The FOMs, analysis and results will be discussed separately for the two segments.

2.1.10.1. Standardizing at a Given Link Layer

The following FOM definitions were adopted to evaluate network layer standardization:

- **Operational Efficiency**: The proportion of mission operations activity that must be performed by humans over the entire mission lifecycle, regardless of location.
- **Robustness**: A compound FOM consisting of: (a) The ease with which additional elements can be added to a mission or mission set (scalability); (b) the ease with which new operational capabilities can be introduced into mission operations systems (evolvability); (c) the ease with which data paths through the network

can be changed in response to changing mission requirements (adaptability); (d) the proportion of the operational time in which the network operates without error (reliability); (e) the ease with which errors can be remedied (maintainability); and (f) the proportion of wall clock time in which the network operates (availability).

- **Infrastructure Capability**: (Communication Infrastructure Development and Maintenance Efficiency): The ease with which mission functionality is developed and maintained over the entire mission lifecycle, at vehicle end user terminals (spacecraft, aircraft, etc.); at ground stations and relay points; and Earth end user terminals (control centers, science centers, test facilities).
- **Ease of Transition**: The ease with which the option can be implemented within NASA, including the acquisition of new equipment, development of new technology, and training of mission operators.
- **Interoperability**: The ease with which users are able to complete all negotiations required to achieve successful and secure communication of mission information among both NASA and non-NASA assets and facilities.
- **Resource Utilization**: Total value of user data delivered, given fixed resources. These resources include link utilization, available memory, available power, visibility windows, and launch mass.

The Operational Efficiency and Infrastructure Capability FOMs were scored based entirely on requirements. Half of the Robustness FOM factors were scored based on requirements. The Ease of Transition, Interoperability, and Resource Capacity plus half of the Robustness FOM factors were scored based on team consensus.

The scores were totaled and normalized against the scores of other options on a scale of 1-10. The Robustness FOM was normalized on a scale of 1-5 for the requirements half of its score, and separately normalized on a scale of 1-5 for the consensus half of its score; still yielding a total scale of 10. Table 6 presents the FOM weighting, with a multiplier of 6 utilized in the scoring analysis. The driving factor was identified in determining the relative weights among the FOMs.

Table 6. Figure of Merit Weighting

Figure of Merit	% Weight	Weight (6x %)	Driven By
Operational Efficiency	23%	1.38	Long-term impact on operational costs
Robustness	28%	1.68	Mission safety
Interoperability	19%	1.14	Long-term costs
Infrastructure Capability	14%	0.84	Ability to offload operational costs from individual missions
Resource Capability	10%	0.60	Short-term development costs
Ease of Transition	6%	0.36	Short-term development costs

Table 7 presents the un-weighted and weighted scoring per architecture option. In most cases, the Application Layer option received the highest scoring. In general, this option has the greatest communication capabilities. The Application Layer capabilities can be exploited to reduce long-term operational costs and increase mission flexibility. With this option, individual missions would not need to implement the following capabilities: data routing, multiplexing, scheduled communications, unscheduled communications, reliability, end-to-end transmission order preservation, timeliness, and traffic prioritization. The disadvantage of standardizing at the Application Layer is the more difficult Ease of Transition. With greater capabilities, the option would require increased infrastructure staff training and implementation hardware. However, as standardization moves down the protocol stack, there would be increased responsibility for the mission to implement its own communication features. Furthermore, all higher-level resource optimizations for link utilization and visibility windows require mission-specific implementations.

Table 7. Weighted and Un-weighted Figure of Merit Scores

FOM	Weight	Score Type	Physical	Link	Network	Transport	Application
Operational Efficiency	1.38	Requirements	3	4	7	8	10
Robustness	1.68	Consensus & Requirements	3	4	9	9	10
Interoperability	1.14	Consensus	4	5	9	8	10
Infrastructure Capability	0.84	Requirements	3	4	7	8	10
Resource Capacity	0.60	Consensus	1	6	7	9	10
Ease of Transition	0.36	Consensus	9	10	7	6	4
Un-weighted Scores			**23**	**33**	**46**	**48**	**54**
Weighted Scores	**6**		**18**	**28**	**47**	**50**	**58**

A Networking Architecture based on a Link Layer Service would require minimal operational changes, since this is the status quo. In addition, moving up the protocol stack, the scoring decreases for the Ease of Transition FOM. This is based on increased implementation equipment costs and staff training. However, over the lifecycle of the mission, transition costs are expected to have a small impact as compared to the operational lifecycle costs.

2.1.10.2. SM Interface

The SM FOMs that impact providers and users are defined as:

- **Transition:** Transition describes the impact each of the SMIOs would have on NASA C&N networks and users of those networks. The main component of transition is the relative effort required to design new custom interfaces (when a standard does not exist) and to implement the new SM interface (either custom or standard). The effort required to develop the standard is not included—this must be factored into the complete trade-off.

- **Operational Complexity:** Complexity is measured in terms of the number of different SM interfaces that have to be maintained by each provider or user. The number of interfaces with each user/provider includes the total number of interfaces and the total number of pairwise differing interfaces.
- **Robustness:** Robustness is the ability of the SM interface to accommodate operational changes, expand capacity, and accommodate design changes to enhance system capabilities, with minimal HW or SW redesign.
- **Interoperability:** Interoperability is the ability for a service provider to support users other than its community of primary users, and for a service user to be able to obtain support from a provider other than its primary provider. For NASA service providers, interoperability with various classes of users and for the various SMIOs is considered. Users include NASA spaceflight missions, other USG spaceflight missions, and international spaceflight missions. For various classes of users, how interoperability with other NASA and external service providers and for the various SMIOs is considered. External service providers include other USG TT&C networks, international agencies' networks, and commercial TT&C networks that implement a standard SM interface.

For each FOM, the relative burden or benefit (as appropriate) of each SMIO was evaluated for each of the categories of participants. For each SMIO/participant category pair, a numerical score has been assigned, based on FOM-specific criteria. The scores for all of the evaluations under the FOM were normalized to a scale of 100. Thus, the normalized score of each SMIO/participant category pair is the percentage of the total value of the FOM represented by that SMIO/participant category pair. The higher the normalized score; the greater the benefit (or the lesser the burden). For each participant category (represented by a row in the table), the results are color-coded: green text indicates the highest score (greatest benefit/least burden) in the row, red text indicates the lowest score (least benefit/greatest burden), and black text indicates intermediate values. Multiple SMIOs may have the same highest or lowest score, thus, more than one entry may be colored green or red.

Each existing NASA C&N service provider currently provides some set of services ("legacy C&N services"). Also, each existing NASA C&N service provider currently has a management interface and set of management services. These management services/interfaces are assumed to be unique to the provider ("custom SM services/interfaces"). Each existing NASA C&N service provider can be expected to add new C&N services in the future, at least some of which will require additional SM services or new/different parameters for existing SM services. For example, additional capabilities to provide information are needed to configure Space Link Extension (SLE), IP, or CCSDS File Delivery Protocol (CFDP) front-ends to TT&C services. The SM interfaces will evolve, so consider was given to whether these should be allowed to evolve in a common way, or with each custom approach.

An assumption that underlies all of these FOMs is that changes to existing SM interfaces will be required whether or not those interfaces migrate to a standard. Thus, having SM interfaces for existing NASA providers remain static is not an option. The issue is whether the necessary changes to SM interfaces will be addressed by an application of standards, or by continuing the current one-off approach.

Table 8 depicts a summary of the normalized scores for the various FOMs and provides the justification of the Networking Architecture team's recommendation of a standard SM interface. Assuming equal weighting of four parts between the new user community, the existing user community, the new providers, and the existing providers, SMIO3 provides the highest benefit.

The burden of implementing a standard SM interface would fall on only existing providers and users with the one-time burden of transitioning to the new interface. The transition impact on existing users (that is, users that use only the existing services of one existing provider will not need the services of any other existing or new providers) would be eliminated for existing users if SMIO3 were adopted instead of SMIO4. This can be traded off against the additional operational complexity to existing providers of operating the legacy custom interfaces as long as existing users require them. If the existing provider has higher weighting against the other communities, then it is necessary to evaluate the burden of transition against the benefits of increased robustness and interoperability.

Table 8. Summary of FOM-Based Trade Analysis for Service Management

SMIOs/ Benefit to Users & Providers	SMIO1 – Status Quo	SMIO2 – Standard SM for New C&N Services Only	SMIO3 – Legacy Users Grandfathered	SMIO4 – Globally-Standard SM Interfaces
Existing Provider Benefit	Transition: 6.8 Op Complexity: 7.5 Robustness: 0.0 Interoperability: 0.0	Transition: 8.1 Op Complexity: 4.4 Robustness: 3.3 Interoperability: 3.6	Transition: 6.8 Op Complexity: 6.2 Robustness: 8.3 Interoperability: 8.9	Transition: 6.8 Op Complexity: 7.5 Robustness: 8.3 Interoperability: 8.9
New Provider Benefit	Transition: 3.7 Op Complexity: 7.5 Robustness: 8.3 Interoperability: 0.0	Transition: 4.3 Op Complexity: 4.4 Robustness: 8.3 Interoperability: 3.6	Transition: 6.2 Op Complexity: 7.5 Robustness: 8.3 Interoperability: 8.9	Transition: 6.2 Op Complexity: 7.5 Robustness: 8.3 Interoperability: 8.9
Existing User Benefit	Transition: 9.3 Op Complexity: 7.5 Robustness: 0.0 Interoperability: 8.9	Transition: 9.3 Op Complexity: 7.5 Robustness: 3.3 Interoperability: 8.9	Transition: 9.3 Op Complexity: 7.5 Robustness: 8.3 Interoperability: 8.9	Transition: 6.2 Op Complexity: 7.5 Robustness: 8.3 Interoperability: 8.9
New User Benefit	Transition: 0.0 Op Complexity: 1.3 Robustness: 5.0 Interoperability: 0.0	Transition: 4.3 Op Complexity: 1.9 Robustness: 5.2 Interoperability: 3.6	Transition: 6.2 Op Complexity: 7.5 Robustness: 8.3 Interoperability: 8.9	Transition: 6.2 Op Complexity: 7.5 Robustness: 8.3 Interoperability: 8.9

2.1.10.3. Conclusions

The conclusions of the tradeoff studies are as follows:

1. Standardization should reach at least to the Network layer, although the benefits of standardization continue to increase above this layer. The Network layer is the "thin waist" of interoperability. There are multiple choices for heterogeneity in the Transport and Application layers above it; multiple choices for heterogeneity in the Link and Physical layers below it; but a minimum requirement for interoperability is that these choices must converge in a homogenous Network layer.
2. In order to support Network layer standardization, standardization of the underlying Physical and Link layers is required when different organizations act as the termini for the individual data links in the end-to-end path.
3. Detailed protocol tradeoffs have not been performed by this study. The choice for a Network layer standard is assumed to be the Internet Protocol, IP. However, since the complete IP suite cannot be sustained across the entire Networking Architecture (which includes disconnected, highly asymmetric or long delay space communications), an enhanced version of Network service – such as Disruption Tolerant Networking (DTN) – should be developed to accommodate environments where the performance of the IP suite is inadequate.
4. A standard SM interface should be adopted and implemented by existing and new NASA C&N service providers. Adoption of a standard SM interface is clearly preferable for new users and providers (under SMIO3 or SMIO4). For new users and providers, SMIO3 and SMIO4 are equivalent, since new providers would support only the standard interface under either SMIO, and new users would use only the standard interfaces even if legacy interfaces were still supported by existing providers.

As the NASA Space Communications Network evolves over the coming decades to add new networking services, NASA users may have an increasing need to be supported by multiple providers. As the NASA Space Communications Network may be increasingly required to support non-NASA missions, the long-term benefits of increased robustness and interoperability in SM may outweigh the one-time transitory costs of implementing a standard SM interface in the existing providers (SN, DSN, and GN).

2.1.10.4. Implications of the Networking Architecture

The recommended Networking Architecture has several implications:

1. The architecture requires a higher level of Agency-wide engineering and management oversight than currently exists. This oversight embraces virtually all providers of current and future NASA network elements. A need for closer coordination also extends to potential national and international partner providers.
2. Such oversight requires that policies must be developed, enforced and updated in order to control the evolution and use of NASA's space communications infrastructure. These policies require an increased ability to levy requirements on NASA's Flight Projects and to process waivers as necessary. To mitigate the effects, NASA will need to invest in developing capabilities that make it easy for projects to comply with policies.
3. The policies need to be backed by a strong consensus standardization activity that evolves as requirements and technology change. The extent of associated

conformance testing, certification, auditing and enforcement authority needs to be studied.

4. An infrastructure evolution plan should be developed that shows how, as systems are upgraded, elements of the Networking architecture will be incorporated.

2.2. Security Architecture

2.2.1. Overview of the Security Architecture

The security of space missions depend on many factors, most notably the ability to secure the communications involved in the command and control of spacecraft. The security architecture provides the capabilities to verify the authenticity of Command and Control (C2) data and to prevent the unauthorized disclosure of data while it is sent through the communications infrastructure. This security architecture covers major aspects of Information Assurance (IA) communications as they pertain to the C2 of NASA's civilian space missions. Although the focus is on C2, the security architecture is relatively generic in terms of the information that it can be used to protect.

The scope of the security architecture focused on Information and Communications Security (INFOSEC, COMSEC). For the studies conducted to date, a full Threat and Vulnerability analysis was not performed; consequently, there are types of threats such as RF jamming that were not assessed. Additional studies need to be performed to address these limitations.

2.2.2. Architectural Drivers

2.2.2.1. Federal and NASA Policy Requirements

NASA is a Federal Agency that is governed by Federal policies. NASA incorporates Federal policies into NASA policies and requirements to ensure that the Federal policies are met. The following is a list of some applicable governing Federal polices:

- Federal Information Security Management Act (FISMA), 2002: Mandates several NIST standards for IT security
- Health Insurance Portability and Accountability Act (HIPAA): Requires confidentiality protections for medical data and accountability of those responsible for the handling of medical data

The following is a list of some applicable NASA governing security policies:

- NPD 2810.1C – NASA Information Security Policy: Requires measures be taken to protect information security
- NPR 2810.1 – Security of Information Technology: Requires protective measures that are commensurate with security risks

2.2.2.2. Architecture Requirements

The security architecture enables missions to configure and manage security capabilities. The missions have the primary responsibility to protect their assets and information, and must have the tools to do so effectively. All missions conduct Threat and Vulnerability (T&V) assessments to determine risk levels associated with the communication of information based upon mission configuration and the communications system design. These T&V assessments help determine a mission's option(s) for managing acceptable risk and for implementing security measures. Key requirements that drive the shape of the security architecture are:

- End-to-end protection of the authenticity of C2 information
  - Prevent unauthorized commanding and alteration of data
- End-to-end protection of the confidentiality of sensitive C2 information
  - Prevent inappropriate disclosure of sensitive data
- Timely delivery of, and access to, critical C2 information with minimal delay caused by security services
- Work within the communications network architecture
  - Continue to support bulk encryption for legacy assets (ISS, Shuttle, TDRSS)
- Provide the ability to manage and control security key material over-the-network
  - Use Federal Information Processing Standard (FIPS)-approved key generation and distribution
- Conduct Certification and Accreditation (C&A) of the security services and the end-to-end system according to FIPS SP 800-37
  - Use FIPS-approved cryptographic modules and devices

2.2.3. Security Architecture Description

The following subsections describe the recommended security architecture, options for alternative security services, and the criteria used for consideration by a mission for selecting a security implementation. The implications of incorporating security services at the following layers were examined (see Figure 11):

- Physical layer (with variations of encrypting at control centers vs. terminals)
- Network layer (with variations for using and not using gateways)
- Application layer (always done at application layer endpoints)

Several possible implementation options at each of these layers were identified. In addition, security measures implemented at the physical layer on legacy programs such as the Shuttle were included to address backward compatibility. In all, 13 security services options were considered for the security architecture:

1. Physical Layer Bulk Security— At ground terminal
2. Physical Layer Bulk Security— At control center
3. Network Layer—Device-to-device, authentication only
4. Network Layer—Device-to-device, encryption only
5. Network Layer—Device-to-device, authentication + encryption
6. Network Layer—Gateway-to-Gateway, authentication only
7. Network Layer—Gateway-to-Gateway, encryption only
8. Network Layer—Gateway-to-Gateway, authentication + encryption
9. Application Layer— authentication only
10. Application Layer—encryption only
11. Application Layer— authentication + encryption
12. Application Layer authentication + Network Layer device-to-device encryption
13. Application Layer authentication + Network Layer gateway-to-gateway encryption

2.2.3.1. *Security Architecture Overview*

The security architecture provides those security services dependent upon the IA needs of a mission: Authentication (with integrity) and Confidentiality. These protection services are provided by network layer and/or application layer security measures.

The Security Architecture provides user missions with three options for security services, selectable based upon mission requirements: (1) Network Layer Security services; (2) Application Layer Security Services; (3) Application Layer/Network Layer Hybrid security services. (See Figure 11)

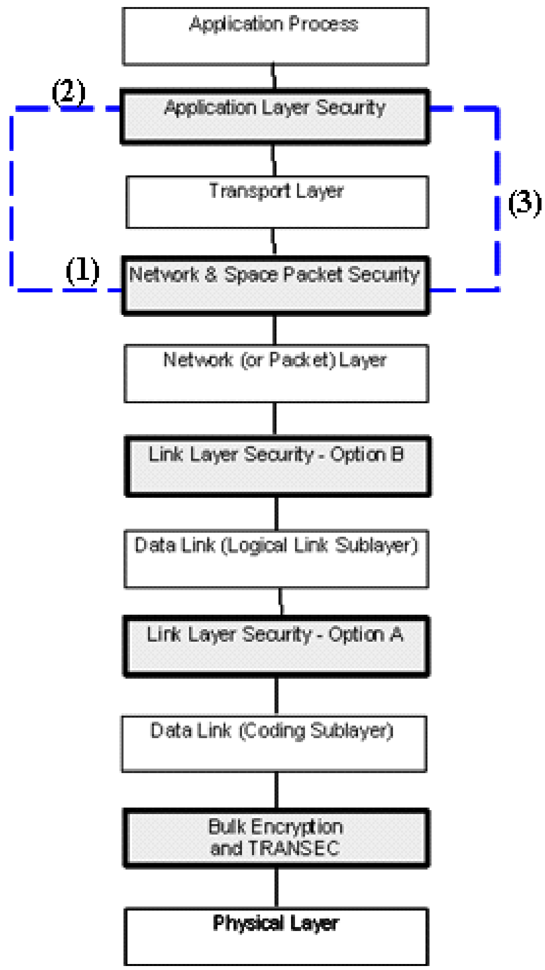

Figure 11. Security Services Layers and Options

The security architecture applies to a network-based communications infrastructure, as described in the Network Architecture section (see Figure 4). The ability to support multi-hop/path communications is a very important aspect of this security architecture.

Overall, a Hybrid security architecture is recommended that employs both network and application layer security services to provide a secure system. However, it is also recognized that sometimes this is not required. For those missions, either network layer security services may be used without any application layer security services or vice-versa. At each layer, "security services" implies that both authentication and/or confidentiality services may be implemented.

The recommendation is to use network layer security services such as IP Security (IPSec)[2] or the CCSDS Space Communications Protocol Specification-Security Protocol (SCPS-SP)[3], coupled with application layer authentication services. Network layer security services, which are implemented between the network and transport layers of the OSI model, provide a means of creating shared security services which can be used by many applications.

If a mission's underlying network protocol suite does not implement security services, and none can easily be added, then application layer security services are a good alternative. However, it must be remembered that network layer security services may be implemented once, certified to be correct once, and used many times by many applications that run above the network layer. Application layer security services must be individually implemented which may result in higher implementation, test, and certification costs.

If fine grained authentication is required (e.g. down to a particular user or operations role), then application layer authentication services should be used.

2.2.3.2. Network Layer Security

Network layer security services are actually implemented between the network and transport layers of the OSI model (see Figure 11). In this way, network headers remain in the clear allowing off-the-shelf routers to continue to perform their routing function with no impact. Everything above the network layer has the required security services applied before being transmitted over the network.

Network layer security may be implemented in each end-system device (e.g., in an on-board instrument, control center workstation, command and control flight computer) or it may be implemented once in a gateway device such as a Command and Data Handling (C&DH) subsystem, a Virtual Private Network (VPN) gateway, a firewall, or a router containing security services. Employing network layer security within the routers at the end-to-end boundaries of control centers and spacecraft is consistent with the operational strategies of most missions.

Certain criteria need to be considered by the mission to select a network layer security approach within the architecture. Ubiquitous services must be available to support multiple applications. These are typically designed, implemented, tested, and certified once while being used by numerous applications and re-used in multiple systems. Course-grained authentication provides verification to the Network level only; however, this provides ample communications security for most missions. The course-grained authentication and confidentiality are sufficient for a wide variety of mission types.

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[2] IPSec is defined by Internet Engineering Task Force (IETF) standard RFC 4301, Security Architecture for the Internet Protocol, December 2005, as modified by IETF RFC 3168, The Addition of Explicit Congestion Notification (ECN) to IP, September 2001.

[3] SCPS-SP is defined by CCSDS standard CCSDS 713.5-B-1, Blue Book. Issue 1. May 1999.

Major programs need to provide end-to-end security in a multi-hop, multi-path communications network. This leads to potentially (but not necessarily) insufficient network performance and may require DTN capability.

2.2.3.3. Application Layer Security

Application layer security services come in a variety of flavors. Some approaches require handshaking at the beginning of communications sessions; others require the pre-placement of keys via some management approach; while others expect Public Key Infrastructures (PKI) to be available for validating identities. This security architecture does not specify what kinds of application layer security mechanisms should be employed because those decisions are dependent on specific aspects of particular missions and the applications they employ.

The proper implementation/integration of application layer security services in each secured application is important and must be tested and certified.

Certain criteria need to be considered by the Mission to select an application layer security approach within the architecture including:

- Protection of data exchanges regardless of the underlying communications infrastructure
- Fine granularity of authentication
- Use of security services that can be based on the content of information exchanges
- End-to-end security in DTN networks
- Implementing application layer security services in each and every application potentially resulting in higher implementation and testing costs
- Some data must reach the application layer before it can be verified or rejected.

2.2.3.4. Application Layer + Network Layer Hybrid

The hybrid approach provides a powerful set of capabilities that can be managed by missions to make the best use of the security services according to their needs. This hybrid architecture is illustrated in Figure 12. IPSec (i.e., network layer security) is used on the space link and Secure Sockets Layer (SSL, an application layer security approach) is used on ground links. Many other configurations of the hybrid approach are also possible.

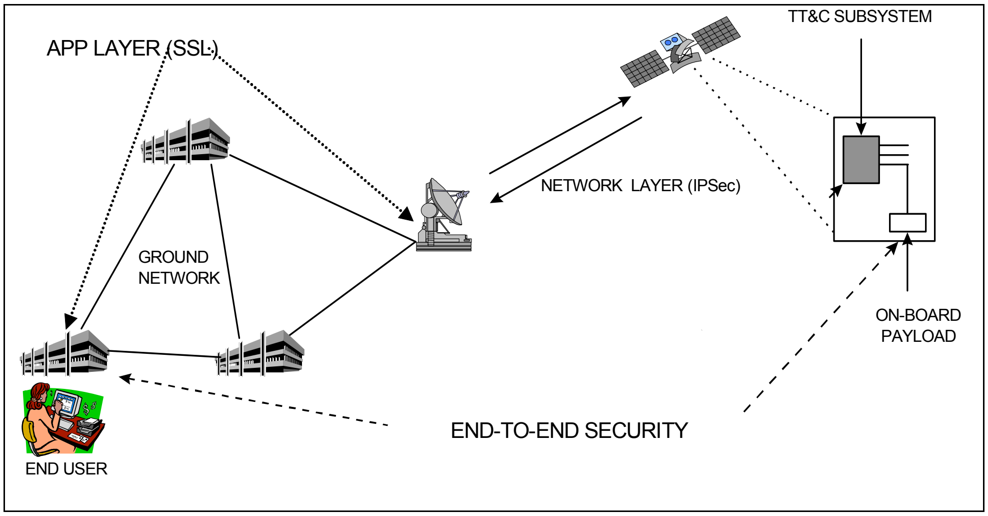


Figure 12. Security: Hybrid Approach

Certain criteria need to be considered by the mission to select a hybrid security approach within the architecture:

- Mitigation of more IA related threats than a single-layer approach
- Flexibility (allows projects to choose security services as appropriate)
- Evolvability
- Support for various key management approaches
- Limited number of security algorithms
- May cost more than a single-layer approach
- More complex than a single-layer approach

2.2.3.5. Symmetric Key Encryption-Based Algorithms

The selection of security algorithms is an important aspect of any security architecture. The interoperability between communicating elements, the processing and bandwidth overhead, and the amount of development, testing, certification, and maintenance are just some of the concerns tied to the selection of security algorithms. The recommended security architecture adopts the use of symmetric key encryption algorithms (such as the Advanced Encryption Standard (AES)) for authentication and confidentiality.

2.2.4. Security Architecture Considerations

Overall there were four basic methodology options evaluated for authentication and encryption:

- Symmetric key encryption-based approach: This security architecture is based on the use of symmetric key encryption algorithms (such as AES) for authentication and encryption. The main advantage of this approach is that the number of security algorithms is limited, thus reducing the amount of the testing and certification required. The main disadvantage of this approach is that the authentication operations will be more computationally expensive than if a Hash-based Message Authentication Code (HMAC) approach were used for authentication.

- Symmetric key encryption and hash-based authentication approach: This security architecture creates an HMAC by combining a symmetric key with the data to be authenticated and running the combination through a hash algorithm. The sender creates an HMAC and sends it to the receiver along with the data. The receiver performs the same HMAC operation (i.e., using the same "shared" key) and compares the result with the HMAC sent by the sender. A positive match shows that the data was not tampered with in transit. This approach has the advantages of NIST compliance (using AES for encryption per FIPS 197 and an HMAC for authentication per FIPS 186) and efficient processing. One disadvantage is that this approach introduces another cryptographic algorithm, i.e., a hashing algorithm, to the architecture.
- Combination of asymmetric key, symmetric key, and hash algorithms: This approach would use digital signatures (i.e., an asymmetric algorithm) for authentication, most likely to take advantage of the capabilities that a PKI can provide. Encryption of data would be performed using symmetric key algorithms because of the speed advantage. This approach has the advantages of being able to make use of a PKI and the added security that comes from not sharing keys (i.e., better non-repudiation, lower likelihood of key compromise). A PKI provides the ability for security processes to retrieve certificates and certificate revocation lists when they are needed. This approach has the disadvantage of requiring more computer processing and memory for authentication processing than the HMAC and symmetric encryption-based MAC. It also has the disadvantage of using communications bandwidth to move around certificates and certificate revocation lists. This approach is typically accompanied by the use of a PKI, which requires Internet-like connectivity.
- Type 1 Symmetric Encryption only: Type 1 cryptographic equipment is National Security Agency (NSA) certified and is capable of being accredited for securing the communication of classified data. In the past, this type of equipment has generally been in the form of in-line devices (i.e., on the hard-wired communications media) that provide bulk encryption between two points. Network layer solutions in the form of High Assurance IP Encryptors (HAIPE) devices are in development through the NSA, and represent the next generation of Type 1 equipment. This approach has the advantage of being able to handle classified data, but the disadvantage of additional logistical and physical security requirements compared to using commercial technology. Thus, this approach may suit some missions where classified data comes into play, but most civilian missions will not require this level of security.

The security architecture was evaluated against a series of options, analyses and considerations that factored into the recommendations. Three important considerations are part of the overall Security Architecture recommendations and are discussed below.

2.2.4.1. *Key Management Infrastructure (KMI)*

The KMI is the set of hardware, software, policies, procedures, and personnel required to create and sustain security keys used in the communications system over the life of that system. The KMI enables the key distribution approach and use by only specific authorized persons and/or machines. The KMI is an important part of any security system implementation, and should be evaluated accordingly. There are two basic keying options for traditional (symmetric) key material; (a) Hardkey (Fixed) and (b) Dynamic Over-The-Air Rekey. Both are more intensive and have less compromise recovery capability than Public Key based systems, but generally are more secure. For the space communications architecture, technology advances in Software Defined Radios will provide the programmability that a dynamic KMI may need, and is thus a likely choice for missions and elements of the SCA.

2.2.4.2. *Certification and Accreditation*

Any Federal system that employs security services as a means to provide IA and/or IT Security will be required to meet C&A at two levels: (a) The Security Service/Mechanism(s) such as FIPS 140-2 for cryptographic modules; and (b), The end-to-end System in accordance with FIPS SP800-37, "Guide for the Security Certification and Accreditation of Federal Information Systems". How and where these security services are implemented may affect the ease with which the C&A occurs on both levels.

2.2.4.3. *Communications Availability*

Security services applied at the information level do not completely address the risks associated with denial of service that can occur at the RF connection level which affect the availability of communications. Proper T&V assessments and mission decisions on risk mitigation should couple the recommended security architecture with proper availability mitigation strategies and approaches.

2.2.5. FOM Selection, Analysis and Conclusions

A set of five FOMs was defined to help perform assessments of the Security Options against the four methodologies that were evaluated to determine the impact for NASA to embed Security into the overall C2 structure:

1. Operational Complexity
2. Robustness
3. Interoperability
4. Overhead
5. Project Life Cycle Burden

2.2.5.1. *FOM Definition*

2.2.5.1.1. *Operational Complexity*

Operational complexity is a measure of the ease-of-use associated with using a system. This FOM is associated with the goals of minimizing workloads and simplifying the tasks, inter-organizational agreements, facilities, and personnel requirements associated with conducting mission activities. The following factors considered in evaluating this FOM were:

- IA Infrastructure needs to assess the difficulty to manage infrastructure and additional steps for operations personnel;
- Facility needs to assess restrictions on facilities (e.g., requiring more compartmentalization, highly secure vaults for security devices, etc.);
- Personnel needs to assess the restrictions placed upon personnel, such as a need for a security clearance, due to the security approach being used;
- Contingency safe mode to determine if a security approach adds complexity (and thus bits, time, or steps) to a contingency operation; and
- Agency-to-Agency agreements (such as a Memorandum Of Understanding or MOU) which may complicate issues such as levying special handling requirements for security equipment and procedural requirements associated with the security option.

2.2.5.1.2. Robustness

The Robustness FOM measures the ability of the secure C2 implementation to allow:

- Scaling of the type and quantity of information to be passed, along with assessing the ability to accommodate multiple data rates, formats and protocols;
- The ability to provide fault tolerance including the ability to maintain a partial capability in case of failure (i.e. failsafe operation mode where perhaps the secure system can accommodate emergency C2);
- The ability to allow use on CCSDS and/or IP-based relay networks with a mixture of configurations, protocols and formats;
- The ability to support multiple levels of protection (multi-suite) for various users and information classes (C2, engineering data, science data, video, audio, etc…); and
- Risk/ threat mitigation breadth for both authentication and confidentiality.

2.2.5.1.3. Interoperability

The Interoperability FOM measures the strength of the secure C2 implementation to allow for operations and usage with commercial, international, DOD and other US agency sectors. This FOM considers: (a) the ability to work with non-NASA IA and IT requirements and certification and accreditation processes; and (b) the complexity of bridging the implementation between NASA and non-NASA Assets and facilities to work together.

2.2.5.1.4. Overhead

This FOM measures the amount of overhead necessary to encrypt data in the link (percent of total data block size and/or throughput). Additional qualitative factors include assessing: (a) the additional processing delay in terms of additional latency needed by software/firmware/hardware to decipher and process security mechanisms;

and (b) the burden due to formatting and/or block size limitations as a result of the implementation used.

2.2.5.1.5. Project Life Cycle Burden

For study purposes, the project life cycle is defined as a four phase process. A measure was assigned for each phase to aid in quantifying the degree of burden:

- Definition (Phase I) focuses on understanding the mission, environment, and architecture to determine the security requirements and level of effort necessary to achieve accreditation. The measure is the number of staff years to develop a system architecture security plan, transition plan and CONOPS.
- Verification (Phase II) verifies the evolving, or modified, system's compliance with the specified security requirements, measured as the number of staff years needed to develop and verify the system.
- Validation (Phase III) validates the fully integrated system's compliance with the security requirements. The measure for Phase III is the number of staff years to validate the system through accreditation.
- Post Accreditation (Phase IV) ensures system management, operation, and maintenance to preserve an acceptable level of residual risk. The measures for Phase IV include number of staff to operate, maintain, and manage the system, the quantity and complexity of utilized equipment, and number of square feet required for security facilities.

2.2.5.2. Security Evaluation Process

The analysis of the security architecture options was conducted in two phases. The first was an assessment of the 13 options against the 4 methodologies with respect to each FOM. The second was the development of a series of impact matrices to assess the methodologies against a set of functional and performance capabilities. The combination of FOM and impact matrices was used to determine the recommendations for the best security service options to use for those Programs and Missions using the SCA when it is determined that INFOSEC and/or COMSEC are required as part of a sound Information Assurance and IT Security approach. The complexity and breadth of this assessment is captured notionally in Figure 13.

The general process for the FOM assessment followed these steps: (1) FOMs and their filters/factors were weighted and scored against the Security Options and Methodologies. (2) A scaling range of 1-10 was selected for each score of a sub-factor as well as for the overall score of each FOM to normalize scaling (via weighting) of the scored value to the overall effectiveness of each option and methodology evaluated. (3) Consensus opinion was used to determine scores and to scale the factors and then summed to arrive at an overall FOM score for each option. (4) All FOM scores were combined with their weighting to provide a single score for each security option-security methodology pair (a 13x4 matrix) to arrive at an overall performance indication of that security option. The Project Life Cycle Burden FOM was determined to have a 1::1 correlation with project life cycle cost and therefore was not used to measure performance of the security options. After removing the Project Life Cycle Burden FOM, the performance FOMs were weighted as follows to compare against security options:

- Robustness = 0.43
- Operational Complexity = 0.43
- Interoperability = 0.07
- Overhead =0.07

FOMS were weighted relative to each other and to their impact to the overall performance effect of implementing security. Weighting values were selected via consensus as opposed to quantitative analysis.

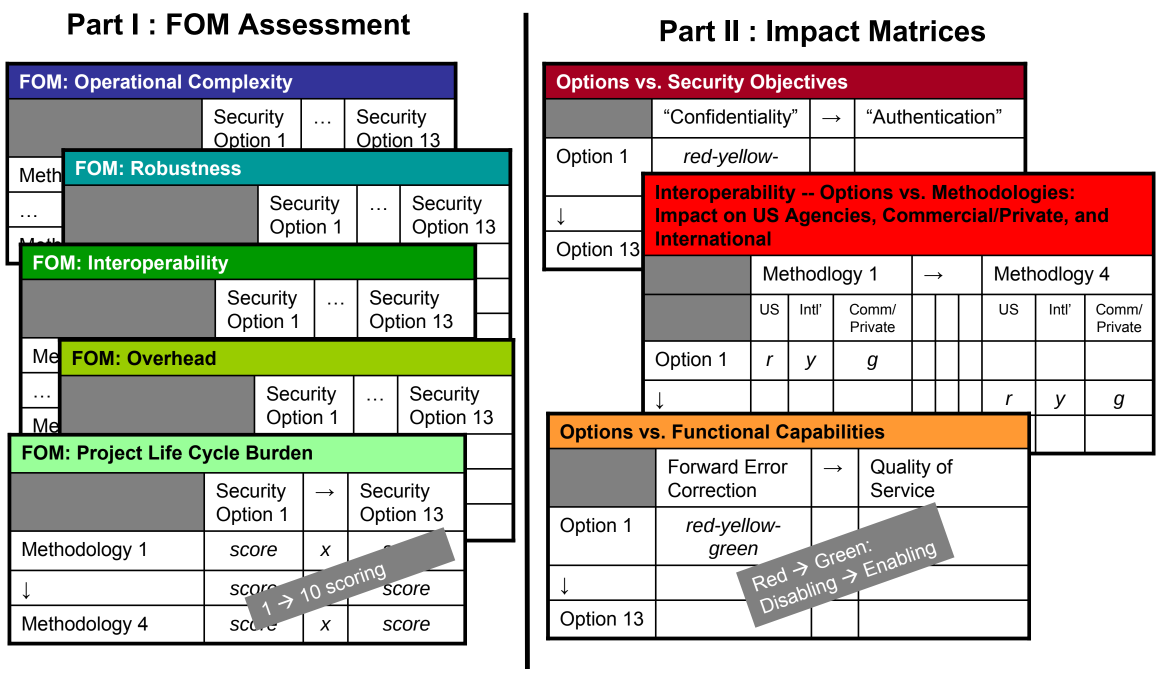


Figure 13. Analysis Process for Security Architecture Assessment

2.2.5.3. Conclusions

The use of FOMs, coupled with the evaluation of Impact Matrices can provide a sense of the attractive options to explore when trying to provide INFOSEC and COMSEC as part of the SCA to meet the needs of Missions.

The weighting of individual FOMs with respect to each other, as well as the weighting of the factors in each FOM with respect to each other, must be representative of the needs and importance to NASA and the SCA. The FOM scores and evaluation of the security options can vary by changing the weighting of the factors and FOMs. Weightings were chosen were by a team with specific membership and experience in evaluating INFOSEC and COMSEC options; consequently, results may be biased and incomplete. However, for the SCA, there is a good deal of confidence in the results of the studies, which recommends that both network and application layer services be used together to provide a secure system. In cases where this is not required, network layer services may be used without any application layer services and vice-versa. At each layer both authentication and confidentiality services may be implemented.

2.3. *Spectrum Architecture*

2.3.1. Overview of the Spectrum Architecture

The spectrum identified as a part of the SCAWG activity is to support all NASA C&N activities for the time frame from 2010 though 2030. Spectrum is needed to support human and robotic missions in the near Earth (including lunar) and Deep Space environments. The *Deep Space* environment is defined by the International Telecommunications Union (ITU) as occurring at a distance of >2 million km and includes Mars. By default, *near Earth* is defined as occurring for missions less than 2 million km from Earth and includes the Moon as well as the Earth orbit environment.

Figure 14 shows the highlights of the spectrum architecture following the overall SCA picture dividing the universe into the four regions of Earth, Moon, and Mars vicinity and Deep Space. Interfaces between the SCA elements (GEE, NER, LR, and MR) are shown to all of the classes of users. GPS is also shown. The type(s) of information sent and/or received are color coded by spectrum band showing the use of UHF, S, L, X, Ku, and Ka bands needed to cover the needs of all users across the solar system.

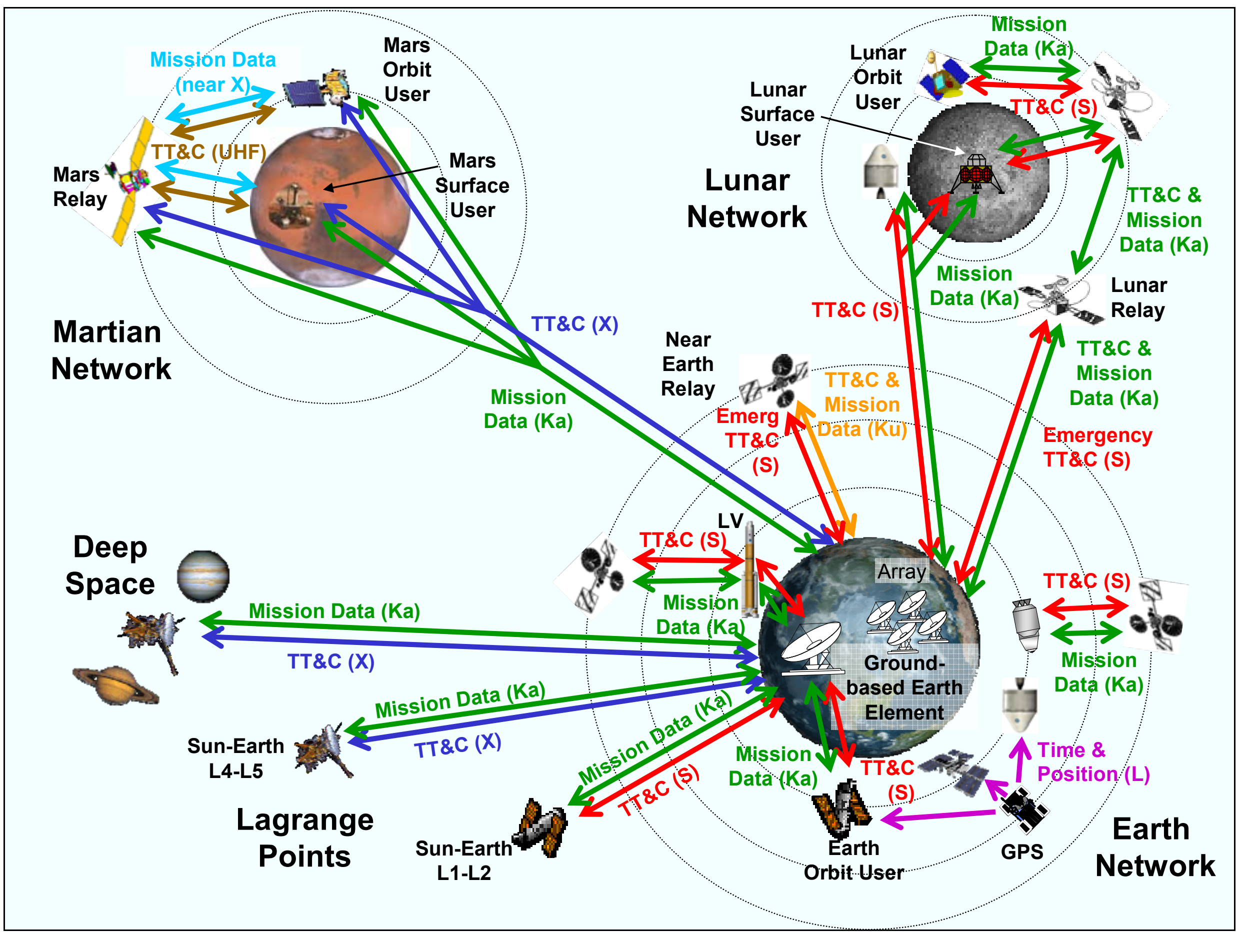


Figure 14. Overview of the Spectrum Architecture

2.3.2. Spectrum Selection Guidelines

The bands considered are either available for Space Science Service use or allocated by the ITU for space use, including all of the currently available Space Research Service (SRS) bands below 41 GHz.

In addition to SRS bands, NASA currently utilizes certain of the Inter-Satellite Service (ISS) bands for communication links between data relay satellites and user vehicles. Specifically, this use includes the 22.55-23.55 GHz band allocated to ISS service and used by the NER Element. The goal of minimizing user hardware complexity led to the selection of an architecture which allows for communication directly from Earth to a spacecraft using a new SRS allocation when the spacecraft is beyond the 30,000 km altitude coverage provided by the NER Element. This band is allocated for ISS and does not currently have a SRS allocation but will need to have its allocation status broadened to include Earth-to-space operation. This will be described in greater detail.

Spectrum was also identified for ranging applications. Because of the general nature of their definition in the ITU for both SRS and ISS services these bands can be used for ranging applications. One other possibility is the use of Radio Navigation Satellite Service (RNSS) bands. Certain of these bands are used by the GPS and are currently used extensively by NASA.

2.3.3. Scope of the Spectrum Identified for the Architecture

The existing allocations for SRS, ISS and RNSS were evaluated for their ability to support the communication elements in two environments:

1. Near Earth
    - Launch to near GEO altitude environment
        - Direct to and from NER Element
    - Near GEO altitude to the lunar environment
        - Direct to and from GEE
        - LR Element to cover lunar surface
2. Deep Space (including Mars)
    - Direct to and from GEE
    - MR Element

2.3.4. Requirements for Spectrum Selection

The top level guidelines used in spectrum selection are described below in Table 9 and are more fully described in the sections below.

2.3.4.1. Select Bands with SRS Co-primary Regulatory Status and Ability to Protect NASA Use

Having a co-primary allocation in the ITU Radio Regulations provides implied protection for NASA. If interference occurs to NASA use of these allocated bands or if interference occurs to others as a result of NASA use, existing regulations and agreements allow for coordinated mitigation of the Radio Frequency Interference (RFI). Without such regulatory status NASA accepts risk and could be forced to shut down use of an unallocated band.

Table 9. Top Level Spectrum Requirements

#	Description of Requirement
1	Select bands with co-primary SRS regulatory status & ability to protect NASA use: • International status with ITU • National status with NTIA
2	Identify a frequency plan allowing simplest user hardware by utilizing the same spectrum bands for direct communications to and from Earth and for use with relay satellites.
3	Identify high reliability bands with sufficient bandwidth for TT&C use
4	Identify bands with sufficient bandwidth for high rate mission data

Obtaining a new band allocation when an allocation does not already exist is not certain and can take up to two conference cycles of the ITU or 5 to 10 years to gain approval. Therefore, use of bands with existing allocations is highly preferred.

2.3.4.2. Identify a Frequency Plan Allowing Simplest User Hardware

This can be accomplished by utilizing the same spectrum bands for direct communications to and from Earth and for use with relay satellites allowing common user hardware for separate communication paths. An example of this selection is the use of Unified S-band (USB) currently used by TDRSS and the NASA GN. These USB bands include the 2025-2110 MHz forward (uplink) band and the 2200-2290 MHz return (downlink) band. Utilizing these bands permits continuous coverage from launch to LEO orbit and on to about 30,000 km using a data relay satellite such as TDRSS. Beyond 30,000 km, continuous coverage can be achieved by the NASA ground networks to the vicinity of the Moon and beyond. These bands are fully allocated for direct to and from earth communications as well as for use with a data relay satellite.

2.3.4.3. Identify High Reliability Bands with Sufficient Bandwidth for TT&C Use

In general, bands below 10 GHz are narrow band and have robust propagation characteristics. Robust propagation characteristics are those characteristics which resist outages due to weather and offer an ability for implementation of omni-directional spacecraft antennas which can provide reliable communications in the event of a spacecraft loss of attitude. These bands below 10 GHz are appropriate for narrowband data to and from Earth. An example of these bands are the USB bands identified earlier and the 7145-7190 MHz and 8400-8450 MHz bands allocated for Deep Space up and downlinks, respectively. A comparable pair of near Earth bands is 7190-7235 MHz and 8450-8500 MHz.

The near Earth band 8450-8500 MHz is generally limited to 10 MHz downlinks by agreement within the Space Frequency Coordination Group (SFCG) which is composed of civil space agencies from space fairing nations. This group includes NASA.

2.3.4.4. Identify Bands with Sufficient Bandwidth for High Rate Mission Data

Bands available below 10 GHz have insufficient bandwidth available to satisfy high rate mission data needs. Bands above 10 GHz have wider bandwidths but are subject to greater rain fading when passing through the Earth's atmosphere during rain. An example of mission data bands above 10 GHz is the paired 37-37.5 GHz and the 40-40.5 GHz bands identified for Deep Space operation. A comparable pair of bands at 37.5-38 GHz and 40-40.5 GHz has been identified for near Earth distances.

Weather outages are not as significant for mission data where real time data flow is not required as for operational data where crew safety or mission assurance is involved. Data storage can be utilized to allow for transmission of mission data when rain outages disappear.

2.3.4.5. Science Systems Operating in Other Bands

In addition to the bands identified for the NASA Lunar and Mars exploration program implementation, other bands, currently in use, may be utilized as a part of the NASA science program. These bands are identified below.

2.3.4.5.1. Deep Space portion of the USB in the 2110-2120 MHz and 2290-2300 MHz Bands

The Deep Space portion of the USB has recently been subjected to restrictions limiting uplink operations to remove possible interference with commercial mobile service in Madrid, Spain. The loss of the uplink makes the use of this Deep Space portion of the band unusable for new missions at the Madrid site but this band continues to be valuable to NASA and will be retained for emergency communications and unique science applications on a very constrained basis. Although not a part of the Lunar and Mars human and robotic exploration, this band is retained as a part of the GEE as described in Section 2.3.5.

2.3.4.5.2. Near Earth SRS X bands in the 7190-7235 MHz and 8450-8500 MHz Bands

The near Earth X bands are used to support near Earth science missions through the foreseeable future. This science use requires retaining these bands as part of the GEE.

2.3.4.5.3. Near Earth EES X band 8025-8400 MHz

The 8025-8400 MHz Earth Exploration Satellite (EES) Service Band remains heavily used by legacy and newly emerging Earth resources missions, but is not planned in any way to support aspects of the Exploration Vision.

2.3.4.5.4. TDRSS Inter-satellite bands in the 13.75-13.8 GHz and 14.9-15.15 GHZ Bands

The recent introduction of commercial high power fixed service uplinks in this band increases the likelihood of harmful interference to TDRSS forward links operating with near Earth satellites operating in this band. This band is also used by Fixed Satellite

Services (FSS) and Radiolocation. Both of these services are primary while SRS is secondary. As a result of World Radio Conference (WRC) activity, only 6 MHZ of the TDRSS forward link is protected from FSS uplinks. This bandwidth is not considered adequate for future DRS services into the 2030 time frame. Further, NASA has been told by NTIA that long term use of the 13.75-13.8 GHz band is discouraged. Therefore, NASA should transition future data relay satellite systems forward and return links to operate in the 22.55-23.55 GHz and 25.5-27 GHz bands and to delete Ku band inter-satellite services on future data relay satellite systems.

NASA retains use of the 13.4-14.05 GHz bands and 14.6-15.225 GHz bands for space-to-Earth and Earth-to-space links for current and future data relay satellite systems. A recent request to NTIA for information indicated that NTIA supports the continued use of these bands for up and down links at White Sands and Guam through the 2030 time frame.

2.3.5. Spectrum Architecture by Element

In the following sections, diagrams indicating spectrum selections between elements are shown (excluding the legacy uses discussed in section 2.3.4.5). A figure is provided to give the spectrum perspective from each of the elements; GEE, NER, LR, and MR.

2.3.5.1. Interfaces with the GEE Spectrum Architecture

The spectrum plan for the GEE is shown in Figure 15. The elements which interface with the GEE are called out separately following the figure and spectrum details are provided.

2.3.5.1.1. NER Element Interface to the GEE

The spectrum selected for the NER Element includes spectrum already allocated and utilized by Earth relays. Analysis indicates that this spectrum can be protected in the future through 2030.

2.3.5.1.2. LR Element Interface to the GEE

The links to and from Earth accommodate both mission data and operational data in the 37-38 GHz and 40-40.5 GHz mission data band. The analysis assumed that the nominal data rate of hundreds of megabits per sec can be decreased to 1 Mbps or less when rain fades occur. This can provide up to 27 dB of rain fade margin at 37.75 GHz. A calculation of availability with this 27 dB margin, using the three current DSN sites as the nominal location for the LR Ground Terminals, yielded about 10 minutes of rain outage per month with this scenario. This is acceptable since currently there is no continuous availability requirement for the LR.

2.3.5.1.3. MR Element Interface to the GEE

Communications from Earth with a MR satellite is expected to be in the Deep Space Ka bands, 31.8-32.3 GHz and 34.2-24.7 GHz, until the manned missions to Mars require moving to the 37-37.5 GHz and 40-40.5 GHz bands in roughly the 2025 time frame.

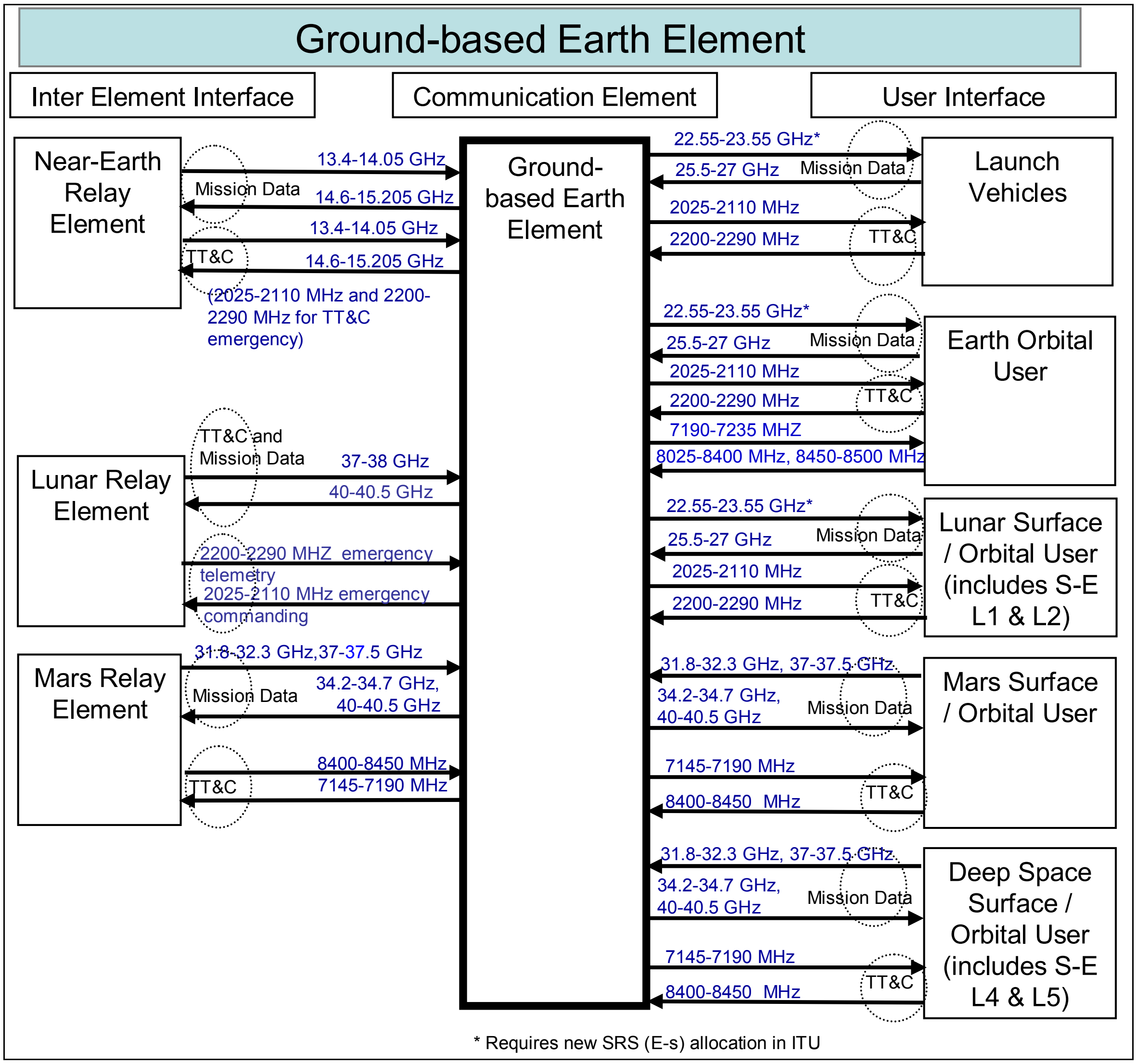


Figure 15. Spectrum Plan for the GEE

2.3.5.1.4. Launch Vehicles Interface to the GEE

These vehicles continue to use the USB bands to talk with ground antennas (and relay satellites not shown in Figure 15).

2.3.5.1.5. Earth Orbital Users Interface to the GEE

Earth orbital users use the USB bands already discussed so that they can communicate with either an Earth Relay satellite or the ground. These bands are limited to a bandwidth of about 5 MHz and require the use of narrow band data. In addition these users use the Earth relay Ka bands at 22.55-23.55 GHz and 25.5-27 GHz to talk to the relay and from earth directly for high rate mission data. The use of the 22.55-23.55 GHz band uplinking from Earth to a space vehicle requires a new SRS Earth-to-space allocation. This allocation is currently in process in the US regulatory process and is expected to be approved at the WRC 2010.

2.3.5.1.6. *Lunar Surface/Orbital User Interface to the GEE*

The lunar surface/orbital user utilize USB and 22.55-23.55 GHz and 25.5-27 GHz to allow re-use of the same bands (same hardware) as used in LEO.

2.3.5.1.7. *Deep Space Surface/Orbital User Interface to the GEE*

Deep Space surface and orbital missions including Mars missions use the same bands as the MR satellite when talking to Earth.

2.3.5.2. Interfaces with the NER Element Spectrum Architecture

The spectrum plan for the NER is shown in Figure 16. The spectrum selected for the Earth relay satellite is similar to that used on the current TDRSS. The major difference is the deletion of the Ku band cross links. It is assumed that all high Ku band users migrate in the future to the Ka band 22.55-23.55 GHz and 25.5-27 GHz crosslinks (see section 2.3.4.5.3 for rationale). This is ultimately necessary since the Ku forward link used by TDRSS is in the 13.75-14 GHz band which has been allocated to high power commercial uplinks which have the ability to overwhelm the TDRSS forward links.

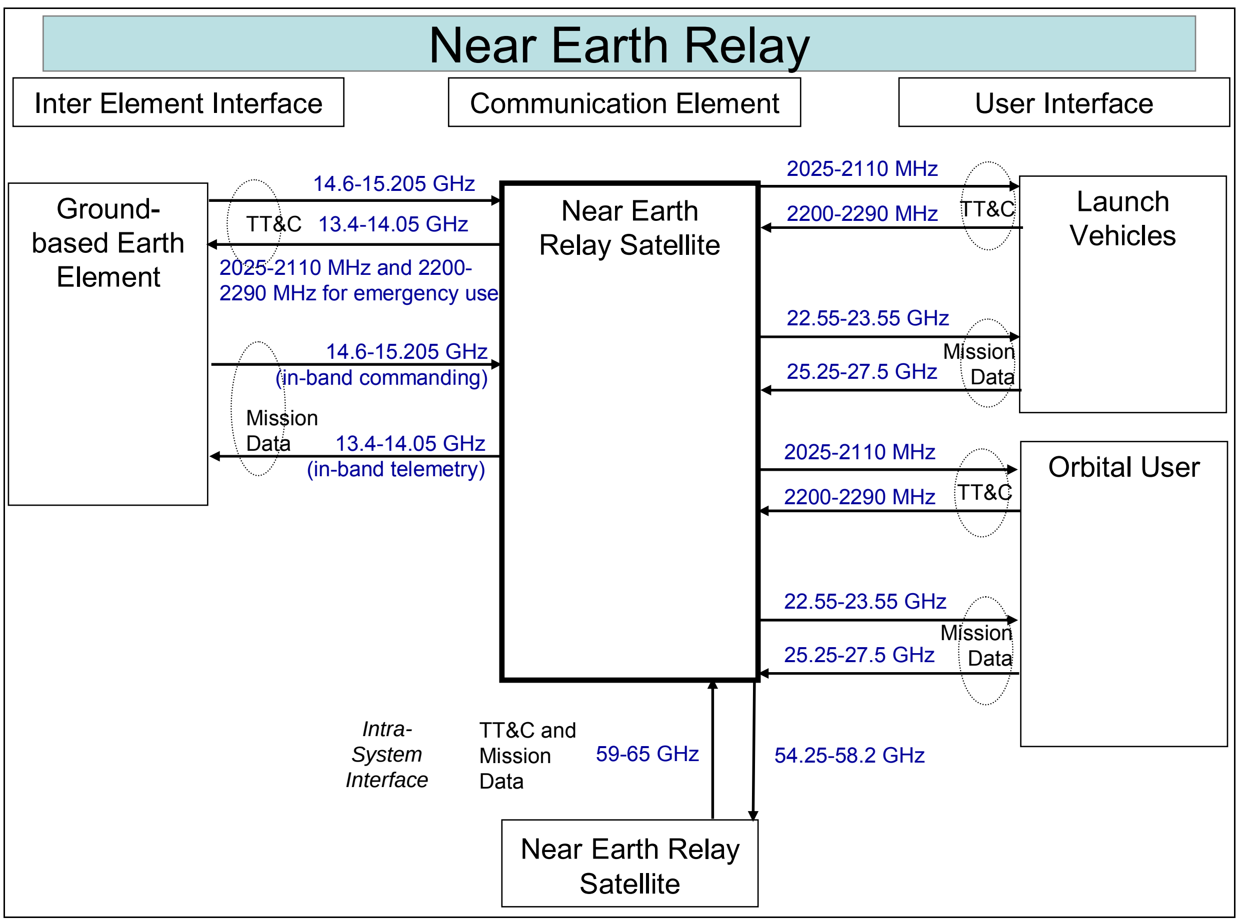


Figure 16. Spectrum Plan for the NER

2.3.5.3. *Interfaces with the LR Element Spectrum Architecture*

The spectrum plan for the LR is shown in Figure 17. The Earth-to-space and space-to-Earth links have already been discussed as a part of the ground antennas.

The lunar orbital and lunar surface users use the same spectrum as near Earth users. The LR has the same frequency plan for the user bands as an Earth relay satellite allowing re-use of the same hardware used in LEO or en route to the Moon.

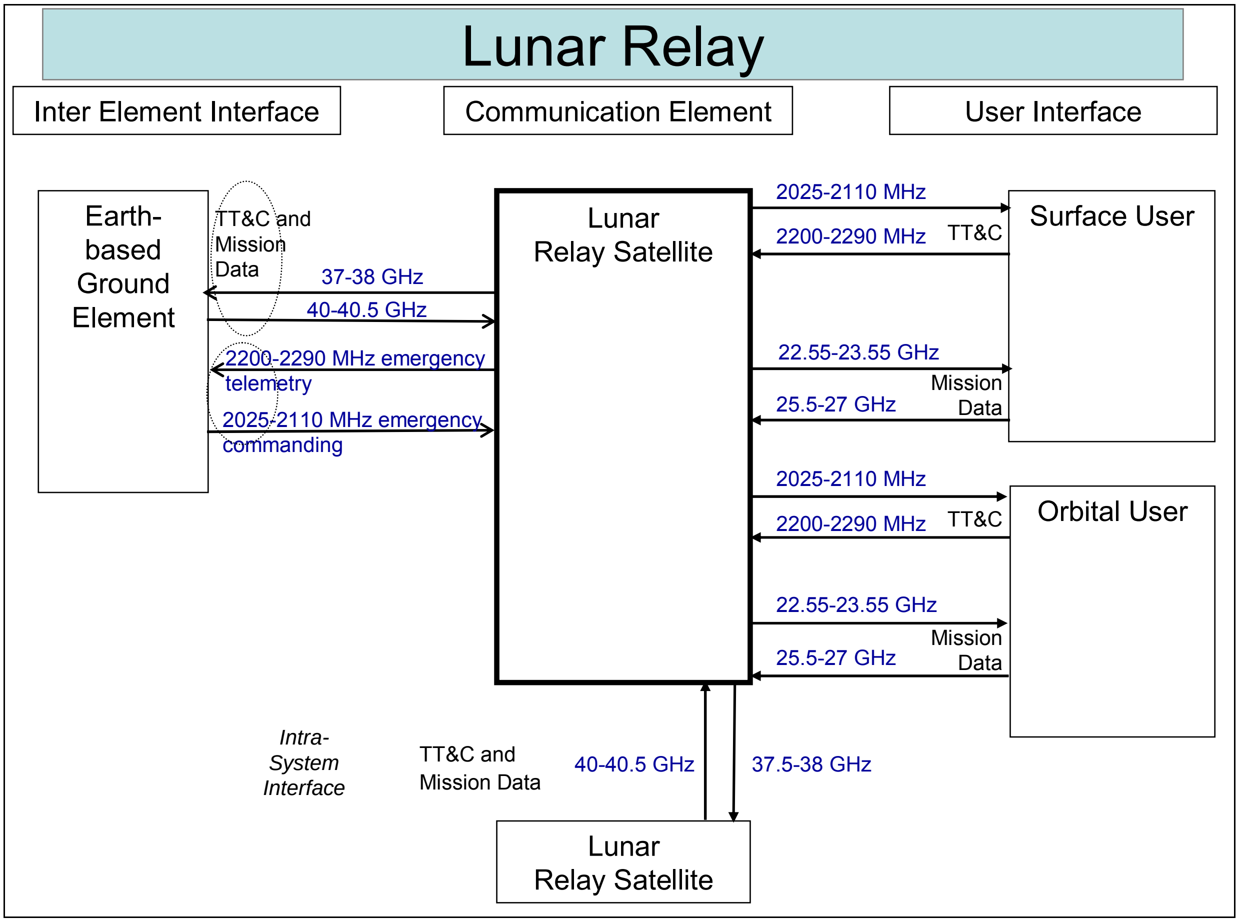


Figure 17. Spectrum Plan for the LR

2.3.5.4. *Interfaces with the MR Element Spectrum Architecture in the 2010-2025 Timeframe*

The spectrum plan for the MR is discussed in two phases: the early robotic phase between 2010 and 2025, and the human phase from 2025-2030. Figure 18 shows the early phase spectrum concept.

The MR satellite early robotic phase from 2010-2025 will utilize the UHF band from 435-450 MHz for forward links and 390-405 MHz for return links. Although these bands are not allocated for SRS they can be used on Mars due to the great distance from Earth which essentially isolate Earth systems and their interference from the Mars environment.

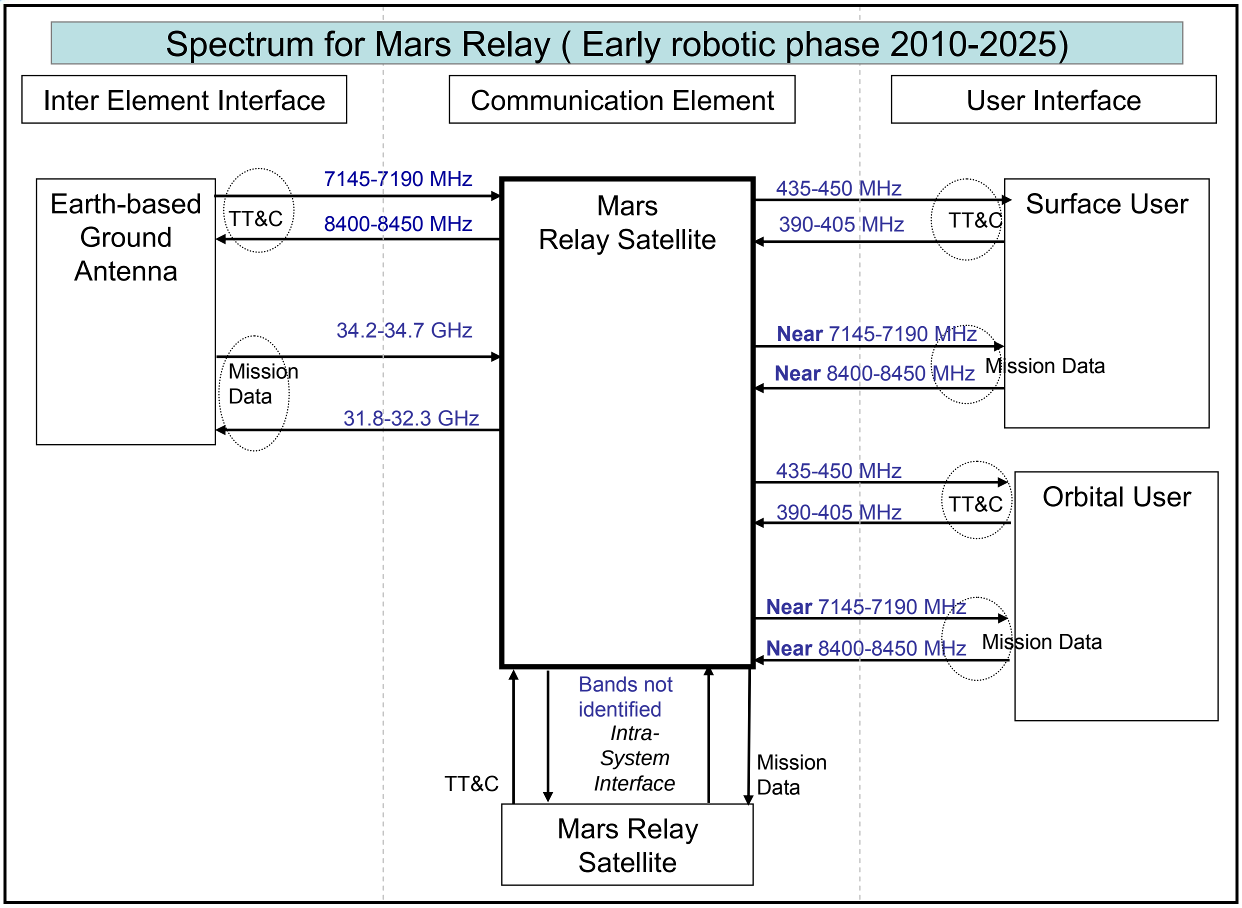


Figure 18. Spectrum Plan for the MR: 2010-2025

The X band user links to and from the relay are ***near*** 7145-7190 MHz and ***near*** 8400-8450 MHz bands. The concern is that, if the same 7145-7190 MHz and 8400-8450 MHz frequencies were used to talk to and from Earth as are used to talk to the users, a self-interference would occur. The idea behind the term ***near*** is to try to re-use the same user hardware slightly offset in frequency to talk to the MR satellite. Again, ***near*** bands which are not fully allocated can be used on Mars due to the strong path loss isolation between Mars and Earth.

The MR feeder links to and from Earth at 31.8-32.3 GHz and 34.2-34.7 GHz are allocated to SRS and, therefore, benefit from regulatory protection in the Earth environment.

2.3.5.5. Interfaces with the MR Element Spectrum Architecture for the Manned Exploration Phase 2025-2030

Following the robotic phase, human exploration is expected in the 2025 to 2030 timeframe. The spectrum plan associated with this phase is shown in Figure 19.

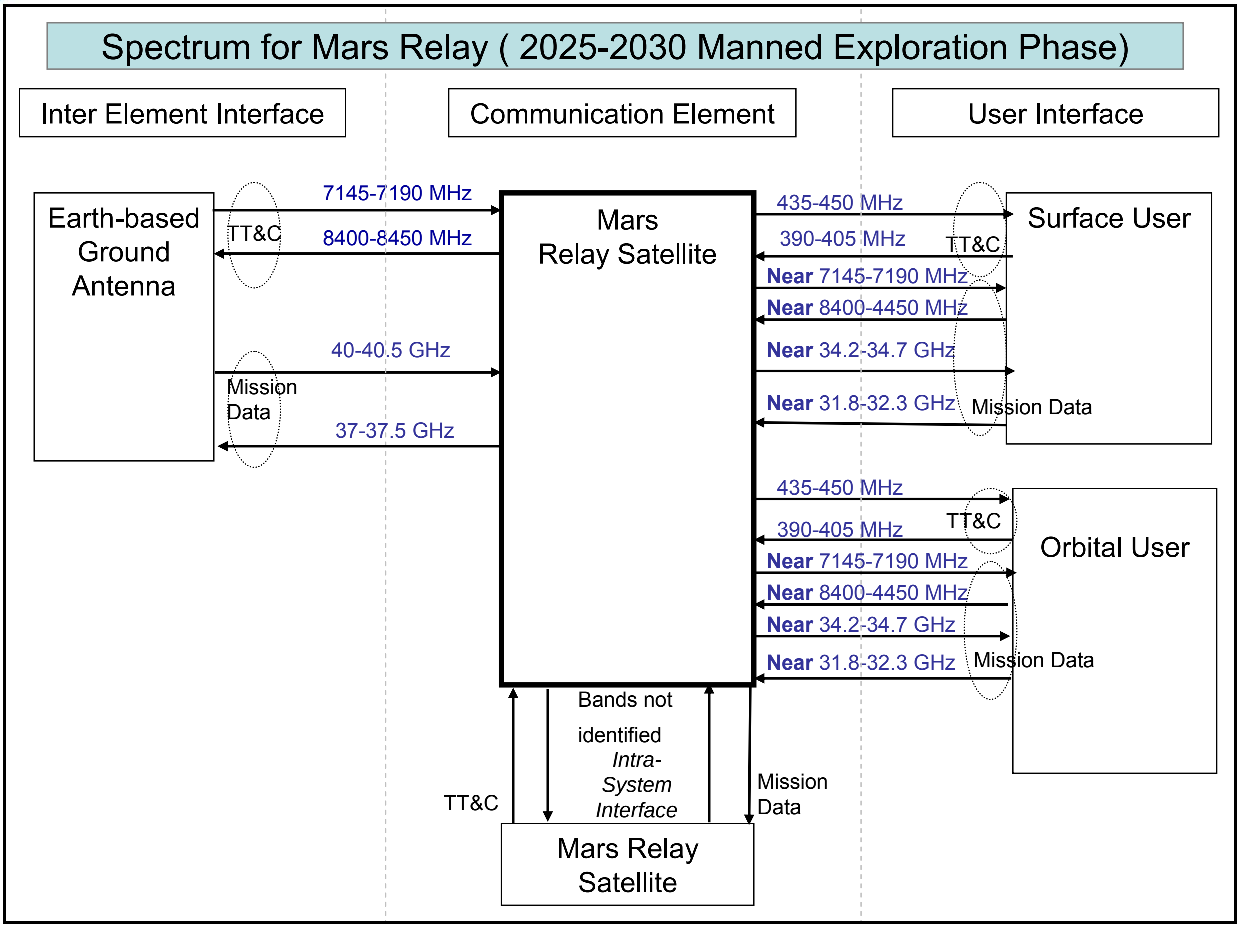


Figure 19. Spectrum Plan for the MR: 2025-2030

The changes which occur in the 2025-2030 time frame when human missions go to Mars is the evolution of the MR feeder links to the 37-37.5 GHz and 40-40.5 GHz bands. This will separate the MR bands from the direct to and from Earth links in the 31.8-32.3 GHz and 34.2-34.7 GHz bands and provide additional bandwidth for the relay to avoid self-interference from the DTE links.

This MR evolution also includes retaining the UHF band user links and the ***near*** X band links plus the addition of ***near*** Ka band user links.

2.3.5.6. Spectrum Selection for Ranging Applications

Spectrum for ranging and position determination is obtained by the use of appropriately allocated bands contained in the Radio Regulations as prepared by the ITU. Bands identified for ranging and navigation include the SRS, ISS and RNSS and are appropriate for ranging and position determination by space vehicles and platforms.

2.3.5.6.1. Use of SRS Bands

All SRS allocations are usable to support ranging and position determination. The definition of the SRS, contained in the ITU Radio Regulations, is provided below. The definition is so general that it can include almost any application, including navigation, as long as the general condition of using the signal in space for research purposes is met. Examples of the use of SRS (space-to-space) allocations for ranging purposes include the 2025-2110 MHz forward link and the 2200-2290 MHz return link used to provide ranging between TDRSS and low Earth vehicles such as the International Space Station.

2.3.5.6.2. Use of ISS Bands

Ranging and position determination may also use the ISS bands allocated by the ITU that are intended for data transmissions between spacecraft and also support the positioning of space vehicles and humans in both near-Earth and Deep Space applications.

2.3.5.6.3. Use of RNSS Bands

In addition to the SRS and ISS bands, the RNSS bands, which include the GPS L1 signal centered on 1575.42 MHz, the GPS L2 signal centered on 1227.6 MHz and the GPS L5 signal centered on 1176.45 MHz, can also be used for navigation and position determination of space vehicles. The GPS system was established using the L1 and L2 signals for terrestrial use. However, both bands have been used by NASA and others for many years for space-to-space navigation and positioning of human and robotic satellites. All three band allocations were modified at WRC-2000 to include RNSS (space-to-space) service. NASA currently utilizes GPS for space applications and the SCA will continue to use these bands in the future for space applications. There are restrictions due to a footnote in the ITU Radio Regulations on NASA's ability to coordinate with new systems overlaying GPS in the L1 and L2 bands. Also this footnote precludes safety of life use in L1 and L2.

NASA, in concert with the world space science community, plans to improve the regulatory status of the L1 and L2 bands for RNSS space-to-space operation and should plan to utilize the L5 band where the regulatory status is better defined and the higher rate civilian code rate allows improved accuracy. Use of multiple GPS bands by NASA will improve availability and reduce the potential for loss of ranging signals due to interference.

2.3.6. Study Process and Rationale for Spectrum Selection

The SCAWG study process (section 1.8) that utilized FOM selection criteria to decide among the various architecture candidates was not suitable for use in spectrum analysis. Due to the 10 year lead time and complex multi-agency and international processes required to approve changes in spectrum allocations, every effort was made to limit the trade space for key decisions to existing allocations. Specific tradeoffs were identified and studies were conducted on the alternatives available without spectrum allocation changes. Additional alternatives requiring spectrum allocation modifications were considered only where no alternatives met anticipated requirements based on existing allocations.

2.3.6.1. *Assumptions*

The basic assumptions used by the SCAWG spectrum team which enabled selection of specific spectrum for each part of the architecture are listed below.

1. To the greatest extent possible utilize spectrum having a primary ITU and US national service allocation useful to NASA. Allocations useful to NASA include SRS, Space Operations (SO) and ISS. Use of allocated spectrum helps to protect NASA hardware infrastructure investment by providing status and a coordination process if interference occurs to NASA or if NASA operations interfere with other users in the band.
2. Provide NASA users with a choice of two bands. One band provides high reliability TT&C and low rate operational data and a second band provides for high rate mission data. The mission data band is also capable of supporting in-band TT&C and operations data. This dual band approach allows users to pick one or both bands for maximum flexibility.
3. To the greatest extent possible minimize the complexity of user hardware. Users should have the ability to use the same hardware to support their mission from launch and early orbit, to LEO and on to the Moon and beyond if needed.

2.3.6.2. *Spectrum Selection Trade Studies and Rationale*

The following sections discuss the tradeoffs and rationale for decisions on spectrum selections for various types of links in the vicinity of the Earth, Moon, and Mars.

2.3.6.3. *Earth Vicinity and Earth Relay*

Missions operating in LEO are assumed to utilize either a Data Relay Satellite (DRS) or ground station support or both. The ability to use a DRS allows the possibility of continuous coverage for a user mission while the ability to use a ground station allows user coverage when outside of DRS coverage. Current TDRSS coverage is not available continuously above ~30,000 km.

2.3.6.3.1. *S band vs. X band for User Links*

Both S band (2025-2110 MHz forward and 2200-2290 MHz return) and X band (7190-7235 MHz and 8450-8500 MHz) have an allocation to support the low rate, high reliability TT&C function. Both bands are highly reliable when communicating to Earth because they are not attenuated by weather. They are also useful in communicating with a tumbling spacecraft since they allow implementation of omni-directional antennas on the spacecraft. Since X band is not allocated for data relay satellite operation, only S band selection allowed the same user hardware to communicate with ground or a DRS allowing continuous coverage. This band is currently used by missions operating with TDRSS

Seeking a new SRS or SO allocation at X band was assessed as a high risk/low probability of success due to incompatibility with other co-primary users in the X band. Therefore, S band was selected for near Earth TT&C and operations data for the NER and the GEE.

2.3.6.3.2. Ka band vs. Ku band for DRS User Mission Data Services

Currently NASA uses both a Ku band (13.75-14 GHz forward and 14.8909-15.1159 GHz return) service and a Ka band (22.55-23.55 GHz forward and 25.5-27 GHz return) service on TDRSS H, I and J. Both bands are allocated but recent ITU rulings have permitted and encouraged small satellite terminal uplinks to proliferate in the Ku forward link band. Ultimately the presence of these links will interfere with DRS forward links to user satellites operating in this band.

As a result, Ka band was selected for future NER use and Ku band was deleted for the next generation NER.

2.3.6.3.3. S band and Ka Band for Ground Antenna Support

The SCAWG identified a need to provide S band (2025-2110 MHz uplink and 2200-2290 MHz downlink) and Ka band (22.55-23.55 GHz uplink and 25.5-27 GHz downlink) ground antenna support for user missions once they go beyond NER coverage which becomes sporadic for user altitudes above 30,000 km. It was visualized that this ground coverage would extend to the Moon and beyond.

The use of the 22.55-23.55 GHz uplink requires obtaining a new SRS and SO Earth-to-space allocation in the ITU for this band. The current use of this band by the TDRSS utilizes an ISS allocation which does not permit Earth-to-space operation.

NASA has decided to seek the new allocation and proceed with the recommended use of the 22.55-23.55 GHz band for Earth-to-space operation.

2.3.6.3.4. Retention of Ku band Feeder Links for Future DRS Operation

The Ku band feeder links having a 13.4-14.05 GHz uplink and a 14.6-15.225 GHz downlink are currently used by TDRSS and are based on a secondary SRS allocation. Despite secondary status these bands may be the only possible feeder links for a future NER satellite. Other bands, such as are used by ESA for their DRS in the 20 and 30 GHz bands into Europe are restricted to military use in the US by the US footnote G117 in the US Government Allocation Table. At this time there are no other known bands for DRS feeder links which could provide sufficient bandwidth without development of new spacecraft hardware in the 70 GHz region and which could be subject to severe rain fading.

Discussion with NTIA indicates that it would be extremely difficult for NASA to gain access from DOD to the 20 and 30 GHz bands. NTIA also indicates that the current TDRSS downlink bands can be protected from other primary users of the bands at the NASA ground locations at White Sands and Guam through 2030. Since there is no known bandwidth requirement forcing NASA to seek the wider band Ka feeder links at this time, retention of the existing Ku band feeder allocations was recommended.

2.3.6.3.5. W band for Crosslinks between DRS Satellites

The bands 59-65 GHz and 54.25-58.2 GHz are allocated for ISS and were identified by SCAWG as appropriate for NASA use as crosslinks for DRS use. At this time, there is no known requirement for these crosslinks, but in anticipation that such a requirement might emerge, these bands were identified. NTIA has confirmed that NASA may obtain access to these bands.

2.3.6.4. Lunar Vicinity and Lunar Relay Satellites

2.3.6.4.1. Use of S band and Ka band for Lunar Satellite and Lunar Surface Users

Reuse at the Moon of the same bands used by a user satellite or vehicle leaving an Earth orbit environment was identified as a means to reduce user hardware complexity. For this reason, the S band (2025-2110 MHz and 2200-2290 MHz) and Ka band (22.55-23.55 GHz and 25.5-27 GHz) links used by missions in LEO orbit at the Earth were recommended for use in the lunar vicinity for communication to and from the Earth GEE and with the LR.

2.3.6.4.2. Use of X band vs. Ka bands for Lunar Relay Feeder Links

The LR satellites require a separate band for communications to and from Earth to remove the possibility of self-interference on the relay spacecraft. The Ka bands at 37-38 GHz and 40-40.5 GHz were the only bands allocated for SRS space-to-Earth and Earth–to-space below 40.5 GHz with sufficient bandwidth for transmitting broadband data (> 50 Mbps).

Narrowband X band links were considered to back up the Ka links for high reliability data but not included in the final selection. Analysis of the feeder links at Ka band assumed that in the event of a rain fade these links would operate at a reduced rate and operate with a roughly 37 dB rain margin providing a rain fade availability of 99.97%, equivalent to an outage of less than 14 minutes a month at the three DSN sites, removing the need for an X band link.

2.3.6.4.3. Use of Reverse-band vs. Alternate Band Selection for Lunar Relay Crosslinks

To reduce the complexity of the LR spacecraft design, the crosslink concept selected uses the Ka band (40-40.5 GHz and 37.5-38 GHz) feeder link hardware as a crosslink when a relay satellite is obscured from Earth by the Moon. This use requires reverse band operation by the obscured LR satellite to avoid self-interference to the LR communicating with Earth. These bands are only allocated for space-to-Earth and Earth-to-space operation but this crosslink operation is an ISS link that should not pose a threat of interference to or from Earth-based systems and therefore should not present a problem.

The alternate approach would require selection of additional bands (Ku, Ka or W bands) with sufficient bandwidth and separation to prevent self-interference.

Using the existing feeder link bands as a Lunar relay crosslink allows re-use of a portion of the existing hardware, such as the gimbaled antenna on the relay satellites normally used to communicate with Earth to be used as part of the crosslink when the Lunar relay is not visible from the Earth. The re-use of hardware is expected to be a mass advantage and therefore, the reverse-band approach re-using the same Ka bands used for feeder links was selected.

2.3.6.5. Mars Vicinity and Mars Relay Satellites Robotic Phase (2010-2025)

2.3.6.5.1. Use of UHF band for Mars Satellite and Mars Surface Users

The UHF bands at 435-450 MHz and 390-405 MHz are not allocated but are currently used at Mars with a Mars relay satellite that communicates directly with Earth in an allocated band. Due to the large path loss to Earth, Mars is isolated from the Earth and no interference occurs from Earth or to Earth allowing this non-allocated operation near Mars. The UHF band is also attractive since it permits use of low mass, power and cost omni-directional antennas on the surface user or Mars orbiter.

2.3.6.5.2. Use of X band and Ka band for DTE/DFE Communications via Mars Relay Satellite (feeder links), Mars User Satellite and Mars Surface User

Currently, X band (7145-7190 and 8400-8450 MHz) and Ka band (34.2-34.7 GHz and 31.8-32.3 GHz) are allocated and are currently used for direct communication with earth for Deep Space missions. There are no issues with use of these bands. Continued use of these bands is recommended.

*2.3.6.5.3. Use of **Near** X band and **Near** Ka band for Surface User and Orbital User Links to Mars Relay*

Use of the same hardware used for Deep Space communication with Earth for communicating with the MR was identified as a means to reduce user hardware complexity. The large path losses between Earth and Mars and the resulting weak signal levels increase the possibility of interference and require shifting the orbital user and surface user frequency needed to communicate with the relay away from the allocated bands used to talk directly with Earth. The use of ***near*** X band (***near*** 7145 - 7190 MHz and ***near*** 8400-8450 MHz) and ***near*** Ka band (***near*** 34.2-34.7 GHz and ***near*** 31.8-32.3 GHz) was studied to achieve this objective. Since the ***near*** frequencies are used only in the vicinity of Mars there will is no possibility of interference with Earth systems due to using these unallocated ***near*** bands.

The ***near*** bands have not been specified but are expected to be close enough to the allocated bands for DTE/DFE communications so that the user hardware used for communicating with the relay has only a minimal frequency offset to talk to the relay satellite, allowing re-use of the same hardware used to talk to the Earth.

2.3.6.6. Mars Vicinity and Mars Relay Satellites – Human Phase (2025-2030+)

The change anticipated during the human exploration phase is to move the feeder links on the Mars relay from 31.8-32.3 GHz and 34.2-34.7 GHz to the 37-37.5 GHz and the 40-40.5 GHz bands. The selection of this new band for the feeder links on the Mars relay doubles the available bandwidth for Mars in the human exploration phase from 500 MHz (31.8-32.3 GHz) to 1 GHz (31.8-32.3 GHz from the Mars surface-to-Earth and 37-37.5 GHz from the MR-to-Earth) to accommodate both human and robotic missions.

2.4. Navigation and Time Architecture

2.4.1. Overview of the Navigation and Time Architecture

The navigation architecture combines mission application level functions for determining position, planning trajectories, and executing maneuvers with infrastructure functions that provide tracking and timing data supporting those mission level applications. The Navigation architecture provides for radiometric tracking services that are available via space relays and ground terminals along with communication services for all users. In addition, the navigation architecture relies on GPS capabilities for those user missions in Earth orbit to GEO needing either high precision orbit determination or low cost, continuous, autonomous position determination. The navigation architecture relies on techniques and methods already established. However, the architecture extends the existing navigation services throughout the overall communication architecture. Tracking services are extended to provide new methods of two-way measurements that are originated by user spacecraft. As an evolution from the current capabilities for disseminating time, the architecture features a single, standard time scale for NASA space applications across the solar system that is interoperable with the existing Earth-based infrastructure, comprising the GPS, the Ground-based Earth, Near-Earth Relay, Lunar Relay and Mars Relay Elements.

2.4.2. Top Level Requirements

Navigation services begin in the pre-launch phase and continue through final landing and recovery of human missions or sample return missions, supporting all required operations in the process. Services required for missions include: radiometric data; delta-differential one-way ranging (ΔDOR); orbit determination; trajectory analysis; maneuver planning and design; natural body ephemeris; modeling and calibration of tracking; gravity modeling; cartography; navigation ancillary data; and time dissemination and synchronization.

Key navigation and time requirements include:

1. Provide required navigation services from the surface of Earth to selected locations at the farthest outer planet distances
2. Provide required navigation services for mission phases from launch and early orbit through end of mission
3. Provide standard radiometric tracking measurements for all Constellation Architecture flight elements using Space Network signal formats
4. Provide one-way radiometric ranging with GPS interoperability
5. Provide continuity of navigation service while crew is aboard a CEV
6. Provide navigation aids that support overall navigation performance as shown in Table 10. Note: The allocation of top level navigation performance to specific requirements for navigation aids by element is still in progress.
7. Report component state vectors with less than 2 s latency discounting transit delay
8. Standardize time dissemination across all elements of the SCA

- Provide a Common NASA Timescale (CNT) synchronized with Coordinated Universal Time (UTC) as provided by the National Institute of Standards and Technology, known as UTC(NIST), modulo one second

9. Provide time transfer with performance comparable to GPS
   - Time transfer capabilities should be evolvable through a new or improved time code format to an accuracy of 10 ns
10. Support interoperability with GPS and the Global Differential GPS (GDGPS)
11. Provide Mars network time service with 1 msec time distribution accuracy with respect to UTC(NIST) (by 2015)

Table 10. Key Navigation Performance Requirements

Capability Needed (3-sigma)	3-D Position	3-D Velocity
Surface Operations	30 m	To Be Deter-mined (TBD)
Global Surface Operations	30 m	TBD
Relay Spacecraft	10 m (1-sigma) reconstructed (To Be Reviewed - TBR); 100 m (1-sigma) predicted (TBR)	TBD
Non-precision Landings	5 km @ landing	
LSAM Landings	1 km (unaided) and 100 m (aided)	
Precision Landings	100 m @ landing	
RLEP Landing	50 m with short latency (post processing)	
Surface Rendezvous	10 m @ landing	TBD
Ascent (surface location)	10 m @ liftoff	Not a Driver
Rendezvous (@ relative navigation initiation)	500 m (relative)	10 cm / s (relative)
Docking and Berthing (assuming inertial navigation available as backup)	1 km	50 cm / s
In-space Servicing (assuming inertial navigation available as backup)	1 km	50 cm / s
Constellations[1]	100 m (absolute)	10 cm / s
Formation Flying[1]—coarse	10 m (relative)	3 cm / s
Formation Flying[1]—precision	3 m (relative)	3 mm / s
Formation Flying[1]—very high precision	3 cm (relative)	0.03 mm / s
Libration Point Stationkeeping	50 km	2 cm / s
Fly-bys, Impulsive Transits	TBD	TBD
Fly-bys, Low-thrust Transits	TBD	TBD

[1] A constellation, i.e. a cluster of spacecraft, requires absolute position and velocity knowledge with respect to Earth. Constellations that require formation flying, i.e. maintaining precise offsets between spacecraft, have requirements for position and velocity relative to each other.

2.4.3. Navigation and Tracking Concept of Operations

The radiometric tracking capability utilized for navigation is incorporated directly into the networks at the Earth (GEE and NER), Moon (LR), and Mars (MR), including the surface and orbiting relay elements at these locations. The GPS is also used at the Earth. Measurements made onboard mission spacecraft including celestial objects, inertial measurements, relative measurements, and landmark tracking, though not provided by the tracking infrastructure, are critical components of the navigation architecture.

This section describes the navigation data types available to users operating over a range of representative flight regimes. The architecture allows users to augment infrastructure capabilities with specialized infrastructure or tracking capabilities to meet unique mission needs.

Missions having very loose navigation requirements can utilize state estimates generated by passive radar tracking of the vehicle, for example North American Air Defense (NORAD)-generated, two-line element sets. This navigation capability is available to all near-Earth spacecraft. The achievable accuracy of these states varies greatly, typically from a few kilometers to hundreds of kilometers.

For spacecraft with tighter navigation requirements, radiometric tracking data may be recorded either on the ground or onboard the vehicle, during dedicated tracking passes with ground stations or contacts with orbiting networks, and then processed to generate more precise vehicle state estimates. These states may be uploaded to the vehicle and propagated onboard for operational use.

Missions have the option to augment these fundamental tracking modes by incorporating additional capabilities onboard the spacecraft. Examples include incorporation of a GPS receiver, a crosslink transceiver, or other sensors for making relative measurements between the spacecraft and other objects or vehicles.

In the various regions of space of interest to NASA, navigation requirements, as well as available data types, are different. Navigation data types appropriate to various mission phases or regions of space are shown in Table 11. The navigation architecture provides the navigation data that are used for processing by these data types.

2.4.4. Navigation Method Alternatives

A series of navigation alternatives were studied. These included one-way, two-way, and autonomous navigation techniques, supported by an extensive set of analyses defining a combined communications/navigation architecture that provides navigation support beyond the Earth. The one-way navigation concept explores the possibility of using a one-way navigation signal similar to GPS. The current GPS could provide navigation information from the near-Earth environment to the Earth-Moon Lagrange point L1. This concept is a synergistic approach that could provide seamless navigation, positioning, and timing, in the Earth-Moon system that utilizes and extends existing infrastructure. The two-way navigation concept could also be interoperable with GPS during transit between the Earth and the Moon.

The navigation architecture includes an option for autonomous navigation. The autonomous system for in-space vehicles utilizes only periodic updates from external radiometric sources. The autonomous component for lunar surface operations could consist of a traverse vehicle wheel odometer, gyro and attitude initialization sensor, lunar feature map, map "benchmark" point, and video camera.

Table 11. Navigation Data Types and Mission Phases

Mission Phases	Navigation Data Types
Launch/Ascent/ Entry/LEO	Launch/Ascent supported by angles-only tracking
	Space-Based Range using GPS and NER
	Entry/LEO supported by Earth-based range/Doppler and GPS pseudo-range
LEO to GEO altitudes	Earth-based range/Doppler
	NER range/Doppler
	GPS pseudo-range and data message
Beyond GEO altitude to Cislunar Space up to Earth-Moon La-grange Point (L1)	Earth-based range/Doppler
	GPS pseudo-range and data message
Lunar Vicinity Navigation	Earth-based range/Doppler can meet needs for all orbiting users
	Lunar-orbiting range/Doppler can meet needs for other orbiting users
	Lunar-orbiting range/Doppler is adequate for surface users given a certain latency with user burden constraints
Mars Vicinity	Earth-based range/Doppler can meet needs for all orbiting users
	Mars-orbiting range/Doppler can meet needs for other orbiting users
	Mars-orbiting range/Doppler is adequate for surface users given a certain latency with user burden constraints
	Mars-orbiting range/Doppler is required for precision approach and landing
Deep Space Navigation	Earth-based range/Doppler and Very Long Baseline Interferometry (VLBI) data types

The proposed navigation alternatives should be integrated in a way that maximizes performance for a given user mission. For instance, although a vehicle autonomous navigation system could determine and provide all required navigation data for intervals of time, past experience indicates its performance may be inadequate unless supplemented with planned vehicle position and velocity vector initializations via radiometric tracking solutions.

The regions of navigation in the Earth-Moon environment are shown graphically in Figure 20.

2.4.5. Tracking Infrastructure

The navigation architecture provides integrated Doppler and range tracking at both ground terminals (at Earth, Moon, and Mars) and orbiting relays (at Moon and Mars) supporting the formation and measurement of radiometric data. The architecture supports both one-way and two-way radiometric measurements. The flexible architecture allows these measurements to be made using many signaling schemes. As shown in Figure 21, techniques implemented in the navigation architecture include:

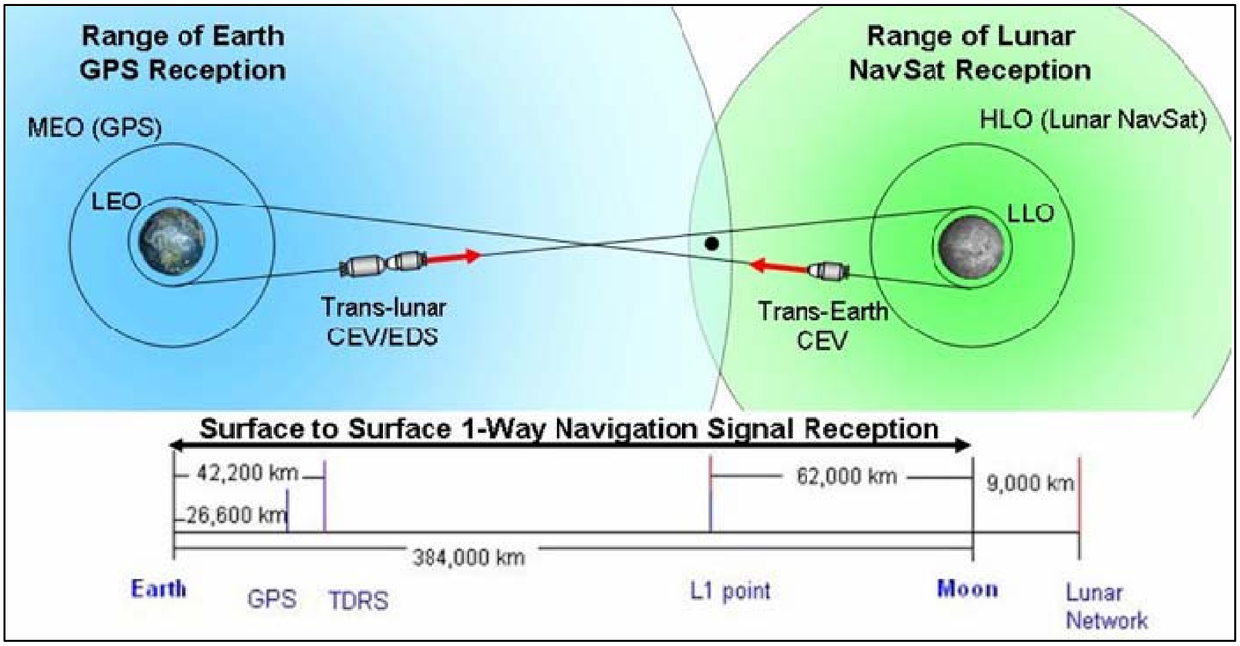


Figure 20. Earth-Moon Regions of Navigation

1. Two-way measurements originated by the user and transponded by an infrastructure element (ground terminal, relay orbiter, or surface beacon), a mode of operation that yields the highest accuracy data with the least latency. The user spacecraft may also telemeter the data to Earth for post-processing. As discussed below, time-transfer by means of two-way radiometric ranging is accomplished by registering the time of the received signal at the transponder and processing with the round-trip light-time measurement made by the active ranging system. This new capability fosters increased spacecraft autonomy; however, it requires communicating knowledge of the infrastructure element position and velocity to the user.
2. Two-way measurements originated by an infrastructure element (ground terminal, relay orbiter, or surface beacon) and transponded by the user. The transceiver collects the radiometric data and telemeters it to the Earth for post-processing or, in the case of real time operations, to the user for near real time navigation updates. This mode of operation yields the highest accuracy with only modest increase in latency relative to user-initiated, two-way measurements.
3. One-way measurements originating from an infrastructure element and taken by the user. This mode of operation yields sufficiently accurate data as long as both the infrastructure element and the user generate their signals using ultra-stable

oscillators. The latency of this data is equivalent to the 2-way case that is initiated by the user.

4. One-way measurements originating from the user and taken by the infrastructure element. As with the previous option, this mode of operation requires ultra-stable oscillators for the data to be useful. This new option fosters increased spacecraft autonomy but introduces the greatest latency, and may even eliminate the ability of the user to get the data and process in-situ.

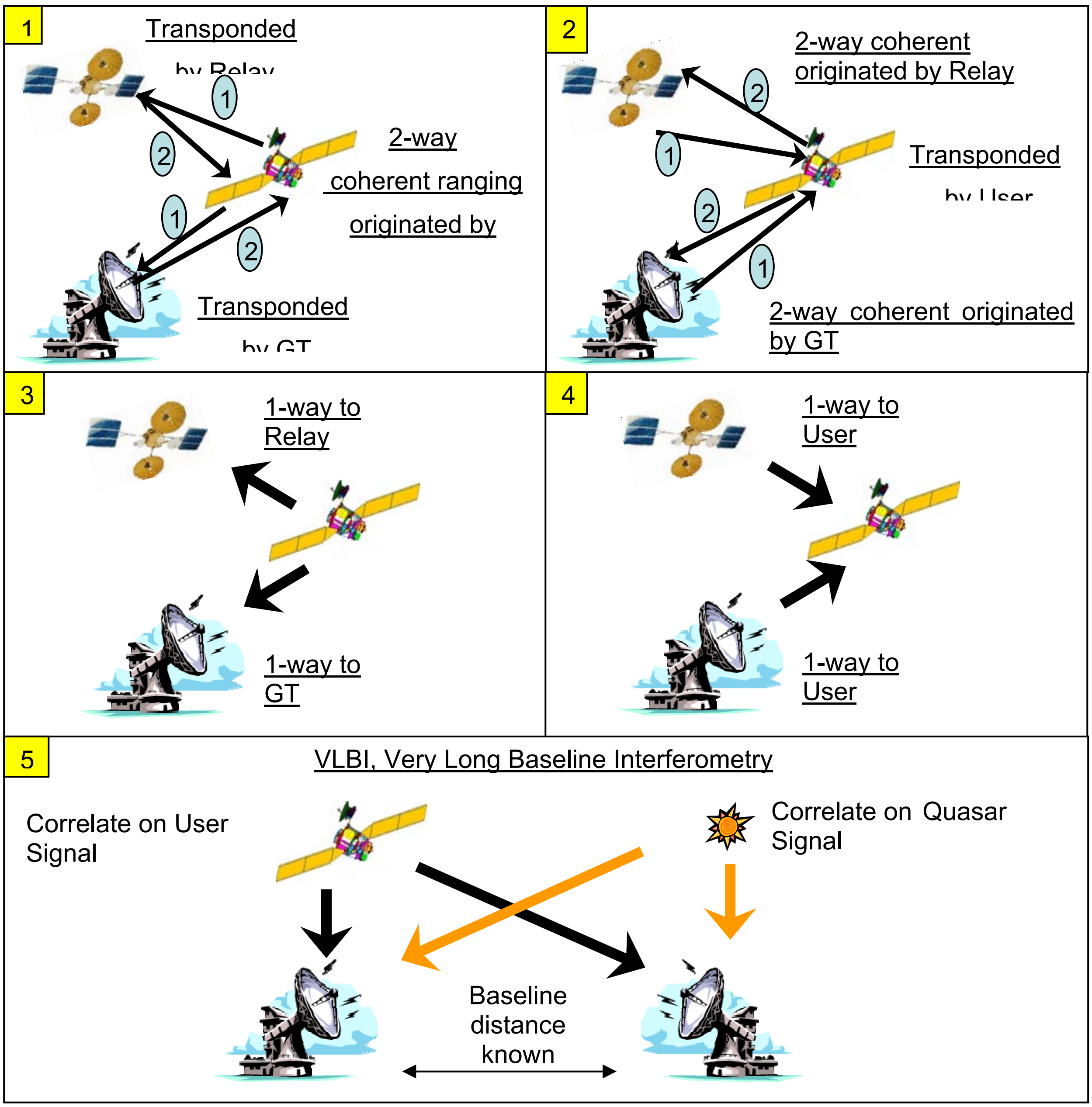


Figure 21. One Way and Two Way Radiometric Tracking Architecture

5. The Earth-based navigation infrastructure provides a capability to formulate Very Long Baseline Interferometry (VLBI) measurements to user spacecraft, in particular,

Delta Differential One-Way Range (ΔDOR). This technique requires a database of celestial objects (e.g., quasars), the specific radio frequencies employed, and user transponders capable of forming DOR-tones.

2.4.6. Utilization of GPS

Many missions are able to satisfy their navigation requirements using the radiometric capabilities that are built into the communications provided by the four elements of the Space Communication Architecture. Missions may decide to use GPS, either in addition to or in place of communications channel tracking. For these missions, use of GPS is recommended as the primary alternative for space vehicle navigation in Earth vicinity as far as GEO. GPS may also be used for navigation during launch (under the SBR concept) and re-entry flight phases. Beyond GEO altitude GPS is recommended as a supplemental means of navigation to improve the performance of other methods, including ground-tracking, two-way communications channel tracking, autonomous navigation, and celestial navigation (see Figure 22).

Navigation up to GEO altitude has been shown to be feasible by analysis and hardware-in-the-loop tests. Advantages of using the GPS include precision, real-time state determination, autonomy, robustness, independence from terrestrial infrastructure, and cost effectiveness. Navigation beyond GEO requires GPS receiver architectures specialized to this application as a supplemental means of navigation. Key features of such receivers include: enhanced acquisition and tracking algorithms; integrated, extended Kalman filters, clock models, and Ultra-Stable Oscillators (USO).

The decision by user missions to use the GPS can be determined by their required mission orbit and navigation precision which can be divided into four categories:

- *Standard Users (LEO to GEO):* The standard space borne GPS receiver processes GPS data onboard in a navigation filter and generates a state vector (ephemeris and clock) onboard. The vehicle ephemeris is contained in vehicle telemetry or communicated directly to cooperative vehicles as needed. GPS measurements (primarily pseudorange and carrier phase) are optionally broadcast to ground for post-processing. GPS estimated state vectors may or may not be actually used onboard without ground-in-the-loop depending on the application. The receiver optionally produces a "point solution" (if available) for fault detection purposes.
- *Highly Elliptical Orbit (HEO) Users:* Standard GPS receivers are inadequate for certain space applications such as HEO defined here as those with apogees up to 12 Earth radii. Specialty GPS receivers designed for such applications permit using GPS without reliance on other navigation methods. Enhancements to these specialty receivers include dynamic solutions, improved orbit models, advanced satellite selection algorithms, tailored Doppler search patterns, special tracking loop designs, and collection and buffering of data. Examples of such NASA-engineered GPS receivers include the GSFC Geomagnetic Event Observation Network by Students (GEONS) and Navigator.

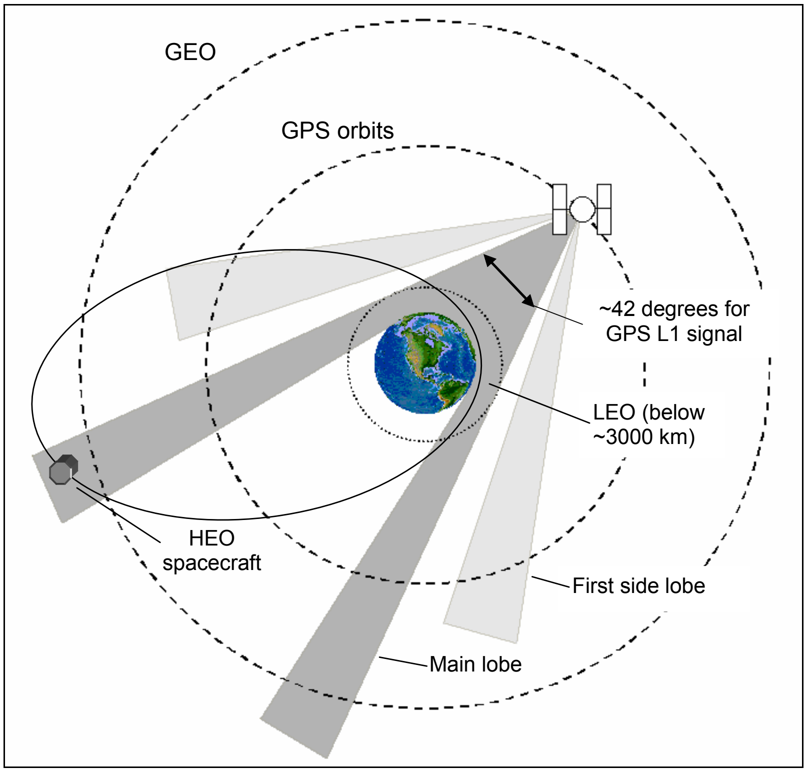


Figure 22. GPS Use for Navigation in Various Orbits

- *Precision Space Users:* A precision user may utilize a similar approach but with the onboard GPS solution augmented with Global Differential GPS. The GDGPS network consists of 70 dual-frequency GPS reference stations operational since 2000. The NER Element disseminates the GDGPS real-time differential correction message to Earth satellites enabling precise autonomous orbit determination, science processing, and the planning of operations in Earth orbit.[4]
- *Human Missions:* At the time of this report, the Constellation Program is evaluating usage of GPS on the CEV. A notional approach for the use of GPS if adopted for human missions is, due to crew safety considerations, to retain the primary navigation functionality through ground-in-the-loop. The onboard navigation functionality would be used in instances where ground tracking may be unavailable or be unable to provide real-time support, such as for rendezvous and docking, powered descent/landing, and abort/contingency scenarios.

2.4.7. Time Synchronization and Dissemination

The time synchronization and dissemination architecture uses a uniform time scale, a unit interval of one second as defined in the International System of Units (SI), and time dissemination traceable to an internationally recognized terrestrial time scale (e.g., UTC modulo 1 second to remove issues associated with leap seconds). This single time scale for system-wide NASA space exploration applications is interoperable with the

[4] The NER incorporates the TDRSS Augmentation Service Satellites (TASS) capability.

existing Earth-based infrastructure and GPS, as well as internationally recognized atomic time scales used for civil and scientific timekeeping.

The time and frequency dissemination architecture is based on five essential ingredients: (1) clocks; (2) timescales; (3) mathematical algorithms; (4) fabrication and calibration of hardware interfaces; and (5) a communication link. The dissemination and transfer of time between remote clocks and spacecraft time registration hardware requires recognition of the appropriate principles of theoretical physics, including general relativity.

The basic elements of a common NASA timescale will be: (1) clocks, (2) measurements of the proper time differences among clocks, (3) relativistic transformations of the local clock readings, (4) formation of the timescale using transformed clock observations, (5) dissemination of individual clock offsets to the common timescale, and (6) synchronization of individual clocks to the common timescale. It is necessary to distinguish between the formal definition of the timescale and a particular realization of the timescale as given by an individual laboratory. Time comparisons may be made via dedicated terrestrial links, satellites, communications links, networks, or the GPS.

Clocks based on both Ultra-Stable Oscillators (USO) and Atomic Frequency Standards (AFS) are used for deep space navigation and, increasingly, for near-Earth missions. USOs are integrated on deep-space satellites, and multiple USOs and/or AFSs can be deployed at each GEE site. Initially GEE sites covering deep-space missions have this capability; eventually GEE sites for near-Earth missions will require the capability. The GEE sites are synchronized to the common time reference to accommodate hand-over from one GEE site to another and to maintain interoperability between NASA missions and correlation of mission data with other scientific research.

The architecture accommodates time-transfer by any of several means. As shown in Figure 23, two-way radiometric ranging is the basis for one such method. Two-way ranging, along with time registration of the received signal at the transponder (Measurement 1) and a round-trip light-time measurement made by the active ranging system (Measurement 2), provides enough information to extract relative clock bias data. A relative velocity input is needed when there is relative motion. Other potential time-transfer methods (requiring further study) include Network Time Protocol (NTP) as used on the Internet, IEEE 1588 (a clock synchronization protocol for networks), and a hybrid architecture using the best features of any of these and/or different but compatible protocols for distinct applications and regions of space. The time transfer processing can be accomplished at either point with the exchange of measurements. Appropriate relativistic corrections are required in the processing of precise time applications.

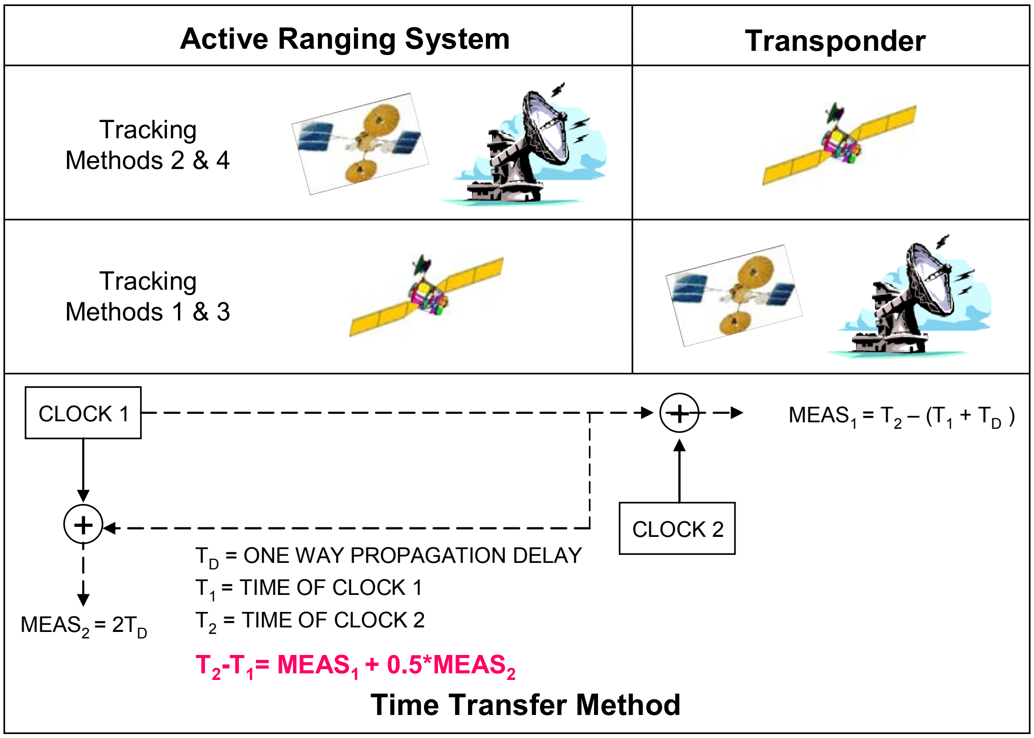


Figure 23. Two-way Radiometric Ranging Modified for Time Transfer

2.4.8. Allocation of Navigation Functions between Missions and Infrastructure

The Navigation Architecture allocates functions between user missions and the SCA which provides the common infrastructure. The infrastructure in each of the four elements (GEE, NER, LR, and MR) provides a combination of physical navigation aids (e.g., radiometric tracking signals and time transfer) as well as navigation services (e.g., support for orbit determination, trajectory analysis, maneuver planning and design; natural body ephemeris; modeling and calibration of tracking; gravity modeling; and navigation ancillary data) that assist programs in designing and operating their missions. This provides users with a high degree of flexibility in determining whether to maximize reliance on infrastructure-provided capabilities or develop unique capabilities to meet mission requirements.

Navigation functionality may be concentrated at a single point or may be distributed among infrastructure elements, depending upon the policy for use of navigation-related information. The location of the control authority governing decisions concerning future vehicle trajectories is one example of a factor playing into this aspect of architecture. The navigation infrastructure supports traditional performance of navigation on the ground, but also supports performance of navigation on board vehicles as we move towards increasing vehicle autonomy.

2.4.8.1. Ground-based Navigation

Basic navigation functions such as orbit determination, ephemeris prediction, maneuver planning and evaluation are nominally performed by mission-specific "Mission Operations Centers" or MOCs. Navigation services are provided on the ground by the Space Communication elements for their users. These services enable NASA to reduce overall costs by capturing commonly used capabilities and improving them over time for the benefit of all missions.

2.4.8.2. Onboard Navigation

Mission designers determine based on mission phase when their spacecraft should provide its own onboard, autonomous navigation and when the ground- or space-based navigation infrastructure should provide primary navigation. Those phases requiring real-time navigation (typically integrated with guidance and control) are primarily autonomous navigation regimes. Real-time guidance, navigation, and control is required during final approach/entry/descent/landing, launch/ascent, rendezvous/docking, and surface roving. In these mission phases the navigation data sources include autonomous vehicle sensors such as Inertial Measurement Unit (IMU), radar, LIght Detection And Ranging (LIDAR), and altimeter as well as radiometric measurement data from orbiting relays or ground terminals. Figure 24 shows some of the options directly supported either by aids within the navigation infrastructure or by user-unique methods allowed for mission flexibility. Mission designers can formulate a navigation approach that integrates the entire suite of data sources including GPS for real-time use. Options for using radiometric data generated onboard include direct onboard use, inclusion in telemetry to the ground, and transmission directly to cooperative vehicles.

2.4.8.3. Software Defined Radios

The use of Software Defined Radio (SDR) technology is allowed in the Navigation Architecture providing an option for integrating autonomous navigation sensor data and radiometric data. One approach uses an SDR, a common clock, and a navigation computer to provide a flexible and robust strategy for autonomous navigation capable of performing two-way and one-way integrated Doppler and range that can be integrated in real-time (or near real-time) and disseminating position, velocity, and time for onboard guidance as well as downlinked telemetry.

2.4.9. Architecture Options Considered

2.4.9.1. Identification of Alternatives

For lunar communications analysis, an initial list of 50 proposed relay alternatives was grouped into seven classes with each class represented by a single constellation or station location (see section 3.3.3). For lunar navigation, these same seven cases were analyzed. These constellations provide continuous global coverage of the lunar surface and included:

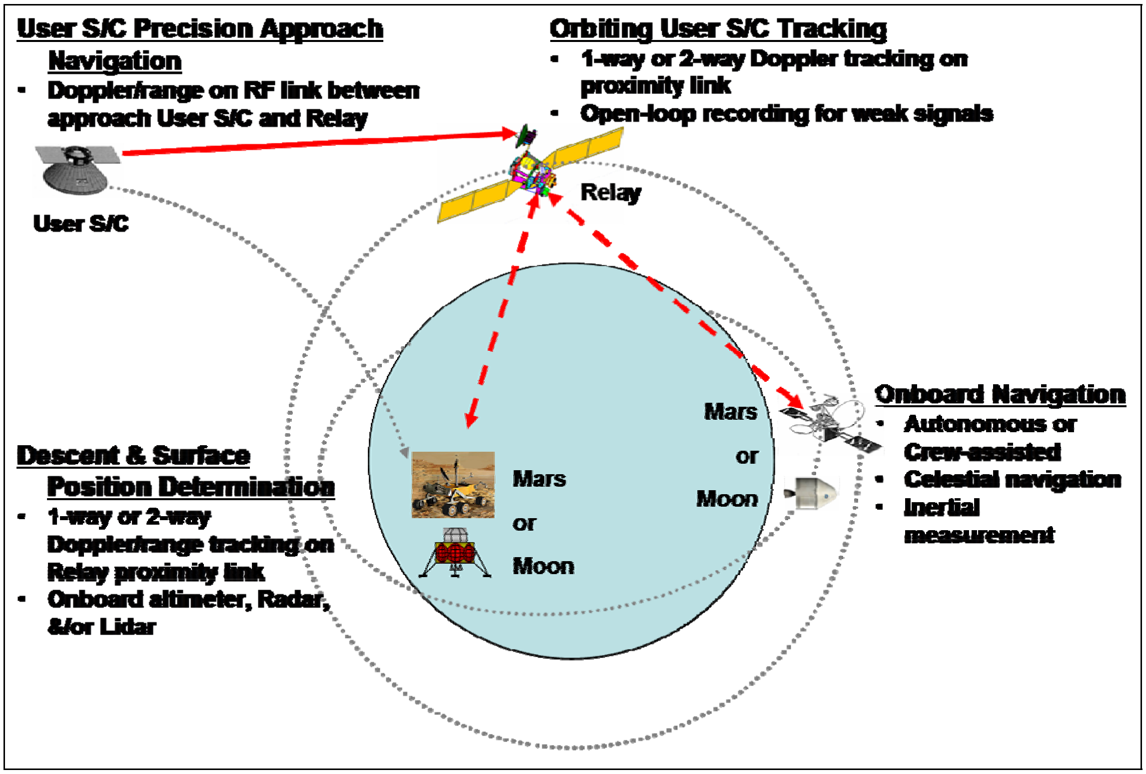


Figure 24. Infrastructure-aided and Onboard Navigation Options

- Multiple plane circular polar orbits (6/2/1, 8/2/1, 12/4/1)
- Standard Walker inclined orbits
- Lang-Meyer constellations
- Highly elliptical orbits

Subsequently a few additional constellations addressing a "cover-where-you-go" paradigm were formulated and analyzed. These latter are repositionable constellations intended to offer full coverage of a mission location over a given time period, as opposed to covering the entire lunar surface on a continuous basis. Study of repositionable constellations was interrupted prior to completion, and the constellations were never subjected to any FOM-based evaluation. Repositionable, or "cover where you go", constellations that provide regional coverage included:

- Constellations of two or three repositionable satellites in various orbits
- A five-satellite constellation, consisting of three satellites in a circular equatorial orbit and two in a polar elliptical orbit

2.4.9.2. Analysis of Satellite Constellations for Lunar Navigation

2.4.9.2.1. "Cover Where You Go" Constellations

If one could save on the number of satellites, it might make sense to bias the coverage towards the hemisphere in which the coverage zone lies and sacrifice some coverage in the opposite hemisphere. This observation takes us back to the polar coverage problem, since the equatorial regions are handled by an equatorial orbit. In developing lunar South Pole constellation alternatives, it was shown that one pole can be covered from a single inclined elliptical orbit of two or three satellites, and that the inclination can be chosen to achieve a "frozen" orbit that makes minimal maintenance demands over a multi-year period. If it were desired to switch this orbit to cover the opposite pole, the satellites could be repositioned within the orbit to do so, at a delta velocity (ΔV) cost quantified subsequently.

Given a two-satellite configuration that can continually cover a pole of choice, the addition of a three-satellite configuration in circular equatorial orbit results in a five-satellite configuration that provides continuous coverage over the lunar surface excepting one polar region, as shown conceptually in Figure 25. The constellation can be reconfigured to cover the other pole by modifying the orbits of the two polar satellites.

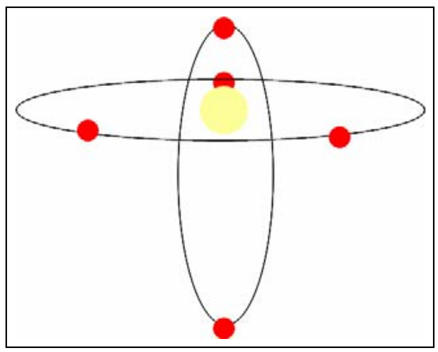


Figure 25. Five-Satellite Constellation Configured for South Pole Emphasis

2.4.9.2.2. Alternatives for Full Lunar Surface Coverage

To provide the greatest flexibility with a more robust constellation design, a constellation of satellites might be considered that would provide continuous, full coverage of the lunar surface. The properties of polar constellations with two planes and six satellites or eight satellites are given in Table 12.

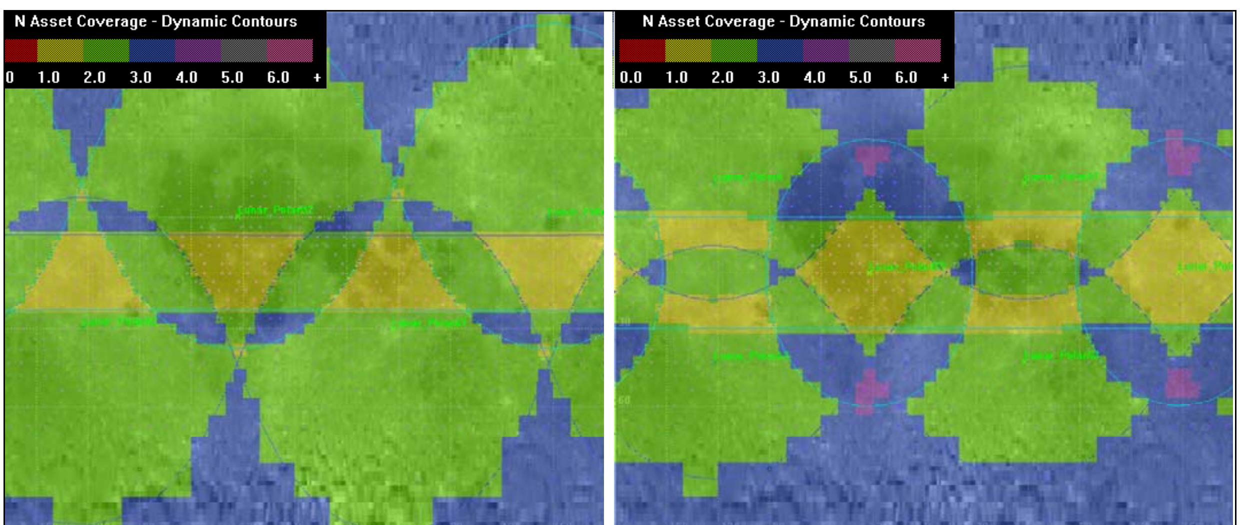
A comparison of the levels of surface coverage provided by the Polar 6/2/1 and Polar 8/2/1 lunar constellations is illustrated in Figure 26. Continuous, 100% lunar global coverage can be achieved with six satellites. An enhanced level of coverage can be achieved with a constellation of eight satellites. Eight satellites would provide a measure of redundancy to maintain a minimum of six satellites for full coverage. There is a potential tradeoff between a constellation of eight single-string satellites and a constellation of six dual-string satellites with greater reliability.

2.4.9.3. Analysis of Satellite Constellations for Mars Navigation

For the vicinity of Mars there are options for constellation not available for lunar exploration. Two satellites in orbit about Mars in areostationary orbit could provide both communications and navigation capability (Figure 27). A receiver supplemented by a stable clock and a terrain database could achieve real time position and time determination. The areostationary orbit is the Mars equivalent of a geostationary orbit where the period of rotation of the satellite and the planet are equal. The radius of an areostationary orbit is 20,427 km.

Table 12. Polar Orbit Constellations (shown for 4 representative orbit radius sets)

Parameter	Polar 6/2/1				Polar 8/2/1			
Number of satellites	6				8			
Number of planes	2				2			
Satellites per plane	3				4			
Phasing between planes	60°				45°			
Inclination	90°				90°			
Central angle	69.3°				60°			
Elevation angle at Edge of Coverage	0.0°	4.2°	6.3°	9.3°	0.0°	10.9°	13.9°	16.1°
Half cone angle	20.7°	16.6°	14.4°	11.4°	30.0°	19.1°	16.1°	13.9°
Orbit radius (km)	4917	6085	6946	8685	3476	5216	6084	6951
Orbit radius / Lunar radius	2.83	3.50	4.00	5.00	2.00	3.00	3.50	4.00
Period of revolution (hour)	8.59	11.83	14.43	17.27	5.11	9.39	13.02	14.45



(a) Polar 6/2/1 Coverage (b) Polar 8/2/1 Coverage

Measured as the minimum # of satellites providing coverage over 1 month/unit area

Figure 26. Comparison of Coverage Level for Polar 6/2/1 and 8/2/1 Constellations

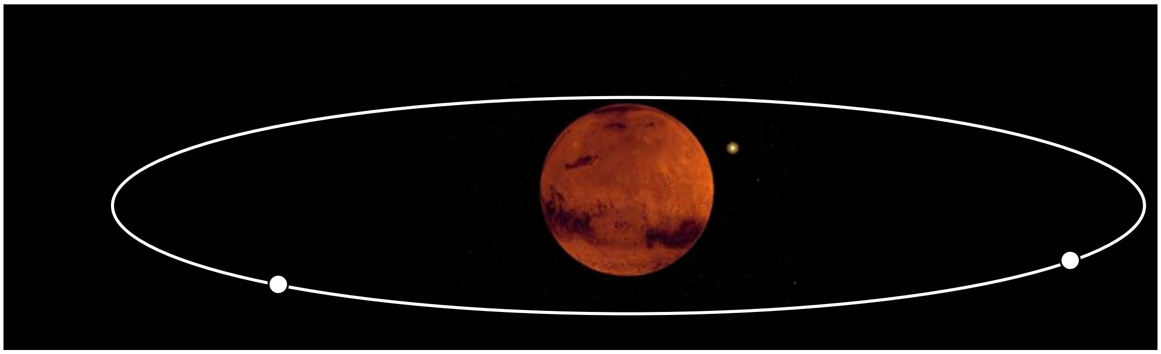


Figure 27. Two Satellites in Areostationary Orbit

Two areostationary satellites could provide ranging data to fixed or mobile receivers on the surface of Mars either by means of a pseudorandom noise code or a two-way communications channel. If the ranging measurements were supplemented by a database of terrain elevations – coupled with timing data using a stable clock, such as an Ultra Stable Oscillator (USO), a cesium atomic clock, or rubidium atomic clock – then real time precise position determination could be achieved.

2.4.10. FOM Definition, Analysis and Conclusions

2.4.10.1. Lunar 2015

All constellations proposed for the Lunar 2015 architecture were categorized with regard to navigation by a single FOM, *Navigation Utility*, which measures the Geometric Dilution of Precision (GDOP) encountered in making an instantaneous position fixed based on navigation signals transmitted to and/or received from the visible satellites for a user within the South Pole exploration region (80-90^{o} S Lat).

Table 13 shows the FOM scores for Navigation Utility as well as the total point scores using all the FOMs (other FOMs not shown). With regard to navigation alone, the chosen constellation would have been the 70^{o}-inclined circular orbit. The elliptical constellation scored a close second. In the overall evaluation, however, the elliptical scored higher and was thus recommended as the Lunar 2015 constellation. No independent navigation recommendation was made.

Table 13. Navigation Utility FOM scores for the Lunar 2015 Evaluation

FOM	Case:	1	7	8	18	24	34	36
	Weight	Elliptical	Hybrid	Inclined	L1	L2	Malapert	Circular
Navigation Utility	0.08	8.06	0.63	8.32	0.24	0.24	0.24	5.39
TOTAL POINTS	**1.00**	**67.60**	**46.83**	**64.40**	**46.23**	**47.86**	**36.79**	**61.63**

2.4.10.2. Lunar Full Coverage

The FOMs used in the Lunar Full Coverage analysis were: Failure Tolerance; Scalability; Crosslink Complexity; Evolvability; Adaptability; Delta-V; Visibility/ Coverage; Navigation System Availability; and Navigation System Latency. Data metrics corresponding to most of these FOMs were collected and analyzed, but a formal FOM-based scoring process was carried out for only a subset of these (see Table 14).

Table 14. FOM Summary for Navigation with Full Lunar Coverage

FOM	Hybrid 4/2/1 + 3	Walker 5/5/1	Lang-Meyer 4/4/1+2	Polar 12/4/1	Polar 6/2/1	Polar 8/2/1	Walker 6/2/0
2-fold coverage	8.5	5.8	8.7	10	8.1	9.2	7.7
Total ΔV	8.0	8.5	7.8	7.4	7.4	7.4	8.1
Crosslink Complexity	5	8	7	8	10	9	10
Composite Score	**21.5**	**22.3**	**23.5**	**25.4**	**25.5**	**25.6**	**25.8**

The conclusion if full and continuous lunar coverage is required, when considering all the inputs from the one-way and two-way studies, is that the Polar 8/2/1 is the recommended constellation, with the additional satellites over the Polar 6/2/1 acting as 'operable' spares.

The “cover-where-you-go” constellations were assessed qualitatively and not ranked. The conclusions were:

- Constellations of two or three repositionable satellites in various orbits can provide local coverage of exploration regions for mission durations of one to two weeks at a modest ΔV cost.
- A five-satellite constellation, consisting of three satellites in a circular equatorial orbit and two in a polar elliptical orbit can provide full and continuous coverage of the lunar surface from either pole up to latitudes of 40° in the opposite hemisphere, while providing high availability connectivity to Earth including continuous coverage of one pole.
- Constellations containing six or eight satellites can provide increased coverage area, availability, and redundancy, as well as improved navigation services. Among those lunar options studied, the polar six-satellite, two orbit-plane constellation has the smallest number of satellites capable of providing global coverage with low latency (15 minute) position fixes.

2.4.10.3. Mars Coverage

No FOM-based evaluation of Mars constellations was undertaken.

2.4.10.4. *Surface Navigation*

No FOM-based evaluation of alternative autonomous architectures was undertaken. With regard to Earth-based ranging for lunar surface position determination, the Navigation Team concluded that positioning of a lunar-surface asset using Earth-based radiometric tracking *on any terrestrial baseline* is insufficient for computing a timely position fix to support near real-time operations (within ~1 hour). Accomplishing such positioning from a single Earth station is probably infeasible in any case. Use of a wider baseline, e.g., two TDRS S/C provides improved angular separation (smaller Positional Dilution of Precision), possibly at the expense of greater uncertainty in the measurement platform locations.

2.4.10.5. *Near Earth Navigation*

A qualitative analysis was performed to determine GPS performance in various near-Earth regions of space. In those regions where the predicted performance did not meet the draft SCAWG requirements, use of GPS as primary navigation source was not recommended.

3. Architecture Element Descriptions

The following sections review the four primary elements of the architecture: the Ground-based Earth Element, the Near-Earth Relay Element, the Lunar Relay Element, and the Mars Relay Element.

3.1. *Ground-based Earth Element*

3.1.1. Overview of the Ground-based Earth Element

The GEE is the collection of the Earth-based communications assets that support NASA's near Earth and deep space missions except those LEO/GEO missions supported by the Near Earth Relay network. In terms of functional scope, it is equivalent to the sum of the present GN and DSN—including all ground-based antennas that are shared among multiple missions. The evolution of the GEE is depicted in Figure 28. Assets within the element support an array of mission types and transition to an architecture that includes dedicated stations supporting polar, launch head, and other LEO-GEO and near Earth missions, monolithic antennas for uplink support, and downlink arrays. Figure 29 gives an overview of the GEE's architecture.

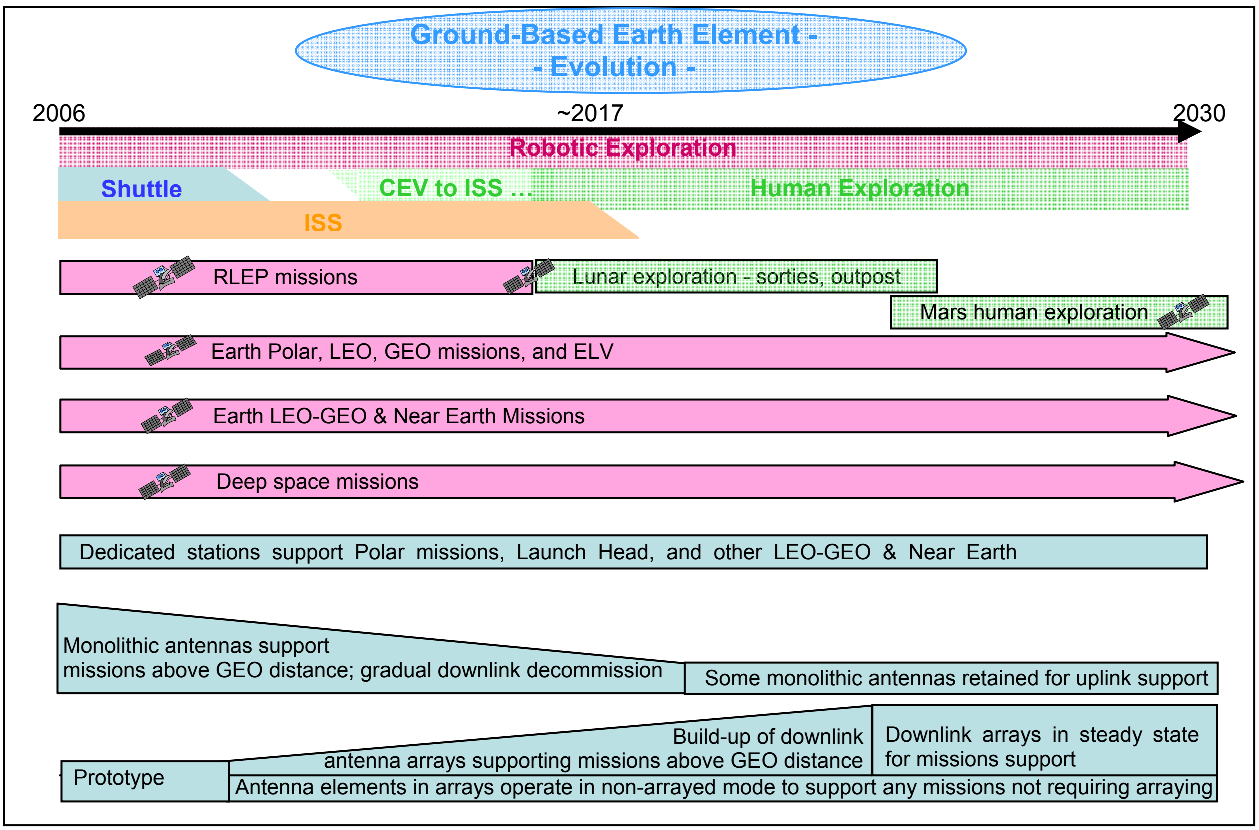


Figure 28. GEE Evolution

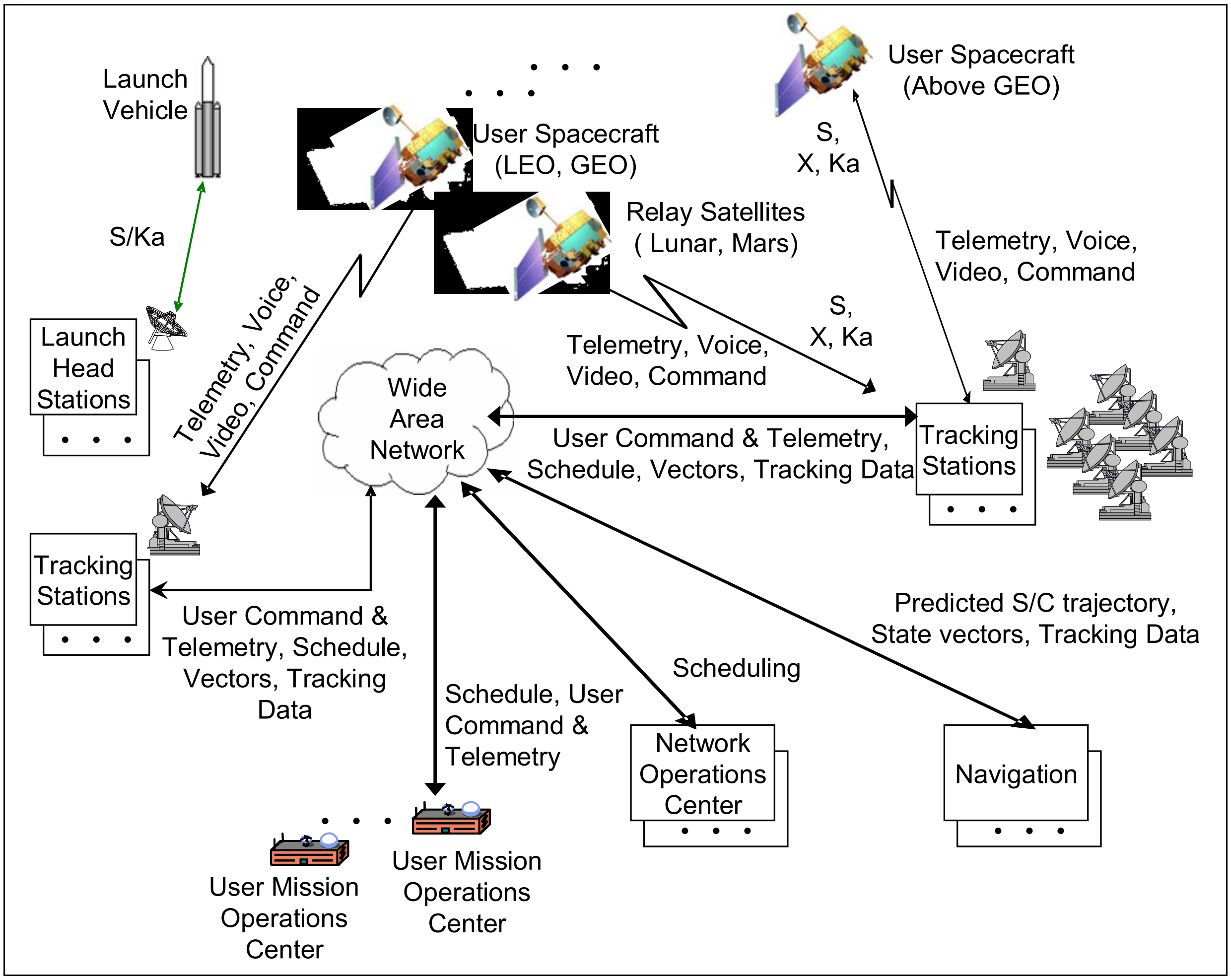


Figure 29. Overview of the GEE Architecture

Depending on programmatic considerations, the GEE may be structured organizationally as a single network serving all of NASA's missions or as multiple networks each of which provides dedicated services to one or more mission domains. For this report, GEE is treated as a single architectural entity encompassing the functions and operations for two distinct categories of communications assets: (a) those supporting the missions beyond GEO distance, i.e. >37,000 km; and (b) those supporting the LEO/GEO missions. The latter includes primarily the stations dedicated to missions in polar orbits, in mid-inclination orbits, and launch head support.

The GEE has the following key features:

- Service-based: The GEE functions as a system providing a set of standard services to missions and conforming to the standard "service provider-service user" interface model.
- Antenna arrays: The GEE uses arrays of small aperture receive antennas to achieve the communications capacity for supporting deep space missions and those above GEO. The arrays are designed to support multiple bands. Arrays are inherently reliable, scalable, and evolvable.

- Non-arrayed operations: The GEE antennas may also be used in a monolithic mode to support missions that do not require an array.
- Monolithic Uplink: Initially monolithic antennas will be used to provide uplink services. Use of uplink arraying will be considered when the technology is proven.
- Global coverage: The GEE assets are deployed at multiple sites to globally track over the entire celestial sphere. Optimally, there will be three mid-latitude sites for GEO-Deep space support. Any gaps at lower altitudes can be filled with lower capability sites.
- Dedicated stations: The GEE architecture includes dedicated stations deployed at ground sites for polar and launch support.
- RF technology-centric: The GEE architecture is based on advanced RF communications technologies. It defers optical augmentation until appropriate technology exists and demonstrations have occurred.
- Network security: The GEE architecture is an integral part of the NASA end-to-end space communications security architecture.

3.1.2. Functional Description

3.1.2.1. Functional Description of the GEE Assets Supporting Missions above GEO

The architecture for the communications assets of the GEE supporting the missions above GEO is based on the antenna array concept, that is, a large number of Earth-based smaller antennas are arrayed to produce an effective antenna aperture equivalent to or larger than that of the large monolithic antennas. Through an integrated network of antenna arrays, the GEE can globally track deep space vehicles, near Earth vehicles, and other radiating sources, over the entire celestial sphere. Figure 30 shows an example of an array system and interconnectivity between clusters.

The array architecture consists of a single cluster of closely spaced antennas at several longitudinal locations around the Earth, and establishes the initial infrastructure for an expansion that might eventually consist of multiple clusters. Each of the clusters includes the antenna structures, the associated electronics, a signal combiner, and software for monitor, control and analysis. The array infrastructure includes the control buildings, roadways, perimeter fences, security system, and the intra-array communications system.

Figure 31 depicts the high-level antenna array architecture, consisting primarily of the arrayed and dedicated non-arrayed antennas. A cluster of small antennas can be arrayed and configured for high-rate communications links, while the other dedicated links within the cluster are configured for TT&C communications. If performance allows, a single antenna may be used in monolithic mode to provide these services.

The aggregated antenna elements in the array are designed to track and receive signals in a coordinated operation that can be performed as if using a single larger antenna. Each element in the array is aligned to account for variations in the atmosphere, pointing offsets, and other equipment variables which impact antenna performance. Array efficiency is maximized when the individual elements are tightly clustered. A prime architectural consideration is to create a widely separated set of clusters of many closely spaced elements.

Each cluster is controlled by a cluster control center. Each cluster control center is connected in turn to an array control center. Such a system configuration enables both a certain amount of tolerance to local weather conditions and direct plane-of-sky measurement of the spacecraft for navigation purposes. Elements in these clusters may be operated as monolithic antennas as needed.

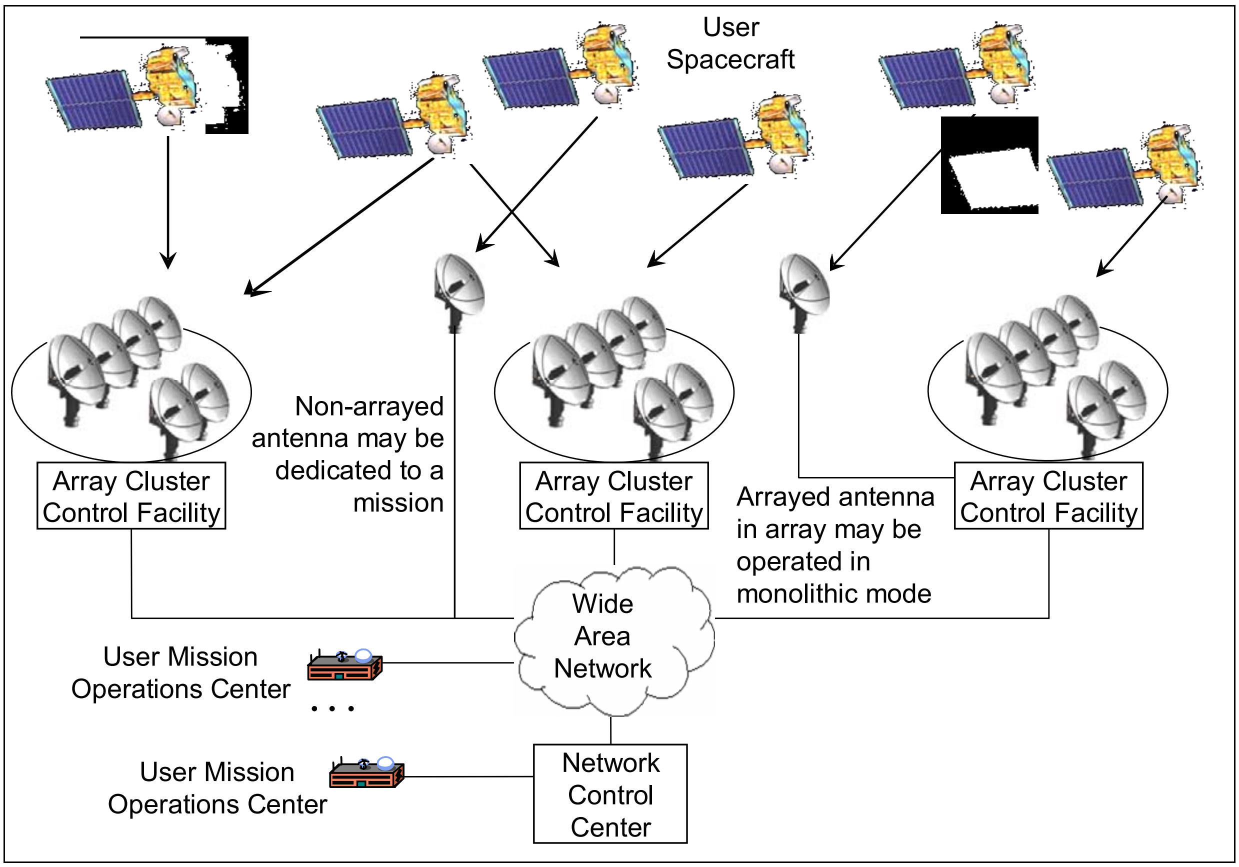


Figure 30. GEE Receive Antenna Arrays

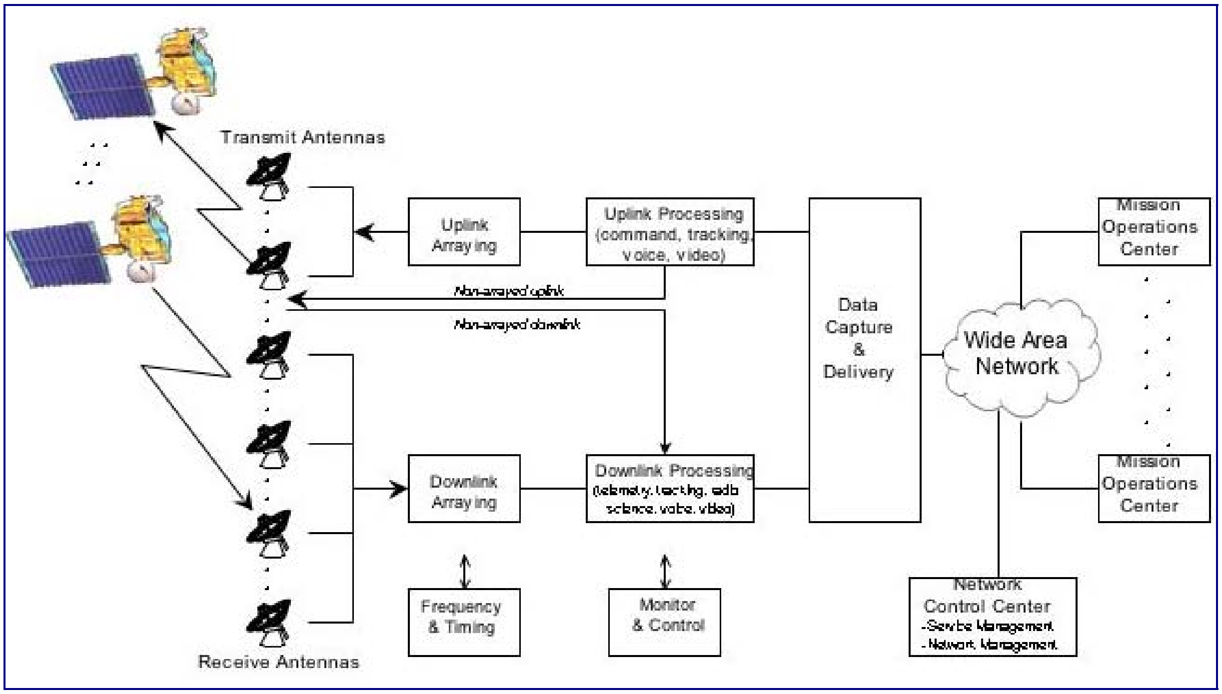


Figure 31. GEE: Functional Description of the Antenna Array

3.1.2.2. Functional Description of the GEE Assets Supporting Missions at LEO/GEO Distance

The architecture for the communications assets of the GEE supporting the LEO/GEO missions is based on the geographic coverage required, that is, a number of Earth-based apertures are sited to enable coverage for the mission inclinations which range from polar to equatorial orbits. Through an integrated network of antennas, the GEE can track near Earth vehicles and orbiting spacecraft over a portion of their orbit useful for C2 and store download communications. Some missions also use a ground-based laser pulse for precision ranging. Figure 32 shows an example of system interconnectivity.

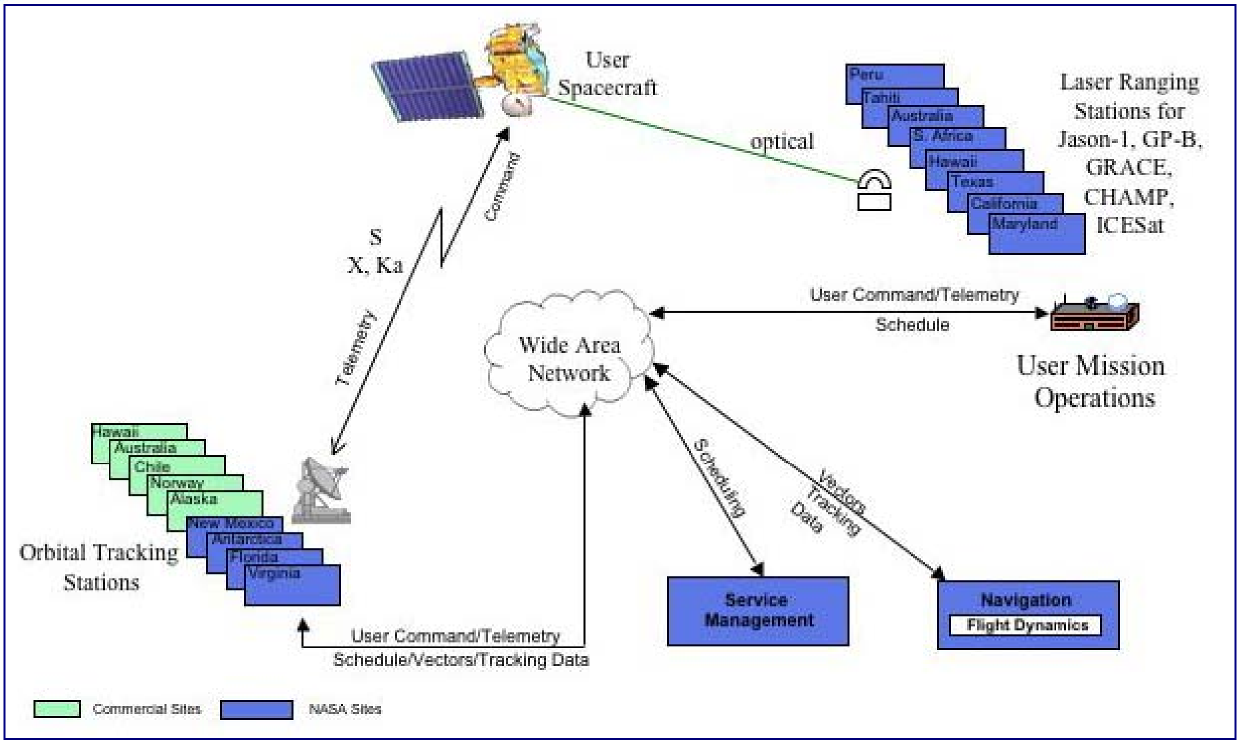


Figure 32. GEE: Functional Description for LEO/GEO Assets

3.1.3. Operations Concept

3.1.3.1. Operations for GEE Assets Supporting Missions above GEO

Array operation is fully automated for nominal operations, including assignment of specific antennas to sub-arrays, and reassignment of antennas during tracks. The array is operated remotely from a central site with the requirement for on-site maintenance staff only. Some level of human intervention may be required for situations when real-time operations are best handled by an operator, such as in cases of: spacecraft emergencies, unforeseen weather events, or system outages. It is likely that an operator may be involved when not all planned tracks can be supported, and mission priorities need to be invoked. Salient features of array operation include:

- A synthesized beam can be formed from multiple signals in an array cluster, *which may consist of a single antenna*, or formed from sub-array signals in multiple clusters.
- An array can consist of all antennas in a cluster, a subset of antennas in a cluster, multiple clusters, or a combination of both.
- A track array could point to a planet, such as Mars, for which two synthesized beams could be used to track two different spacecraft.
- For TT&C operations, the array is interoperable with other partner agencies via the CCSDS Space Link Extension (SLE) interfaces.
- Demand Access operation is provided, including support of Beacon Mode communications and the use of single aperture antennas whenever applicable.

- The array can be operated to meet specific operations requirements relating to: data transfer quality of service, increase in link margin, and the negotiated use of external non-NASA assets.
- Human exploration missions can use the array to communicate data, voice and video to Earth complying with the Constellation C3I Interoperability Specification.
- Shared monolithic antennas that are *not* part of the array may be used to support missions as needed.

3.1.3.2. Operations for GEE Assets Supporting Missions at LEO/GEO

The Integrated Mission Set (IMS, a synonym for the SCAWG Mission Model) indicates a continuing future set of missions in polar orbit. Support for polar inclination orbits requires assets at high latitudes to maximize the amount of coverage with a minimum amount of ground stations. Such contacts enable on-board stored data to be delivered without undue latency to the customer, and allow on-board storage space to be freed for uninterrupted observation of physical phenomena such as weather, natural hazards, and climate. Ground station locations within or near the Arctic Circle and the Antarctic Circle are ideal. Support for S-band TT&C, and also X-band or Ka-band high-rate data downlinks is needed in high latitudes for the foreseeable future. Existing infrastructure and access agreements at Alaska, Svalbard Norway, and Antarctica make those locations preferred. Commercial operators currently manage two of the three locations under subcontracts to a NASA-held O&M contract. It is expected that commercial service providers will continue to service this market, and that competition will yield best-value for NASA. Evolution to a Ka-band capability will allow higher data rates and potentially fewer contacts/orbit where low latency is not required.

To provide launch head coverage for LVs including the Constellation Program, ground stations will be required at the launch site with diversity to meet safety requirements and mitigate propellant exhaust plume effects. As the Space Based Range requirements mature, these ground stations are intended to meet those requirements.

The NASA IMS also forecasts an increasing number of equatorial and low-inclination orbit missions. The plan is to retain the current mid-latitude stations (including commercial sites) and add a Ka-band capability in the future.

3.1.3.3. Shared Antennas for Special Applications for GEO and Below

There will be a need for monolithic antennas to support unique mission requirements. Some of these may be 24x7 dedicated systems and some may allow for time-sharing with other missions. Examples of missions with dedicated ground antennas are the Solar Dynamics Observatory (SDO) and Lunar Reconnaissance Orbiter (LRO).

3.1.4. Key Functional and Performance Requirements

The GEE provides the space communications services described in section 3.1.2, and it is intended that the GEE functional and performance requirements will meet or exceed existing DSN and GN service requirements. High-level requirements that drive the development and implementation of the GEE are shown in Table 15. These requirements are neutral to whether the network architectures are array-based or monolithic antennas. Required performance is based on the SCAWG Mission Model.

Table 15. Key Functional and Performance Requirements for the GEE

GEE Requirements and Supporting Rationale
Provide global tracking of deep space vehicles, near Earth vehicles, and other radiating sources, over the entire celestial sphere. *Rationale:* All S/C need knowledge of position and ephemeris.
Support LVs by providing the required coverage at the launch heads at Kennedy Space Center (KSC) and Wallops Flight Facility (WFF). *Rationale:* Coverage may consist of multiple sites to provide the expected robustness requirement and coverage during possible plume attenuations.
Support the full range of NASA robotic deep space and near Earth missions including orbiters, flybys, landers, rovers, observatories, penetrators, aerovehicles and other micro-spacecraft, on or around planets, satellites, comets, or asteroids. *Rationale:* Supports NASA's ability to send missions of any size or type to any location.
Support Earth polar high-rate and mid-latitude missions. *Rationale:* For example: Global Precipitation Monitor (GPM).
Provide communications during critical events, such as Launch & Early Orbit Phase (LEOP), rendezvous, docking, and reentry *Rationale:* Needed for rapid response to anomalies and for post-failure analysis.
Provide tracking coverage of CEV, Lunar Surface Access Module (LSAM), and service modules in LEOP *Rationale:* Necessary for support to Constellation Program for ISS, lunar, and Mars missions.
Provide telecommunications links to and from spacecraft at the outer planets and outside the heliosphere to 200 Astronomical Units (AU). *Rationale:* Supports NASA's ability to send missions to any location.
Support human spaceflight missions to Moon and Mars. *Rationale:* Supports the Constellation Program.
Support Space Based Range requirements for LVs. *Rationale:* TBR depending on approval of SBR requirements.
Provide the following space communications services: command, telemetry, tracking, time, video, voice, and radio science. *Rationale:* Supports the functions and operations identified in the CONOPS.
Provide the number of downlinks (return links) shown in Table 16, Table 17, and Table 18. *Rationale:* A downlink (D/L) is a single-frequency-band, single-polarization link from a single target to GEE. When one spacecraft communicates on two separate frequency bands, on two polarizations, or with two carriers on the same frequency band, this is considered to be two D/Ls. Multiple D/Ls may be supported on a single antenna, or on a single array of antennas all with common pointing.
Provide the number of uplinks (forward links) shown in Table 19 and Table 20.

GEE Requirements and Supporting Rationale

Rationale: An uplink (U/L) is a single-frequency-band, single-polarization link to a single target from GEE. Multiple U/Ls may be supported on a single antenna, or on a single array of antennas all with common pointing. U/Ls and D/Ls may be provided simultaneously using the same antenna.

Provide simultaneous number of downlinks (return links) shown in Table 16, Table 17, and Table 18 to support missions in the same view.

Rationale: The number of simultaneous links is defined as the minimum number of the links that GEE must provide continuously.

Provide simultaneous number of uplinks (forward links) shown in Table 19 and Table 20 to support missions in the same view.

Provide sufficient antenna gain-to-noise-temperature (G/T) for the space downlinks required by the user missions.

Provide sufficient Effective Isotropic Radiated Power (EIRP) for the space uplinks required by the user missions.

Downlink Data Rates and Throughput

Provide maximum D/L data rate for deep space missions on a per link basis as follows:

2005	2010	2015	2020	2025	2030 (- H)	2030(+ H)
6 Mbps	6 Mbps	6.4 Mbps	6.4 Mbps	125 Mbps	125 Mbps	150 Mbps

Rationale: 2030 (-H) is the requirement for Science only; 2030 (+H) is the requirement for supporting human exploration.

Provide maximum D/L data rate for near Earth missions above GEO distance on a per link basis as follows:

2005	2010	2015	2020	2025
2 Mbps	2 Mbps	28 Mbps	125 Mbps	125 Mbps

Rationale: In 2010, LRO data rate at 100 Mbps is not counted here as its communications asset is a project-specific element.

Provide mission data transfer rate of at least 150 Mbps with maximum of 1 Gbps (TBR) in supporting Polar orbiter missions.

Provide mission data transfer rate of at least 150 Mbps with maximum of 1 Gbps (TBR) in supporting CEV and Lunar Relay.

Provide mission data transfer rate at the launch head of at least 1 Mbps for CEV in ~2012.

Provide a maximum uplink data rate capability at 4 kbps.

Provide a maximum uplink data rate capability from the launch head at 25 Mbps for the Crew LV (CLV) by ~2012.

Rationale: This requirement is under study by the Constellation Program but is also a projected need to support SBR requirements.

Provide a maximum uplink data rate capability at 25 Mbps for human trans-lunar missions by 2018.

Provide a maximum uplink data rate capability at 25 Mbps, if needed to support human Mars missions by 2030.

Track LVs and Earth-orbiting spacecraft with a slew rate of up to 15 degrees/second (for LEO).

Provide precision tracking and ranging services.

GEE Requirements and Supporting Rationale
Rationale: This includes centimeter precision for geocentric location and orbit determination, precise calibration of radar altimeters, and separation of long-term instrumentation drift from secular changes in ocean topography. GEE provides isochronous data and voice communications link with low latency between customer platform and customer ground operations center.
Provide an interface between GEE and the user MOC for SM. *Rationale:* Data exchanged are primarily in the form of service requests conveying information for scheduling, link configuration, predicted spacecraft ephemeris or state vectors, and other control directives.
Provide and interface between GEE and the user spacecraft for acquiring and transmitting TT&C data, voice, video, and high-rate science data for service execution.
Provide an interface between GEE and the user MOC for delivering TT&C data, voice, video, and high-rate science data as results of service execution.
Availability of services to robotic missions for critical events ≥ 98%.
Availability of services to robotic missions for nominal events ≥ 95%.
Availability of services to human exploration missions ≥ 99.5%.
During mission critical events, the maximum time to restore service to the missions after the loss of service ≤ 5 minutes for 90 % of the time.
During nominal mission events, the maximum time to restore service to the missions after the loss of service ≤ 30 minutes for 90 % of the time.
Provide 98% coverage for polar orbits from high-latitude sites.
Availability for supporting LEOP for Polar orbiter missions ≥ current GN.
The number of uplinks and downlinks is expandable without interruption to scheduled operations of the existing links.
Network is configurable to provide varying link capacity based on the needs of the individual and total missions at any given time
Interoperate with the communications assets owned by US agencies and other foreign space agencies in providing the same types of space communications services to jointly support collaborative missions. *Rationale:* It is a goal to create an open architecture to which other parties can interface in the future when specific MOAs are executed.
Comply with the Networking, Security, and Spectrum Architecture defined in this report.

Table 16. Space Downlinks for GEO and Beyond[5]

Above GEO	2005	2010	2015	2020	2025	2030H	2030S
GEO to 2,000,000 km							
Total Potential S-band Downlinks	14	12	5	12	13	50	50
S-band Simultaneous D/Ls for Whole Network	6	5	2	5	5	19	19
Total Potential X- & Ka-band	0	1	6	54	21	16	16

[5] 2030H includes requirements for human exploration while 2030S includes only science requirements.

Above GEO	2005	2010	2015	2020	2025	2030H	2030S
D/L							
X- & Ka-band Simultaneous D/Ls for Whole Network	0	1	3	20	8	6	6
Beyond 2,000,000 km							
Total Potential S-band Downlinks	1	0	1	0	0	0	0
S-band Simultaneous D/Ls for Whole Network	1	0	1	0	0	0	0
Total Potential X- & Ka-band D/L	18	17	22	31	25	35	29
X- & Ka-band Simultaneous D/Ls for Whole Network	7	7	8	12	10	13	11
Totals							
Total Potential D/Ls	33	30	34	97	59	101	95
Total Simultaneous D/Ls for Whole Network	14	13	14	37	23	38	36

Table 17. Space Downlinks for Polar LEO/GEO Missions

Polar LEO/GEO	2005	2010	2015	2020	2025	2030
Total Potential S-band Downlinks	TBD	22	15	24	TBD	TBD
Total Potential X-band Downlinks	11	16	18	16	15	TBD
Total Potential Ka-band Downlinks	0	3	8	12	15	13

Table 18. Space Downlinks for Low Inclination LEO/GEO Missions

Low Inclination LEO/GEO	2005	2010	2015	2020	2025	2030
Total Potential S-band Downlinks	TBD	38	26	TBD	TBD	TBD

Table 19. Space Uplinks for GEO Missions and Beyond

Above GEO	2005	2010	2015	2020	2025	2030H	2030S
GEO to 2,000,000 km							
Total Potential S-band U/Ls	14	12	5	12	13	50	50
S-band Simultaneous U/Ls for Whole Network	6	5	2	5	5	19	19
Total Potential X- & Ka-band U/Ls	0	0	4	41	7	7	7
X- & Ka-band Simultaneous U/Ls for Whole Network	0	0	2	15	3	3	3
Beyond 2,000,000 km							
Total Potential S-band U/Ls	0	0	0	4	6	5	5
S-band Simultaneous U/Ls for Whole Network	0	0	0	2	3	2	2
Total Potential X-band U/Ls	14	14	21	29	23	30	27
X-band Simultaneous U/Ls for Whole Network	6	6	8	11	9	11	10

Above GEO	2005	2010	2015	2020	2025	2030H	2030S
Totals							
Total Potential U/Ls	32	28	30	86	51	97	91
Total Simultaneous U/Ls for Whole Network	14	12	12	33	21	37	35

Table 20. Space Uplinks for LEO/GEO Missions

LEO/GEO	2005	2010	2015	2020	2025	2030
Total Potential S-band U/Ls	30	38	26	24	TBD	TBD

3.1.5. Architecture Options Considered

3.1.5.1. Architecture Options for GEE Assets Supporting Missions above GEO

Considering alternatives, the GEE is limited to the following options:

1. Baseline – use the current monolithic antennas as permitted by the existing budget level until major unrecoverable capability failure occurs;
2. Baseline with Refurbishment – refurbish the current monolithic antennas to maintain the existing capability for another 25 years;
3. Create an optical network; or
4. Replace the existing monolithic antennas with new arrays to meet future performance requirements, that is, replace all antennas with arrays of small antennas.

A FOM and cost-benefit analysis comparing the various alternatives was conducted and option 4 is selected based on rationale in section 3.1.6.

The concept of antenna arrays was seriously considered in response to the need for an alternative to single antennas much larger than those already in existence. Analysis has shown that an array of smaller antennas would offset the prohibitive cost of building a larger antenna and yields a significant decrease in cost per decibel of link margin. In addition to reducing the cost of the ground assets, there is a corresponding reduction in spacecraft hardware complexity and on-board power consumption. The advantages that led to the array network architecture can be summarized as follows:

- Flexible scheduling as the array enables simultaneous tracking of multiple spacecraft over a wide area of the sky;
- Improved pointing stability resulting in more accurate ranging and Doppler measurements needed for spacecraft navigation;
- Improved reliability due to graceful degradation of the array performance if individual antenna elements fail;
- Modular upgrading and expandability of the antenna array elements and capabilities which enables gathering significant increases in scientific data throughput for data-rate-limited missions;
- Enables new types of missions such as radio occultation measurements with very distant spacecraft; direct reception of Lander/Rover/Penetrator signals on Earth;

multi spacecraft Very Long Baseline Interferometry (VLBI) arrays; spacecraft with no on-board storage; and downlinks with both high data rates and long duty cycle; and,
- Reduced long term costs for O&M.

For the case of uplink (spacecraft commanding), the viability of using an arrayed uplink as a replacement of a single antenna uplink has not yet been firmly established. The engineering and operational characteristics of an uplink array are more complex than those associated with the downlink array and require additional study and analysis.

3.1.5.2. Architecture Options for GEE Assets Supporting LEO/GEO Missions

The following options for the GEE were considered:

- Move support to alternate existing assets: This approach has five sub-options:
  - Increase NER capabilities beyond the current SN/TDRSS: A larger on-board communications package would be required. Additional relay heads would need to be considered to support missions using X-band.
  - DOD Integrated Satellite Control Network (ISCN): This option is limited by DOD funding to meet DOD missions. For example, ISCN will not complete the upgrade to USB until 2016. It can be used where low-rate S-band support is needed; however, X and Ka-band missions are incompatible. ISCN has only a single Polar site at Thule, Greenland, meaning support for polar missions would require added sites.
  - Commercial sites: Commercial sites currently support 65% of GN passes. Universal Space Network, Inc. (USN) is in the process of obtaining certification to support the Small Explorer (SMEX) class of missions. Consequently, support by commercial sites is expected to grow n the immediate future. Beyond that, additional commercial growth offers significant potential for offloading NASA sites for supporting Earth-orbiting missions if NASA acts as the anchor customer.
  - Relocate polar passes to mid-latitude sites: While mid-latitude sites are capable of communicating with polar satellites, orbital dynamics dictate that four or more mid-latitude sites would be required to replace a single existing polar site. This makes the trade between high and mid-latitude sites very cost ineffective. The Earth Observing System (EOS) mission-unique ground station low rate processing system, the Ground Station Interface Facility/Ground Station Interface Processor, would have to be replicated or relocated adding a major transition cost.
  - Foreign agency tracking sites: This option is investigated as a last resort since there are many associated issues. Lack of interoperability, capacity, and competing priorities would make the interfaces difficult. Technology transfer limits due to the International Traffic in Arms Regulations (ITAR) may preclude export of key communications capabilities and limit future growth.
- Use potential new capability: This approach has two sub-options:
  - NPOESS SafetyNet: The National Polar-orbiting Operational Environmental Satellite System (NPOESS) is implementing a data routing and retrieval

architecture called SafetyNet to provide users with near-real time data delivery using commercial data networks. SafetyNet consists of 15 globally distributed ground receptors designed to frequently receive stored mission data from NPOESS satellites. The unmanned ground receptors are interconnected and linked to central data processing centers in the United States by commercial fiber optic networks. Placement of the ground receptors provides NPOESS satellites with frequent downlink opportunities and long contact duration, averaging 55 percent of each orbit. Use of Ka-band, operating at 25.65 GHz, permits high-speed, high-capacity transmissions of stored mission data. This data is transmitted to the ground receptors at 150 megabits per second. Northrop Grumman has a patent pending for SafetyNet. NPOESS will cut the latency between observation and delivery from hours to minutes. Current tests of the prototype system are demonstrating that nearly 80% of the processed global NPOESS data will be available to users within 15 minutes and 95% of the data will be available within 24 minutes. However, a larger on-board communications package is required for users because of the small ground apertures used and X and S-band missions would be incompatible.

- Phased-array technology: Several advanced Research and Development (R&D) efforts are under way to make phased-array antennas feasible for ground stations. The Smart Antenna concept is being developed by the Georgia Institute of Technology but is currently at a Technology Readiness Level (TRL) of 3. The Air Force Research Lab is working on a geodesic dome concept. Additional funding and time is required for any phased-array option.

3.1.6. FOM Definition, Analysis, and Conclusions

3.1.6.1. FOM Definitions

A systematic evaluation was conducted to determine the comparative merits of alternative GEE architectures. FOMs for each option were defined (Table 21) predicated on specified evaluation criteria and assessed in relation to mission support beyond GEO distances. The FOM analysis provided a means of performing reasonable evaluations from known data. The FOM scoring was qualitative, and for this reason, only a three-level color system was used. *Green* indicates full compliance with the FOM, *Yellow* indicates partial compliance, and *Red* indicates an identified predisposition for noncompliance.

Table 21. FOM Definitions for GEE Architecture

FOM	Definition
Reliability	Ability to meet Level 1 requirements for science missions and human rating requirements
Communications Performance	Ability to meet Level 1 requirements for communications out to the year 2030
Navigation Performance	Ability to meet Level 1 requirements for navigation out to the year 2030
Technology Readiness	Implementation of technology with a minimum level of engineering involvement
Life Cycle Cost	Funding required to develop facilities and equipment to operate for a period of 25 years
Evolvability	Ability of architecture for any expansion and modification with evolving requirements
Operations Flexibility	Ability for easy accommodation of missions to utilize assets with provisions for alternative options

The architectural options that were assessed by FOM analysis were limited to the following:

1. Continued operation of the DSN baseline without refurbishment – utilization of the current DSN assets at the existing budget level until major unrecoverable capability failure occurs;
2. Continued operation of the DSN baseline with refurbishment – refurbishment of current DSN assets to maintain current capability for another 25 years;
3. Creation of an optical communications network;
4. Replacement of existing DSN facilities with new RF antenna arrays to meet future performance requirements with one of the following options:
    a. Replacement of all of the current DSN assets with arrays of 12m antennas;
    b. Replacement of all of the current DSN assets with arrays of 34m antennas.

All of the options (other than first) require some critical DSN refurbishment until the new capability becomes operational.

3.1.6.2. Scoring the Options

The FOM scores are shown in Table 22. The rationale for the FOM color scores is as follows:

Table 22. FOM Scores for the GEE Architecture

OPTION	Reliability	Communications Performance	Navigation Performance	Technical Readiness	Life-Cycle Cost	Ability to Evolve	Operations Flexibility
1. Continued Operation of the DSN Baseline without Refurbishment	Red	Red	Red	Green	Red	Red	Red
2. Continued Operation of the DSN Baseline with Refurbishment	Green	Red	Red	Green	Yellow	Red	Red
3. Creation of an Optical Communications Network	Yellow	Yellow	Red	Red	Red	Green	Red
4. Replacement of all the Current DSN Assets with Arrays of 12m Antennas	Green	Green	Green	Green	Green	Green	Green
5. Replacement of all the Current DSN Assets with Arrays of 34m Antennas	Green	Green	Green	Green	Yellow	Green	Yellow

Option 1. Continued Operation of the DSN Baseline without Refurbishment

- **Reliability (Red)** – The purchasing power of the current DSN budget decreases with time. Since this option does not include investments for future operations and maintenance, the O&M demands will eventually consume the entire budget, resulting in a decline in O&M performance. This inevitably leads to a lower expectation of system reliability.
- **Communications Performance (Red)** – The SCAWG IMS has predicted what orders of magnitude will be required for future demands in communications performance. Since this option does not involve increasing the DSN ground capability, it would necessarily shift the implementation burden to the space segment. This approach is considered inappropriate, since the DSN is a multi-mission element that can initiate most of the needed improvements in a more cost-effective manner.
- **Navigation Performance (Red)** – The SCAWG IMS has predicted that future missions will require significant improvements in the areas of navigation. The requirements will involve substantial improvements in the measurement accuracy and precision of the radiometric data delivered by the DSN. These future requirements for improved radiometric data accuracy will not be achievable with this option.
- **Technology Readiness (Green)** – This option does not require new technology.
- **Life-Cycle Cost (Red)** – This may appear to be a low-cost option. However, in order to achieve significant strides toward the communications and navigation capabilities predicted by the IMS, there needs to be significant investments in the space segment hardware and software. Typically, improved capabilities are more

costly to implement in the space segment than at the corresponding ground segment. In addition, there is the higher likelihood of a major system failure in the DSN due to the level of reliability associated with this option.

- **Evolvability (Red)** – By definition, this option does not allow new capabilities to be added.
- **Operations Flexibility (Red)** – The use of large (34m and 70m) antennas reduces the ability to service multiple mission types on short notice. For cases of lunar missions, about 80% of the 34m antenna inherent capability will be effectively underutilized if this option is implemented.

Option 2. Continued Operation of the DSN Baseline with Refurbishment

- **Reliability (Green)** – The current DSN reliability is excellent. By investing in continual refurbishment, the overall reliability can be maintained at this level.
- **Communications Performance (Red)** – The SCAWG IMS has predicted what orders of magnitude will be required for future demands in communications performance. Since this option does not involve increasing the DSN ground capability, it would necessarily shift the implementation burden to the space segment. This approach is considered inappropriate, since the DSN is a multi-mission element that can initiate most of the needed improvements in a more cost-effective manner.
- **Navigation Performance (Red)** – The SCAWG IMS has predicted that significant improvements in navigation performance will be required by future missions. This involves substantial improvements in the accuracy of the radiometric products delivered by the DSN, which will not be achievable with this option.
- **Technology Readiness (Green)** – This option does not require new technology.
- **Life-Cycle Cost (Yellow)** – The same problems exist for this option as described in the *Continued Operation of the DSN Baseline without Refurbishment* option. However, since in this case the DSN undergoes continual refurbishment, reliability is maintained with a significant reduction in major DSN system failures.
- **Evolvability (Red)** – By definition, this option does not allow any new capabilities to be added.
- **Operations Flexibility (Red)** – The use of large (34m and 70m) antennas reduces the ability to service multiple mission types on short notice. For cases of lunar missions, about 80% of the 34m antenna inherent capability will be effectively underutilized if this option is implemented.

Option 3. Creation of an Optical Communications Network

- **Reliability (Yellow?)** – It is difficult to accurately assess the reliability of optical communications systems since they are not as widely used as standard RF systems. A ground-based optical system is more susceptible to weather uncertainties that impact the overall system reliability. However, the reliability of optical systems can be improved using spatial diversity, where multiple ground stations are situated at different geographical locations to overcome the effects of weather. Spatial diversity for optical systems necessarily increases the optical systems implementation and operations costs.

- **Communications Performance (Yellow?)** – Although communications links using optical technology are generally adaptable, many of the IMS missions would experience link problems due to the unique characteristics of optical links. For example, the pointing accuracy of an optical telescope would be significantly degraded during spacecraft spinning maneuvers. In addition, the intense mechanical vibration experienced by planetary atmospheric probes would also severely degrade the link performance.
- **Navigation Performance (Red?)** – Although "light metrics" (the optical equivalent to "radio-metrics") provide a new approach for navigation, additional studies are needed to fully understand all of the implications of using this measurement technique. The use of optical systems for purposes of spacecraft navigation is considered to be more risky than when used for space communications.
- **Technology Readiness (Red)** – The grading of this FOM carries no uncertainty. The technologies needed to implement viable optical communications systems have not been developed sufficiently. NASA needs to continue to invest in this area of technology development.
- **Life-Cycle Cost (Red?)** – At the present time, optical communications ground stations are more costly to implement than conventional RF stations. Also, substantial investment in the space segment will become necessary, since the deep space optical terminals currently do not exist.
- **Evolvability (Green?)** – No major problems have been identified with the ability of optical systems to evolve. Optical array architectures actually mimic the RF array options and are described below.
- **Operations Flexibility (Red)** – The use of large (34m and 70m) antennas reduces the ability to service multiple mission types on short notice. For cases of lunar missions, about 80% of the 34m antenna inherent capability will be effectively underutilized if this option is implemented.

Option 4. Replacement of all Current DSN Assets with Arrays of 12m Antennas

- **Reliability (Green)** – RF Arrays are inherently reliable since they degrade gracefully as elements fail. Hot backups can be created from the multiple elements of an array. Also, only a very small number of the total array capacity would to be inoperable during maintenance periods, at any one time.
- **Communications Performance (Green)** – The array capacity can be scaled with additional elements to meet increases in required capability, as needed.
- **Navigation Performance (Green)** – The array can provide standard radiometric techniques and also offers the potential for improved VLBI techniques when the array clusters are separated with long baselines.
- **Technology Readiness (Green)** – This option does not require new technology. (note: not applicable for uplink operations)
- **Life-Cycle Cost (Green)** – The array options have the lowest life-cycle cost among the options considered.
- **Evolvability (Green)** – RF arrays are inherently able to evolve into networks with larger capacities and increased capabilities.

- **Operations Flexibility (Green)** – The use of 12m antennas as the basic array elements means that very few missions will be supported with underutilized capacity. In addition, the arrayed antennas can be dynamically switched in and switched out of the clustered elements to optimize link performance.

Option 5. Replacement of all Current DSN Assets with Arrays of 34m Antennas

- **Reliability (Green)** – RF Arrays are inherently reliable since they degrade gracefully as elements fail. Hot backups can be created from the multiple elements of an array. Also, only a very small number of the total array capacity would to be inoperable during maintenance periods, at any one time.
- **Communications Performance (Green)** – The array capacity can be scaled with added elements to meet increases in required capability, as needed.
- **Navigation Performance (Green)** – The array can provide standard radiometric techniques and also offers the potential for improved VLBI techniques when the array clusters are separated with long baselines.
- **Technology Readiness (Green)** – This option does not require new technology. (note: not applicable for uplink operations)
- **Life-Cycle Cost (Yellow)** – The array options have the lowest cost among the other options considered. The life-cycle cost of the 34m arrays is higher than that of 12m arrays. It should be noted that this cost difference is limited by the accuracy of the estimation process itself. A more accurate cost estimate would require additional study and analysis.
- **Evolvability (Green)** – RF arrays are inherently able to evolve into networks with larger capacities and increased capabilities.
- **Operations Flexibility (Yellow)** – The use of 34m antennas as the basic array elements would result in underutilized DSN capability. It is also considered less likely that antennas could be easily switched in and out of the array cluster during mission support activity, due to the increasing demands for mission support and the limited availability of the 34m antennas.

3.1.6.3. Rationale for Conclusion

The FOMs for option 4 indicate full compliance with all of the evaluation criteria. This leads to the conclusion that implementation of the 12 meter antenna array would be the optimal choice for enhancing the DSN capability to meet evolving requirements and the increased demands for space communications services.

The rationale for this conclusion is based on the following:

1. Evaluation criteria were determined through exhaustive collective discussions by the SCAWG team. The evaluation criteria were assumed to be equally weighted to mitigate uncertainties arising from the interpretation of the scoring method.

2. The options were assessed and scored qualitatively by the SCAWG team. To avoid the controversy of a numerical scoring system based on subjective assessment, the FOM scoring levels were limited to 3 basic colors: green, yellow and red.

3. FOMs determine the comparative merits of the options with respect to the evaluation criteria. The FOM method provides a reasonable qualitative assessment of the options without the need for quantitative estimating methods that produce unverifiable results. The simple tri-level color scheme facilitates the scoring of the collective assessment process.
4. The FOM approach is deemed valid and reliable when the overall merit scores reflect the essential differences of each of the candidate options. In this case, the *option 4* FOM scores uniquely indicate full compliance with all of the evaluation criteria in comparison to the other options considered.

3.2. *Near-Earth Relay Element*

3.2.1. Overview of the Near-Earth Relay Element

The NER element consists of a constellation of Earth-orbiting relay satellites and the supporting ground segment. The relay satellites primarily provide two-way connectivity with space-based and suborbital users that include: Earth-orbiting spacecraft at GEO altitudes and below; launch vehicles, scientific balloons and other suborbital platforms; and Exploration vehicles during Earth/lunar transit while in close Earth proximity (e.g., within ~30,000 km). Two-way prime or backup connectivity may also be provided to users at more remote locations – including the Moon, Sun-Earth libration points, and even beyond – subject to visibility and communication link constraints.

The supporting ground segment provides two-way space/ground connectivity with the relay satellites and accommodates all user-service data and relay satellite command/control. The ground segment also serves as the NER ground interface with the end-user locations.

A range of wideband and narrowband user services are provided by the NER element, which encompasses both schedulable and on-demand services. Service provision and monitoring is highly automated and ensures highly reliable operations. Figure 33 depicts the evolution of Near-Earth Relay capability; transitioning from the current constellation of TDRSS assets to the future relay architecture.

3.2.2. Top Level Functional Description

3.2.2.1. Reference Architecture

Figure 34 provides a top-level depiction of the reference architecture for the NER element, including the principal space-segment/ground segment functions and interfaces. The specific relay constellation and ground segment characteristics including orbits, quantity, locations, connectivity, and detailed functionality are not explicitly addressed here. Instead, these are derived via technical/cost trades, based on specific assumptions and analysis applied to a range of architecture options as discussed below.

3.2.2.2. Operations Concept and Interfaces with User Missions

An overview of the NER operations concept is illustrated in Figure 35, which emphasizes network elements, interfaces and data flows. For illustrative purposes, the "users" shown are depicted as spacecraft or launch vehicles, but are representative of the ensemble of space-users and non-space-users expected to be supported by the NER element. Also, the NER space and ground segments are generically illustrated, and the operations concept is independent of the specific architecture ultimately selected.

User vehicle data flow through the network is described by solid arrows, while service-management-related data (e.g., scheduling and status) is described by broken arrows.

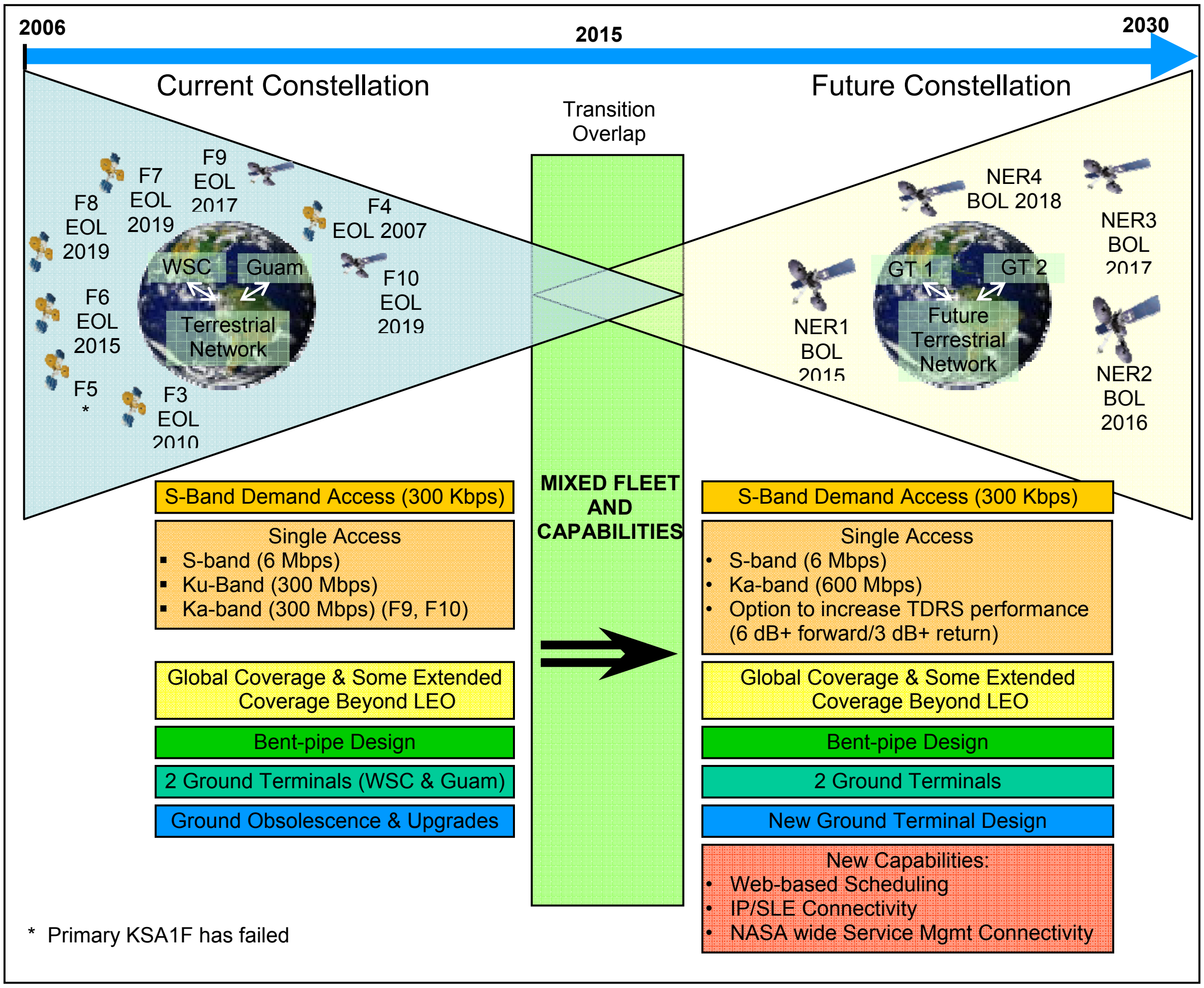


Figure 33. Near-Earth Relay Evolution

User ground elements consist of: Mission Operations Control Centers (MOCC) that execute user vehicle command and control and End User Sites that process mission (e.g., science) data. The operations concept addresses these elements as distinct functions, but they may or may not be physically collocated.

All operations and data flow across interfaces are executed in a highly automated manner, thereby minimizing manpower requirements and maximizing reliability. All ground interfaces are also expected to reflect well established standards, thereby benefiting from ongoing industry developments.

The standardized SM Interface applies across all NASA architecture elements, as shown. This is crucial since users: (1) may operate via multiple NASA architecture elements simultaneously (e.g., a LEO user that obtains TT&C support via the NER and dumps wideband data to terminals within the GEE; or, (2) seamlessly transition from one element to another (e.g., CEV support transitions from the NER to the GEE during lunar transit).

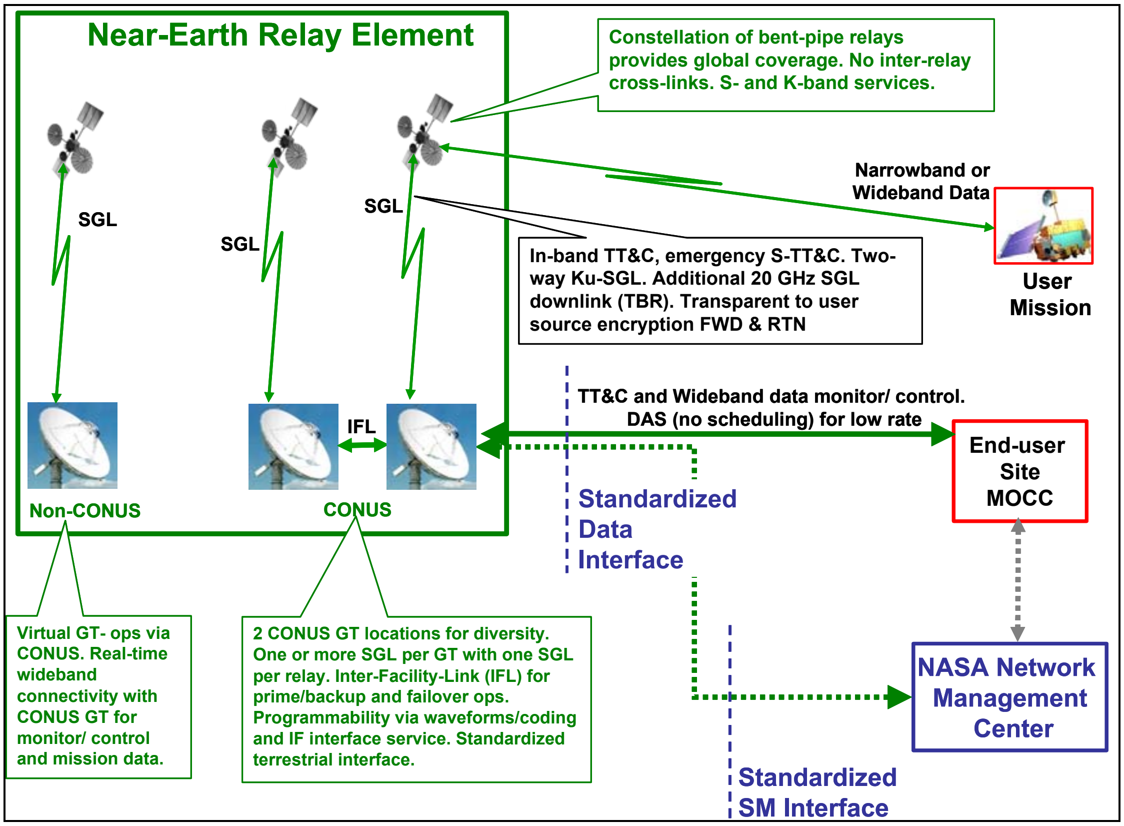


Figure 34. Near-Earth Relay Reference Architecture – GEO

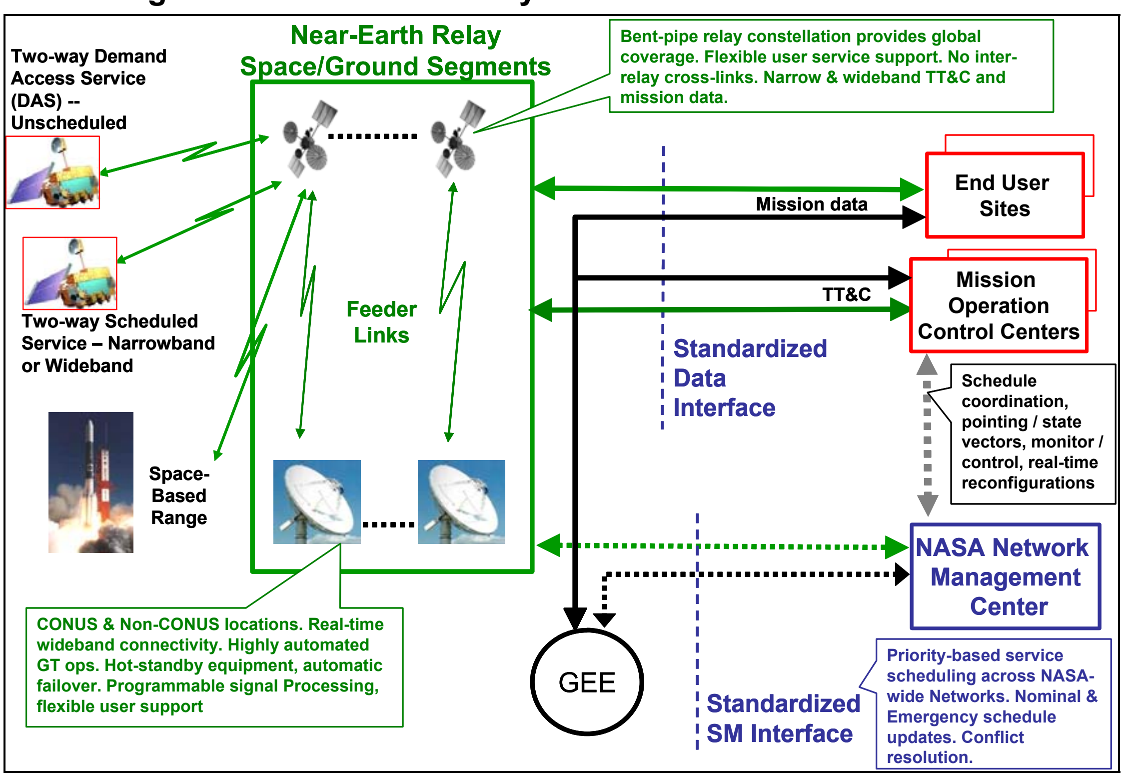


Figure 35. NER Operations Concept – Elements, Interfaces, and Data Flow

Another key aspect of the operations concept is the specific user interaction with the network and the process/sequence of events. While many distinct scenarios can be envisioned, with specific aspects unique to each, some high level insight can be gained via the "Day in the Life of the User" example illustrated in Figure 36. The figure focuses on a single user and the sequence of events beginning with the service scheduling process. Each of the four blocks illustrates which elements of the network are engaged and the nature of interactions across interfaces including both user vehicle data and SM-related data.

The first block begins with the service scheduling process that nominally allows for updates up to ~1 week prior to service. This reflects the current SN and allows for suitable mission planning of required communication events to be supported. "Emergency" updates are accommodated with high flexibility, e.g., reflecting unanticipated mission safety issues or the appearance of unanticipated science events/opportunities. A web-based scheduling request system allows missions to see and schedule available unused time for near real-time support.

User operations eventually transition to the mode wherein TT&C support is provided via the NER and wideband mission data is provided by the GEE. The data flow arrows and their colors explicitly address the handover, and the overall event sequence emphasizes the centrality of the standardized SM interface to a NASA-wide Network Management Center that coordinates activities across the SCA elements.

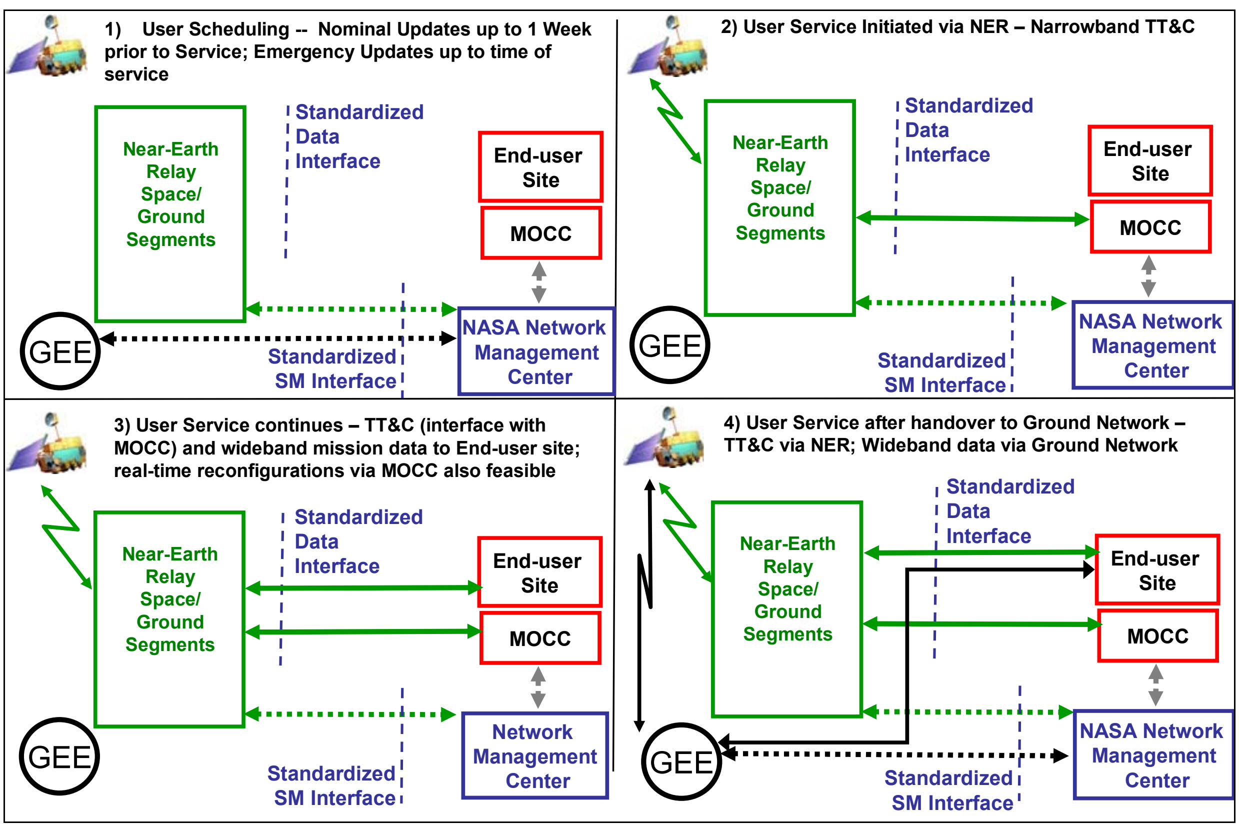


Figure 36. Near-Earth Relay: Illustrative "Day in the Life of a User"

3.2.3. Key Functional and Performance Requirements

Table 23 and Table 24 summarize the key functional and performance requirements, respectively, of the NER element. These top-level assumed requirements were extracted from existing requirements documents, an analysis of the integrated mission set, and the expert knowledge of team members. Additional insight is provided by identifying associated drivers for each requirement and how the specific requirement is expected to be satisfied by the NER Architecture that is ultimately selected.

Table 23. Key NER Functional Requirements

NER Function	Key Driver(s)	How Accomplished
Provide real-time relay of user data between user platform and its ground facility(ies)	Highly-limited, or non-existent, line-of-sight visibility	Ensemble of relay-satellites and ground terminals that provide required degree of visibility and connectivity
Provide scheduled telecommunication services	Cost, complexity limits quantity of certain high-performance space-relay resources, relative to size of user population; thus, scheduling required to allocate limited resources	▪ Configurable (electronic and mechanical) space relay resources ▪ Ground-based control with suitable Service Management interface
Provide 24 x 7, on-demand telecommunication services	▪ Science alerts (e.g., gamma ray bursts) ▪ E911 ▪ Housekeeping broadcasts, acknowledgements	▪ Phased array antenna, with ground-beamforming (or equivalent) ▪ Broad-beam, beacon broadcast
Provide narrowband (e.g., TT&C) telecommunication services	User housekeeping	S-band service(s)
Provide wideband telecommunication services	▪ Wideband mission data ▪ High Definition Television (HDTV)	One or more of the following representative services: Ku, Ka, optical
Provide tracking services	▪ GPS not-cost-effective for all users ▪ GPS not available or insufficient for user altitudes near and beyond GEO	Signal structures enable derivation of radiometric data via communication links
Provide users with operational flexibility	▪ Diverse user set, with diverse requirements ▪ Signaling, waveform flexibility needed for various mission phases	▪ Bent-pipe relays or highly flexible, programmable on-board processing ▪ Programmable ground equipment – signal

NER Function	Key Driver(s)	How Accomplished
	▪ Long-life of NER relays imposes need on relays to accommodate degree of unanticipated evolution of user needs	processing; monitor & control ▪ Flexible Service-Management interface

Table 24. Key NER Performance Requirements

NER Performance	Key Driver(s)	How Accomplished
Provide global coverage to altitudes up to 30,000 km (TBR)	▪ Continuous communications support to CEV and other lunar vehicles during flight phases not accommodated by NISN ▪ Must accommodate certain 24 x 7, on-demand services	▪ Sufficient quantity and spacing of relay satellites on orbit ▪ Relay antennas with sufficient field-of-view and steerability
Provide global coverage to Earth surface for latitudes up to 70° N & S (TBR)	Enable near-global operations capability for sub-orbital missions (e.g. launch vehicles; balloons)	
Provide Mission Data Transfer Rate of at least 1 Gbps	▪ Accommodate advanced science (e.g., hyperspectral imagery) ▪ Accommodate high-rate multiplexed data from CEV	▪ Relay accommodates wide bandwidths at Ka and/or optical ▪ Relay space/ ground link provides sufficient BW ▪ NER provides efficient modulation/coding
Provides at least 3 dB user burden reduction in communication/ tracking (relative to current SN)	▪ Reduce cost/complexity of emerging users (e.g., SBR; integrated launch + CEV voice) ▪ Amortize NER cost over large user population, resulting in net NASA savings	▪ Increased relay EIRP, G/T ▪ Accommodation of powerful coding techniques
End-to-end system availability meets or exceeds that of current SN (TBD)	Must accommodate time critical user needs (e.g., human spaceflight)	▪ Space/ground subsystem redundancy ▪ Automated, hot-standby failover ▪ Ground-site diversity for physical, weather diversity
One-way latency < 0.5 sec (TBR) between user platform and user mission operations center	▪ SBR / range-safety ▪ CEV crew voice	▪ Relay in altitude no higher than GEO ▪ Low-latency ground processing and connectivity

3.2.4. Architecture Options Considered

As Figure 37 illustrates, a broad range of competing considerations present themselves, and no single NER space/ground architecture optimally satisfies the ensemble of all constraints. For example, the GEO relay offers maximum heritage, reduced transition complexity, and operational simplicity (due to the static nature of the space/ground interface). On the other hand, lower relay orbits offer lower latency, reduced spacecraft mass and per-relay launch cost for a given level of user burden. As such, the need arises to identify and address a sufficiently complete, discrete set of architectures that:

- A comprehensive and credible comparative technical/cost assessment across key constraints of interest is permitted; and
- The need for a set to be so large as to preclude a timely assessment process is avoided.

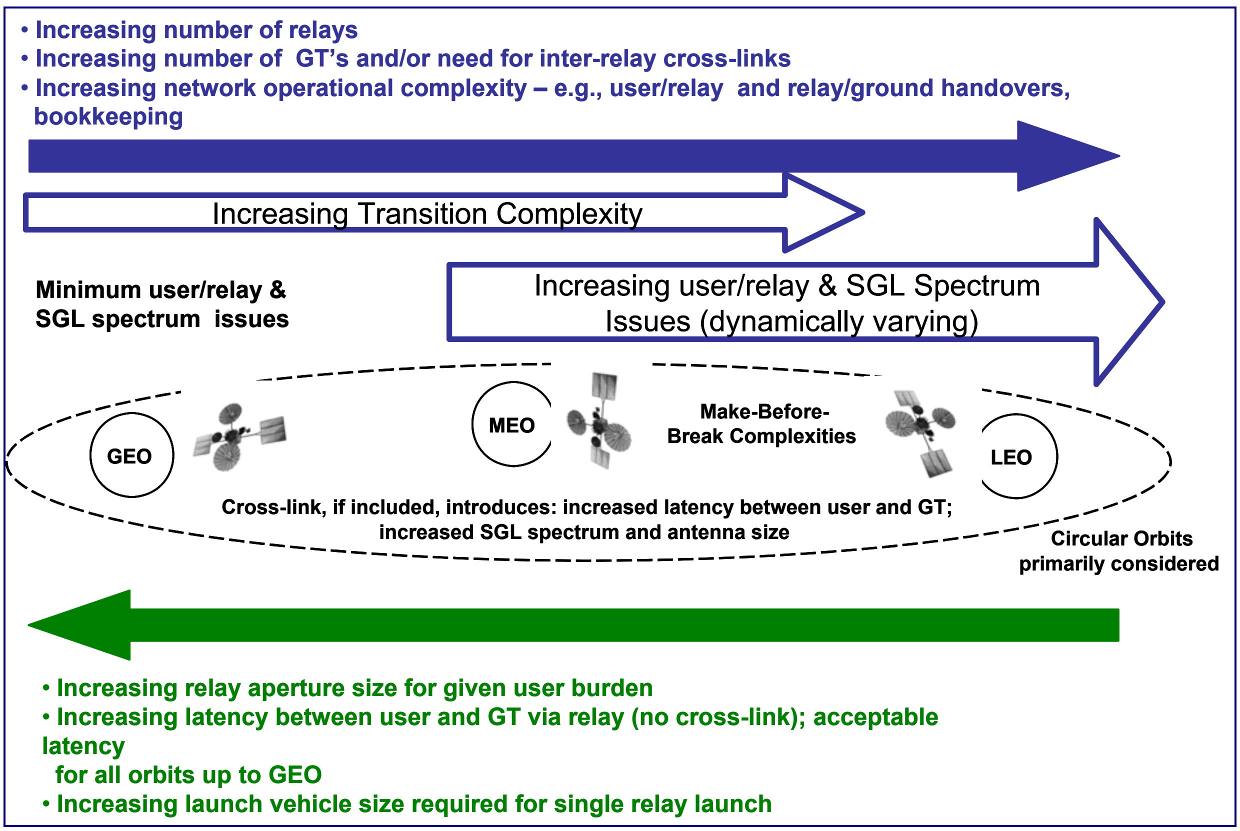


Figure 37. Near-Earth Relay Architecture Trade Space and Considerations

Toward this end, a range of architecture options was identified spanning GEO, MEO, and LEO orbits and the option set is shown in Table 25. These options also reflect uniform, key system parameter values relating to narrowband/wideband user services, coverage, capacity, and user burden, so that mutually consistent, "apples-to-apples" comparisons could be made. Ground Terminal sites were analyzed for a variety of Continental US (CONUS) and Outside of CONUS (OCONUS) locations.

Table 25. Specific Near-Earth Relay Architecture Options Evaluated

Constellation (exclude spares)	Quantity of Relays	Inter-Relay Crosslink	User Burden Considerations	#Ground Station Locations
▪ GEO ▪ Equatorial	3 + 1 spare	No	▪ Nominal ▪ 3.5 dB reduction	2 (1 CONUS; 1 US OCONUS)
▪ MEO ▪ ½ Synchronous ▪ ~20,000 km altitude ▪ Equatorial	6 + 1 spare	No	▪ Nominal ▪ 3.5 dB reduction	4 (1 CONUS; 1 US OCONUS; 2 non-US OCONUS)
▪ MEO ▪ ½ Synchronous ▪ ~20,000 km altitude ▪ Equatorial	6 + 1 spare	▪ Yes ▪ RF, bent-pipe; or optical, OBP	Nominal	1 (CONUS)
▪ MEO; ¼ Sync ▪ Equatorial	7 + 1 spare	No	Nominal	4 (1 CONUS; 3 non-US OCONUS)
▪ MEO; ¼ Sync ▪ 2 planes @ 70° inclination; ▪ 4 relays per plane	8 + 1 spare per plane	Yes	Nominal	3 (1 CONUS; 2 non-US OCONUS)
▪ 1/7 Sync ▪ 2 planes @ 90° inclination; ▪ 6 relays per plane	12 + 1 spare per plane	Yes	Nominal	4 (1 CONUS; 1 US OCONUS; 2 non-US OCONUS)
▪ 1000 km altitude ▪ 5 planes @ 90° inclination; ▪ 9 relays per plane	45 + 1 spare per plane	Yes	20 dB reduction	> 16 globally distributed ground stations

Results were obtained via a thorough, efficient evaluation process, involving a range of mutually consistent, "apples-to-apples" comparisons. The following approach and assumptions were pursued:

- User services addressed reflect the baseline S-band and Ka-band services, available via the current SN, and satisfy the Driving Requirements of Table 23 and Table 24. Current Ku-band services were not included since they were not required. Also, it is likely that these will be phased out due to spectrum pressures; phase-out of Shuttle operations; and the planned evolution to Ka-band for ISS and Exploration. The elimination of Ku-band from the relay SA antennas increases antenna efficiency at both S- and Ka-bands, thereby automatically reducing user burden. The technical/cost impact of including or excluding Ku SA, however, is very small, and therefore, should be subject to further programmatic study.

- For each architecture option, a minimally sized relay constellation plus on-orbit sparing was assumed that provides global coverage to a surface latitude of at least ~60°–70°N and S, with a minimum MA, SA global service complement that is consistent with a 3-node constellation of current TDRSS relays. All relays in the constellation were assumed identical, in order to minimize recurring cost. Specific relay quantities, per architecture, are summarized in Table 25.
- Relays were assumed to be bent-pipe for all non-crosslink architectures, since trades found this to be lower-risk and more cost-effective. For the crosslink scenarios, both RF/bent pipe, and optical/on-board-processed (OBP) were addressed and evaluated.
- The Ground Segment conceptual design was tailored to the specific relay constellation and unique operational aspects, if any. For example, for the GEO constellation, a single ground antenna per relay is required, with very little steering needed due to the nearly stationary satellites. On the other hand, a MEO or LEO constellation requires 2 ground antennas per SGL due to relay motion and the need for Make-before-Break operations.

Within the above framework, the initial evaluation focused on the GEO, MEO ½ sync, and MEO ¼ sync options indicated in Table 25, and included the additional assumption of a user RF link burden consistent with that provided by the current SN. This user burden assumption led to the specific sizing of relay service antennas per architecture, with the specific antenna size a function of relay altitude. Conceptual design, sizing and cost estimation led to the relative costs illustrated in Figure 38 (see section 3.2.7.3). For additional insight, the space, ground and launch component relative costs are also included.

The following key observations apply:

- The addition of an inter-relay crosslink into the architecture imposes a considerable cost impact, due to the added relay mass and power required, which directly leads to increased relay and launch cost. This crosslink impact on the space segment outweighs the modest GS benefit arising from fewer ground locations needed when the crosslink is present.
- The GEO option offers the most significant cost benefits for several reasons:
  - Fewer relays must be procured and launched
  - No inter-relay crosslink is used
  - Fewer ground terminals must be procured than the MEO, non-crosslink options
- The operational complexity FOM was found to highly favor the GEO architecture due to the static nature of the SGL. For example, a given ground segment antenna is dedicated to a specific relay on an extended time basis, and is only changed during maintenance or infrequent SGL assignment changes. On the other hand, every non-GEO architecture requires a much more complex make-before-break mode of operation to accommodate the moving relay constellation.

- Transition from the current SN to the new NER is greatly simplified via the GEO architecture, given: (1) the continuity in GEO operations; (2) no need to simultaneously operate GEO and non-GEO architectures during a several year transition period; and (3) the ability to maintain operations at the same ground locations with no need for any new Construction of Facilities (CofF).
- The above cost and technical considerations are also found to favor the GEO architecture over other lower orbiting relay architectures, such as the MEO ¼ sync option. As noted, this architecture requires a large number of relays. Also, inter-relay crosslinks are needed, since analysis indicated that this is the only way to reduce the quantity of ground segment locations to a manageable level, which still turns out to be a quantity of four (greater than the two needed for the GEO case). Similar observations apply for the 1000 km LEO relay architecture.

The above cost/technical considerations strongly suggest the attractiveness of a GEO architecture, with the closest contender the MEO ½ sync, non-crosslink option. This conclusion was further "tested" and validated by addressing "reduced user burden scenarios". Specifically, the following three scenarios were examined and cost estimates obtained:

- Increased service antenna size on GEO (from 4.5 m to 6.9 m) to reduce user burden by > 3.5 dB
- Increased service antenna size on MEO ½ sync (from 2.9 m to 4.5 m) producing an equivalent reduction in user burden
- 4.5 m service antenna size on 1000 km LEO providing ~16 dB reduction in user burden

Cost assessments, analogous to the above, were conducted:

- For the first two cases, the apples-to-apples comparison once again demonstrated the cost-effectiveness of the GEO architecture. Here, the cost impacts were primarily incurred due to mass increases in the relay, but the results still highly favored the GEO.
- The 1000 km case was addressed to gain some feel for what it would take to obtain a truly significant reduction in user burden. It was found that the cost for this benefit is very high. Not only is the number of ground segment locations (> 16) and associated operational complexities probably unacceptable, but even if 5 relays are launched at a time, the resulting launch costs are ~2.5 times that of the GEO launch costs. These launch costs are above and beyond the much greater cost of procuring the large number of LEO relay spacecraft required.

Based on in-depth technical/cost assessments to date, the conclusion is that the GEO architecture is the most attractive candidate for the NER architecture.

3.2.4.1. Potential Impacts of Driving Requirements

Within the framework of the reference architecture, SBR warrants specific consideration, given its potential importance within the future NASA architecture. SBR requires continuous, real-time, low-latency two-way communications service between a launch vehicle and the range safety station via the relay satellite during the launch phase. This service conveys the health and welfare of the launch vehicle via a return telemetry link while providing a highly reliable command link to the launch vehicle that can transmit a destruct command to the vehicle if necessary. Among the architectural considerations that must be addressed is the strong desire (if not need) to increase two-way link margin as much as feasible, with particular emphasis on the command link. This translates into the appropriate combination of increased relay SA antenna gain and transmit power at S-band (i.e., SSA), and is a prime motivation for the NER Performance Requirement of Table 24 that addresses a reduced user burden >3 dB relative to the current SN. Toward this end, technical assessments have addressed the feasibility and impacts of increasing the SA antenna aperture size and the associated transmit power. These assessments indicate the feasibility of increasing the nominal SA aperture from 4.5m to at least 6.9m and increasing the transmit power from a nominal value of ~30W to 60–100W, thereby offering the potential of a command link EIRP increase approaching 8 dB. Associated impacts on payload and bus mass and power must, of course, be incorporated.

3.2.5. Reliability and Availability

Architecture reliability and service availability are driven by the relay space and ground segment designs, the quantity of equipment produced, and the relay Space-Ground Link (SGL) RF interfaces. The same principles apply across all architectures considered; although the cost/complexity associated with achieving a given reliability/availability level will be unique to each architecture. Additional reliability/availability considerations must also be addressed regarding the terrestrial connectivity between the NER and end-user-sites, and between the NER and the Service Management component.

3.2.5.1. Relay Space Segment

Space segment reliability is a complex statistical parameter that addresses the probability that a sufficient number of relays, and the services they provide, will be functional over a prescribed time frame, so that the required user population needs will be met over that timeframe. It is assumed that the relay lifetime is at least 15 years. This reliability parameter is determined by the: quantity of spacecraft built; expected lifetime of each spacecraft; strategy for maintaining on-orbit spares; and strategy for relay replenishment. The expected relay lifetime may be further parameterized by the lifetime of each service provided (e.g., Demand Access vs. Scheduled). Over 20 years of TDRSS experience to date has provided valuable insights into how to maximize relay life as a function of the service parameter to be optimized.

Given the high cost of the space segment including launch costs and the long operational life desired in between relay system procurements, proper levels of redundancy must be incorporated into the most critical relay subsystems (e.g., the SGL transmitters). Furthermore, once operational, the proper balance must be maintained between maximizing relay operational timeframe and adequate replenishment rate, to ensure that the procured spacecraft cover the full timeframe of interest, while avoiding any gaps in service support due to on-orbit failures.

Since overall space segment reliability is directly related to the ensemble of failure rates of spacecraft components, it follows that the more complex the spacecraft, and the greater the number of components, the more costly it will be to achieve a desired level of spacecraft lifetime. As such, the more complex architectures (such as those that employ inter-relay crosslinks and on-board processing) can also be expected to incur higher levels of implementation cost.

From the relay space segment perspective, service availability, at any given point in time, is determined by having a sufficient number of relays operating simultaneously, so that the required geometric coverage and service capacity is provided. Robustness in coverage is obtained by having sufficient overlap of the relay coverage areas; this aspect has been explicitly accounted for in arriving at the constellation options of Table 25 above.

3.2.5.2. Relay Ground Segment

Ground Segment (GS) hardware and software reliability is sustained over an extended timeframe via its Operations and Maintenance (O&M). GS O&M is clearly simplified for architecture candidates that minimize the number of discrete GS locations, since the geographical distribution of staffing can be minimized, as can the quantity of distributed hardware depots.

Availability is a function of the specific design and implementation. Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) determine the frequency of outages, and the down time when a failure occurs, respectively. Built-in redundancy combined with automatic failover will greatly reduce the need for unanticipated repairs in between scheduled maintenance periods. This is an aspect that is common to all architectures under consideration, with the cost a direct function of the quantity of ground terminals required by the architecture under consideration.

3.2.6. Expandability, Scalability, and Adaptability

3.2.6.1. Expandability and Scalability

The architectures considered may be divided into two classes: those with inter-relay crosslinks and those without crosslinks. The architectures without inter-relay crosslinks reflect maximum flexibility in achieving expandability/scalability; this is based on the feature that each addition of a relay and a companion ground terminal provides the desired level of capacity increase. On the other hand, an architecture with inter-relay crosslinks is not as flexible, since a single relay addition offers only limited additional capacity (i.e., only when it is in direct view of a ground station). As such, multiple relays may have to be launched, and relay-to-relay connectivity may also have to be adjusted, in order to achieve a desired level of capacity increase. In the recommended architecture this can be achieved by adding additional satellites to the constellation with the corresponding ground antennas in the SGL complex.

3.2.6.2. *Adaptability*

The recommended architecture includes a bent-pipe design (vs. a store/forward approach). Adaptability to meet new user requirements waveforms, data rates, modes of operation etc. can continue to be incorporated via ground upgrades, without the need to launch new relay satellites.

3.2.7. FOM Definition, Analysis, and Conclusions

A set of FOMs was used to assess the NER options and generate the recommended reference architecture. These FOMs included:

- Visibility/Coverage
- ΔV
- Failure Tolerance
- Robustness
- Transition
- Operational Complexity

Of the set of six FOMs, several are not strong discriminators between the architecture options either by way of design or simply because the strengths and weaknesses are well balanced. These FOMs are described briefly in Table 26.

The two FOMs that are the primary architecture discriminators are Transition and Operational Complexity. The most competitive options were evaluated in detail for the GEO and ½ synchronous MEO cases.

3.2.7.1. *Transition*

The Transition FOM measures the impact of migrating from the legacy system(s) to the new C&N architecture. Included in transition are the impacts of introducing new network elements and new modes of operation, both legacy and new operations being simultaneously active during the transition period, and regulatory actions. Specific items captured by the Transition FOM are: (a) new construction of facilities within CONUS and abroad; (b) the quantity of new ground terminals to be implemented at existing and new sites; (c) the transition to a new relay constellation if applicable; (d) the time period over which new relays are launched to provide global capability; (e) whether both legacy and new scheduling systems must be operational during transition; (f) whether users must operate via legacy and new systems during transition; and (g) the regulatory impacts of new infrastructure and new user service spectrum. Each item is quantitatively scored as outlined in Table 27. For the case of transition, low scores correspond to low impact which is desirable. Note that the raw quantitative scores based on the algorithms described in the figure, are converted to normalized scores on a 0-100 scale to simplify the later combining of multiple FOM scores.

3.2.7.2. *Operational Complexity*

The Operational Complexity FOM measures the degree of difficulty of operating systems in the new C&N architecture. Operational complexity includes the impacts associated with satellite dynamics (both user and relay), as well as dynamic control of architecture elements and security issues. Specific items captured by the operational complexity FOM are: (a) user service scheduling; (b) nominal relay Telemetry & Command (T&C) (not during handover); (c) relay T&C crypto handling; (d) on-board satellite SGL antenna control; (e) SGLT antenna control complexity; (f) inter-relay crosslink complexity; and (g) contingency operations. Similar to the Transition FOM assessment, the options are scored quantitatively with low scores equating to desirable low-impact characteristics. Table 28 identifies the algorithms for scoring the operational complexity FOM and the results for the three options.

Table 26. Low Impact NER FOMs

FOM Definition	Application
Visibility / Coverage: Measure of the availability of a communication link based on approximate line-of-sight coverage	All options are designed to provide 100% line-of-sight visibility to all users at low-earth-orbiting altitudes and above. For GEO and MEO equatorial constellations, visibility gradually decreases with decreasing user altitude, but 100 % visibility still is ensured within + or – 70^{o} latitude. The MEO-inclined and LEO-polar options offer the slight advantage of 100% visibility to latitudes above 70^{o}.
ΔV: Measure of the maneuvering (and therefore fuel) required to maintain and dispose of a S/C in orbit. It also reflects the operational dynamics/ complexity/risk of the given alternatives.	Focus is on in-orbit maintenance, since launch establishment is addressed as part of the cost of development/deployment. The GEO constellation requires virtually no station-keeping fuel once on orbit, if it is launched into a ~ 7.5^{o} inclination; there is the small disadvantage that it must be disposed of (into graveyard orbit) at end-of-life. For the decreasing altitudes of the MEO, LEO constellations, on-orbit delta-v requirements grow with decreasing altitude, due to increasing drag, but may offer the advantage (depending on orbit) of not requiring end-of-life disposal.
Failure Tolerance: Measures the degree of global coverage remaining after the loss of a relay satellite	The degree of instantaneous global coverage lost is highest for the GEO constellation: up to ~ 15% loss for user LEOs at low altitudes ~ 200 km. Such a loss also includes the loss of multiple service apertures. The % coverage lost decreases with decreasing relay altitude, given that the quantity of nominally operating relays increases with decreasing altitude. A relay loss at lower altitude incurs fewer lost service apertures. On-orbit sparing is explicitly accounted for in the architecture designs and quantity/deployment costs associated with this FOM are accounted for as part of the detailed cost assessment.
Robustness: Accounts for the two dimensions: ▪ Adaptability: the flexibility of the system to accommodate operational changes without HW or SW redesign ▪ Evolvability: the ability of the system to expand capacity and accommodate design changes to enhance system capabilities	Adaptability: The GEO and MEO bent-pipe constellations offer maximum adaptability; new waveforms, operational modes, and work-arounds can be incorporated over many years, via ground refinements. In contrast, On-Board Processing (OBP) relays, e.g. the MEO and LEO optical-crosslink architectures that require OBP, are limited by the programmable flexibilities introduced at time of launch. Evolvability: Bent-pipe-constellations are most attractive since whatever can be incorporated via programmable OBP can largely be incorporated via ground upgrades, while the reverse is not necessarily true. For scalability, the non-X/L GEO and MEO constellations are most advantageous since incremental capacity increases can be addressed by a single relay/SGL terminal at a time. For the crosslink constellations, additional relay capacity cannot simply be added one relay at a time, due to fact that each new relay must have one or more crosslink counterparts available (otherwise only partial coverage would be available, thereby limiting the degree of capacity increase).

Table 27. Transition FOM Scoring

Factor	Definition	Algorithm	GEO	MEO (no X/L)	MEO (X/L)
New Construction of Facility (CofF)	Measure of number of new ground sites to be introduced in support of transition (CONUS or non-CONUS)	• 6; if N ≥ 5 • N+1; N=# new sites • 0; eliminate 1 or more sites	1	3	0
New Non-CONUS CofF	Measure of number of distinct countries requiring new CofF	• 6; if N ≥ 5 • N+1; N=# new sites • 0; eliminate 1 or more sites	1	3	0
Ground Terminals	Measure of total number of new Space-Ground Link Terminals (SGLT) to design and build (include spares)	• 2 ; more than 6 • 1; 4 - 6 • 0; 3 or less	1	1	1
Relay Orbital Transition	Measures need to operate multiple distinct constellations during transition	• 3; if N ≥ 4 • N-1; need to operate N distinct constellations	0	1	1
Earth Relay Transition Period Completion	Estimates transition duration by determining minimum quantity of new relays required for global capability (include spares)	• 2 ; more than 6 • 1; 4 - 6 • 0; 3 or less	1	2	2
User/Network ops concept	Measures *user and network* needs to operate via multiple networks/ scheduling-systems during transition	• 3; if N ≥ 4 • N-1; need to operate via N networks	0	1	1
Regulatory – Infrastructure	Measures need to file for totally new infrastructure orbits, spectrum (SGL or X/L)	• 2; new constellation and spectrum • 1; new constellation or spectrum • 0; no infrastructure change	0	2	2
Regulatory – User	Measures need to file for totally new user service spectrum	• 3; if N ≥ 4 • N-1; number of new user spectral bands	0	0	0
	Max Range: 0-27	Raw Totals	4	13	7
	Converted to 100 pt. scale	**Normalized Scores**	**14.8**	**48.1**	**25.9**

Table 28. Operational Complexity FOM Scoring

Factor	Definition	Algorithm	GEO	MEO (no X/L)	MEO (X/L)
User service scheduling	Measures complexity of user service scheduling and related constraints	Sum of following: • Relay constellation: static=0; dynamic=1 • Constellation with overlapping coverage: Yes=0; No=1	0	1	1
Nominal Relay T&C (not during handover)	Measures complexity of providing Relay T&C – e.g. multiple hops	• 2; >1 X/L hops • 1; 1 X/L hop • 0; single relay/ground interface	0	0	1
Relay T&C Crypto handling	Measures complexity, logistics of handling T&C cryptos	• 1; each GT must dynamically update • crypto as relays move • 0; fixed relay/GT crypto	0	1	1
On-board S/C SGL antenna control complexity (nominal and handover ops)	Measures quantity, complexity of controlling/ allocating on-board SGL antenna(s)	• 2; 2 dynamic on-board SGL antennas • 1; 1 dynamic on-board SGL antenna • 0; 1 nearly static on-board SGL antenna	0	2	1
SGLT antenna control complexity (nominal & handover ops)	Measures quantity, complexity of controlling/allocating GT antenna(s)	• 2; 2 dynamic antennas per SGLT • 1; 1 dynamic antenna per SGLT • 0; 1 nearly static SGLT antenna; no handover/slewing	0	2	2
Inter-relay X/L complexity	Measures complexity of X/L operations under nominal tracking conditions, if applicable	• 2; ≥2 X/L antennas per relay • 1; 1 X/L antennas per relay • 0; 0 X/L antennas per relay	0	0	2
Contingency Operations	Measures complexity/logistics associated with critical link dropouts/outages	• 2; ≥2 links (relay/relay or relay/ground) that must be reinitiated after dropout • 1; 1 link that must be reinitiated • 0; 0 links that must be reinitiated	1	1	2
	Max Range: 0-13	Raw Totals	1	7	10
	Converted to 100 pt. scale	**Normalized Scores**	**7.7**	**53.8**	**76.9**

3.2.7.3. Cost

Cost was estimated for the NER architecture options including launch, space segment, and ground segment estimates. Launch costs were calculated based on spacecraft mass estimates, available data on launch vehicle capacity and price. Primarily, the family of Delta class launch vehicles was used for the study due to availability of both capacity and cost information. Several launch configurations were studied for each option based on assuming a maximum of one, two, or three spacecraft per launch vehicle. In each case, the most cost effective combinations of vehicles were selected.

The space segment costs were estimated using the NASA-Air Force Cost Model (NAFCOM). Design, Development, Test & Engineering (DDT&E) starts at Authorization To Proceed (ATP) and continues through checkout of the first flight article. Costs include labor, materials, test equipment and tooling, and other direct and allowable indirect expenses required to determine compliance with all design requirements documentation and to perform the subsequent analysis, design, development, and redesign of test and development hardware. Flight unit costs begin with the start of production initiated by long lead procurements and ending with the delivery of the flight unit. Production costs reflect the flight unit costs multiplied by the quantity with an assumed learning curve of 95%.

Ground segment costs were estimated in a bottoms-up fashion, and accounted for the non-recurring and recurring costs for the antenna and RF front-end, User Services Subsystem (USS), TT&C equipment, installation, levels 2-4 integration and testing, Control and Monitor (C&M), control center Automated Data Processing Equipment (ADPE), custom software, maintenance test group, data interface subsystem, program management and system engineering. The results of the cost estimation are shown by component (launch, relay/space, and ground), and as total values in Figure 38.

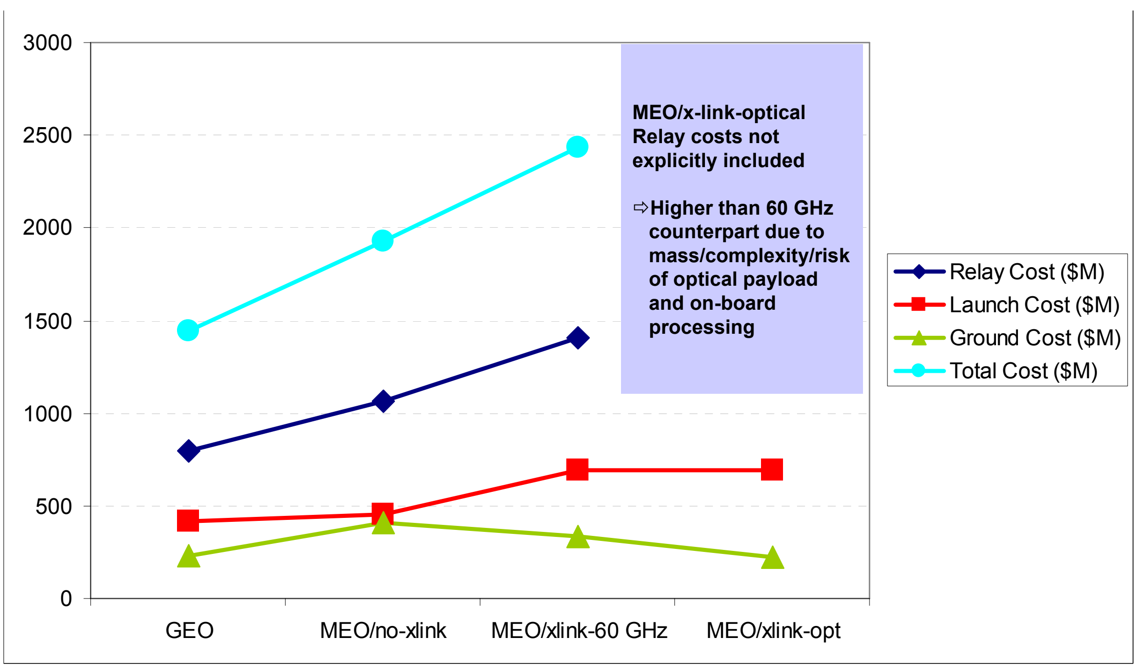


Figure 38. Cost Estimate Results for the NER Element Options

3.2.7.4. Conclusions

The detailed FOM assessment of the GEO and ½ synch MEO options was based on the assumption of a common capability baseline for an "apples-to-apples" comparison. Based on the results the GEO option appears most attractive with the lowest system implementation cost, lowest operational complexity, and simplest transition. As compared to the GEO option, the non-cross-linked MEO case was: modestly lower cost per relay but more costly overall; more costly for the space segment due to increased number of relays required, and more costly for the ground segment as four sites (2 non-US) are required. If the MEO option with cross-links is compared to the GEO, it becomes clear that the GEO is more favorable as both per-relay and total costs for the MEO are higher, technology risk is greater, and both operational and transition complexity are greater.

3.3. Lunar Relay Element

3.3.1. Overview of the Lunar Relay Element

The LR Element has one architecture that allows flexible implementation to accommodate future changes in lunar exploration strategy, and respond to the exploration and science requirements that are still evolving within NASA. It supports human and robotic exploration and science missions. Relays carried on RLEP missions are used as precursors to human missions following an evolutionary path toward Constellation C3I Interoperability capability. During the human sortie phase, the LR network handles fixed equipment such as science and In Situ Resource Utilization (ISRU) experiments plus mobile rovers operating between sorties with peak loads occurring during the lunar surface human operations. During the outpost phase, network traffic rises to accommodate continuous human operations with peaks occurring after the arrival of new equipment and during EVAs. The Lunar Relay Satellite (LRS) constellation is adjustable based on requirements including the number and location of sortie and outpost sites. A constellation of 1-2 satellites in an elliptical orbit is sufficient if coverage is limited to the South Pole region, whereas a constellation of up to 6 satellites may be required to support the “go anywhere” capability. By the sortie phase, the LR meets the Constellation C3I Interoperability Specification providing on-board Internet Protocol-based routing with a store and forward capability. It also provides multiple simultaneous links to support LSAM, outpost, EVAs, rovers, and emplaced science/ISRU packages that are out of sight of each other. A range of wideband and narrowband communication services, as well as navigation aids, can be scheduled or provided on-demand. Service provision and management will be highly automated to ensure highly reliable operations and to reduce operations costs. Additional flexibility is envisioned by supporting more than one LRS deployment method including launching on dedicated ELVs, on Constellation missions, and/or as a secondary payload on other missions.

The LR consists of the lunar space segment, the lunar surface segment, and the supporting Earth ground segment. The lunar space segment primarily provides:

- Two-way connectivity with Earth
- Navigation aids for space-based and lunar surface users, which include scientific spacecraft and Constellation vehicles during earth/lunar transit while in close lunar proximity.

The lunar surface segment provides two way connectivity and navigation aids to users in the vicinity of the Lunar Outpost by way of the Lunar Communications Terminal (LCT), which provides Wide Area Network (WAN) service and acts as an access point to the LRS, and navigation beacons.

The supporting Earth ground segment provides two-way space/ground connectivity with the LRS by means of the GEE, and accommodates all user-service data and relay-satellite command/control with the LR Mission Operations Center (LMOC).

The evolvability of the LR element, from robotic through human exploration, is captured in Figure 39, showing the best solution identified to date for each phase. The timeline reflects the current SCAWG Mission Model with sortie missions beginning in 2018 at a rate of 2 per year, and outpost missions beginning in 2022 at a rate of 2 per year in addition to cargo flights.

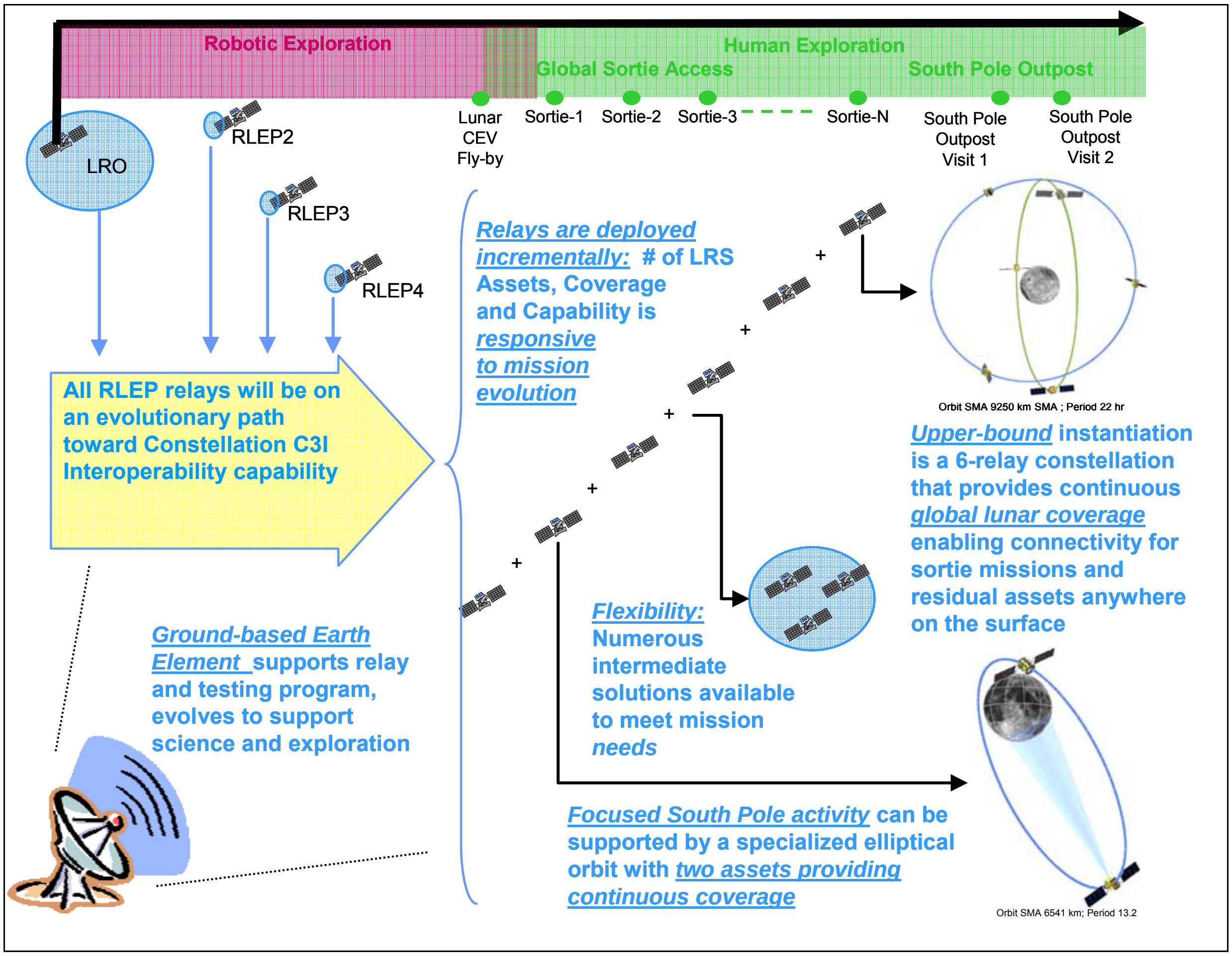


Figure 39. Evolvable Lunar Network Implementation Concepts

3.3.2. Top Level Functional Description

The LR architecture accommodates the range of expected communications and navigation aid requirements for the Constellation Program as well as assumed science mission requirements. The LR architecture evolves over three major phases of lunar science and exploration missions:

3.3.2.1. Robotic Precursors

The evolution should start with the Robotic Lunar Exploration Program (RLEP) and continue to human sorties and human outpost missions. The LR Element architecture is one in which any relay C&N systems flown as part of the RLEP are on a path to achieving the Constellation Communications Architecture, including the Constellation C3I Interoperability Specification, by the first Human Sortie mission. Initial RLEP relay communications do not have to be fully compliant with the C3I Interoperability Specification but there does need to be a clear roadmap identifying opportunities to use

RLEP missions for technology risk mitigation, space qualification of C&N components, and accumulation of operational experience feeding forward to the next phase.

3.3.2.2. Human Exploration – "Go Anywhere" Sortie

The LR architecture allows for support of missions that may land anywhere on the Moon. Relay satellites will be deployed as needed to provide coverage for individual missions and remain available for future Constellation and science missions. An initial LRS could periodically cover some sortie locations, while a full constellation would provide continuous coverage to multiple sites, including far-side, limb and polar sites, dependent on requirements. Radiometric tracking is provided by the relays. As relays are incrementally added and beacons are deployed, the navigation accuracy for orbit determination, landing site targeting, and rendezvous improves and latency decreases.

3.3.2.3. Human Exploration – Outpost / Regional

For the Outpost phase, the LR will be configured to provide near continuous coverage to the outpost location. The current exploration strategy is based on locating the outpost within 5° of the South Pole. While the LR architecture supports this strategy, it is readily adaptable to locating the outpost anywhere. Radiometric tracking continues to be provided by the relays supported by surface beacons. The LCT is added to the surface assets prior to outpost habitation to provide a gateway into the LR for the outpost. Surface users outside the range of the outpost LCT continue to be supported by the relay satellites, as are orbiting users. Figure 40 provides a top-level overview of the LR elements, including the principal lunar surface segment, space relay segment, and ground segment functions and interfaces.

3.3.3. Architecture Options Considered

As Figure 41 illustrates, a broad range of competing considerations present themselves, and no single LR architecture optimally satisfies the ensemble of all constraints. For example, a space relay implementation including a Lagrange 2 relay orbiting at ~60,000 km coupled with a polar relay orbiting at ~10,000 km offers consistent far side coverage and acts as a stable node for the lunar vicinity trunk. But this particular architecture option involves greater communication distances that drive a higher communication system performance and cost. As such, a more detailed concept, consistent with this overall architecture, is currently being developed to:

- Allow a framework for analysis of implementation approaches meeting known requirements
- Allow expansion of capabilities or reallocation of assets to meet future defined requirements
- Permit a comprehensive, credible, and comparative technical/cost assessment across key constraints of interest
- Avoid the need for a trade space to be so large as to preclude a timely assessment process

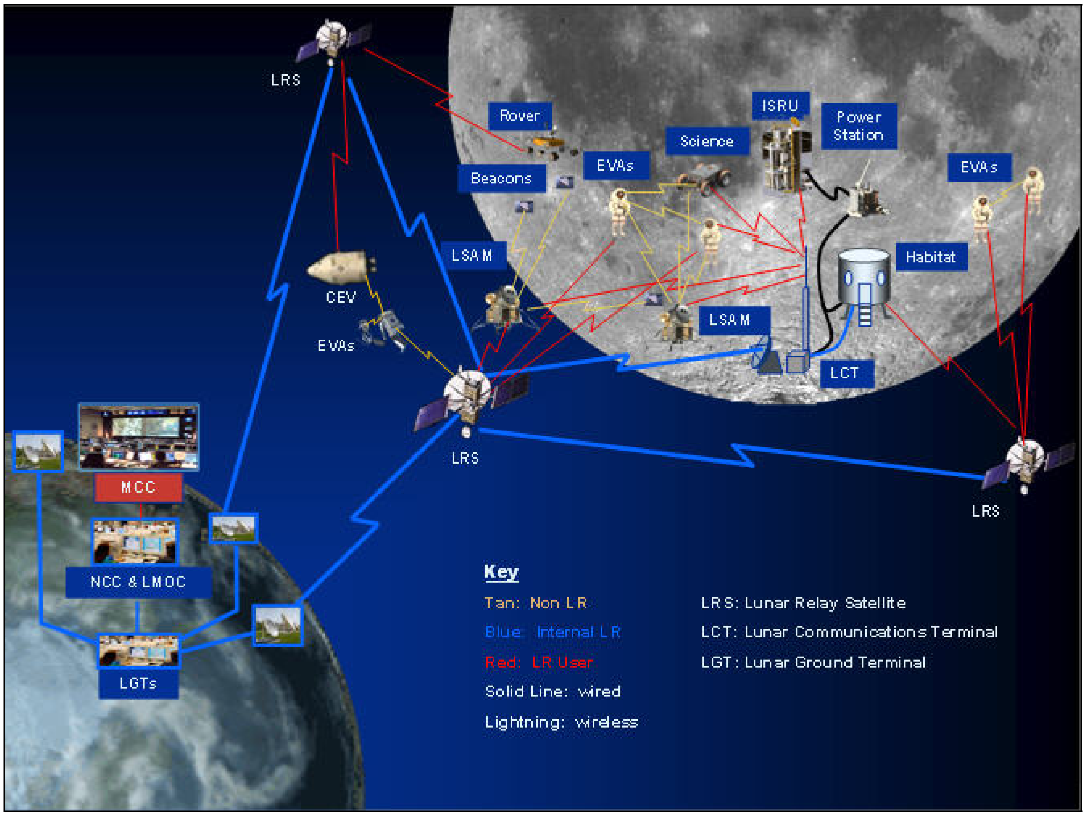


Figure 40. Lunar Relay Element Top Level Functional Description

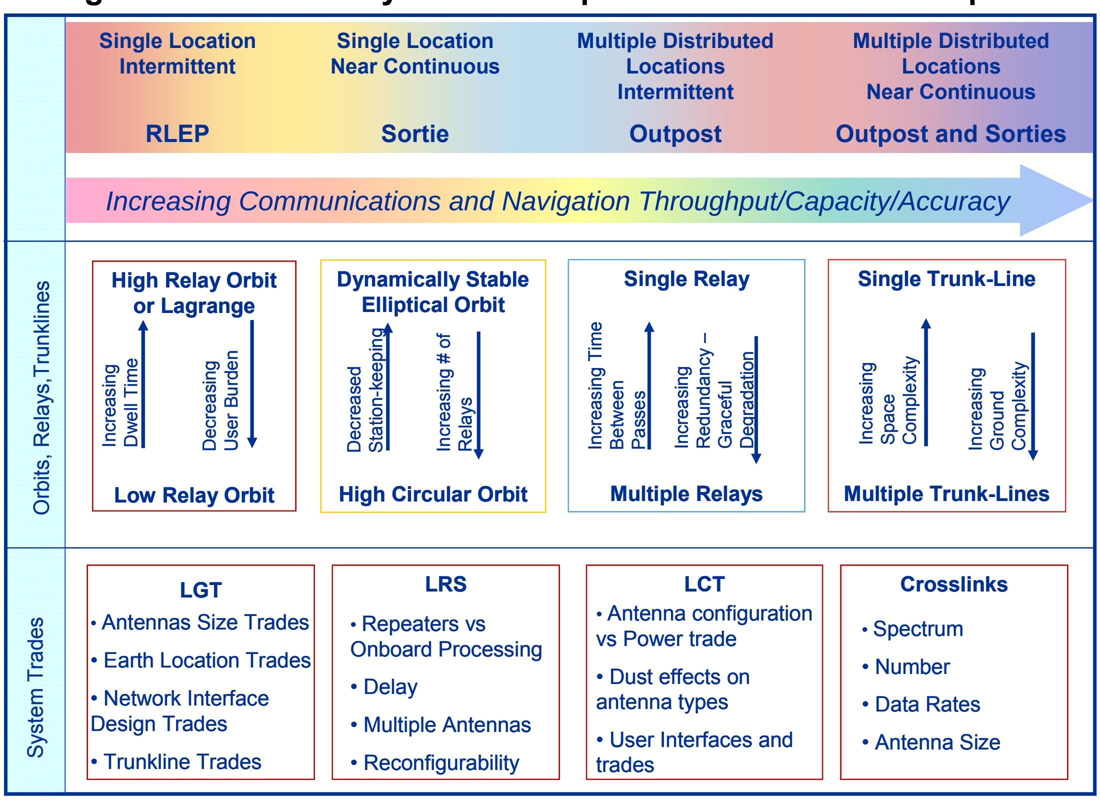


Figure 41. Architecture Trade Space and Considerations

Several analyses are being performed that will continue to shape the Lunar Network architecture. Foremost among them is the analysis for providing crosslinks between relay elements with a single high rate link to Earth (trunk) versus having each relay communicate directly to Earth. Another is whether the relay assets (both surface and flight) will have a bent pipe capability in addition to the store and forward capability already specified by the Constellation Program. Another analysis is determining the utility of beacons (both active and passive), and the incorporation of tracking navigation aid functions into the architecture. A major trade study will determine the recommended method(s) for launching and deploying the relay satellites. Finally an analysis is currently underway that looks at the role of residual payloads in the architecture. Various flight relay orbit options were identified by previous SCAWG studies – spanning circular, elliptical and Lagrange orbits – and the option set is shown in

Table 29. The challenge is to maintain a flexible architecture that allows us to choose the most cost effective solution as user requirements evolve.

Originally, 50 specific cases were defined for study as described in section 2.4.9.1. Preliminary analysis of lunar surface coverage and Earth visibility for all 50 cases provided sufficient information to narrow further study to the best case from each class. Table 30 identifies all 50 cases and highlights the seven cases shown in

Table 29 selected for further analysis for the initial the LR and Navigation studies.

Table 29. Specific Lunar Relay Orbit Options Evaluated

Lunar Relay Alternatives Studied		
South Pole Study	Constellations	Elliptical Orbit Class – 2 Relays in a single orbit plane with semi-major axis of 6540 km and an eccentricity of 0.6. The apoapsis of the orbit dwells over the South Pole providing continuous coverage and high amounts of dual coverage.
		Hybrid Orbit Class – 3 Relays in a circular equatorial orbit and 3 in a circular polar orbit. Orbit radius 9200 km.
		Inclined Circular Orbit Class – 3 Relays in a 70° inclined plane at a radius of 6430 km.
		L1 Lagrange Halo Orbit – 5 Relays in a large circular halo to provide continuous SP coverage, near and far-side
		L2 Lagrange Halo Orbit – 5 Relays in a large circular halo to provide continuous SP coverage, near and far-side
		Polar Circular Orbit Class – 3 Relays in a 5300 km radius orbit
		Landed Communications Tower at Malapert Mountain near the South Pole. Does not provide coverage of the entire Pole.
Full Coverage	Constellations	8 Relays: 4 Relays spaced equally in a single, polar plane with a circular orbit with another set of 4 Relays spaced equally in a polar plane perpendicular to the first. Orbit radius 9250 km.
		12 Relays: 3 Relays spaced equally in each of four polar circular planes. Orbit radius 9250 km.
		6 Relays: 3 Relays spaced equally in a single, polar plane with a circular orbit with another set of 3 Relays spaced equally in a polar plane perpendicular to the first. Orbit radius 9250 km.
		6 Relays: 3 in an inclined circular plane and 3 in a plane perpendicular to the first. Orbit radius 8050 km, inclination 52.2°.
		5 Relays: Five separate planes, each with one relay, where the position of each relay relative to others is phased to provide continuous global coverage. Orbit radius 9150 km, inclination 43.7°.
		6 Relays: The "Lang-Meyer" configuration consists of four inclined circular planes with one relay in each, properly phased, plus two relays in an equatorial circular orbit. Orbit radius 8050 km, inclination 58.9°.
		7 Relays: A hybrid configuration of four relays in elliptical orbits, one orbit with a northern apoapsis the other southern, plus 3 relays in an inclined circular plane perpendicular to the elliptical planes. The inclination of the elliptical plane is 56.1°, semi-major axis 6541 km, eccentricity 0.6. Circular orbit radius 11575 km, 33.9° inclination.
	Notes:	The 8 and 12 relay configurations are specific additions from the Navigation Team to the global coverage study. Interim Recommendation: Six relay configuration or eight, where the additional two can be treated as increased redundancy and provide increased coverage and navigation performance.
Deployment Trades		Small deployable communications package for far-side critical event coverage only. Deploy from the carrier vehicle during after trans-lunar injection vs. deploy after lunar orbit insertion.
		Pre-deployment of complete or partial constellations using ELVs vs. single relay deployment via piggyback on Constellation vehicles to build assets over time
		"Cover as you go": Provide continuous coverage to humans only vs. to humans and science / robotics left at prior sortie sites. Build up relay assets incrementally as needed.

Table 30. Orbit Cases Representing Classes of Lunar Relay Orbits

Class	Case #	Name
Elliptical	1	Elliptical-Single Plane-2 Sats- a=6541 km
	2	Elliptical-3 Planes-3 sats- a=6541 km (~JPL)
	3	Elliptical-Single Plane-3 Sats- a=6541 km
Hybrid	4	L2-Malapert-Hybrid
	5	L2-Malapert-3 Circular Polar Sats Hybrid
	6	Polar + Equatorial Hybrid- 6 sats- 9210 km- No Phasing
	7	Polar + Equatorial Hybrid- 6 sats- 9210 km
Inclined Circular	8	Inclined 70deg Circular-Single Plane-3 Sats- 6430 km (SATEL)
	9	Inclined 52.2deg Circular- Single Plane- 3 sats- 7995 km
	10	Inclined 48.2 deg Circular- Single Plane- 4 sats- 4360 km
	11	Inclined 52.2 deg Circular-2 Planes-6 Sats- 7995 km
	12	Inclined 52.2 deg Circular-2 Planes-6 Sats- 7995 km-No Phasing
	13	Inclined 48.2 deg Circular-2 Planes-8 Sats-4360 km
	14	Inclined 48.2 deg Circular-2 Planes-8 Sats-4360 km- No Phasing
	15	Inclined 60deg Circular- 4 planes- 12 Sats- 6000 km
L1 Halo	16	L1 Halo - Ideal Perpendicular Circular - 3 Sats- Radius 62000 km
	17	L1 Halo - Ideal Perpendicular Circular - 4 Sats-Radius 44000 km
	18	L1 Halo - Ideal Perpendicular Circular - 5 Sats-Radius 38000 km
	19	L1 Halo - Ideal Perpendicular Circular - 6 Sats-Radius 62000 km
	20	L1 Halo - Ideal Perpendicular Circular - 8 Sats-Radius 44000 km
	21	L1 Halo - Ideal Perpendicular Circular - 10 Sats-Radius 38000 km
L2 Halo	22	L2 Halo - Ideal Perpendicular Circular - 3 Sats-Radius 68000 km
	23	L2 Halo - Ideal Perpendicular Circular - 4 Sats-Radius 48000 km
	24	L2 Halo - Ideal Perpendicular Circular - 5 Sats-Radius 42000 km
	25	L2 Halo - Ideal Perpendicular Circular - 6 Sats-Radius 68000 km
	26	L2 Halo - Ideal Perpendicular Circular - 8 Sats-Radius 48000 km
	27	L2 Halo - Ideal Perpendicular Circular - 10 Sats-Radius 42000 km
L4 Halo	28	L4 Halo - Ideal Perpendicular Circular - 3 Sats-Radius 390000 km
	29	L4 Halo - Ideal Perpendicular Circular - 4 Sats-Radius 270000 km
	30	L4 Halo - Ideal Perpendicular Circular - 5 Sats-Radius 240000 km
L5 Halo	31	L5 Halo - Ideal Perpendicular Circular - 3 Sats-Radius 390000 km
	32	L5 Halo - Ideal Perpendicular Circular - 4 Sats-Radius 270000 km
	33	L5 Halo - Ideal Perpendicular Circular - 5 Sats-Radius 240000 km
Surface Tower	34	Surface Communications Tower at Malapert Mountain Direct to Earth
Polar Circular	35	Polar Circular-Single Plane-3 Sats- 5138 km
	36	Polar Circular-Single Plane-3 Sats- 5300 km
	37	Polar Circular-Single Plane-3 Sats- 9210 km
	38	Polar Circular-Single Plane-4 Sats- 3061 km
	39	Polar Circular-Single Plane-4 Sats- 5015 km
	40	Polar Circular-2 Planes-6 Sats- 3738 km (BEACON)
	41	Polar Circular-2 Planes-6 Sats- 5076 km-No Phasing
	42	Polar Circular-2 Planes-6 Sats- 5076 km
	43	Polar Circular-2 Planes-6 Sats- 5150 km
	44	Polar Circular-2 Planes-6 Sats- 8738 km
	45	Polar Circular-2 Planes-6 Sats- 9210 km- No Phasing
	46	Polar Circular-2 Planes-6 Sats- 9210 km
	47	Polar Circular-2 Planes-8 Sats- 3027 km- No Phasing
	48	Polar Circular-2 Planes-8 Sats- 3027 km
	49	Polar Circular-2 Planes-8 Sats-5015 km- No Phasing
	50	Polar Circular-2 Planes-8 Sats-5015 km

3.3.4. Operations Concept and Interfaces with User Mission

All operations and data crossing interfaces are executed in a highly automated manner, thereby minimizing manpower requirements and maximizing reliability. All ground interfaces are also expected to reflect well established standards, thereby benefiting from ongoing industry developments. Elements, RF interfaces, and data types are depicted in Figure 42. The LR space, surface, and ground segments are generically illustrated, and the operations concept is independent of the specific implementation approach ultimately selected but consistent with the Constellation C3I Interoperability Specification.

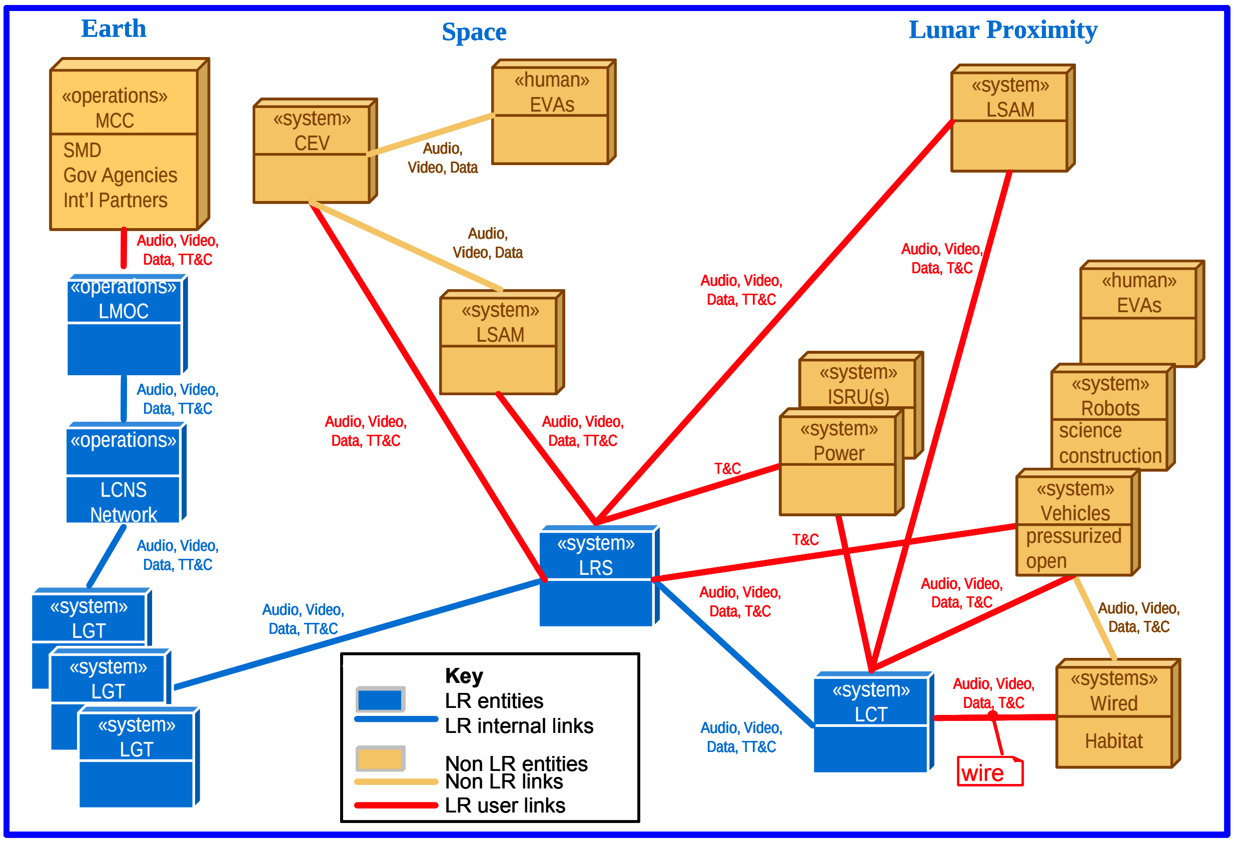


Figure 42. LR Operations Concept – Elements, Interfaces, and Data Flow

Another key aspect of the operations concept is the specific user interaction with the network and the sequence of events. While many distinct scenarios can be envisioned, some high level insight can be gained via the "Day in the Life of the User" example illustrated in Figure 43. The figure focuses on EVA or robotic operations and the sequence of events beginning with the service scheduling process. The vertical lines identify which system element is involved while each of the two horizontal blocks illustrates the nature of interactions across element interfaces including both user vehicle data and service-management-related data. The Exploration C&N System (ECANS) acts as the single interface between Constellation elements and non-Constellation portions of the Space Communications and Navigation Architecture.

The "day in the life" depicted in the figure shows the flow of connectivity during EVA operations. There are three types of activity indicated: infrastructure connectivity that is beyond the scope of the LR Element, connectivity to and from vehicles and astronauts via the LR assets, and internal commanding and control for the LR. Command, control, voice, and navigation data are shown originating at the CEV Mission Control Center (MCC), passing through the ground network and terminals to the LRS. From the LRS the data may be transmitted to the CEV, LSAM, lunar surface terminal (LCT), or surface lander. The LCT distributes information to robotic missions, surface landers, or astronauts performing EVA. The return paths are reversed, providing telemetry, status, voice, and navigation (where applicable). The complexity of the operations are somewhat simplified by identifying primary and redundant communications paths. For example, the primary path between the LRS and the surface lander goes through the LCT with the redundant path being direct.

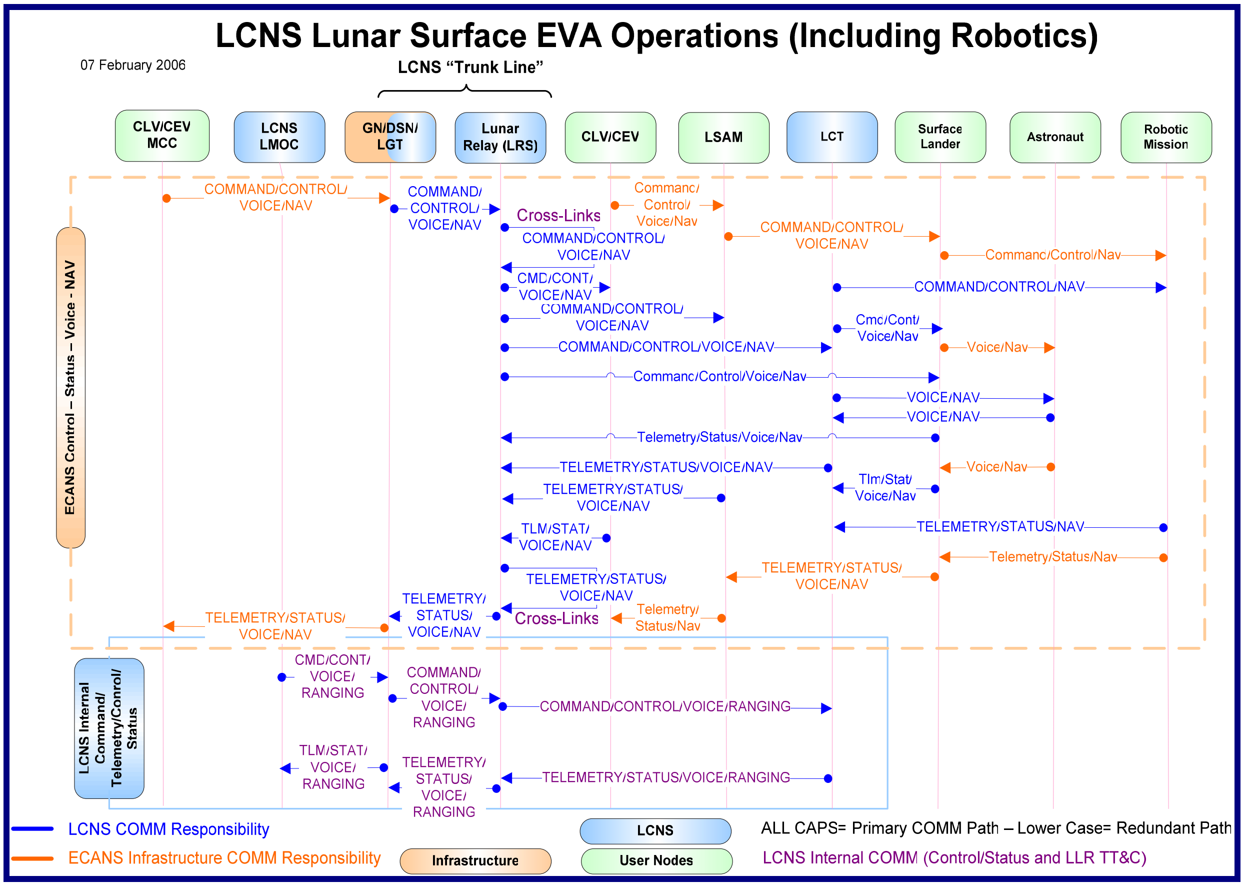


Figure 43. LR Element: Illustrative "Day in the Life of a User"

3.3.5. Key Functional and Performance Requirements

Lunar Network requirements are still evolving within the Constellation Program, and other user requirements have not yet been derived. The requirements in Table 31 summarize the primary functional and performance requirements of the LR element as they are known today, and identify other proposed requirements which may be placed on the LR in the future.

Table 31. Key LR Requirements

Requirements
Communicate with the Constellation Architecture using SN signal formats for relay and long distance (greater than 100 km) communications and tracking
Use the Internet Protocol for routing packets between Constellation elements, providing data stream quality of service, using IP-based file transfer, command and telemetry transfer, voice, and video capabilities over one-way and two-way
Implement Code Division Multiple Access (CDMA) to support simultaneous communications between Mission Planning Training & Flight Operations (MPTFO) and the CEV, as well as other Constellation elements in close proximity.
Comply with the C3I Interoperability Specification in support of Constellation elements
Interface with Constellation Elements for transmission and reception of commands using the Advanced Encryption Standard.
Provide support to a lunar outpost located within 5° latitude of the lunar South Pole.
Support data rates up to 24 kbps of low rate data to the CEV in any attitude using S-band signals
Support data rates up to 1 Mbps of high rate data to/from CEV using S-band signals
Support data rates up to 150 Mbps of high rate data to CEV using Ka-band signals
Simultaneously support at least two users in lunar orbit, on the lunar surface, or a combination of the locations.
Comply with the Networking, Security, Spectrum, and Navigation Architectures defined in this report.

3.3.6. Reliability and Availability

Reliability and availibility requirements will evolve with the Exploration initiative. The architecture supports deploying initial capabilities via residual C&N assets on multipurpose RLEP S/C and landers. If available in the sortie phase, these assets will be able to support later science missions, and will be used to augment Crewed vehicles on an *ad hoc* basis. Depending on the reliability built into the residual C&N payload and the host spacecraft, however, they may not be acceptable for primary or backup support to crewed missions.

For crew support, the level of LR availibility is still under discussion, however, it is clear that assured continuous coverage of the sortie or outpost is not required at this time. For the purposes of the architecture, critical event coverage is assumed to be required, and LR reliability is assumed to be 2 fault tolerant without factoring in the availibility of residual assets in the vicinity. These assumptions are being reviewed with the Constellation Program.

3.3.7. Expandibility, Adaptability and Scalability

The LR architecture is based on *modularity*, a *layered network*, *open standards-based interfaces*, and *automation* as applicable. Modularity dictates that the system be designed using a small number of reusable components that can provide increasing capacity merely by adding more components. Like terrestrial computer networks, the LR can grow by flying additional relay satellites and navigation aids.

Dividing the network into layers as defined in Section 2.1 encapsulates network functions and separates implementation of each layer at standard interface boundaries allowing the evolution of each layer independently while minimizing the impact of changes on adjacent layers. The LR is the only portion of the SCA that requires an entirely new system to be developed. This new system will be "born flexible" by incorporating concepts from terrestrial telecommunications and the Internet.

The performance of the resulting LR architecture can be increased or decreased by adding or subtracting relays and other assets to meet individual and cumulative mission needs and available budget. It provides NASA with an unprecedented degree of adaptability to changes in mission and program strategy on relatively short notice. Finally, layering and standardization provide a framework for incrementally inserting new technologies to meet evolving and expanding lunar exploration and science objectives.

3.3.8. Architecture Implementation Concepts

In the presence of emerging and evolving requirements for the lunar communications infrastructure, the SCAWG has studied possible implementations of the architecture. The extent of unknowns indicates that the architecture must be flexible and responsive to the exploration and science activities as they become defined. Table 32 characterizes implementation concepts of the flexible architecture.

3.3.9. FOM Selection, Analysis, and Results

The LR Element architecture was studied in two phases corresponding to different assumed mission scenario requirements. The first focused on the South Pole while the second explored options for providing full lunar coverage. The FOMs, analysis, and results for both series of studies will be discussed briefly.

3.3.9.1. The South Pole Study

The South Pole Study was the first phase of the lunar architecture assessment and focused on evaluating architecture options that meet the requirements for continuous coverage of the South Polar cap from 80-90° South latitude.

FOMs were generated to assess the relative quality or performance of the architecture options. The set of FOMs used during this study included both quantitative and qualitative measures: (a) visibility/coverage; (b) orbit stability; (c) failure tolerance; (d) navigation utility; (e) mission evolvability; (f) adaptability; (g) link capacity; (h) scalability; (i) partial life cycle cost; (j) sustainability; and (k) user burden. The architecture options being evaluated against this set of FOMs are highlighted in Table 30.

Table 32. Characteristics of Implementations of a Flexible Lunar Architecture

<table>
<tr><th colspan="2">Architecture Implementation Concept Characteristics</th></tr>
<tr><td>Robotic Phase</td><td>Use RLEP to mitigate Constellation technical risks, test prototypes, space qualify standard components, and gain operational experience. Demonstrate the ability to comply with the Constellation C3I Interoperability Spec and prepare for network expansion to support human missions to Mars.</td></tr>
<tr><th colspan="2">Human Sortie and Outpost Phases</th></tr>
<tr><td colspan="2"><u>Responsive To:</u> Changes in sortie location, sequence, and scheduled buildup of assets.</td></tr>
<tr><td colspan="2"><u>Relay Orbit Description</u>: High lunar orbits provide maximum lunar surface coverage & increase surface connectivity time.</td></tr>
<tr><th>Global “Go Anywhere” Access:
Upper Bound 6 LRS Configuration</th><th>South Pole Outpost Missions:
2 LRS Configuration</th></tr>
<tr><td><u>Responsive To:</u> Changes in sortie location and sequence. Ability to support landing anywhere on Moon.</td><td><u>Responsive To:</u> Requirement for regional outpost</td></tr>
<tr><td>Source Study Assumptions:
• Up to continuous full coverage of the lunar surface
• Continuous availability 24 x 7 x 365
• Initial Operational Capability (IOC) by 2018</td><td>Source Study Assumptions:
• South Pole defined as the 80-90°S polar region
• Continuous availability 24 x 7 x 365
• IOC by 2020</td></tr>
<tr><td><u>Unknowns & Impacts:</u> Primary unknown is level of coverage required. If continuous coverage is not a requirement, constellation is reduced to meet the need.</td><td><u>Unknowns & Impacts:</u> Primary unknown is level of coverage required. Current concept provides continuous coverage with ~6 hr periods of dual coverage each orbit.</td></tr>
<tr><td><u>Relay Orbit Description:</u> 3 relays in each of two planes. High lunar orbit ~9200 km radius. Studies of inclined and polar circular orbits resulted in equal cost and performance.</td><td><u>Relay Orbit Description:</u> Two relays in dynamically stable highly elliptical orbit (Ref. [108]) with apoapsis in the southern Lunar hemisphere</td></tr>
</table>

Visibility: Assets anywhere on the polar cap must have at least one visible relay back to Earth at all times (for human missions) with a 10° minimum elevation angle. Because every option was developed to meet this threshold, the discriminating factor of percent time with 2 relays visible was used. Using this metric, the elliptical orbit case was found to have the highest level of performance, with dual coverage to the pole for 46% of the orbit period. In contrast, the three other lunar orbits ranged between 2 and 15%, and the Lagrange halo orbits had only single coverage by design. Malapert Station presented a unique case. Three assumptions regarding Malapert were made based on literature regarding Lunar South Pole sites of interest:

- Location: 86° South Latitude, 0° Longitude
- Altitude: 5 km above mean surface level

- Malapert design concept employs a 200m tall deployable antenna mast

Visibility of the lunar polar cap surface from a fixed point, even at the 5.2 km Lander elevation, is only partial; maintaining an assumption of a 10° elevation requirement results in visibility of less than 1% of the polar cap surface.

Orbit Stability: This FOM measures the effort required to maintain the satellite orbits. Effort was quantified as ∆V for station-keeping for a five year period. Orbit insertion and end-of-life maneuver ∆V was not included. The computation for orbit maintenance is structured on the idea that, although not optimized, quantifying the secular orbit change over time (and therefore the ∆V required to correct the orbit) provides relative comparison between options in the study. The cases that require the least station-keeping are the elliptical, and the single polar and single inclined plane cases. The highest station-keeping cost is associated with the hybrid case, in part due to maintaining the relative position of the two planes, which is not an issue in the other cases.

Failure Tolerance: This FOM is defined as the percent visibility with one satellite out (i.e., equal to the percent of daily data volume sent with one satellite out). In the multi-satellite constellations, results varied depending on which satellite was removed. As a result, each case was evaluated a number of times to determine which relay loss had the greatest impact. As an example, in the Hybrid case, the results are especially dependent on which relay is removed from the constellation. If an equatorial relay were removed, the South Pole visibility is not impacted at all, as the equatorial relays have no visibility to the polar cap to begin with.

Navigation Utility: This FOM assesses the ability of a constellation to support S/C navigation using Geometric Dilution of Precision (GDOP), a unit-less measure of the impact of the spatial distribution of navigation data source errors. Some of the architecture cases required special comment or consideration. The Malapert Station case provided a single-point, stationary signal source that has no navigation utility unless combined with satellite constellations or pseudolite sources placed on the moon. For this reason, Malapert was excluded from further navigation analysis. The two Lagrange orbit cases were not evaluated as the visibility results indicated no more than one relay was visible at a given time and the duration between two maximally separated observations could be rather extended due to the multi-day orbit periods. The relative navigation utility between the cases indicated that two cases have the greatest potential: 1) the elliptical inclined two relay case; and 2) the inclined circular three relay case. These two cases have improved utility primarily because the ground tracks of the orbits do not cross directly over the South Pole region. These results might change if Doppler were incorporated into the solution.

Mission Evolvability: This FOM is a compound assessment defined as the ability to easily modify assets by inserting technology and modifying the design to meet Exploration and Science goals from 2010-2030+. It measures the accommodations made in the design to allow future design expansion or modification to meet changes in mission needs over the potential life of the system. It is quantified by five criteria: Programmability, Pre-Planned Product Improvement (P3I), Open Architecture, Planned

Technology Insertion, and Planned Utilization. The resulting scores were generated by averaging the qualitative judgments of the team members.

Adaptability: Adaptability is a compound assessment that measures the ability to change operations or be changed to fit changed circumstances (i.e., to handle changes in operations or support new requirements *without* design changes). It is quantified by two criteria: Programmability and Operational Flexibility. The resulting scores were generated by averaging the qualitative judgments of the team members.

Link Capacity: This FOM is a compound assessment measured by a combination of aggregate data rate, data volume, and real-time latency. This FOM was normalized across the options by design removing it as an effective discriminator among options.

Scalability: Scalability is a compound assessment that measures the ability of a system to expand capacity beyond initial deployment. It is quantified by eight criteria: ability to add satellites, ability to add transponders, ability to add frequencies, ability to reuse spectrum, ability to increase efficiency (of modulation, topology, etc.), ability to increase locations served, ability to increase data rates, and other growth features. The resulting scores were generated by averaging the qualitative judgments of the team members.

Partial Life Cycle Cost: Only the space segment of the system is modeled for non-recurring DDT&E and recurring cost of flight units aimed at assessing the *relative* cost comparison between options. Cost estimates were developed using the software package ACEIT™ and Cost Estimating Relationships (CER) derived from NAFCOM. The primary inputs to the CERs are spacecraft subsystem mass estimates. In addition to point estimates, risk-adjusted cost estimates were generated to capture risk sources such as uncertain mass estimates, inherent uncertainty in the CERs, and the relative risks of the options created by their inherent design. As an example, the relative risk weight applied to the elliptical case captures the fact that the design of the specialized stable orbit is dependent on an improved understanding of the lunar gravity field, which requires additional gravitational mapping of the Moon.

Sustainability: This FOM is measured by the cost to replace S/C to maintain the constellation for 5 years where the cost of replacement S/C and ELVs to launch them are based on a S/C design life of 3 years (requires replacement) or 6 years (no replacement required).

User Burden: This FOM is defined as the effort required by users to use communication services provided. This was measured in terms of user antenna size, broadcast power, and complexity of user's communication subsystem. User burden is intended to be standardized, so this FOM is used to penalize options that fail to meet the standard or reward options that reduce user burden beyond the standard (i.e., required) level.

Before creating a composite FOM score, the relative importance of the FOMs with respect to one another was determined. The SCAWG members voted internally on the FOM weights. Individual assessments of FOM weights were combined and averaged to determine a consensus weighting. The results are shown in Figure 44, and indicate that the most important FOM is visibility, or coverage provided by the relays, followed by link capacity, evolvability, and failure tolerance.

To make sense of the composite performance and enable direct comparison between FOMs, the engineering-unit scores for the quantitative FOMs were normalized on a 100-point scale. The FOM weights were applied to the normalized scores and each architecture option's performance was tallied from 0 (worst) to 100 (best). The composite scoring results are shown in Figure 45.

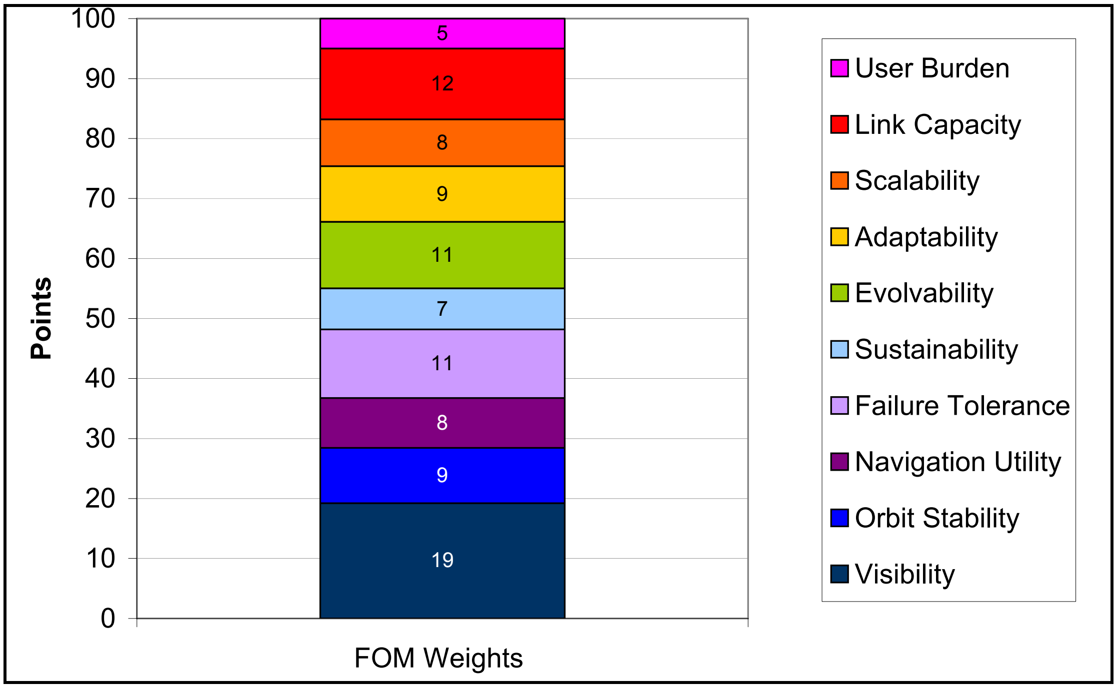


Figure 44. FOM Relative Weights for the Lunar South Pole Study

A cost-benefit scatter plot of the lunar constellation and design options is shown in Figure 46. Both point estimate costs and risk-adjusted costs (reported at 70% confidence) are included for each case. The point estimates are labeled with their associated confidence level using small icons while the risk-adjusted values use larger versions of the same icon for each option. The risk adjustment has the effect of shifting the cost estimate to the right (i.e., higher cost) without impacting the option's performance. The best value options show up in the upper left quadrant where performance is highest and cost is lowest.

The study concluded that the two satellite elliptical orbit option provided the most cost effective solution for South Pole coverage.

FOMs	Weighting Assignment	1 Elliptical	7 Hybrid	8 Inclined	18 L1	24 L2	34 Malapert	36 Circular
Visibility[1]	0.19	14.02	11.05	9.89	9.61	9.61	1.92[2]	9.80
Orbit Stability	0.09	9.08	0.00	8.40	5.38	5.38	9.24	8.77
Navigation Utility	0.08	8.06	0.63	8.32	0.24[3]	0.24[3]	0.24[3]	5.39
Failure Tolerance	0.11	8.34	8.22	7.77	9.14	9.14	0.00	7.65
Sustainability	0.07	5.63	1.25	4.52	1.76	1.76	6.87	4.52
Evolvability	0.11	4.87	5.15	5.01	4.74	4.74	2.58	5.01
Adaptability	0.09	1.80	2.84	3.43	0.87	2.50	1.03	3.43
Scalability	0.08	4.04	5.92	5.31	3.25	3.25	3.67	5.31
Link Capacity	0.12	8.25	8.25	8.25	8.25	8.25	8.25	8.25
User Burden	0.05	3.50	3.50	3.50	3.00	3.00	3.00	3.50
	TOTAL POINTS	67.60	46.83	64.40	46.23	47.86	36.79	61.63

[1] All architectures have 1 relay visible 100% of the time, so performance with 2+ visible is reported to enhance the results table
[2] Malapert has visibility of < 1% with 10 deg elevation angle. This is relaxed to 0 deg elevation angle resulting in 20% viewable polar region.
[3] GDOP for L1, L2, & Malapert cases was not analyzed – highest score was assigned to show worst performance (but not infinite)

Figure 45. South Pole Study FOM Results: Normalized

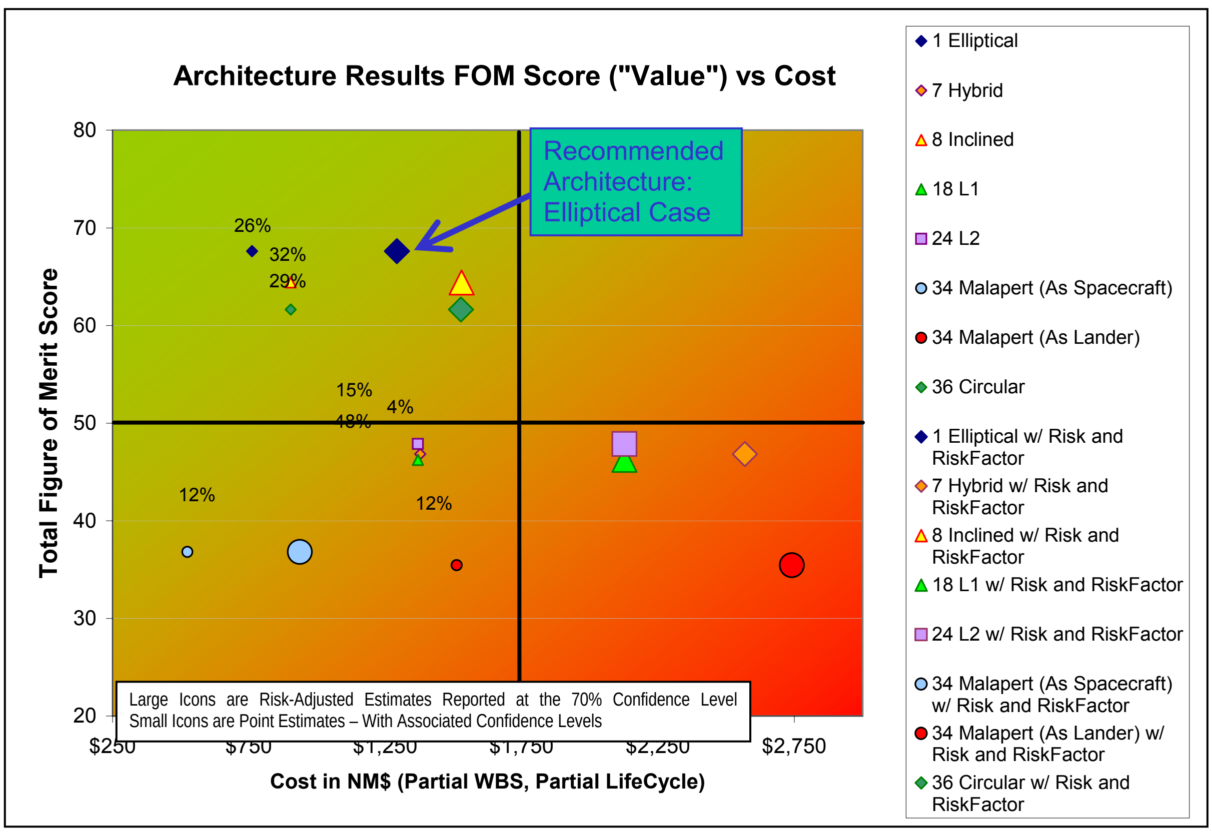


Figure 46. Lunar South Pole Study Results: Composite FOM (Benefit) vs. Cost

3.3.9.2. The Full Lunar Coverage Study

The second phase of study conducted on the lunar architecture was intended to address the possibility of global lunar coverage. The basis for the technical alternatives was the Lunar Relay 2015 South Pole Study, and additional architecture options were developed along with improvements and alterations to some of the FOMs and an expanded cost model. The architecture options being evaluated for this study are listed in

Table 29 under the Full Coverage heading.

FOM Update: Several updates were made to the FOM list based on lessons learned from the South Pole study. The first change was the deletion of "user burden" because the options were designed with the same user burden standard eliminating this metric as a useful discriminator. The second change was to eliminate sustainability. The previous definition of sustainability made it a cost-derived metric. When included with the other FOMs and used to create cost-benefit comparisons, this meant that cost was being "double counted" (or at least over-weighted). Third, the ∆V analysis previously focused on station-keeping over the lifetime of the constellation, was extended to include orbital insertion costs and end-of-life (EOL) disposal maneuvers. The last update was an exercise to weight the FOMs, much like in the South Pole study, to adjust for the two deleted FOMs and the expanded definition of the ∆V FOM. The resulting set of revised FOMs and their weights are shown in Figure 47.

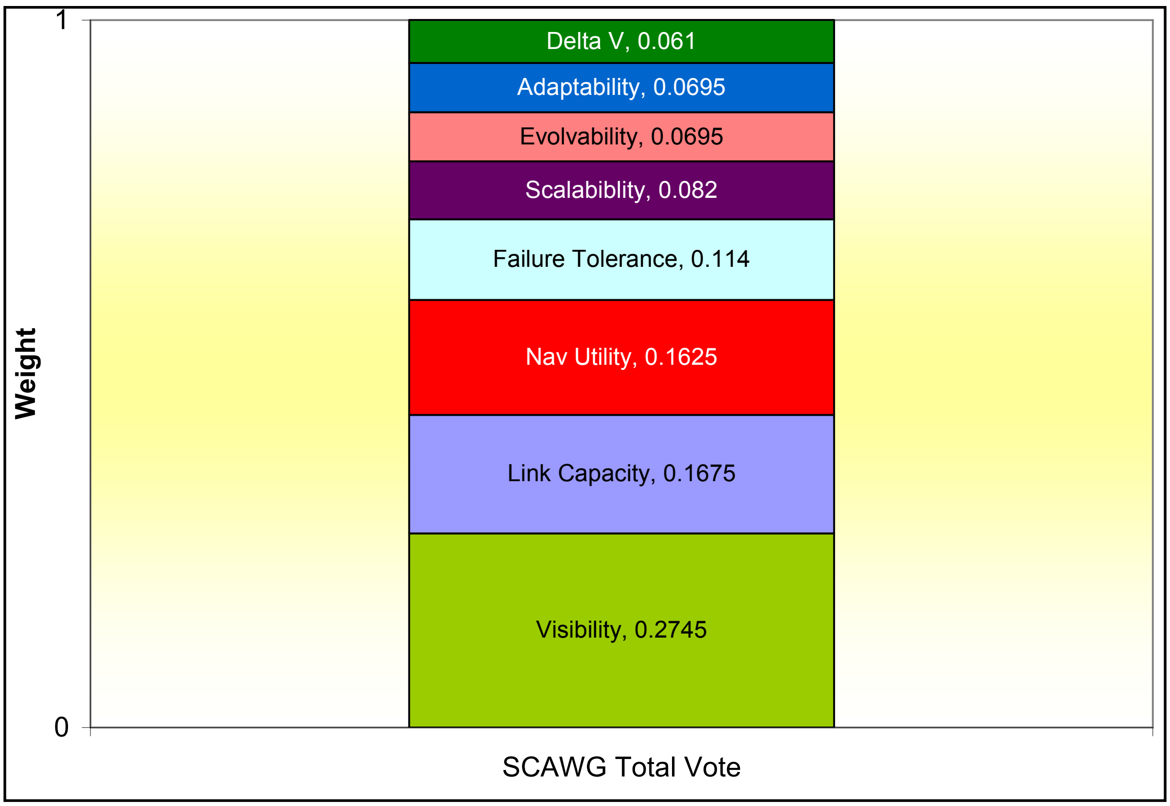


Figure 47. FOM Relative Weights for the Lunar Full Coverage Study

Expanded Cost Estimate: The ACEIT™-based cost model from the South Pole study was modified to meet the goals of the full coverage study. Ground system and operations phase costs were added to provide a first order Life Cycle Cost (LCC) estimate. Eight sensitivity cases in the cost model covered 17 orbit configurations and 2 of 3 design concepts. The three design concepts are: an evolved payload on an Orbital Star-2 bus; a next generation communications payload on a next generation bus; and a TDRS derivative. The TDRS derivative was dropped from consideration because it was not necessary to use such a large bus to meet the communication payload requirements. The orbit configurations that were sampled correspond to a range of spacecraft quantity and launch approaches, varying both launch vehicle type and number of spacecraft per launch vehicle. With the introduction of a time-phased program in the cost model, it was also possible to schedule launches to field the S/C one plane at a time. Assuming that lunar operations start small and build up assets over time, half of the cost model cases staggered their launches to fly one plane of S/C per year gradually building up to the full constellation. This approach offers additional operational flexibility to the Exploration Program and allows the recurring costs of S/C manufacture and test, ELV acquisition, launch, and operations checkout to be staggered in order to spread costs out over a longer period of time. It also enables program costs to have a lower peak annual funding level. The resulting LCC cost estimates are shown in Table 33 including non-recurring and recurring costs. The risk confidence level of each estimate is shown in parentheses. The study concluded that a six satellite constellation populated in two launches (3 satellites per plane placed by one launch vehicle) would best meet the full coverage requirements for nearly the lowest cost of all the options.

Table 33. Cost Estimates for Full Lunar Coverage Cases (in $M)

Cost Model Case	NRE Total	RE Total	LCC Estimate
5 SmallSats-2 LVs	$1,190.3 (68%)	$1,250.7 (68%)	$2,441.0 (70%)
5 StarBus-2 LVs	$1,533.8 (66%)	$1,489.7 (67%)	$3,023.5 (70%)
6 SmallSats-2 LVs	$1,193.2 (68%)	$1,361.3 (68%)	$2,554.5 (70%)
6 StarBus-2 LVs	$1,597.9 (66%)	$1,641.2 (67%)	$3,239.1 (70%)
6 StarBus-4 LVs	$1,838.6 (66%)	$1,641.2 (67%)	$3,479.8 (70%)
7 SmallSats-3 LVs	$1,376.4 (68%)	$1,496.1 (68%)	$2,872.5 (70%)

3.3.10. Conclusions

The recommended solutions are derived from quantitative and qualitative FOM analysis as well as cost estimation, and represent the best value options. The differing results of the two studies indicate the importance of the mission scenario and needs in crafting an architectural solution. The South Pole and full coverage studies can be seen as the lower and upper bounds of the Lunar Relay Element configuration. As a result, the deployment approach should strive for flexibility to meet the range of possible requirements, from localized coverage (e.g. the South Pole) to global coverage.

3.4. Mars Relay Element

3.4.1. Overview of the Mars Relay Element

The MR Element refers to an evolving set of relay spacecraft in orbit at Mars, along with their associated Earth-based mission operations centers, providing relay telecommunications, navigation, and timing services to user spacecraft in the vicinity of Mars, including users on the Martian surface, in the Mars atmosphere, in Mars orbit, or on approach to Mars.

The MR offers significant advantages over conventional Direct-to-Earth/Direct-from-Earth (DTE/DFE) link services, enabling and enhancing Mars exploration activities. By offering access to telecommunications services over relatively short slant ranges, as opposed to the extremely long Earth-Mars distance of up to 400 million kilometers required for DTE/DFE links, the MR allows user spacecraft to achieve increased data return and increased energy efficiency, while reducing the mass, volume, and operational complexity of its telecommunication system components. The MR can offer telecommunications services when the Earth is out of view (e.g., at night on the Martian surface, in orbit when the Earth link is occulted, or at the Martian poles when Earth is seasonally below the horizon.) Navigation services provided by the MR are inherently tied to the Martian reference frame, based on the orbital tie of the MR element spacecraft to the Mars center of mass.

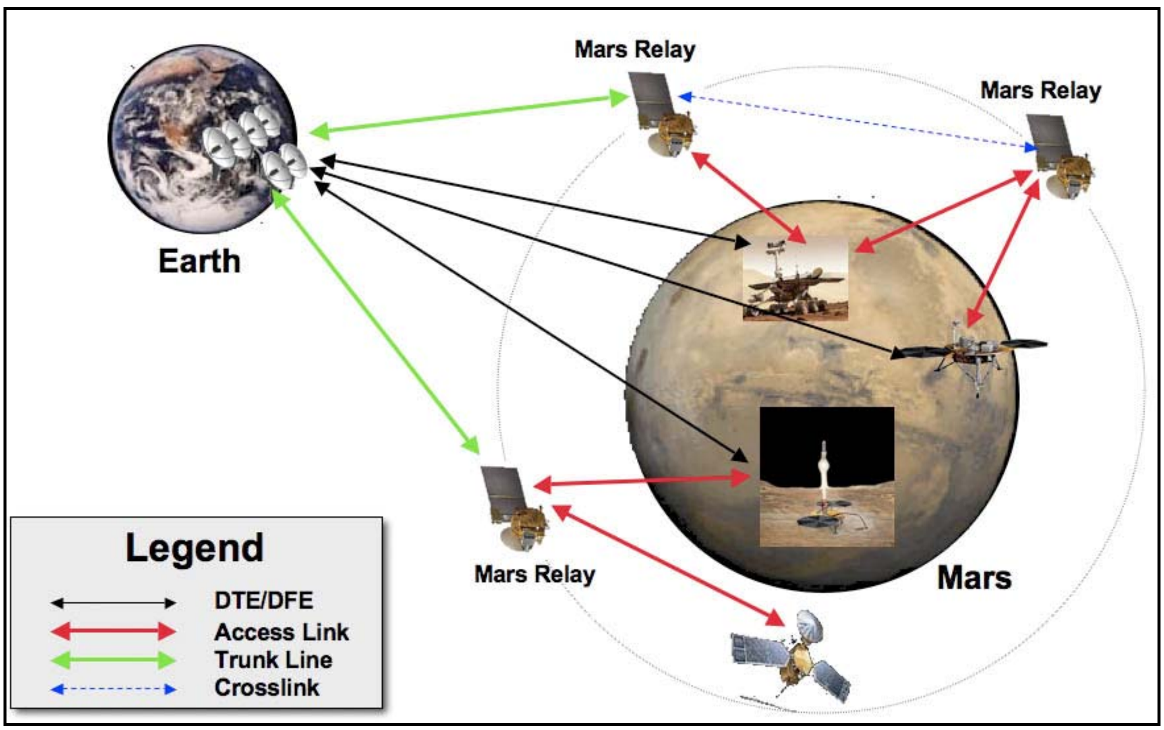


Figure 48. Mars Relay Element Overview

Figure 48 provides a high-level overview of the MR element. MR element orbiters provide access links to users on or near Mars, while also establishing trunk line communications to the GEE. The MR Element thereby provides store-and-forward command and telemetry services between a user spacecraft and Earth, and can also support communications between two or more user spacecraft through an MR element. Optional crosslinks between MR elements can maintain connectivity with relay spacecraft during occultation of their trunk line link to Earth.

Orbit and spectrum strategies will evolve in response to the evolving needs of exploration users. Based on current mission plans, the following phased MR architecture is envisioned:

Phase 1: Initial elements of the MR are hybrid science/relay orbiters. This approach provides an extremely cost-efficient means to establish relay infrastructure; however, the design, implementation, and operation of these orbiters must satisfy both the mission's own science objectives as well as the provision of relay services to other Mars missions. Functional relay capabilities are driven by robotic mission requirements. UHF (390-450 MHz) access links are supported, with an option to add directional X-band access links for increased link performance. MR trunk lines use existing Category-B deep space spectrum allocations at X-band (7/8 GHz) and Ka-band (34/32 GHz). Intermittent coverage is provided to users anywhere on the planet with multiple contact opportunities per sol. Robustness is addressed by maintaining two or more on-orbit MR spacecraft over time.

Phase 2: The increased needs of human missions are met by overlaying a constellation of dedicated relay satellites in the decade prior to the first human mission. While detailed orbit design depends on the site selection for a human landing, a working strawman concept is a pair of longitudinally-offset areostationary relay satellites providing redundant, continuous coverage of a large regional zone while always offering one low-latency trunk line path free of occultation by Mars. In addition to the legacy UHF band, access links are supported at X-band (7/8 GHz) and Ka-band (34/32 GHz), allowing user spacecraft to utilize common RF systems for their access links as well as their own DTE/DFE links. MR trunk lines are supported at X-band (7/8 GHz) and Ka-band (40/37 GHz).

3.4.2. Top Level Requirements

MR Element requirements are derived from the forecasted needs of anticipated Mars exploration missions. As extracted from the overall SCAWG Mission Model (Appendix E), the Mars mission queue reflects plans to launch one or more spacecraft to Mars in each 26-month Mars launch window. The current and next decade of Mars exploration are characterized by robotic science missions, while in the third decade the mission queue includes specific precursor missions driven by human exploration goals, leading to the first human Mars mission in ~2030. It is acknowledged that this is an aggressive schedule for a piloted Mars mission, given that the first robotic sample return is not scheduled to return samples to Earth until 2027; nonetheless, it is useful to include this first human mission within the planning horizon of the architecture to understand the transition from robotic to human mission requirements and the resulting evolution of the MR Element. Table 34 summarizes key driving requirements of the MR Element.

Table 34. MR Element Driving Requirements

Requirement	Need Date
Provide telecommunications, navigation, and timing services to user missions on the Martian surface, in the Martian atmosphere, in Mars orbit, or on final approach to Mars.	2005
Provide forward and return store-and-forward relay telecommunications services between a user and Earth.	2005
Support real-time telecommunications services (voice, video, data) between two or more user assets at Mars via a relay through a MR Element orbiter.	2025
Support access links compliant with the CCSDS Proximity-1 Space Link Protocol, as specified in CCSDS 211.0-B-1, B-2, and B-3.	2005
Support access links compliant with the Constellation C3I Interoperability specification.	2025
Support radio metric tracking on the access link to a user spacecraft on approach to Mars, with the capability to provide an RSS position knowledge uncertainty (3-sigma) of [<300 m] at the Mars entry interface (125 km altitude).	2015
Support radio metric tracking on the access link to a user spacecraft on the surface of Mars, with the capability to provide [<30 m] RSS (3-sigma) user position knowledge within [1] sol.	2005
Provide navigation signals on the access link with the capability to continuously maintain [<30 m] RSS (3-sigma) user position knowledge.	2030
Support Orbiting Sample (OS) orbit determination to an accuracy of [1 km], sufficient to initialize the autonomous rendezvous system.	2020

3.4.3. Functional Description

MR elements provide store-and-forward relay telecommunications between user spacecraft at Mars and Earth, supporting delivery of commands and return of science and engineering telemetry. In addition, MR orbiters will support communications among multiple Constellation assets at Mars, enabling over-the-horizon connectivity between a human base and mobile human or robotic explorers. Two-way handshaking protocols on these links will support reliable, gap-free data transmission. Near-term robotic missions will utilize UHF access links supporting instantaneous data rates of up to 4 Mbps and aggregate data return of 250 Mb/sol for support of the 2009 Mars Surface Laboratory mission, and 1 Gb/sol by the time of the 2016 Astrobiology Field Laboratory (AFL) mission. Longer-term support of human missions will provide continuous access link availability, with X-band support for operational data exchange (up to 10 Mbps) and Ka-band support for higher-rate mission data flow (up to 150 Mb/s).

Formulation of carrier phase (Doppler) and range observables on the access links, coupled with accurate trajectories for the MR orbiters, provides information on the navigation state of the user spacecraft in the Martian reference frame. While the limited number of MR Element orbiters precludes full GPS-like kinematic positioning capabilities, acquisition of radio metric tracking observables on MR element access links can support a diverse range of navigation scenarios, including precision approach navigation for pinpoint landing, accurate surface position determination, trajectory determination for Mars Ascent Vehicles, and orbit determination in support of on-orbit rendezvous for robotic sample return and human exploration missions.

MR orbiters will have a full spectrum recording capability, allowing signals received on the access link to be open-loop sampled and stored for subsequent post-processing. This full spectrum capability provides a highly reliable means of capturing high-dynamic, potentially low-Signal to Noise Ratio (SNR) signals during critical event scenarios such as EDL. Post-processing on the ground of the recorded samples maximizes the information that can be extracted in the event of a user mission anomaly.

MR orbiters will also support timing services, broadcasting a timing reference signal and supporting a time correlation service to accurately reference user clocks to a common time standard. Accurate user clock knowledge will support proper execution of user activity sequences, as well as accurate spatial-temporal correlation of network science measurements (e.g., seismic signals) acquired at multiple sites.

3.4.4. Architecture Options Considered

A variety of options were considered as candidates for individual elements of an evolving MR infrastructure. The candidate options fall into three categories:

- *Dedicated relay satellites:* High-performance satellites with orbit and telecommunications payload optimized for the relay function. Several orbit options were considered, including areostationary orbits for continuous coverage a given region, high-altitude circular and elliptical orbits providing global coverage, and mid-altitude near-equatorial orbiters for enhanced low-latitude coverage.
- *Hybrid science/telecom orbiters:* Long-lifetime Mars science orbiters for which a standardized relay payload is added. The current Mars Global Surveyor (MGS), Odyssey, and Mars Reconnaissance Orbiters are examples.
- *Cruise stage conversions:* Minimal cruise stage vehicles needed to deliver a lander to Mars, upgraded with propulsion, telecom, and other necessary spacecraft subsystems to enable insertion into Mars orbit and extended operation as a relay asset.

In addition, direct user-to-Earth communications was included as a zero-base option, against which the various MR Element orbiter capabilities could be evaluated. The detailed list of architecture options is shown in Table 35. The orbit defined as “Critically-Inclined Elliptical” has its Apoapse at a Constant time of day Critically Inclined (ACCI).

Table 35. Mars Relay Architectural Elements Considered

Architecture Element	Definition/Comments
Direct-To-Earth/ Direct-From-Earth	Establishes baseline for performance without MR Element infrastructure. (Many user missions will likely utilize a combination of DTE/DFE links and MR Element-supported relay links for increased robustness.)
Science/Telecom Hybrid Orbiter	Use MRO, MSTO as reference designs to provide capability range: • MRO: 255 x 320 km, 93° inclination (sun-synchronous); UHF LGA • Mars Science and Telecommunications Orbiter (MSTO): 400 x 2000 km relay orbit, 75° inclination (non-sun synchronous); steered UHF MGA
Cruise Stage Converted to Telecom Orbiter	Use Network Lander Mission as conceptual reference; baseline science/telecom hybrid telecom capability level. Note: The coupled mission design constrains relay orbit options.
Dedicated Telesat: Circular Inclined (MTO Baseline)	4450 km, 130° inclination (sun-synchronous)
Dedicated Telesat: Areostationary	17,030 km altitude, circular/equatorial; longitude selected for continuous contact to surface outpost. (Latitude limits could be addressed w/ inclined areosynchronous orbit)
Dedicated Telesat: Critically-Inclined Elliptical (ACCI)	Critically inclined (inclination=117°), 1/4-sol, sun-synchronous orbit; line of apsides tuned for latitudinal coverage needs
Dedicated Telesat: Low-Altitude Circular Equatorial	Inclination = 30°; 1000 km circular orbit (Includes option of CEV serving as a relay node during surface mission)

3.4.5. Operations Concept

The MR Element utilizes relay-equipped Mars orbiters to provide communications, navigation, and timing services to robotic and manned spacecraft at and near Mars. The MR Element Service Management Office represents the point of contact for making commitment to customers on MR Element services. The SM functions include: (a) planning and resource allocation during service selection, agreement, and negotiation phases, (b) configuring and controlling the MR Element assets for service production during service utilization phase, and (c) asset maintenance and calibration activities to ensure successful execution of MR Element services. The MR Element planning and coordination of the services must be automated to the extent that it can support rapid turn-around planning and scheduling of MR network and GEE network resources to anticipate unforeseen variations in spacecraft and external conditions.

The MR Element communication services provide end-to-end data delivery over the trunk line between the GEE and the MR orbiters, and over the access links between the MR orbiters and the user elements at and near Mars. Communication data types for robotic mission support include vehicle engineering telemetry, science instrument telemetry, spacecraft commands, software uploads, images, and video for public engagement. For human mission support, additional data types such as voice, messaging, crew biomedical and physiological data will be supported.

The MR Element navigation services consist of radio metric tracking data derived from the proximity links between the relay orbiters and user spacecraft. The radio metric tracking data service types include 1-way and 2-way coherent Doppler data, ranging data, and open-loop signal recording data (for Earth-based Doppler data extraction).

The MR Element timing services support clock correlation and time reconstruction of the Mars spacecraft. The radio onboard the orbiter supports the exchange of dual 1-way time correlation packets. A series of these exchanges is used to collect user-to-orbiter clock correlation data, which is relayed to Earth for use in reconstructing the clock epoch at the user spacecraft.

The MR Element supports user missions with the indicated support in the following phases:

- Pre-launch
  - Relay compatibility testing
- Post-launch
  - In-flight relay testing
- Mars final approach
  - Proximity link radio metrics for navigation
- EDL or Mars Orbit Insertion
  - Relay communications
  - Relay radio metrics
- Mars post-arrival operations
  - Relay communications
  - Relay radio metrics
  - Timing correlation
- Mars ascent and orbit departure
  - Relay communications
  - Relay radio metrics

3.4.6. Key Functional and Performance Requirements

Specific functional requirements are detailed in Table 36. Near-term capabilities exhibit steady growth in data return capabilities, from the current 50 Mb/sol level of support for the Spirit and Opportunity Rovers to 1 Gb/sol capability projected for the 2013 MSTO, available for support of mid-next-decade robotic exploration. Significant increase in performance is forecast for support of human missions, including higher instantaneous data rates and provision of continuous relay coverage.

Table 36. Mars Relay Key Functional and Performance Requirements

Mars Relay Element Requirement	Need Date
Coverage:	
Provide at least two contact opportunities per sol to a user anywhere on the Martian surface, with each opportunity providing at least [5] min of contact above [10]° elevation.	2005
Provide contact opportunities with a maximum gap time between contacts of no more than [14] hrs.	2005
Provide continuous access link coverage of a single outpost on the surface of Mars.	2030
Telecommunications Modes:	
Provide forward and return store-and-forward relay telecommunications services between a user and Earth.	2005
Support real-time telecommunications services (voice, video, data) between two or more user assets at Mars via a relay through a MR Element orbiter.	2025
Support full duplex, [half-duplex] and simplex communications modes on its access links.	2005
Support [2] simultaneous access links within the footprint of a given MR Element orbiter.	2015
Support [12] simultaneous access links within the footprint of a given MR Element orbiter.	2025
Support user-initiated communications sessions, [with MR Element arbitration of service conflicts based on dynamic user priorities].	2025
Telecommunications Performance:	
Support the following access link data rates	

Access Link Data Rates (Mbps)

	2005	2010	2015	2020	2025	2030
UHF:	0.008-0.256	0.001-4.096	0.001-4.096	0.001-4.096	0.001- 4.096	0.001-4.096
X:	-	-	-	-	[10]	[10]
Ka:	-	-	-	-	[150]	[150]

Support the following data volumes per sol:

Access Link Data Volumes (Gb/sol)

	2005	2010	2015	2020	2025	2030
UHF:	0.05	0.25	1.0	1.0	1.0	1.0
X:	-	-	-	-	[900]	[900]
Ka:	-	-	-	-	[13,000]	[13,000]

Mars Relay Element Requirement	Need Date
Timing and Navigation	
Support acquisition of one-way and two-way Doppler observables on all access links with an accuracy of [0.1] mm/s.	2005
Support acquisition of one-way pseudorange observables on all access links with a precision of [1] m.	2015
Support acquisition of two-way range observables on all access links with an	2015

Mars Relay Element Requirement	Need Date
accuracy of [1] m.	
Time-tag all radio metric observations with an accuracy of [1 ms] with respect to UTC.	2015
Provide an access link service to determine the bias of a user clock epoch with an accuracy of [1 s] relative to UTC.	2005
Provide an access link service to determine the bias of a user clock epoch with an accuracy of [1 ms] relative to UTC.	2015
Note: Text in brackets [] indicates requirements that are TBR.	

3.4.7. Interfaces with User Missions

The MR Element supports end-to-end data transfer between a user Ground Segment (GS) on Earth and user spacecraft Mars, as well as longer-term support for data transfer among and between multiple user spacecraft at Mars. Figure 49 depicts the end-to-end information system architecture, identifying key interfaces. At Mars, the access links establish one essential user interface, currently defined by the CCSDS Proximity-1 Space Link Protocol. Compliance with this standard assures interoperability and has served to enable interagency cross-support between NASA and the European Space Agency (ESA) for Mars relay services. On the time frame of human exploration, it is likely that new protocol standards will be introduced and defined within the Constellation C3I Interoperability Specification.

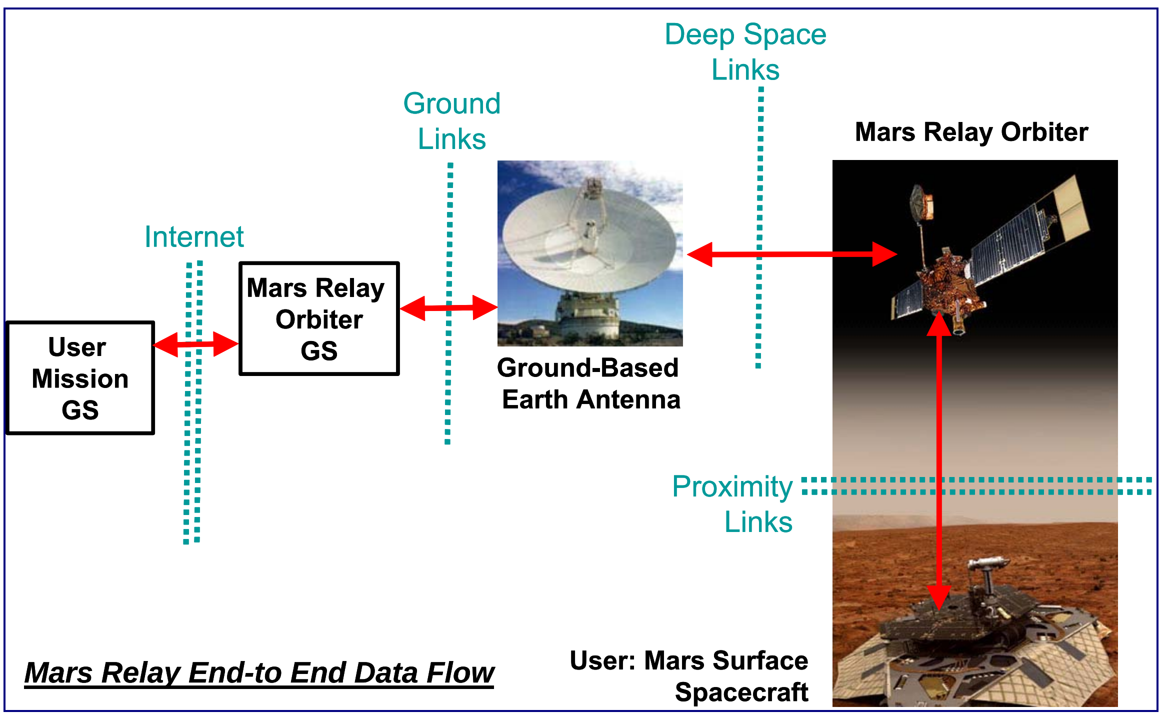


Figure 49. Mars Relay End-to-End Data Flow and Key Interfaces

The other key user interface is on the ground, between the user mission's GS and the MR Element GS. In addition to delivery of command and telemetry products, this interface will also support MR Element relay SM, including service preparation and planning activities as well as service monitoring and accounting. This service interface will provide the user with forward and return link latency commitments accounting for MR Element orbit trajectories and occultations, GEE tracking schedule, and MR Element processing times. For near-term activities using hybrid science/telecom orbiters for the MR Element, the service planning must integrate the orbiter's science-driven remote sensing activities with requested relay services. Longer-term dedicated telesats will be able to provide a more transparent service interface with continuously available, demand-accessible services.

3.4.8. Reliability and Availability

For user missions planning to utilize MR Element services, it is essential that at the time of their development and launch, they have high confidence that required MR Element services will be available when they arrive at Mars. This is particularly true for missions, like the 2007 Phoenix Lander, which have no DTE link and are solely reliant on relay communications to achieve their mission goals. Assuring high confidence in the MR Element infrastructure is achieved through a combination of high-reliability spacecraft design coupled with redundancy of on-orbit relay assets over time. Individual MR Element spacecraft will incorporate redundant spacecraft subsystems, conservative design margins, and large propellant loads to achieve a specified lifetime of at least 10 years, with a goal for significant extended life beyond that. Maintaining a nominal MR Element deployment plan that provides for redundant on-orbit assets ensures availability of relay services even in the event of a failure of a single MR Element orbiter.

3.4.9. Expandability, Adaptability and Scalability

The MR Element is inherently expandable through launch of additional relay orbiters. Near-term robotic support is being addressed by a strategy of adding a standardized access link payload to science orbiters. If additional near-term relay capability were needed, the next lowest-cost option would be to upgrade the cruise stage of a robotic lander mission to enable it to insert into Mars orbit and serve as a long-term MR Element. Dedicated MR Element telesats are envisioned to meet the more demanding requirements of human exploration, and could be introduced earlier if more ambitious robotic mission concepts are pursued.

Given that individual MR Element orbiters are designed for long (<10 yr) operational lifetimes, and that user mission requirements over this time frame will not be completely understood at the time the relay asset is launched, adaptability will be an essential characteristic of the MR Element. Aspects of adaptability include orbit evolution as well as signal processing and protocol evolution.

In terms of orbit flexibility, individual MR Element orbiters include significant propellant allocations to provide for orbit flexibility over the mission duration. For example, individual science/telecom hybrid orbiters are at a minimum capable of in plane orbit phasing to support critical event communications, while longer-term areostationary relay satellites are capable of longitudinal repositioning between successive Mars arrival windows.

The capability of introducing new signal processing capabilities and accommodating new protocol suites over the lifetime of the relay asset strongly motivates a strategy of implementing the MR Element access link functions in flight-reprogrammable spacecraft components. Utilization of a SDR architecture also provides maximum flexibility to respond to unforeseen mission scenarios, and increases robustness to address MR Element or user anomalies.

3.4.10. Reference Architecture

The near-term architecture for the MR Element calls for a continuation of the cost-effective strategy of deploying relay payloads on long-life science orbiters. Even as the relay-equipped Odyssey and MGS science orbiters continue to provide telecommunications and navigation services to the Spirit and Opportunity rovers, the next science/telecom hybrid orbiter, the 2005 MRO has arrived at Mars. With its software-defined Electra radio, MRO provides flexible and evolvable access link services for the 2007 Phoenix Lander and 2009 MSL. Both the MRO and Odyssey spacecraft are capable of supporting operations through 2020. Nonetheless, as these orbiters age it will be essential to replenish the relay infrastructure, to ensure robust support for second-decade robotic exploration. To this end, the MSTO is planned for launch in either the 2011 or 2013 opportunity. Another cost-effective science-telecom hybrid orbiter, this mission advances relay capabilities well beyond MRO through infusion of a steered, directional UHF access link antenna, originally developed for the 2009 MTO, and by upgrade of the propulsion capability to allow achieving a higher-altitude orbit for the extended relay phase of the mission. As an option, MSTO could carry a high-rate X-band access link capability, as a stepping stone towards capabilities that will ultimately be needed for support of human missions. The combination of Odyssey, MRO, and MSTO will provide high confidence in the availability of relay services through 2020. If unanticipated mission failures jeopardize the infrastructure robustness, the option exists to convert one of more lander cruise stages to become additional MR elements.

While timelines and detailed requirements for human exploration are very uncertain at this point, it is instructive to consider the MR Element developments that would pave the way for a first human Mars mission in 2030. Assuming the need for continuous over-the-horizon connectivity between a landed base and mobile expeditionary assets, a strong candidate for human mission support would be a pair of longitudinally-offset areostationary telesats. Such a configuration would offer redundant coverage of a human outpost, with one of the two telesats always offering a minimum-latency, occultation-free path for communications with Earth. These human-era MR Element telesats would be deployed and confirmed safely on-orbit prior to sending the crewed mission to Mars. Another option which should be considered, either for primary or backup relay support to a human outpost, is to use the orbiting CEV itself during the surface phase of the mission. Figure 50 depicts the phased MR Element strategy.

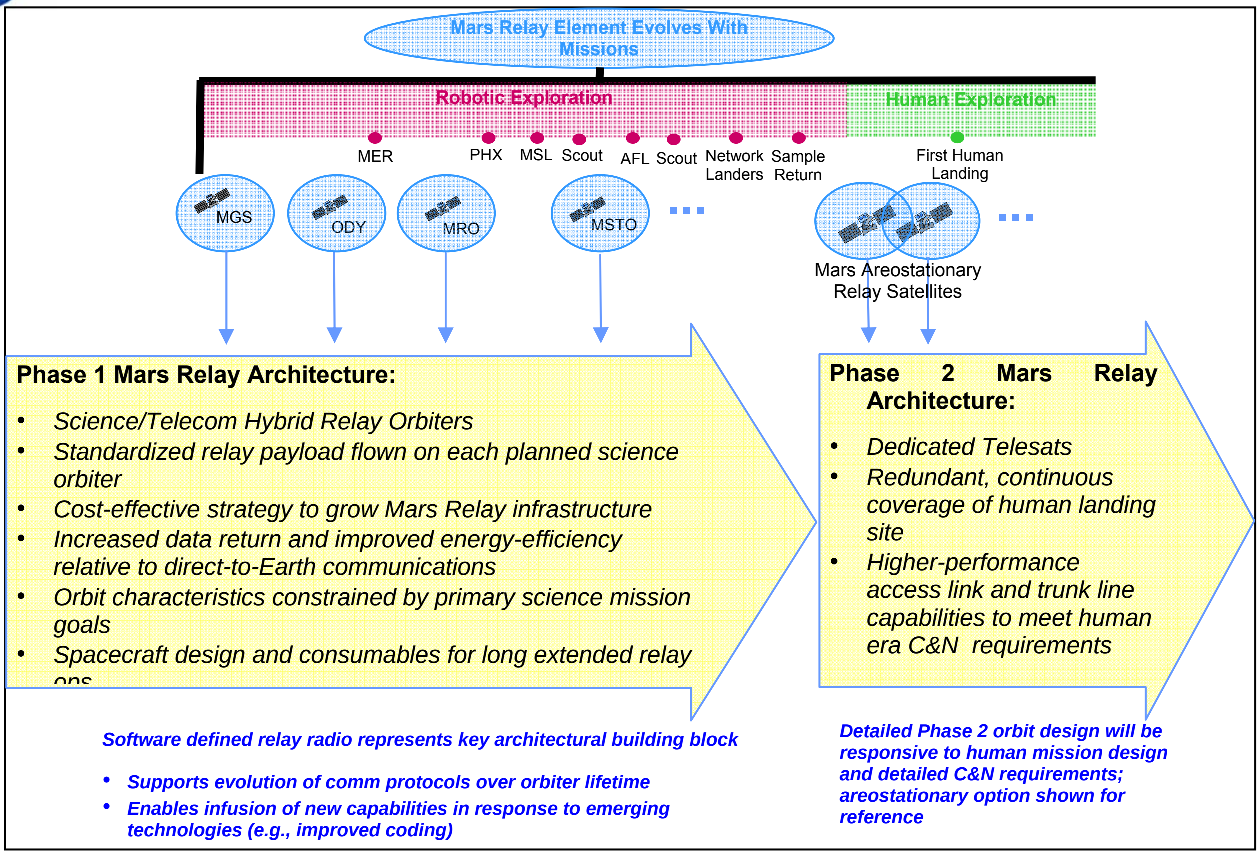


Figure 50. Mars Relay Element Evolution Strategy

3.4.11. FOM Definition, Analysis and Results

The Mars architecture options were evaluated on the basis of a set of four FOMs, each of which is composed of a set of factors. There are both qualitative and quantitative assessments made to complete the evaluation. The four major FOM categories are:

- Geometric visibility / coverage
- Telecommunications link capacity
- Navigation performance
- "-ility" Factors (User operability & Evolvability/Adaptability/Scalability)

In combination with cost estimates, effective trade studies were made and the best architecture was recommended.

3.4.11.1. Geometric Visibility / Coverage

The architecture alternatives were assessed in with respect to coverage in five ways: (a) the instantaneous footprint is calculated as the percentage of the planet covered by the relay footprint; (b) the integrated swath as a percentage of the arrival sphere; (c) the contact time per sol calculated as the total time that the line of sight is above the mask angle per sol, measured in hrs/sol; (d) the maximum communications gap time measured as the largest non-contacting time between surface user and services (hrs); and (e) global vs. regional coverage capability.

For both coverage and telecom calculations a 10-deg horizontal mask to the orbiters (or DSN) was assumed, and the analysis spanned a 24-sol period. The results are shown in Table 37.

Table 37. Visibility / Coverage Results for the MR Element Options

Option:	DTE	Science/ Telecom Hybrid Orbiter		Cruise Stage Converted to Telecom Orbiter		Dedicated Telesat			
Visibility/ Coverage	**34m X-Band, 20° DSN mask, 10° surface mask**	**MRO-Class (400 km Circular)**	**MSTO-Class (400 x 2000 km)**	**MRO-Class (400 km Circular)**	**MTO-Class (4450 km Inclined)**	**Circular Inclined (MTO 4450S Baseline)**	**Aerostationary**	**Critically-Inclined Elliptical (ACCI)**	**Circular (1000km 30° Inclined)**
Instantaneous Footprint (% of planet)	41%	2.5%	13%	2.5%	21%	21%	33% (continuous view of regions of interest)	7-28%	7%
Integrated Swath (% of arrival sphere)	41%	31%	66%	31%	82%	82%	33% (continuous view of regions of interest)	73%	51%
Global/Regional Coverage (% of surface viewable)	seasonal pole coverage	All	All	All	All	All	±70°(lat)	All	±60°(lat)
Contact Time Per Sol (hrs/sol)	9.0 (±2.6)	0.36	2.09	0.36	5.23	5.2	25	5.2	2.0
Average Contact Duration (min)	540	6.8	26.8	6.8	79.7	80	1480	102	21
Maximum Comm. Gap Time (hrs/sol)	15.6	13.9	11.5	13.9	10.2	10	0	12	14

In general, the dedicated telesat options have more favorable results, and as expected, the MTO-class-cruise-stage-converted case with the significantly raised orbit outperforms the lower orbit option.

3.4.11.2. Telecommunications and Link Capacity

The link capacity for the MR element options is analyzed in four components: (a) the largest single data burst per sol (Mb/sol) from an energy starved surface element, with the pass constrained to 10 minutes maximum and the UHF data rate remaining fixed throughout the pass; (b) the data volume per sol (Mb/sol) out of the two best passes from an MSL-class surface lander with an adaptive UHF data rate; (c) the total data volume per sol (Mb/sol) using a UHF adaptive data rate from an MSL-class surface lander; and (d) the EIRP required by a human-era lander to close the Ka-band link at 150 Mbps.

For the link analysis, the UHF radio on the surface element is assumed to be similar to that of MSL and would be applicable for robotic missions in the 2010-2020 timeframe. The received power at the orbiter is computed based on the telecom configuration and the instantaneous slanted range, cone and clock angles at each time instance. The fixed-rate data volume is computed by seeking the best possible single rate for which the data volume is maximal. The adaptive-rate data volume is computed by optimally varying the data rate over the pass to always operate at the maximum possible rate. For the EIRP calculations each orbiter is assumed to carry a 1m diameter antenna with 50% efficiency. The Earth station is assumed to be a 34m DSN antenna or equivalent array of fifteen 12m antennas. The DTE link is performed at 2.7 AU and the link margin is 3 dB for all links. The results for the link analysis are detailed in Table 38.

Table 38. Link Capacity Results for the MR Element Options

Option:	DTE	Science/ Telecom Hybrid Orbiter		Cruise Stage Converted to Telecom Orbiter		Dedicated Telesat			
Link Capability (Mb/sol)	34m X-Band, 20° DSN mask, 10° surface mask	MRO-Class (400 km Circular)	MSTO-Class (400 x 2000 km)	MRO-Class (400 km Circular)	MTO-Class (4450 km Inclined)	Circular Inclined (MTO 4450S Baseline)	Aerostationary	Critically-Inclined Elliptical (ACCI)	Circular (1000km 30° Inclined)
Configuration Used for Link Analysis		MSL-MRO	MSL-MSTO	MSL-MRO	MSL-MTO	MSL-MTO	MSL-MTO	MSL-MTO	MSL-MTO
Energy Constrained Lander (10-min fixed rate)	0.024 (40 bps)	310	1950	310	310	310	21	800	1200
MSL-Class Lander (2 best adaptive passes)	16.3 (504 bps)	720	5980	720	3100	3100	3100	3350	6200
MSL-Class Lander (all adaptive passes)	16.3 (504 bps)	860	9750	860	4400	4400	3100	4100	11,800
Human-Era Lander (EIRP req'd for 150 Mbps)	124.40	64.84	68.26	64.84	71.92	71.92	81.02	75.86	66.33

3.4.11.3. Navigation

Navigation performance of the MR Element options is captured by the following four characteristics: (a) position determination availability; (b) position determination latency; (c) trajectory determination availability; and (d) trajectory determination latency.

The DTE option underperforms the orbiter options in all categories. Position determination availability is the best for the hybrid and cruise stage cases as well as the dedicated telesats in circular inclined and areostationary orbits. For these cases good relative motion yields good information content in each pass and the diversity of passes provides <10m solutions. Position determination latency is optimum, with kinematic position fix possible, for dual spacecraft in the dedicated areostationary case. The higher orbit cases all provide adequate trajectory determination availability as they have reasonable visibility to lower altitude satellites. However, gimbal/pointing are required for approach navigation. For the trajectory determination latency, most orbiter cases provide good relative motion yielding accurate Mars-centered solutions for orbit determination and approach. The exceptions are the areostationary and circular inclined (1000 km, 30°) cases. In both cases the information content of the data is degraded because of the similarity between the approach plane and the orbital plane. Also, relative to other lower altitude orbiters, an areostationary satellite does not perform as well because of less relative motion.

3.4.11.4. "-ilities" – Operability/Evolvability/Adaptability/Scalability

A qualitative assessment of the MR Element options includes a ranking of user and network operability as well as general robustness characteristics. In general, the user operability is highest for the dedicated telesats and higher orbiting options. The dedicated telesats are also more ideal from the perspective of network operability. The science/telecom hybrids and cruise stage conversions all have conflicts between the science or lander mission needs and those of the telecom portion. The characteristics of each option in terms of evolvability are captured in Table 39.

Table 39. MR Element Option Evolvability Characteristics

MR Element Option	Evolvability
Direct-to-Earth	Ground network inherently evolvable/adaptable
Science/Telecom Hybrid Orbiter	Naturally sustains infrastructure with regular launch of science orbiters
Cruise Stage Converted to Telecom Orbiter	Opportunity for delivering infrastructure with every lander mission
Dedicated Telesat: Circular inclined (MTO Baseline)	Two orbiters can provide full coverage of critical events with only an in-plane phasing maneuver.
Dedicated Telesat: Areostationary	Longitude of areostationary relay satellite can be readjusted between Mars arrival opportunities at low Delta-V cost
Dedicated Telesat: Critically Inclined Elliptical (ACCI)	Nodal and apsidal precession can be induced to tailor orbit between Mars arrival opportunities, but over relatively long time scales (~1 yr or more) and at significant ΔV cost
Dedicated Telesat: Circular (1000 km, 30° Inclination)	Constrained to equatorial-band coverage

3.4.11.5. Cost Estimates

Cost estimates were obtained for three of the MR Element options based on Mars Program experience: (1) the science/telecom hybrid orbiter drawing on Odyssey and MRO actual experience as well as MSTO pre-Phase A studies; (2) the cruise stage converted to telecom orbiter based on two options considered during a JPL Team X study for a Network Lander mission; and (3) the dedicated telesat using MTO as the baseline with cost derived from multiple JPL Team X studies followed by a full bottoms-up estimate. All costs are relative to a near-term robotic exploration-era infrastructure capability. Results are provided in Figure 51 .

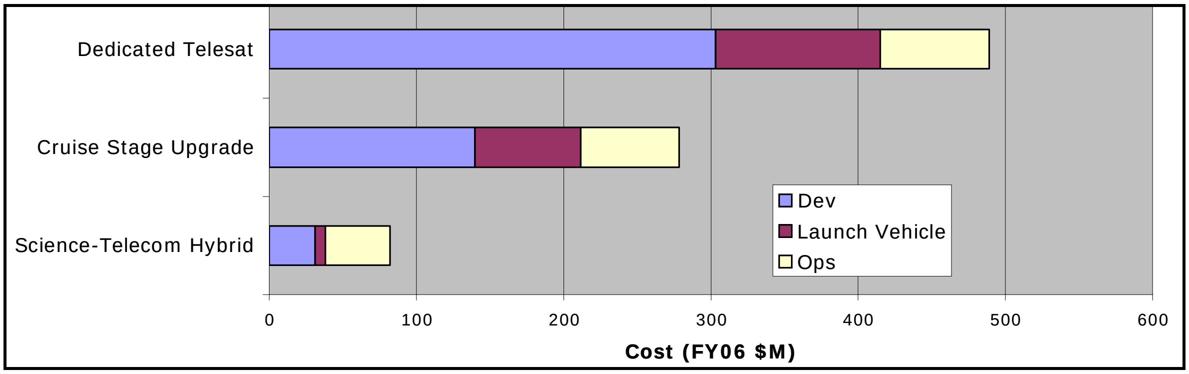


Figure 51. Cost Estimates for Selected MR Element Options

3.4.11.6. Process

The FOM analysis is synthesized to provide a complete picture of performance for the various options. FOM weights were generated based on consensus judgment of the team, factoring in overall relative importance of each of the four FOM areas as well as relative performance of sub-FOMs within each area. The results of this weighting process along with the resulting scores for the options are shown sorted in descending order of scores in Table 40. Combining the cost analysis and the integrated FOM scores for the options provides a cost-benefit view of the architecture, as shown in Figure 52.

3.4.11.7. Conclusions

Evaluation of the figures of merit for each of the considered MR element options provides a quantitative basis for comparison. As expected, all of the MR options exhibit a significant advantage over DTE communications. The areostationary dedicated telesat option yielded the highest FOM score, based on its continuous coverage characteristics, followed closely by the two other high-altitude dedicated telesat options. However, the incremental cost to upgrade a lander cruise stage to become a long-term relay asset represents less than 60% of the full telesat cost, based on leveraging the lander's cruise stage capabilities and sharing the launch vehicle. Even greater savings are obtained in the hybrid science/telecom orbiter strategy: based on the low incremental cost of adding a standardized relay payload to a core science orbiter, and even after including costs for extended operation, increased propellant load, and increased mission operations system functionality, this option represents well under 20% of the full cost of a dedicated telesat.

Table 40. FOM Weighting for MR Element Analysis

Option	Visibility/ Coverage	Telecom Performance	Navigation Performance	Operability/ Evolvability	Total
Weight:	35%	35%	15%	15%	
Dedicated Telesat: Areostationary	79.2	52.2	93.8	100.0	**75.2**
Dedicated Telesat: 4450 km	57.6	63.6	93.8	92.9	**70.4**
Dedicated Telesat: ACCI	54.9	67.0	81.3	92.9	**68.8**
Cruise Stage Con-version (MTO-Class)	57.5	63.6	87.5	69.0	**65.8**
Sci/Telecom Hybrid (MSTO-Class)	43.1	73.0	81.3	61.9	**62.1**
Dedicated Telesat: 1000 km Equatorial	33.9	73.3	43.8	76.2	**55.5**
Cruise stage Conver-sion (MRO-Class)	26.9	52.4	81.3	54.8	**48.2**
Sci/Telecom Hybrid (MRO-Class)	26.9	52.4	75.0	54.8	**47.2**
DTE Reference	58.5	10.1	23.8	54.8	**35.8**

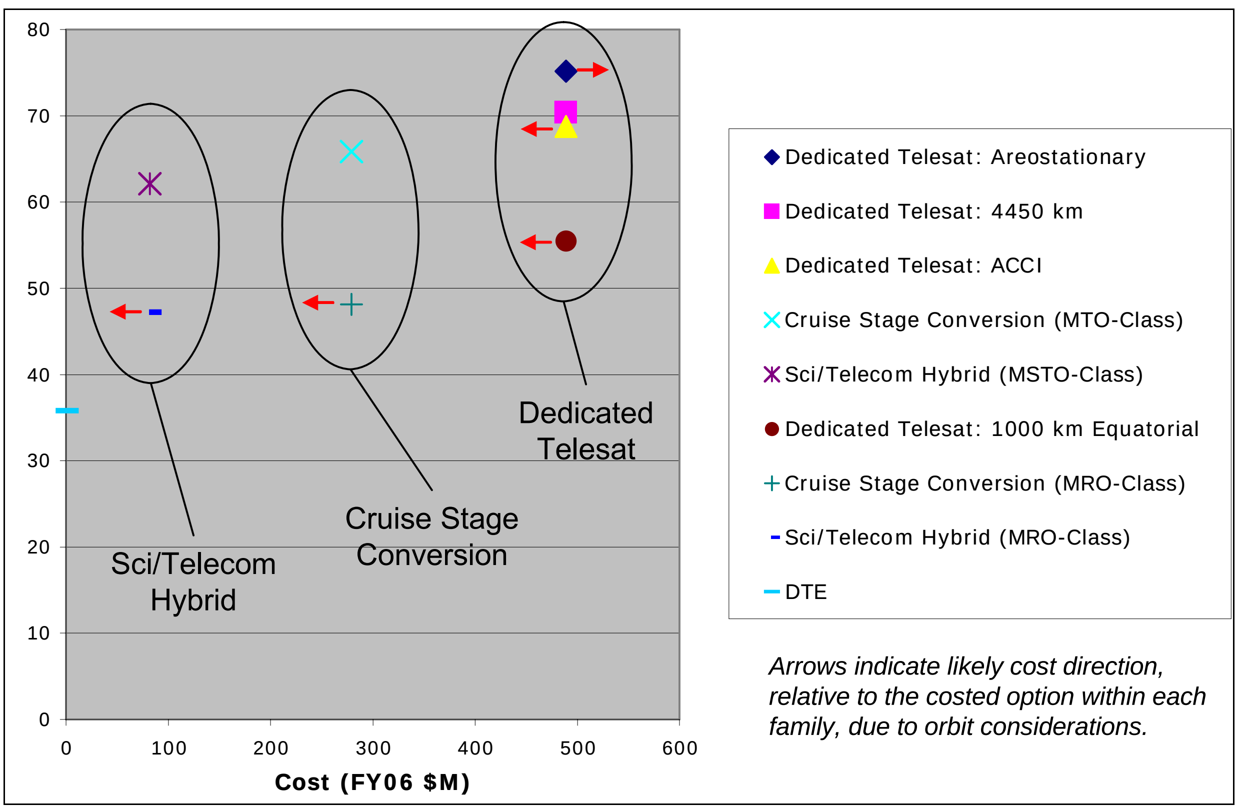


Figure 52. Cost-Benefit Results for the MR Element

4. Technology Areas

4.1. Overview

The C&N capability is an existing capability that serves today's missions. The roadmap for continuation of this capability originates at this current state and evolves into the future. This evolution, required to meet the expanding needs of the exploration and science programs, involves the development of both architecture and enabling technology. The architecture has been described in previous sections. Therefore the technology capability described in this section supports the evolution of exploration and science missions.

Six technologies areas are recommended for focused efforts in the future.

- Uplink arraying,
- Optical communications,
- Spacecraft RF technology,
- X-ray navigation,
- Network technology, and
- Programmable communications systems (software defined radio).

The SCAWG is recommending strategic investments in these six technology areas to provide opportunities that will enable more capable communications and navigation. The next section discusses the top level requirements leading to these technologies, followed by a section describing the technologies and supporting rationale for the needed technologies. The considerations discussed below include the collaboration and experience of other U.S. government agencies.

4.2. Top Level Requirements

The following technology development supports the development and evolution of the architecture described in the earlier sections of this document. Opportunities to increase data rates, decrease cost and user burden, or increase flexibility or reliability can be realized through investment in these technology areas; whereas X-ray based navigation and networking have the potential of "transforming" the C&N capability to revolutionary new ways of performing C&N functions. The major objectives of investments in the six technology areas are identified in Table 41.

Data rates will be a major requirement driver for the C&N architecture as it evolves to meet the exploration and science mission needs. For example the Mission Model for Mars distances calls for data rates of 100s of Mbps, not for Gbps. Future exploration scenarios may involve using instruments similar to those flying now on earth science missions for exploration at Mars. In order for this scenario to achieve productivity similar to today's earth science data, transport rates would have to significantly increase over those identified in the current Mission Model. The SCAWG has investigated the technologies that could provide these higher data rates and is recommending that NASA invest in their development in order to preserve options for future exploration missions.

Table 41. Objectives of Technology Recommended for Further Development

Technology	Objectives
1. Uplink arraying	Decreased cost, increased flexibility
2. Optical communications	Increased data rates, decreased user burden
3. Spacecraft RF technology	Increased data rate, increased availability
4. X-ray navigation	New capability (autonomous onboard navigation throughout the solar system)
5. Network technology	New capability (Extension of terrestrial capability to space)
6. Programmable communications systems (Software Defined Radio)	Increased flexibility, decreased user burden, maintainability of assets in space

4.3. Discussion of the Six Technologies

4.3.1. Uplink Arraying

As discussed in the GEE Architecture (Section 3.1), arraying of small aperture receive antennas is the recommended approach to meet NASA's future downlink needs. Arrays are flexible, reliable, scalable and evolvable. The concept is valid for uplink as well as downlink. Downlink arraying is a mature technology while uplink arraying requires further development. The concept is to use small aperture antennas in arrays to transmit a beam. This uplink transmit array may provide more cost-effective mission support, enable simpler spacecraft receivers, and provide more robust support in emergencies. If this concept proves feasible it will be possible decommission the 34-m antennas and replace them with arrays of small antennas that can provide a scalable transmit architecture similar to that recommended for the downlink function.

This application is planned for deep space missions using X-band. While uplink arraying has been demonstrated for near Earth applications, the deep space requirement is much more difficult. The difficulties are associated with the extremely large distances for deep space missions and the different atmospheric conditions above the antennas in the array. Requirements for duration and accuracy of the open-loop operations of uplink arraying are also challenging. Closed-loop operations to maintain uplink signals alignment does work for near earth operation. As shown in Figure 53, the signals must be aligned to a few millimeters at the spacecraft. Therefore, the delay and phasing effects of electronics and atmospheric changes during an eight hour pass contribute to the difficulty.

Recommendation: Develop uplink arraying technology and prove the concept with appropriate flight demonstration.

To reach TRL 6, there is no requirement for any flight system or precursor mission. Uplink arraying can be demonstrated through deployment of ground equipment and uplinking to an appropriate cooperative mission. If NASA is unable to implement uplink arraying capability, the "off ramp" option will be to build more 34-m antennas and maintain the present network of large antennas.

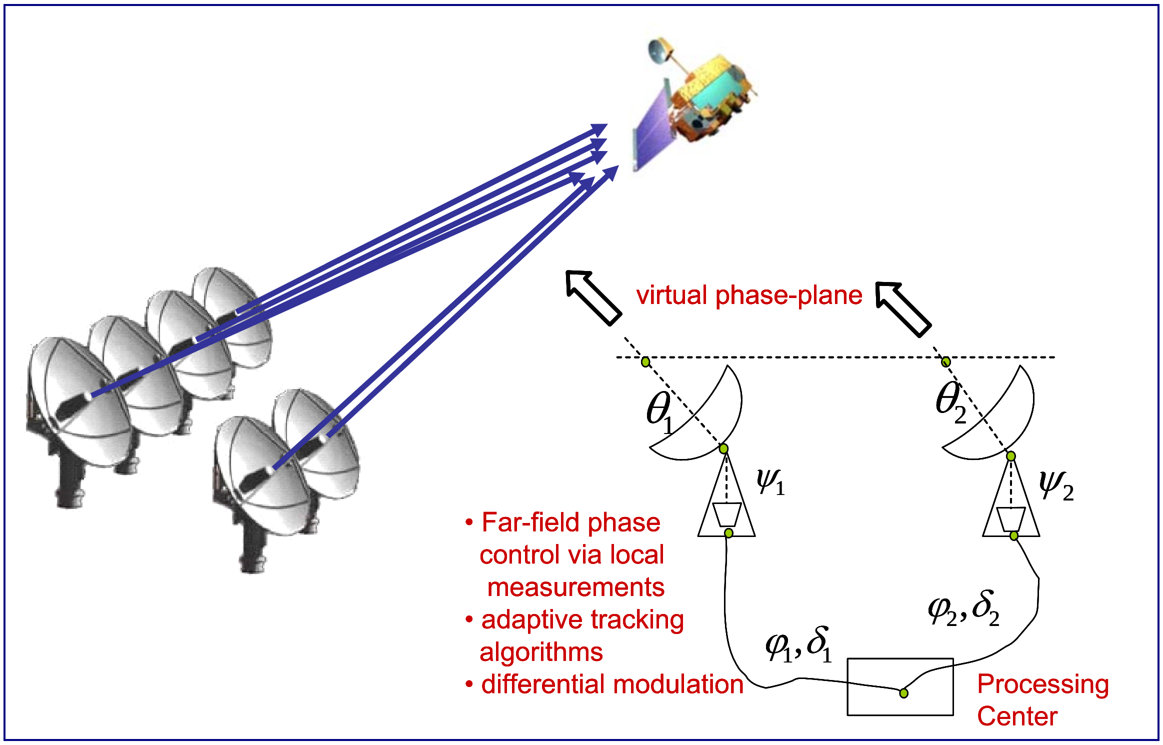


Figure 53. Example of Uplink Arraying (Greek symbols represent electronic delays, phase shifts and effects of atmospheric distortion)

4.3.2. Optical Communications

Free space optical or laser communications for deep space applications is a promising area for development. Compared with RF communications that require large antennas and heavy feed systems, optical communications can possibly be implemented with lower mass and can reduce the user burden for the same data rates as RF.

A study was performed to compare optical and RF communications capability to deploy an operational system by 2020. The focus was to compare the spacecraft burden of mass and power. Both optical and RF systems analyses were allowed technology improvements through 2015. Figure 54 summarizes the study conclusions, in terms of distance from earth and where optical communication has a clear advantage. These data points were computed assuming a set of assumptions relative to both the RF and optical systems. The study ignored the weather related availability issues for both links (a greater problem for optical than RF) and the ground receive terminal was assumed to be roughly comparable in cost. As both RF and optical technology development recommended in this report are executed, this analysis should be frequently revisited and refined.

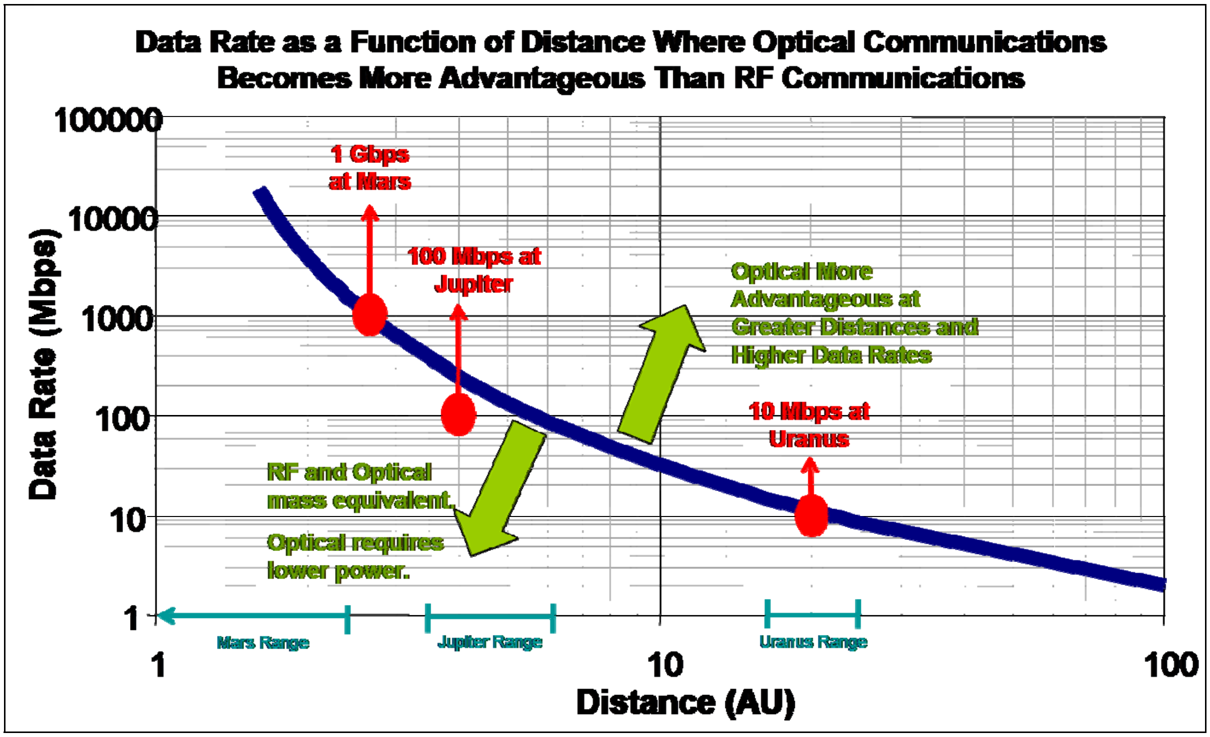


Figure 54. Data Rate as a Function of Distance Where Optical Communications Becomes More Advantageous than RF Communications

Optical communication is advantageous for data rates of 10 Mbps at distances of 20 AU (Uranus), for data rates of 100 Mbps at distances of 4 AU (Jupiter), for data rates of 1 Gbps at distances of about 2.67 AU (Mars maximum range) optical is advantageous. Below these ranges and rates, the masses associated with optical and RF are roughly equivalent and optical enjoys an improvement in power consumption. However the additional power required for RF communications results in a small increase in mass at only 0.011 kg/W. That is, an additional 1 KW requires a mass of only 11 kg more than say 100W. For high data rates on missions with severely constrained power and mass, optical communications is a better solution; however, this needs to be assessed for each mission. Some missions are more sensitive to mass and power.

Recommendation: Invest in optical communications technology leading to a series of "proof of concept" flight demonstrations.

Technical challenges remain for operational optical systems. These include providing space qualified sensitive detectors; efficient and stable sources (amplifiers and lasers); large, lightweight spacecraft telescopes; and electro-optical mechanical devices for beam pointing and steering systems. The beam pointing and steering system may be the greatest challenge. Present designs require three inputs to the system to maintain directionality and correct for spacecraft jitter. The small electro-optical mechanical devices used in the pointing system must operate over many cycles and withstand launch vibration. But the benefits strongly suggest that we proceed with investment in this area.

4.3.3. Spacecraft RF Technology

Radio Frequency (RF) has been the mainstay of space communications for many years. RF communications is reliable and will continue to be the major portion of the NASA space communications architecture as discussed in all four architecture elements identified in Section 3. However, NASA can get more out of the available bandwidth. More efficient coding is being used commercially and by other government agencies. These coding techniques will be even more efficient when implemented in software radios. Lighter, more efficient large antennas and higher-power transmitters are being developed. With these advancements and using the GEE array, RF communications can produce greater than 1 Gbps data rates at Mars maximum range (2.67 AU) and several Gbps at Mars minimum range (0.38 AU). There are no physics laws that would limit the data rate, but there is a penalty to pay for higher mass and power.

Recommendation: Fund RF technologies needed for higher data rates for deep space distances.

The recommendation is to further develop the promising technologies that will enable higher capacity communications from Mars distances and beyond. Technologies that can increase availability and reliability at greater distances include (Figure 55):

1. Efficient power amplifiers, e.g. high power Traveling Wave Tube Amplifiers (TWTA) and distributed Solid State Power Amplifiers (SSPA);
2. Large, light-weight, deployable antenna technologies such as mesh and inflatable antennas; and,
3. Power-efficient modulation and coding techniques.

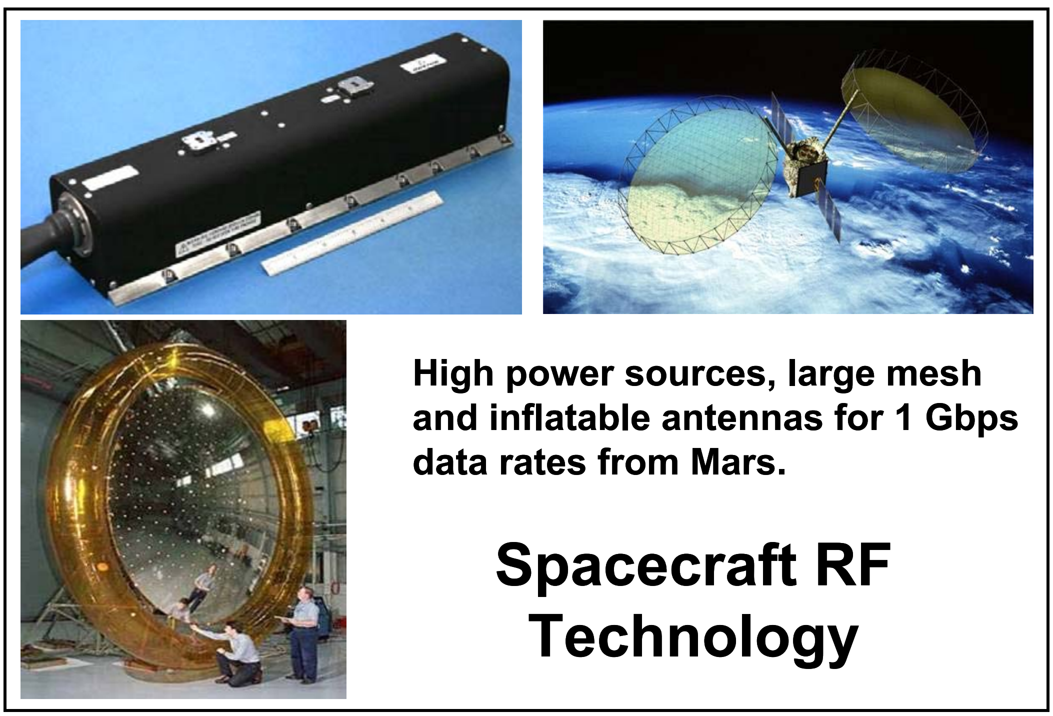


Figure 55. Spacecraft RF Technology Examples

High capacity spacecraft RF communications depends upon high-power transmitters, large antennas, and the ground receive antenna arrays. To the extent that target data rates do not appreciably exceed 1 Gbps, power-efficient modulation and coding, e.g. turbo and Low-Density Parity Check (LDPC) codes, can buy 3 dB or more link efficiency relative to today's standard practices. For data rates well beyond 1 Gbps, improvements in the power levels required to support bandwidth-efficient modulation will be needed. Here is the status of these items:

- **Ka band transmitters to greater than 1 KW with over 100X increase in data rate.** While high-capacity (>100 KW) TWTAs are currently available for terrestrial applications, kilowatt tubes are not yet space qualified. But the concept to enable greater than 1 KW power is well understood.
- **Large antennas enable over 50X increase in data rate.** Areal density of future Ka Band antennas may be below 1 kg/m^2 including support mechanisms. Large deployable mesh antennas up to 12 meters in diameter are currently flying in commercial applications and even large are planned. However these are at lower frequencies. Mesh antenna technology is currently in the seventh generation of development and manufacturers are confident that Ka-band antennas will be available shortly. Inflatable antenna technology—the potential leader in low-mass density apertures—is newer and continues to be developed.
- Power-efficient modulation techniques and bandwidth-efficient codes are available now and enable over a five-fold increase in data rate. They are used in some commercial and military applications. The power to enable these technologies will be reduced by the application of SDRs. The mass and power impact on the system is small.

Large antenna and high power transmitters are being used at other frequencies and for other applications. Leveraging off of this technology base—and the fact that most of the technology features are well understood—the major accomplishments and milestones in spacecraft RF technology can be accomplished prior to 2015. The demonstration of high-capacity RF communications in the 2015 timeframe will require a decision to commit to a development program in the next year (FY07).

This net result of the proposed technology recommendations will be a capability to support Gbps data return from Mars, using large antennas, high power transmitters, and bandwidth efficient modulation, assuming effective ground apertures roughly equivalent to a single 70-m antenna.

4.3.4. X-Ray Navigation

The navigation architecture (Section 2.4) recommends radiometric tracking for each spacecraft and GPS for near earth. An autonomous navigation method would be extremely desirable as an alternative to radio-navigation and time distribution techniques. Pulsars are celestial sources of extremely stable X-rays. These sources can serve as natural navigation beacons having sufficient repeatability and predictability that they can be utilized to produce a full navigation solution of position, velocity, and time for a spacecraft. The objective is to enable spacecraft autonomy through self navigation and precision time determination. The concept has potential application for future NASA space missions (Figure 56). X-ray navigation is being developed by DARPA and is planned for a demonstration on the ISS in FY08/09 to validate the concept. The particular demonstration is called XNAV.

Recommendation: Complete the XNAV demonstration.

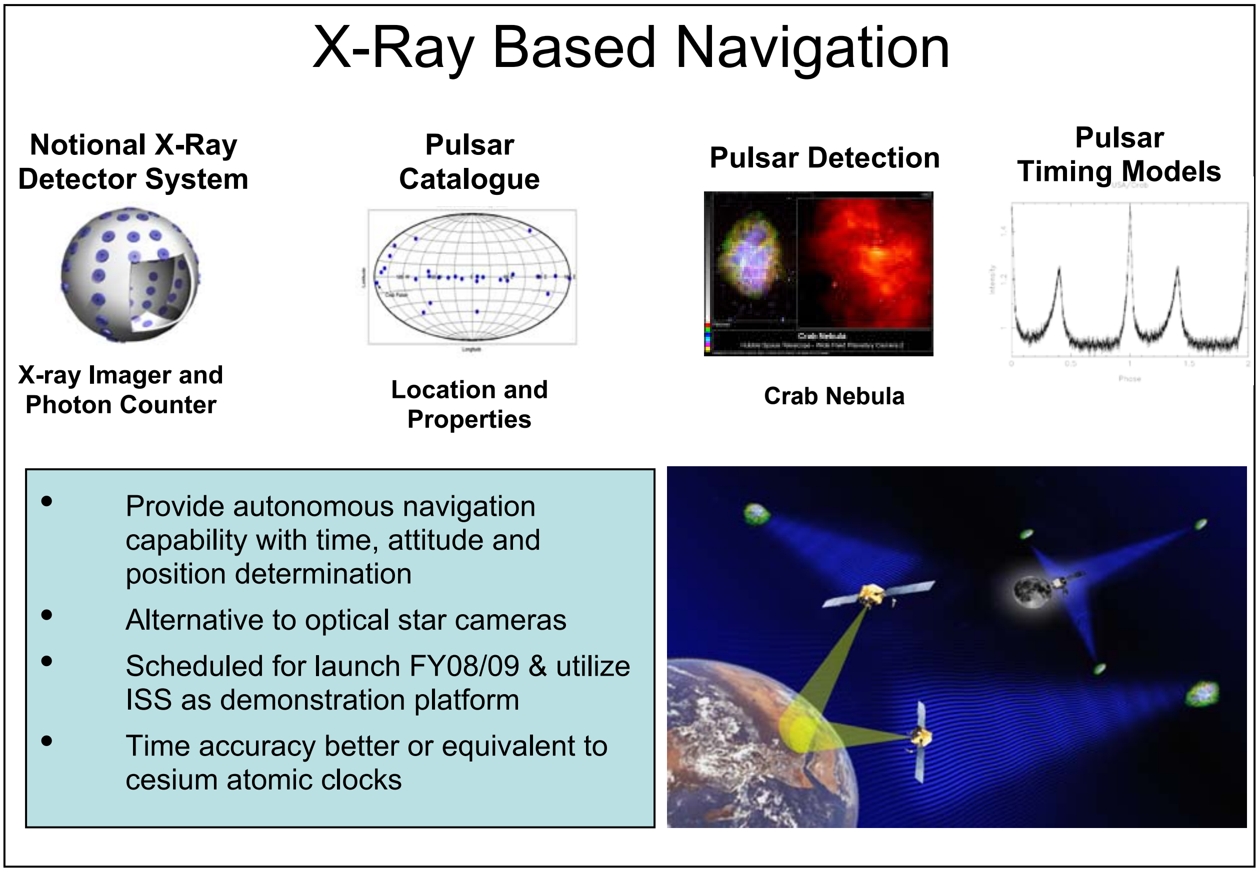


Figure 56. X-Ray Based Navigation Concept

4.3.5. Networking Technologies

As described in Section 2.1, the Space Communications Architecture features standardized, automated end-to-end data networking that will allow users in space and on Earth to intercommunicate using Internet-like techniques. In short delay, richly connected, stable environments the Internet Protocol (IP) suite is expected to form the underpinning of the network. Running under IP will be a variety of standardized space and ground links and running above IP will be multiple standard Internet-based applications. However, the space communications environment is not as benign as the terrestrial Internet and in many cases the end-to-end communications path will be subject to disruption, disconnection, and delay causing conventional Internet dialog to fail. Disruption may be caused by signal noise or momentary obscuration; disconnection may be caused by space vehicle contact geometry; and delay may be caused by signal propagation time or the effects of disruption and disconnection.

Since the complete IP suite cannot be sustained across disconnected, highly asymmetric or long delay space communications, an alternative flavor of space networking service – known as Disruption Tolerant Networking (DTN) – needs to be developed to accommodate environments where the performance of the IP suite is inadequate. By adding DTN to the SCA protocol suite, a full range of Internet-like user dialog can be maintained even in the highly stressed communications environments that often characterize space exploration.

Recommendations:

1. An integrated test and validation capability is needed to experiment with network-centric mission operations, including measuring performance in degraded and emergency modes. Actual flight testing is highly desirable.

2. Further technology development investment is required to fully realize the benefits of building on the Internet protocol base and development model. In particular, the architecture will require the rapid maturation of the core DTN protocols from their current moderate TRL to flight readiness (a high TRL). In parallel there is a need to quickly advance supporting DTN protocols (e.g., security and multipoint delivery) from their current low TRL status.

3. An enhanced time code format and distribution capability should be developed to support establishment of a single solar system-wide time distribution standard.

Generic DTN technology development is currently being developed within the DTN Research Group (DTNRG) of the Internet Research Task Force. DARPA is a primary sponsor of this work and intends to apply DTN to extend Internet operations in highly stressed military tactical communications environments. However, there is currently no funded effort to develop "DTN for space" that is optimized for the unique environment of space communications and is ready to fly on NASA missions. It is therefore recommended to develop this space-optimized profile of the generic DTN protocol suite and to mature the technology use on NASA's space missions.

In addition, the proposed time distribution architecture relies on establishing an improved time code format standard which upgrades the current standard to a format capable of providing time transfer with a resolution down to 10 ns. Development of the standard is required as well as experiments to test the accuracy of time transfer at various distances (Moon, Mars, and beyond). Experiments also need to be performed to compare the accuracy of this time dissemination system to GPS to establish means of interoperating between the SCA and GPS.

4.3.6. Programmable Communications Systems (Software Defined Radio)

Throughout out the previous sections describing the architecture, use of programmable devices has been mentioned. SDRs primarily use software functionality to perform traditional C&N functions allowing specific operating characteristics such as data-handling and waveform implementations to be provided by selectable software loads. SDRs are inherently digital radios where analog signal processing is minimized or eliminated. SDR benefits include mission-specific and mission phase reconfigurability, capability enhancement through post-launch upgradeability, autonomous operation according to *in situ* parameters unknown before launch, and post-launch technology infusion for improved performance. SDRs can also provide for integration of data communications with autonomous navigation, collection of radiometric data, and networking services.

Any mission-specific implementation with defined requirements would benefit from a point-solution digital radio. However, the evolving nature of NASA's exploration and science programs, the evolving communication standards as well as the evolving capabilities of the space communication infrastructure require a measure of adaptability that can be provided through SDR technology. The reconfiguration capabilities of the SDR can adapt to transitions in capability, protocols, waveforms, and network structure by allowing multiple configurations within a single mission, removing the need for multiple radios or for a single complex multi-function hardware radio.

Recommendations:

1. Develop open architecture for hardware and software.

2. Research radio components needed to improve performance such as higher data rates.

The SDR architecture shown in Figure 57 describes a library of hardware and software modules that can be combined as necessary to produce radios to meet mission or vehicle-specific requirements. Each of these modules is defined by internal functional attributes and external interfaces. The types of modules specified include processing modules, radio frequency modules, security modules, and external interface modules for connection to other radio equipment or a spacecraft bus. The architecture description does not require a specific implementation, nor does it mandate the standards or ratings of the hardware used to construct the radios. For example, it does not mandate the bus construction or the radiation tolerance required of the electronic components. But it does include detailed descriptions of standard-compliant SDR design implementations provided to developers for reference only. The architecture thus provides flexibility to allow different implementations for various mission classes, and allows developers to use proprietary module designs as long as module functional and interface standards are met.

Current state of the art in space qualified software data radios is exemplified by three radios: the Electra radio designed for the MRO launched in August 2005, the Electra-Lite radio for the Mars Science Laboratory (MSL) planned for 2009, and the Low Power Transceiver for TACSAT2 to launch in 2006. These transceivers are reprogrammable post-launch and are built using a "slice" architecture allowing mission or vehicle-specific hardware components to be selected. Development is ongoing through various technology programs for an X-band transceiver slice and an Application-Specific Integrated Circuit (ASIC) version of the baseband processor. There are also research tasks in place to explore wide band tuning of transceiver frequencies and to implement special GPS processing capabilities that enable C&N functions to run in the same box.

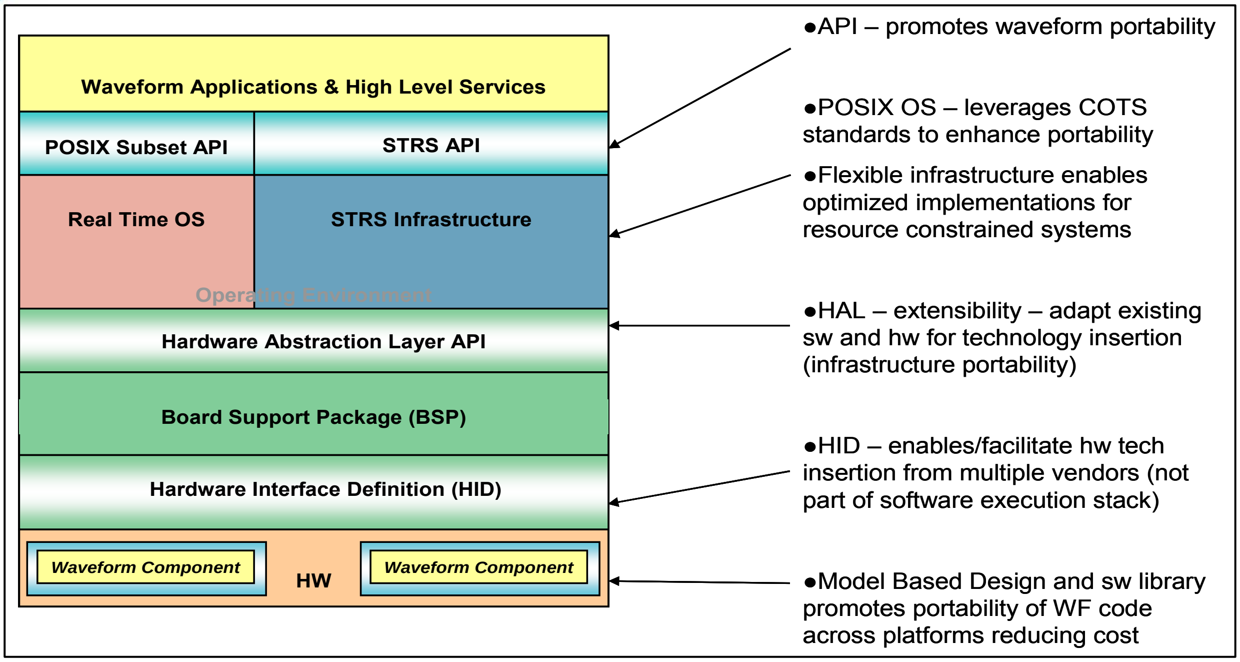


Figure 57. Notional SDR Architecture

Appendix A. Acronyms and Definitions

ΔV	Delta Velocity
AAS	American Astronautics Society
ACCI	Apoapse at Constant time of day Critically Inclined
ACE	Automated Cost Estimator
ACEIT	Automated Cost Estimating Integrated Tools
ACS	Attitude Control System
ACTS	Advanced Communication Technology Satellite
ACWT	Attitude Determination Control System (ADCS) Subsystem Weight
ADCS	Attitude Determination Control System Subsystem
ADPE	Automated Data Processing Equipment
AES	Advanced Encryption Standard
AFL	Astrobiology Field Laboratory
AFS	Atomic Frequency Standards
AFSCN	Air Force Satellite Control Network
AIAA	American Institute of Aeronautics and Astronautics
AKM	Apogee Kick Motor
AKMWT	AKM Suite Weight
ALECAN	Affordable Lunar Evolvable Communication And Navigation
AMA	Analytical Mechanics Associates, Inc.
APL	Johns Hopkins University Applied Physics Laboratory
ARC	NASA Ames Research Center
ASIC	Application-Specific Integrated Circuit
ASRC	Alaskan Slope Research Corporation
ATP	Authorization To Proceed
AU	Astronomical Unit
AXAF	Advanced X-ray Astronomy Facility
bps	bits per second
BOL	Beginning Of Life
BOLP	Beginning Of Life Power
BPF	Bandpass Filter
BPSK	Binary-Phase Shift Keying
BUSNR	spacecraft BUS Non-Recurring cost
BUSREC	spacecraft BUS Recurring cost
BWG	Beam Wave Guide
C&A	Certification and Accreditation
C&M	Control and Monitor
C&N	Communications and Navigation
C2	Command and Control
C3I	Command Control Communications and Information
C&DH	Command and Data Handling system
CANsat	Communication and Navigation Satellite
CCRM	Continuous Cost Risk Methodology
CCSDS	Consultative Committee for Space Data Standards

CDH	Command and Data Handling
CDMA	Code Division Multiple Access
CE	Concurrent Engineering
CER	Cost Estimating Relationship
CEV	Crew Exploration Vehicle
CFDP	CCSDS File Delivery Protocol
CFO	NASA Office of the Chief Financial Officer (OCFO)
CHAMP	CHAllenging Microsatellite Payload
CLASS	Communications Link Analysis and Simulation System
CLV	Crew Launch Vehicle
CNT	Common NASA Timescale
CofF	Construction of Facilities
COMM	Communications Subsystem
COMSEC	Communications Security
COMT1	Communications Total First Unit Cost
COMWT	Communications Subsystem Weight
CONOPS	Concept of Operations
CONUS	Continental US
CO$TAT	COST STATistical analysis package (part of ACEIT cost estimating toolset)
CRRES	Combined Release and Radiation Effects Satellite
CSC	Computer Sciences Corporation
CW	Clockwise
CCW	Counter-Clockwise
D/L	Downlink
DARPA	Defense Advanced Research Projects Agency
DC	Direct Current
DDOR	Delta-Differential One-way Ranging (also ΔDOR)
DFRC	NASA Dryden Flight Research Center
DMSP	Defense Meteorological Support Program
DOD	Department Of Defense
DOR	Differential One-way Ranging
DRS	Data Relay Satellite
DSAN	Deep Space Array-Based Network
DSCS	Defense Support Communication Satellite
DSN	Deep Space Network
DSP	Defense Support Program
DFE	Direct-from-Earth
DTE	Direct-to-Earth
DTN	Delay Tolerant Networking
DTNRG	DTN Research Group
ECANS	Exploration Communication and Navigation Systems
EDL	Entry, Descent, & Landing
EES	Earth Exploration Satellite service
EIRP	Effective Isotropic Radiated Power
ELV	Expendable Launch Vehicle

EOL	End Of Life
EOS	Earth Observing System
EPF	Europa Pathfinder
EPS	Electrical Power Supply subsystem
EPSWT	EPS Subsystem Weight
ESA	European Space Agency
ESMD	Exploration Systems Mission Directorate
ESS	Exploration System of Systems
EUT	Electra UHF Transceiver
EVA	Extravehicular Activity
EXPER	EXPERimental variable
FDMA	Frequency Division Multiple Access
FIPS	Federal Information Processing Standard
FISMA	Federal Information Security Management Act
FLTSAT	Navy Fleet Satellite program
FOM	Figure of Merit
FPGA	Field Programmable Gate Array
FSS	Fixed Satellite Services
FY	Fiscal Year
G	Giga (billion)
G/T	antenna Gain-to-noise-Temperature
Gbps	Gigabits per second
GDGPS	Global Differential GPS
GDOP	Geometric Dilution of Precision
GEE	Ground-based Earth Element
GEO	Geostationary Orbit
GEONS	Geomagnetic Event Observation Network by Students
GHe	Gaseous Helium
GHz	Gigahertz
GOES	Geostationary Operational Environmental Satellite
GP-B	Gravity Probe B mission
GPM	Global Precipitation Monitor
GPS	Global Positioning Satellite
GR&A	Ground Rules and Assumptions
GRACE	Gravity Recovery and Climate Experiment
GRC	NASA Glenn Research Center
GRO	Gamma Ray Observatory
GS	Ground Segment
GSFC	NASA Goddard Space Flight Center
GTO	Geosynchronous Transfer Orbit
HAIPE	High Assurance IP Encryptors
HDTV	High Definition Television
HEMT	High-Electron Mobility Transistor
HIPAA	Health Insurance Portability Accountability Act
HMAC	Hash-based Message Authentication Code
HQ	Headquarters

IA	Information Assurance
IA&T	Integration, Assembly and Test
ICESat	Ice, Cloud, and land Elevation Satellite
IETF	Internet Engineering Task Force
IMS	Integrated Mission Set (a.k.a., SCAWG Mission Model)
IMU	Inertial Measurement Unit
in.	inch
INFOSEC	Information Security
IOC	Initial Operational Capability
IPSec	IP Security
IRU	Inertial Reference Unit
ISCN	Integrated Satellite Control Network
ISRU	In Situ Resource Utilization
ISS	International Space Station
ISS	Inter-satellite Service
IT	Information Technology
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunications Union
JHU	Johns Hopkins University
JPL	NASA Jet Propulsion Laboratory
K	degrees Kelvin
kg	kilogram
km	kilometer
KMI	Key Management Infrastructure
KSC	NASA Kennedy Space Center
ksps	kilo samples per second
L1	Earth-Moon Lagrange Point 1
L2	Earth-Moon Lagrange Point 2
LAN	Local Area Network
LaRC	NASA Langley Research Center
LCC	Life Cycle Cost
LCNS	Lunar Communications and Navigation System
LCT	Lunar Communications Terminal
LDPC	Low-Density Parity Check
LDR	Low Data Rate
LDRS	Lunar Data Relay System
LEOP	Launch & Early Orbit Phase
LGA	Low Gain Antenna
Li	Lithium
LIBS	Laser-Induced Breakdown Spectrometer
LIDAR	LIght Detection And Ranging
LMOC	LR Mission Operations Center
LNA	Low Noise Amplifier
LOS	Line Of Sight
LR	Lunar Relay
LRE	Lunar Relay Element

LRO	Lunar Reconnaissance Orbiter
LRS	Lunar Relay Satellite
LV	Launch Vehicle
LSAM	Lunar Surface Access Module
m	meter
M	Million/Mega
MA	Multiple Access
MAC	Message Authentication Code
MARISAT	Maritime communication Satellite
Mbps	Megabits per second
MCC	Mission Control Center
MDR	Medium Data Rate
MER	Mars Exploration Rover
MGA	Medium Gain Antenna
MGS	Mars Global Surveyor
MHz	Megahertz
MIL	Military
MILSTAR	MILitary, Strategic, Tactical, And Relay system
MIT/LL	Massachusetts Institute of Technology/Lincoln Laboratory
MMIC	Monolithic Microwave Integrated Circuit
MOA	Memorandum of Agreement
MOC	Mission Operations Center
MOCC	Mission Operations Control Center
MOU	Memorandum Of Understanding
MPTFO	Mission Planning Training & Flight Operations
MR	Mars Relay
MRE	Mars Relay Element
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MSTO	Mars Science and Telecommunications Orbiter
MTBF	Mean Time Between Failures
MTO	Mars Telecom Orbiter
MTTR	Mean Time To Repair
MUSIC	MUltiple SIgnal Classification
N	Newton
NAFCOM	NASA-Air Force Cost Model
NATO	North Atlantic Treaty Organization
NC	Normally Closed valve
NER	Near-Earth Relay
NISN	NASA Integrated Services Network
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Air Defense
NPD	NASA Policy Directive
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPR	NASA Procedural Requirement

nrad	nano-radians
NRL	Naval Research Laboratory
NSA	National Security Agency
NSPD	National Security Presidential Directive
NTO	Nitrogen Tetroxide
NTP	Network Time Protocol
O&M	Operations and Maintenance
O&S	Operations and Sustaining cost
OCONUS	Outside of CONUS
OMB	Office Management and Budget
ORS	Operationally Responsive Space
OSI	Open Systems Interconnection
OS	Orbiting Sample
OSO	Office of Space Operations; Orbiting Solar Observatory
OTA	Over-The-Air
P3I	Pre-Planned Product Improvement
PA	Power Amplifier
P/B	Piggyback
PC	Personal Computer
PCC	Proximity Communications Capability
PI	Principal Investigator
PKI	Public Key Infrastructure
PL (or P/L)	Payload
PN	Pseudo-random Noise
PO	Program Office
POD	Point of Departure
POP	Program Operating Plan
POST	Program Office Support Tool (part of ACEIT cost estimating toolset)
PA&E	NASA Program Analysis and Evaluation Office
PRCS	Propulsion-Propellant Reaction Control System
PRCSWT	Propulsion Propellant RCS Suite Dry Weight
R&D	Research and Development
RCS	Reaction Control System
RF	Radio Frequency
RFI	Radio Frequency Interference
RI$K	cost RISK analysis capability provided inside ACEIT toolset
RLEP	Robotic Lunar Exploration Program
RNSS	Radio Navigation Satellite Service
RSS	Root Sum of Squares
ROM	Rough Order of Magnitude
RS-422	A standard for serial bus data communication
S	second
SA	Single Access
SASx	Security Architecture Study
SAST	Security Architecture Study Team
SAT	SDR Architecture Team

SBU	Sensitive But Unclassified
SC (or S/C)	Spacecraft
SCAWG	Space Communications Architecture Working Group
SCCIB	Space Communications Coordination and Integration Board
SCNR	Spacecraft non-recurring cost
SCT1	Spacecraft Total First Unit Cost
SCPS-SP	Space Communications Protocol Specification-Security Protocol
SDO	Solar Dynamics Observatory
sec	second
SEPM	System Engineering and Program Management
SERC	Satellite Engineering Research Corporation
SFCG	Space Frequency Coordination Group
SGL	Space-Ground Link
SGLT	Space-Ground Link Terminal
SLE	Space Link Extension
SM	Service Management
SMD	NASA Science Mission Directorate
SMEX	Small Explorer
SMS	Synchronous Meteorological Satellite
SNR	Signal to Noise Ratio
SOMD	Space Operations Mission Directorate
SSPA	Solid State Power Amplifier
SRS	Space Research Service
SSL	Secure Sockets Layer
SSM	Sun-Synchronous Magnetometer on DMSP
STD	Standard
STK	Satellite Toolkit© analysis package from Analytic Graphics, Inc.
STR	total nonrecurring STRucture subsystem cost in FY00 $K excluding fee
STRATCOM	US Strategic Command
STRWT	Structure Subsystem Weight
SVNR	Non-recurring Space vehicle cost
SVREC$	Space Vehicle Recurring Cost
SZM	Shielded Zone of the Moon
T&C	Telemetry & Command
T&V	Threat and Vulnerability
TASS	TDRSS Augmentation Service Satellites
TDRS	Tracking and Data Relay Satellite
TDRSS	Tracking and Data Relay Satellite System
TH	total nonrecurring THermal subsystem cost in FY00 $K excluding fee
THM	THerMal subsystem
THWT	THermal subsystem WeighT
TOPEX	Ocean Surface Topography Exploration
TRL	Technology Readiness Level
TT&C	Telemetry, Tracking & Control
TTCWT	TT&C Subsystem Weight
TWTA	Traveling Wave Tube Amplifier

Typ	Typical
UL	Uplink
UHF	Ultra High Frequency
UMD	University of Maryland
URSI	Union Radio-Scientifique Internationale
USA	United Space Alliance
USB	Unified S-band
USCM8	Unmanned Space vehicle Cost Model
USN	Universal Space Network, Inc.
USO	Ultra-Stable Oscillator
USS	User Services Subsystem
UTC	Coordinated Universal Time
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VHF	Very High Frequency
VPN	Virtual Private Network
W	Watt
WAN	Wide Area Network
WBS	Work Breakdown Structure
WFF	Wallops Flight Facility
WRC	World Radio Conference
X/L	Crosslink

Appendix B. References

This appendix contains an annotated bibliography of all references cited by or used by the various SCAWG teams in developing the SCA. References include detailed study reports written by the study teams as well as external references. Hyperlinks have been inserted to direct the reader to applicable reference files.

B.1. Top Level Architecture References

[1] SCAWG Mission Model, Jim Schier, Doug Abraham, Al Levine, 14 Dec 2006
This Excel file is exported from the MS Access database that contains the full IMS. The IMS Access database contains all of the mission and related communications information used by the SCAWG for use in communication capacity analysis. This version contains the baseline established for the round of studies addressed by the current SCAWG Architecture Report.

[2] Mission Model Update, presentation to SCAWG, 15 Dec 2006, Jim Schier, Doug Abraham, Al Levine
This presentation documents the effort to extend the Mission Model in response to SCCIB direction to include predicted missions in addition to current Mission Directorate planned missions. It discusses the relationship between the SCAWG Mission Model and the Agency Mission Planning Model (AMPM), defines the methodology used to create the Predicted Mission Model, and summarizes the trend analysis done with the resulting extended mission set for near Earth and deep space missions. Backup includes the complete DSMS trend analysis presentation.

[3] Communications for Lunar Exploration, Version: Draft 2.0, Michael Hadjitheodosiou, John S. Baras, Ayan Roy-Chowdhury, Nicolas Rentz, Hui Zeng, University of Maryland, Center for Satellite & Hybrid Communication Networks, 4 Jan 2006
In this report we present work related to designing a communication network for lunar exploration. We discuss the requirements for future space missions that influence the design. We list characteristics of the network, and highlight important issues and constraints related to performance, cost, and evolution. The proposed network can be considered as a prototype for future missions to the Moon and beyond. This network shares similarities with terrestrial wireless networks and sensor network architectures. However, the issues related to performance, robustness and security are different due to the long delay over the inter-satellite links, the limited power of the space nodes, the special hardware required in space, and lunar surface environment. Solutions that are geared towards terrestrial wireless networks might not be suitable for the interplanetary network we consider. We simulate the lunar mission network in software and provide a few performance results. We also discuss the security issues for the space exploration networks and suggest algorithms and protocols that can be implemented for ensuring secure communication while maintaining the performance of such networks.

B.2. Networking Architecture References

[4] Space Communications Architecture Working Group, Networking Architecture Team Data Networking and Service Management Report, Navigation Team, February 2006.
This report discusses the driving mission requirements that will impact future Networking Architectures. Based on these driving requirements, the advantages and disadvantages of various network layer options are discussed in the context of defined figures of merit (FOMs). These FOMs are measured and scored per network layer option. Based on the scoring, this report presents a recommended network layer for consideration in the future Space Communication Architecture.

B.3. Security Architecture References

[5] SAST_Report_contents_030206.doc, SAST Document, 3 March 2006, SAS Team, **Sensitive But Unclassified (SBU)**
This report summarizes the efforts of the Security Architecture Study Team to study and evaluate the impact to the SCA, Programs, and Missions to provide security services. The report provides detail about the security options studied, the security methodologies studied, and the usage of FOMs to shape analyses and results. The report discusses the details of security options, methodologies in the form of algorithms, FOM summaries, and the conclusions of the FOM evaluations. The report focuses on looking at Impact Matrices to show the relative differences in using security options with different methodologies, and how these choices affect Functional Capabilities of the communications architecture, as well as the impacts against Security Objectives, Interoperability goals and relative cost. The report provides some discussion of key performance considerations such as Key Management Infrastructure, C&A and Availability, and discusses some issues to still be addressed. Ultimately, the report recommends a security approach in terms of options that should be implemented

[6] SAST_Results_030206.ppt, SAST Presentation, 3 March 2006, SAS Team, **(SBU)**
The PowerPoint presentation represents a "living" document that is modified during the course of the study to reflect the activity of the SAS Team after and in between telecons and face-to-face meetings. It captures the efforts to select security options, methodologies and FOMs. Included in the document are some analyses results and table matrices reflecting the results of the FOM studies, analyses and evaluations. Included are Data Network option diagrams and examples of how security options "fit" into these. The document provides results, conclusions and recommendations that are consistent with the report in above. Backup slides include some examples of existing NASA architecture and segment configurations as they exist today.

[7] Interoperability-vs-4Methodologies.xls, Spreadsheet Analysis file, 1 March 2006, James Sammon, SAS Team
The spreadsheet file contains the Interoperability FOM scoring analysis for evaluating Security Options versus Methodologies.

[8] Project Life Cycle Burden-vs-4Methodologies.xls, Spreadsheet Analysis file, 3 March 2006, Leonard Schuchman, SAS Team
The spreadsheet file contains the Project Life Cycle Burden FOM scoring analysis for evaluating Security Options versus Methodologies.

[9] Op_Complexity-vs-4methodologies.xls, Spreadsheet Analysis file, 1 March 2006, Mike Pajevski, Howard Weiss, SAS Team
The spreadsheet file contains the Operational Complexity FOM scoring analysis for evaluating Security Options versus Methodologies.

[10] Overhead-vs-4methodologies.xls, Spreadsheet Analysis file, 1 March 2006, Howard Weiss, SAS Team
The spreadsheet file contains the Overhead FOM scoring analysis for evaluating Security Options versus Methodologies.

[11] Robustness-vs-4methodologies.xls, Spreadsheet Analysis file, 1 March 2006, Fred Stillwagen, Hugh LaMaster, SAS Team
The spreadsheet file contains the Robustness FOM scoring analysis for evaluating Security Options versus Methodologies

[12] NASA KM white paper.doc, SAST document, 8 February 2006, Jerry Pelch
This white paper discusses the options for employing Key Management for the security services as part of the study. It discusses the two options of Fixed (HardKey) key generation and storage/loading versus Dynamic (OTA Re-key) key generation and storage/loading. Advantages and disadvantages for both options are outlined.

[13] Option Definitions.04.ppt, SAST Presentation document, February 2006, Mike Pajevski, Howard Weiss, Richard Orr
This presentation document graphically illustrates the security options and methodologies selected for evaluation by the SAST. The document provides a laymen's overview of the options and the methodologies.

[14] Security&LinkAvailability.doc, SAST document, March 2006, Richard Orr, **(SBU)**
This write-up discusses the issues associated with link availability, some mitigation strategies to overcome "denial of service" effects, and provides an overall description of the link issues that are outside of the information and communications security study

B.4. Spectrum Architecture References

[15] Results of SRS spectrum evaluation by SCAWG spectrum subgroup, 21 April 2004, Spectrum Team
This document provides the technical evaluation of various Space Research Service bands for interference from other services sharing these bands and an evaluation of the allocation status on which the NASA use of the bands depends for Lunar and Mars missions. Results are identified for each band including

allocation and interference status as well as comments which support the assessment.

[16] NASA Policy on Utilization of Spectrum for Future Communication Architecture, Robert Spearing, July 2004.
This letter contains a tabular summary of the band evaluations identified in Reference [15] and makes the recommendation that, if possible, spectrum selected for future communication with the Moon be in the 2 to 3 GHz band to minimize interference with possible Radio astronomy use. The letter also identifies other possible bands for use in the vicinity of the Moon.

[17] Analysis of the number of CDMA channels as a function of data rate which can occupy a common bandwidth, prepared by ITT Industries, 23 May 2005.
This document describes the number of S-Band (5-6 MHz spectral occupancy) Code Division Multiple Access (CDMA) users which can simultaneously overlay and use the same spectrum as a function of user data t rate. This result was needed to address the ability to support multiple space users in the same spectral bands.

[18] Availability Analysis of the Lunar Relay using Only Ka band (37-38 GHz) for Operations Data and Mission Data vs. Using X band for Operations Data and Ka band for Mission Data, D.L. Brandel, 15 December 2005.
This analysis shows the expected weather outage of operations data is 0.2 hrs /month vs. virtually no weather outage for X band. Overall outage due to geometry alone of Lunar coverage is as great as 2 hours /month when the 3 DSN sites are used . An attempt was made to determine interference in X band due to the large number of users expected at the Moon and using the same band in low Earth orbit but this analysis needed further modeling to complete the assessment,

[19] Interference Calculations for Various Bands on the Moon Used as Proximity Links, D.L. Brandel, 19 April 2004 and 15 May 2005.
This set of four documents provides the RFI calculations for various bands studied by the Spectrum Team. The bands analyzed are not allocated to Space Research Service but are needed to support proximity links in the vicinity of the moon. The bands analyzed included 420-450 MHz, 902-928 MHz and 2.4-2.5 GHz. The interference sources analyzed were Earth based radar systems radiating in the direction of the Moon and causing interference to Lunar proximity links.

[20] Spectrum Consideration for Lunar Proximity Links, D.L. Brandel, Spectrum Team, 14 April 2004.
This analysis summarized the interference at the Moon in a number of bands assessed for ability to support proximity links at the Moon’s surface. These bands are not allocated to Space Research Service but offer hope that due to the distance from Earth, they might provide additional spectrum for NASA to use as proximity links. Reference [19] was used to support this assessment.

[21] Frequency Plan for Architecture Elements, Dave Struba and D.L. Brandel, Spectrum Team, 9 February 2006.
This document was presented to the SCAWG for review and approval and was used as the basis for the final report on spectrum to the SCCIB.

[22] NASA Memorandum to NTIA Stating Position on Use of Ku and Ka Spectrum, David Struba, IRAC Document 31536/1, 10 January 2000.
This memo documents NASA's position to the NTIA on the use of Ku and Ka spectrum bands by the National Space Transportation System (Shuttle), ISS, and Earth Observing System in view of the capabilities of TDRSS H, I, and J.

[23] NTIA Response to NASA Memorandum on Use of Ku and Ka Spectrum, William Hatch, IRAC Document 31478/1, 28 April 2000.
This memorandum provides NTIA's response to NASA's position stated in Reference [22]. NTIA will support spectrum certification for the existing TDRS 13.75-13.8 GHz forward link operations only for Shuttle and ISS, and will consider limited modifications for these operations on a case-by-case basis.

B.5. Navigation Architecture References

[24] Lunar Navigation System Alternatives for Continuous Full Surface Coverage, Phase 1 Report, Navigation Team, 18 August 2005.
The report presents a series of navigation alternatives, including one-way, two-way, and autonomous navigation techniques, supported by an extensive set of analysis defining a combined communications/navigation architecture that provides navigation support to a user located anywhere on or near the Moon. This one-way navigation concept explores the possibility of using a one-way navigation signal similar to the Global Positioning System (GPS). The current GPS could provide navigation information from the near-Earth environment to the Earth-Moon L1 Lagrange point. This concept is a synergistic approach that could provide seamless navigation, positioning, and timing, in the Earth-Moon system that utilizes and extends existing infrastructure. The two-way navigation concept could also be interoperable with GPS during transit between the Earth and the Moon.

[25] Navigation Options for Planetary Exploration, Phase 2 Report, Navigation Team, 9 February 2006.
This report continues the investigation of the full coverage analysis (Ref. [24]). The previous report concerned requirements, current capabilities, satellite constellations, and navigation methods for lunar vicinity exploration. This report extends these investigations for general solar system exploration. The final selection of FOMs for evaluation of navigation architectures includes both generic and navigation-unique FOMs. These FOMs will be used to evaluate alternatives discussed in this report.

[26] NASA Mission Impact Analysis of the Use in Space of Future GPS Constellation Options, GPS Report, Navigation Team, 17 October 2005.
The Navigation Team investigated the use of GPS for spacecraft navigation in Earth orbit, in particular analyzing the effects of proposed changes in the GPS

constellation. The GPS space segment consists nominally of 24 operational Block II, IIA, and IIR satellites distributed in six orbital planes. The DoD is studying a recommendation to decrease the number of GPS orbital planes from 6 to 3, and increase the number of satellites to 27, or more. As a result of this recommendation NASA requested an analysis of the impact of a change to a 27-satellite, three-plane GPS constellation. This has been accomplished by comparing this constellation to a 27-satellite, six-plane constellation. In examining these constellations, each has been subjected to scrutiny from a variety of viewpoints in order to minimize the chance that a significant discriminator among them goes undetected. Four criteria capture the dominant impacts of the constellations for space users: (1) availability using only the GPS Earth-pointing (or nadir-pointing) antenna; (2) availability including a zenith-pointing antenna; (3) GDOP; and (4) Orbit Determination Latency.

[27] Solar System Time Dissemination, Navigation Team, 8 March 2006.
This report deals specifically with those areas that involve considerations of time and frequency within the SCA. Relevant portions of the previous reports have been selected for inclusion in this report. Additional details to these areas have been incorporated.

B.6. Ground-based Earth Element References

[28] Supporting Material for the SCAWG Ground-Based Earth Element Architecture Recommendation, GEE Team, April 2006.
The supporting information for the GEE recommendation provided in this report covers the following topics: (a) FOMs and Analysis of the GEE Options; (b) Antenna Array Rationale-- A Relative Cost Comparison of Arrayed and Non-Arrayed Antennas for Similar Levels of Downlink Performance; (c) Array Sizing FOMs; (d) Ground Sites for the Architecture supporting LEO and GEO missions; (e) Advantages and Disadvantages of Uplink Arraying; and (f) Projected Uplink and Downlink Requirements

[29] Future Ground Network with High Rate Communications for Polar/Low-Mid Inclination Earth Orbit Applications, Curtis Emerson, 25 January 2006.
This presentation describes the GN Architecture for LEO applications. This study assumed a continuing need for the S-band TT&C requirement, including Launch and Early Orbit, critical event coverage, and nominal TT&C support for low/mid/high inclination missions and SBR concentrating on high rate communications. It addresses the driving requirements, geometric analysis, spectrum issues, architectural plan, and alternatives concluding with a summary of results.

B.6.1. External Publications

[30] Bagri Durgadas S., "Status Report on Array-based Deep Space Network for NASA", International SKA Meeting, Pune, India, Oct 31- Nov 4, 2005
This paper briefly describes the array-based Deep Space Network being proposed for NASA and presents current efforts and planning for the instrument.

[31] Bagri, Durgadas S., Joseph I. Statman and Mark S. Gatti, " Array-based Deep Space Network for NASA" , Union Radio-Scientifique Internationale (URSI) 28th General Assembly, New Delhi, India, Oct 23-29, 2005

The Array-based Deep Space Network (DSN-Array) will provide 40 times increase in the downlink/telemetry capability over the current DSN for cost effective, robust TT&C services to the space missions of NASA and its international partners. Instead of using the array as an element of DSN and relying on the existing infrastructure, we explore a broader departure in establishing a more modern Concept of Operations. This paper gives the architecture, including a system block diagram, operation's philosophy, customer's view of operations, operation's management and logistics, maintenance philosophy, and anomaly analysis and reporting for DSN-Array.

[32] Bagri, Durgadas S., Joseph I. Statman and Mark S. Gatti, "Operation's Concept for Array-based Deep Space Network", IEEE Aerospace Conference, Big Sky, Montana, USA, March 5-11, 2005

The DSN-Array will be a part of more than 103 times increase in the downlink/telemetry capability of the DSN. The key function of the DSN-Array is to provide cost-effective, robust TT&C services to the space missions of NASA and its international partners. It provides an expanded approach to the use of an array-based system. Instead of using the array as an element in the existing DSN, relying to a large extent on the DSN infrastructure, we explore a broader departure from the current DSN, using fewer elements of the existing DSN, and establishing a more modern Concept of Operations. This paper gives the architecture and operation's philosophy of DSN-Array. It also describes the customer's view of operations, operations management and logistics, and maintenance philosophy, anomaly analysis and reporting.

[33] Bagri, D. S. and J. I. Statman, "Preliminary Concept of Operations for the Deep Space Array-Based Network," IPN PR 42-157, pp. 1-13, May 15, 2004.

The Deep Space Array-Based Network (DSAN) will be an array-based system, part of a 1000-fold increase in the downlink/telemetry capability of the DSN. The key function of the DSAN is provision of cost-effective, robust telemetry, tracking, and command services to the space missions of NASA and its international partners. This article presents an expanded approach to the use of an array-based system. Instead of using the array as an element in the existing DSN, relying to a large extent on the DSN infrastructure, we explore a broader departure from the current DSN, using fewer elements of the existing DSN, and establishing a more modern concept of operations. For example, the DSAN will have a single 24x7 M&C facility, while the DSN has four 24x7 M&C facilities. The article gives the architecture of the DSAN and its operations philosophy. It also briefly describes the customer's view of operations, operations management, logistics, anomaly analysis, and reporting.

[34] [Bagri, D. S., "A Proposed Array System for the Deep Space Network," IPN PR 42-157, pp. 1-16, May 15, 2004.

This article briefly describes the initial design of the proposed array of small diameter antennas for the DSN. It will provide receive capability in deep-space communication bands at 8.4 GHz (X-band) and 32 GHz (Ka-band) equivalent to one 34-m existing DSN beam-waveguide antenna. The array, its expected performance, and initial tests planned to bring up the array and evaluate its performance are described.

[35] Bagri, D. S., "A Proposed Frequency Synthesis Approach to Accurately Measure the Angular Position of a Spacecraft," IPN PR 42-163, pp. 1-7, November 15, 2005.
This article describes an approach for measuring the angular position of a spacecraft with reference to a nearby calibration source (quasar) with an accuracy of a few tenths of a nanoradian using a very long baseline interferometer of two antennas that measures the interferometer phase with a modest accuracy. It employs (1) radio frequency phase to determine the spacecraft position with high precision and (2) multiple delay measurements using either frequency tones or telemetry signals at different frequency spacings to resolve ambiguity of the location of the fringe (cycle) containing the direction of the spacecraft.

[36] Bagri, D. S., "The Effect of Atmospheric Phase Fluctuations on Uplink Arraying," IPN PR 42-157, pp. 1-7, May 15, 2004.
This article investigates the effect of atmospheric phase variations on uplink array losses if the phase variations are not measured and corrections applied to the signals radiated from individual antennas. For an interferometer with a baseline of about 1.6 km and working at 7.2 GHz (X-band), the loss of signal due to phasing errors caused by atmospheric variations, if not corrected, is expected to be ≤0.7 dB for 95% of the time at elevations ≥18° at Goldstone. Therefore, it may not be necessary to continuously monitor the atmospheric variations and apply the phase corrections for arrays smaller than about a kilometer at X-band. However, for arrays spread over much larger areas or for an array of even one kilometer working at higher frequencies, such as 32 GHz (Ka-band), it may be necessary to monitor the atmospheric variations and apply the corrections to keep the phasing losses below an acceptable level (say, about 1 dB).

[37] Bruce E. MacNeal and William J. Hurd, “Parametric Cost Analysis Of NASA’S DSN Array”, Space Ops 2004, Montreal, Canada, May 2004
NASA faces a growing demand for increased data return from its deep-space missions. To meet this demand, the agency must increase its ground-based communications capacity. One approach is to add coherent arrays of small-aperture (12m) antennas to the DSN rather than the large-aperture (up to 70m) antennas used now. Cost-effective arrays will combine technologies and implementation strategies to achieve an optimum balance of performance and cost over the expected 30+ year life of the array. This paper describes a flexible method of cost analysis based on system parameters used for trade studies of the DSN Array. The analysis system uses a parametric description of costs, the array design and the implementation schedule. MS EXCEL workbooks generate individual cost elements within a hierarchical WBS structure. The system models burdened, full life-cycle costs over the 30+ years duration of the project. Random (Monte Carlo) analysis is used to estimate overall cost uncertainty. Operations

and maintenance (O&M) costs are compared to construction costs by computing the present value of 35 years of O&M. The analysis system was used to determine the most economical antenna diameter. Large numbers of small antennas must be used to achieve the required total G/T. Large amounts of electronics, roads, power cables, etc. produce high project costs. At the other extreme the increasing cost of large antenna construction dominates project costs. A broad minimum in costs is seen, roughly between 12m and 24m. Within this range, the differences in cost are much smaller than the cost uncertainty.

[38] Cooper, H., "An Antenna Servo Test Bed for the Deep Space Array Network," IPN PR 42-157, pp. 1-7, May 15, 2004.
This article presents the development and functions of the servo test bed and the antenna pointing computer as a first step in the development of the DSAN antenna servo system. The test bed will assist in the development of servo control algorithms, monitor and control interfaces, and antenna pointing and calibration software. The test bed is used in a laboratory environment and contains motors 1/10 the actual size and many of the same components that will be used in the larger 6-m breadboard antennas.

[39] D'Addario, L. R., "An Architecture for the Electronics of an Uplink Array," IPN PR 42-160, pp. 1-5, February 15, 2005.
Using a phased array of antennas on the ground to transmit signals to a distant spacecraft requires a method for keeping the carrier phases properly aligned at the separate antennas. One approach is to implement a receiving capability at each antenna along with the transmitting capability, and to use measurements of the relative phases of received signals to align those of the transmitted signals. This can be effective if phase errors are similar in the two directions. An architecture that facilitates this approach is proposed.

[40] D'Addario, L. R., "Estimates of Atmosphere-Induced Gain Loss for the Deep Space Network Array," IPN PR 42-160, pp. 1-7, February 15, 2005.
Decorrelation of carrier phases among the antennas of the DSN Array may occur due to turbulence in the Earth's atmosphere, leading to a reduction in signal-to-noise ratio for both received and transmitted signals if no correction is made. In this article, available statistical data on the turbulence are collected and analyzed in an attempt to predict the magnitude of such a loss.

[41] Gatti, M. S., "Introduction to This Special Issue on Array Developments in the Deep Space Network," IPN PR 42-157, pp. 1-2, May 15, 2004.
The DSN is facing a challenge of supporting the many future demanding missions that NASA plans for the next 25 years in a cost-effective manner. To this end, NASA Headquarters and the Interplanetary Network Directorate have commissioned studies of how best to increase the DSN capability, not simply by many factors, but by orders of magnitude. Options included ground-based RF and either ground-based or orbital optical communication systems. One promising architecture for future RF communications leverages the technologies being developed by the radio astronomy community—arrays of a large number of

small antennas. Recent developments by the privately funded Allen Telescope Array and both the international and U.S. groups proposing a large array with a square kilometer of collecting aperture suggest that such a capability may be implemented, operated, and maintained for a fraction of the cost of the comparable functioning monolithic single aperture. These developments include advances in both electronics and manufacturing. During the past 2 years, we have investigated how an array-based capability could be implemented in the DSN, paying particular attention to both implementation and operations costs. This special issue of The Interplanetary Network Progress Report provides a summary of many of the areas under study. Starting with a description of the science applications of the array (Jones and Connally), we lay the foundation for making a clear science case to migrate the DSN to arrays. A general summary of the array concept (Gatti), a more detailed architecture description (Bagri), and the considerations and options for configurations of the antenna elements (Jones) follow. Given an array and the location/configuration of its elements, one must calibrate the phases and amplitudes of the elements for optimal combining. Calibration in the presence of atmospheric turbulence (Bagri) is presented, from which we can iterate with the configuration modeling to achieve the right balance between the two. We then delve into the optics design for the breadboard antennas (Imbriale and Abraham) and a description of a breadboard antenna currently in development (Imbriale et al.) as well as a new multiple-frequency wideband feed (Hoppe and Reilly) and a novel cryogenic low-noise amplifier system (Britcliffe et al.). Next we describe the current plans for combining the many signals in a digital signal processing system (Navarro and Bunton), and we describe the servo control system design for the breadboard antennas (Gawronski and Cooper) and a servo system test bed used to develop the pointing algorithms and controls (Cooper). Finally, a preliminary concept of operations is proposed that suggests new and unique ways to consider scheduling, operating, and maintaining such an array system (Bagri and Statman).

[42] Gatti, M. S., "The Deep Space Network Large Array," IPN PR 42-157, pp. 1-9, May 15, 2004.

In recent years it has become evident that, if future science needs are to be met, the capacity of the telecommunications link between planetary spacecraft and the Earth must be increased by orders of magnitude. Both the number of spacecraft and higher data rates demand the increased capacity. Technologies to support the increased capacity include even larger antennas, optical receiving systems, or arrays of antennas. This article describes a large array of small antennas that would be implemented for a fraction of the cost of an equivalent 70-m aperture. Adding additional antennas can increase the sensitivity many fold over current capabilities. The array will consist of 400 parabolic reflector antennas, each of which will be 12 m in diameter. Each antenna will operate simultaneously at both X-band (8 to 8.8 GHz) and Ka-band (31 to 38 GHz) and will be configured with RF electronics, including the feeds, low-noise amplifiers, and frequency converters, as well as the appropriate servo controls and drives. The array also includes the signal transmission and signal processing to enable the system to

track from between 1 and 16 different signals. A significant feature of this system is that it will be done for relatively very low cost compared to the current antenna paradigms. This is made possible by the use of low-cost antenna reflector technology, the extensive use of Monolithic Microwave Integrated Circuits (MMIC), and, finally, by using commercially available equipment to the maximum extent possible. Cost can be further reduced by the acceptance of lower antenna element reliability. High system availability will be maintained by a design paradigm that provides for a marginal set of excess antenna elements for any particular tracking period. Thus, the same total system availability is achieved for lower element availability. The "plug-and-play" aspects of the assemblies will enhance maintainability and operability. The project plans include a modest start of 12 antennas at the U.S. longitude.

[43] Gatti, Mark S., "Deep Space Network Array", Workshop on Very Large Microwave Arrays for Radio Astronomy and Space Communication, IEEE Microwave Symposium, Long Beach California, June 2005.

Future plans for the DSN include the possibility that communications will be through an array of antennas in order to realize the needed 1000 fold increase in performance that NASA is projecting. This array would consist of three sites around the world each containing up to 400 12-m downlink. Uplink capability is required, however, it is yet to be determined the architecture for this aspect of the new DSN. The siting assumptions are that the initial US array would be located at the current Goldstone Deep Space Communications complex. The requirements on the array have been drafted such that antenna sizing and electronics may be developed. The system design has been drafted and a breadboard array of three elements located in Pasadena has been implemented. Initial technology investigations for the antenna system, electronics, signal processing and monitor and control have been completed with the fabrication of each of these units for the breadboard. Results are that such a system can be constructed at a fraction of the cost of the same capability using larger monolithic antennas.

[44] Gatti, Mark S., "The Deep Space Network Large Array", American Institute of Aeronautics and Astronautics (AIAA) Space 2003, Long Beach, California, September 2003.

The DSN is primarily used for telecommunications with scientific spacecraft engaged in solar system exploration. The network consists of three deep-space communications complexes, which are located on three continents. Each of the three complexes consists of multiple deep space stations equipped with ultra-sensitive receiving systems and large (34-m and 70-m diameter) parabolic dish antennas. Both the number of spacecraft and the data rates planned for the future will demand even more performance from these assets. Technologies to support the higher data rates include even larger antennas, optical receiving systems, or arrays of antennas. This paper describes a large array of small antennas that would be implemented for a fraction of the cost of an equivalent 70-m aperture. Adding additional antennas can increase the sensitivity many fold over current capabilities. The array will consist of 50–400 parabolic reflector

antennas, each of which is 12-m in diameter. Each antenna will operate simultaneously at both X-band (8–9 GHz) and Ka-band (30–38 GHz) and be configured with RF electronics including the feeds, low noise amplifiers, and frequency converters, as well as the appropriate servo controls and drives. The array also includes the signal transmission and signal processing to enable the system to track from between 1 and 16 different signals. A significant feature of this system is that it will be done for relatively very low cost compared to the current antenna paradigms. This is made possible by the use of low cost antenna reflector technology, the extensive use of MMICs and finally, by using commercially available equipment to the maximum extent possible. Cost can be further reduced by the acceptance of lower antenna element reliability. High system availability will be maintained by a design paradigm that provides for a marginal set of excess antenna elements for any particular tracking period. Thus the same total system availability is achieved for lower element availability. The "plug-and-play" aspects of the assemblies will enhance maintainability and operability. The project plans include a modest start of 50 antennas at each complex and the installation of an infrastructure that is capable of growing to a full compliment of 400 antennas per complex.

[45] Gawronski, W. and H. Cooper, "Control System of the Array Antenna Test Bed," IPN PR 42-157, pp. 1-12, May 15, 2004.

The array antenna test bed is a scaled model of the array antenna, designed and built to test antenna control system hardware, to test the development of control software, and to verify the control system algorithms. This article presents the development of the test-bed control system model of an array antenna and the analysis of its performance. It starts with the models of the mechanical hardware, which are combined into the rate-loop model and finally into the position-loop model. The control system algorithms consist of the command preprocessor, the position controller, the rate controller, and the backlash controller. The simulation results of the rate-loop model and the position-loop model show close coincidence with the test data. The analysis showed that the test-bed rate-loop bandwidth is 70 Hz and the position-loop bandwidth is 16 Hz, which exceed the expected system performance requirements.

[46] Hoppe, D. J. and H. Reilly, "Simultaneous 8- to 9-GHz and 30- to 40-GHz Feed for the Deep Space Network Large Array," IPN PR 42-157, pp. 1-16, May 15, 2004.

A dual-band feed for the DSN large array is described. The feed covers the 8- to 9-GHz and 30- to 40-GHz bands using a coaxial configuration. A saturated corrugated horn controls the radiation pattern in the low frequency band, and a dielectric rod is used as the radiator in the high-frequency band. The major requirements for the feed are described, and a summary of several possible feed configurations is presented. Next, the analysis tools used to perform the design are described. The bulk of the article covers the mechanical configuration of the feed, measured radiation patterns, and measured scattering parameters. Finally, the predicted performance of the feed–reflector antenna combination is presented.

[47] Imbriale, W. A. and R. Abraham, "Radio Frequency Optics Design of the Deep Space Network Large Array 6-Meter Breadboard Antenna," IPN PR 42-157, pp. 1-8, May 15, 2004.
This article describes the RF design of the 6-meter breadboard antenna planned as part of the DSN Large Array three-element interferometer. The design process, the expected RF performance using both the calculated and measured feed patterns, and the degradation due to mechanical displacements are shown. Using an estimated noise temperature for the LNA, the maximum and minimum G/T performance is computed.

[48] Imbriale, W. A., "Radio Frequency Optics Design of the 12-Meter Antenna for the Array-Based Deep Space Network," IPN PR 42-160, pp. 1-9, February 15, 2005.
Development of very large arrays of small antennas has been proposed as a way to increase the downlink capability of the NASA DSN by two or three orders of magnitude, thereby enabling greatly increased science data from currently configured missions or enabling new mission concepts. The current concept is for an array of 400 12-meter antennas at each of three longitudes. The DSN array will utilize radio astronomy sources for phase calibration and will have wide bandwidth correlation processing for this purpose. JPL currently is building a 3-element interferometer composed of 6-meter antennas to prove the performance and cost of the DSN array. This article describes the RF design of the 12-meter reflector that will use the same feed and electronics as the 6-meter antenna. The 6-meter antenna utilized Gregorian optics to enable tests with a low-frequency prime focus feed without removing the subreflector. However, for the 12-meter antenna, maximum G/T is the overriding requirement, and a trade-off study demonstrated that Cassegrain optics is far superior to Gregorian optics for maximum G/T. Hence, the 12-meter antenna utilizes Cassegrain optics.

[49] Imbriale, W. A., S. Weinreb, A. Feria, C. Porter, D. Hoppe, and M. Britcliffe, "The 6-Meter Breadboard Antenna for the Deep Space Network Large Array," IPN PR 42-157, pp. 1-12, May 15, 2004.
Development of very large arrays of small antennas has been proposed as a way to increase the downlink capability of the NASA DSN by two or three orders of magnitude, thereby enabling greatly increased science data from currently configured missions or enabling new mission concepts. The current concept is for an array of 400 12-meter antennas at each of three longitudes. The DSN array will utilize radio astronomy sources for phase calibration and will have wide-bandwidth correlation processing for this purpose. A program currently is under way to develop the technology and prove the performance and cost of a very large DSN array. The program includes a three-element interferometer to be completed by late 2004. This article describes the design and development of the low-cost 6-meter breadboard antenna to be used as part of the interferometer.

[50] Jones, D. L. and M. J. Connally, "Science Applications of Large Deep Space Network Arrays," IPN PR 42-157, pp. 1-8, May 15, 2004.
The DSN has begun work on vastly expanding its downlink capacity with the overall goal of increasing the telemetry data by about an order of magnitude

every 10 years for the next 30 years. Large arrays of small antennas (several meters in diameter), operating at radio frequencies, are a leading technology being investigated to meet this goal. Large arrays promise more than just an increase in total ground aperture for reception of telemetry signals. They also could be used for direct scientific observations in the fields of radio astronomy, radar astronomy, and flight radio science, much like the single-aperture antennas of the DSN are now. In this context, large arrays have the potential to increase the signal-to-noise ratio of these observations and provide multiple, simultaneous beams and deep radio frequency images. As with the current DSN, science observations with large arrays could provide direct benefit to NASA projects as well as create avenues for the infusion of technology and techniques that enhance spacecraft tracking. This article examines the potential of large DSN arrays to enable new scientific observations and identifies key design issues of large arrays to maximize their potential for science in addition to their primary use for spacecraft tracking.

[51] Jones, D. L., "Geometric Configuration Constraints for Large Deep Space Network Arrays," IPN PR 42-157, pp. 1-9, May 15, 2004.
The problem of selecting the relative positions of antennas in a large radio array has many degrees of freedom. This article considers ways to constrain this problem and arrive at geometric configurations that optimize array performance parameters of relevance to spacecraft tracking applications. A comparison with configurations developed for radio astronomy arrays illustrates the differences between the constraints that apply to spacecraft tracking and to aperture synthesis radio imaging. Despite these differences, many of the techniques and tools used in the design of radio astronomy array configurations are also applicable to DSN array configurations.

[52] Joseph I. Statman, Durgadas S. Bagri, Christopher S. Yung, Sander Weinreb, Bruce E. MacNeal, Mark S. Gatti, Barry Geldzahler, “Low-Cost, Large Aperture For Deep-Space Applications”, 6th International Symposium on Reducing the Cost of Spacecraft Ground Systems and Operations”, Darmstadt, Germany, June 2005
JPL, in conjunction with the NASA SMD, is evaluating methods of obtaining large apertures at low cost by arraying small diameter antennas. The key driver is the desire to greatly increase the amount of information received from and transmitted to deep-space missions - both human and robotic. This report enumerates the factors affecting the selection of the antenna diameter and recommends antenna diameter(s) that minimize the cost of the project. The methodology has two steps. In Step 1 we develop an antenna-related LCC as a function of the antenna diameter. The antenna-related LCC is approximated by the sum of the capital costs for the antenna-related components and the O&M costs for the antennas over 20 years (assuming that the RE is amortized over 20 years as well). Note that the DSN Array system will include many other components whose cost is independent of the antenna diameter and are ignored in this study. Step 1 results in a rather flat minimum, providing a range of antenna diameters that are close to the LCC minimum. Step 2 incorporates other factors

that are mostly related to cost but harder to model. Examples are the impact of antenna size on navigation, the trend of the cost model over the next few years and the impact of the points of discontinuity in the model (e.g. when a change in antenna diameter forces a change in technology). We use these factors to select the antenna size from the range determined in Step 1. The article shows results from the application of this methodology to the proposed DSN array.

[53] Lanyi, G., J. Border, J. Benson, V. Dhawan, E. Fomalont, T. Martin-Mur, T. McElrath, J. Romney, and C. Walker, "Determination of Angular Separation Between Spacecraft and Quasars with the Very Long Baseline Array," IPN PR 42- 162, pp. 1-16, August 15, 2005.

The interferometric technique of phase referencing was used to determine the relative angular positions of the Mars Exploration Rover B (MER-B) spacecraft with respect to angularly nearby quasars. The final cruise state of MER-B was observed in three sessions by the Very Long Baseline Array (VLBA) as part of a larger feasibility study to determine the accuracy of this technique. This article summarizes the VLBA observations and reductions of the nominal 10-station (45-baseline) observables, the incorporation of the delay data within the Orbit Determination Program, and the comparison of the VLBA and the DSN-based ΔDOR results. The pathway from VLBA observations to navigation use of the data is well-defined. The analysis shows that the formal accuracy of the VLBA-determined approximately declination-projected position of the spacecraft is 1.2 nano-radians (nrad) when the correlation among different-station delay observables is ignored. This formal accuracy, deduced from observed residual delay scatter, is about two times smaller than the corresponding result from the DSN ΔDOR observations. While the effect of quasar position and station location errors was included as a priori error in the estimate of formal errors, note that, to highlight the impact of improved measurement precision, the formal accuracy values do not include the larger Mars ephemeris and planetary-to-inertial frame tie and the effects of possible modeling errors. These contributions, as well as those from tropospheric refraction errors and the assumed 0.7-nrad uncertainty of the particular quasar position, must be reduced in order to obtain more accurate positions in the future.

[54] Larry R. D'Addario, "Large transmitting arrays for deep space uplinks, solar system radar, and related applications." URSI 28th General Assembly, New Delhi, 2005 Oct 25.

NASA's DSN is now being re-designed to provide the next generation of ground based equipment for communicating with spacecraft throughout our solar system. In the receiving (downlink) direction, it seems clear that large arrays of relatively small antennas provide the most cost-effective method of increasing the interplanetary data rate by at least 100 times over present capabilities, as is now desired. However, data must also be sent at increasing rates in the other direction, and the best approach to this has only recently been studied intensively. Two-way links are also important for supporting spacecraft navigation and radio science measurements. In addition, the ability to generate very high EIRP makes possible radar studies of planets, asteroids, and other objects. The situation is further complicated by projections that dozens of deep space missions will be simultaneously active in 2020 and beyond, requiring enough ground resources to support them all. This paper describes a conceptual design for arrays of antennas that provide transmitting capability to deep space for all these purposes. For a phased array of N identical antenna systems, the transmitting performance measured by EIRP scales as N^2, whereas the receiving sensitivity scales as N. This strongly affects the optimum antenna size and other parameters. Safety concerns suggest that power flux should be limited to less than 10 W/m^2, implying large area for high EIRP. With an extended array, controlling the carrier phase at the distributed elements so as to achieve coherence at the distant target becomes difficult in the face of uncertainties in the element positions, antenna construction tolerances, phase drifts in the electronics, and variations in the delay through the Earth's atmosphere. This implies a need for periodic in situ calibration. Design of the instrumentation is largely driven by the choice of calibration method. Calibration is facilitated when a signal from the target (downlink) is received at the same time as the transmission to it. Otherwise, a nearby strong source may be used in a manner similar to the calibration of synthesis radio telescopes. In either case, the array must have a receiving as well as a transmitting capability. To the extent that the receiving and transmitting signal path delays are not identical, a separate calibration of their difference is also needed. The conceptual design described here accounts for these considerations and provides a total EIRP of more than 1012W in the 7.2 GHz space research band. It includes 217 antennas of 3.8 m diameter, each with a 430W power amplifier, along with appropriate signal processing. No claim is made that this arrangement is optimum in any sense, nor that it will be adopted for the DSN; rather, the concept is an example of what is possible. Other possibilities achieving similar EIRP are considered briefly. These include using millions of sub-wavelength-size printed antennas, and using a small number of very large antennas with high-power transmitters.

[55] Navarro, R. and J. Bunton, "Signal Processing in the Deep Space Array Network," IPN PR 42-157, pp. 1-17, May 15, 2004.
This article describes the requirements and architecture of a signal processing subsystem for a DSAN being designed for the DSN. The emphasis is placed on hardware structures and signal flow. A methodology for sampling a 500-MHz bandwidth signal at 1280 MHz is examined. Two possible architectures for the digital signal processing are presented.

[56] Rogstad, D. H., "The SUMPLE Algorithm for Aligning Arrays of Receiving Radio Antennas: Coherence Achieved with Less Hardware and Lower Combining Loss," IPN PR 42-162, pp. 1-29, August 15, 2005.
Analysis and simulations are presented to show that coherence between the set of receiving antennas that form an array can be achieved with hardware and processing that are proportional to the number of antennas rather than the square of the number of antennas.

[57] Statman, J. I., D. S. Bagri, C. S. Yung, S. Weinreb, and B. E. MacNeal, "Optimizing the Antenna Size for the Deep Space Network Array," IPN PR 42-159, pp. 1-8, November 15, 2004.

JPL, in conjunction with NASA Headquarters, is conducting a feasibility study for a DSN Array. The DSN Array will have a G/T that is equivalent to ten times the G/T of the 70-m antenna subnet at <8.4 GHz (X-band) by arraying a large number of small antennas. (At <32 GHz (Ka-band), the G/T is four times higher!). Similarly, the DSN Array achieves the flux density of several 20-kW X-band transmitters by arraying smaller transmitters on smaller antennas. The LCC of the DSN Array, including development, installation, and operations, will vary depending on the antenna size. This article updates prior work by Weinreb and MacNeal on optimizing the antenna size for the downlink, and adds a similar study for the uplink antennas. The basic methodology is to compute the antenna-related LCC as a function of antenna diameter and select the antenna diameters that minimize the LCC. The antenna-related LCC is approximated by the sum of the recurring engineering cost for the antenna-related components and the O&M costs for the antenna part of the DSN Array for 20 years, assuming that the recurring engineering cost is amortized over 20 years as well. To compute the full DSN Array LCC, one has to add the non-recurring engineering and the non-antenna recurring engineering cost and O&M costs. The key result is that, for downlink, the selected antenna size is 12 m and, for uplink, the selected antenna size is around 34 m.

[58] Deutsch, L., Statman, Joseph I. and Noreen, Gary K., "Low Cost Communications Support of Lunar Missions," to appear in Transactions of the 6th Reducing Cost of Spacecraft ground System Operations Symposium, July 2005.

NASA has proposed a comprehensive program of robotic and human lunar exploration of the Moon as a step toward human exploration of Mars. The program includes characterization of the Moon by robotic orbiters and landers, development of a CEV to carry humans, and possible establishment of a human base on the lunar surface. The schedule is aggressive, with the first robotic mission launching in 2008 and the return of humans to the Moon around 2015. We present a concept and architecture for a low-cost communications infrastructure for these missions. There are two major elements: Earth stations and a small lunar relay constellation. The Earth stations will leverage the development of the DSN array. A small number of antennas would be used to provide services to the initial robotic missions. Capability would be added to support the more ambitious human missions, taking advantage of the modularity and expandability of this design. The lunar relay constellation will consist of low-cost spacecraft in elliptical orbits providing continuous coverage of the South lunar pole and some backside cover-age of critical events. This architecture can be established quickly, enabling early missions. It will then grow with the expanding mission requirements and eventually support human missions to the moon and Mars.

[59] Britcliffe, M. J., Hanson, T. R., Franco, M. M., “Cryogenic Design of the Deep Space Netowrk Large Array Low-Noise Amplifier System”, IPN PR 42-157, May 15, 2004.
This article describes the cryogenic design and performance of a prototype LNA system for the DSN Large Array task. The system is used to cool a dual-frequency feed system equipped with high-electron mobility transistor (HEMT) LNAs and the associated support electronics. The LNA/feed system operates at a temperature less than 18 K. The system is designed to be manufactured at minimum cost. The design considerations, including the cryocooler to be used, vacuum system, microwave interconnects, mechanical components, and radiation shielding, are discussed.

[60] Lee, C. H., Vilnrotter, V., Satorius, E., Ye, Z., Fort, D., Cheung, K-M., “Large-Array signal Processing for Deep-Space Applications, IPN Progress Report 42-150, pp. 1-28, August 5, 2002.
This article develops the mathematical models needed to describe the key issues in using an array of antennas for receiving spacecraft signals for DSN applications. The detrimental effects of nearby interfering sources, such as other spacecraft transmissions or natural radio sources within the array’s field of view, on SNR are determined, atmospheric effects relevant to the arraying problem developed, and two classes of algorithms (MUltiple SIgnal Classification (MUSIC) plus beam forming, and an eigen-based solution) capable of phasing up the array with maximized SNR in the presence of realistic disturbances are evaluated. It is shown that, when convolutionally encoded Binary-Phase Shift Keying (BPSK) data modulation is employed on the spacecraft signal, previously developed data pre-processing techniques that partially reconstruct the carrier can be of great benefit to array performance, particularly when strong interfering sources are present. Since this article is concerned mainly with demonstrating the required capabilities for operation under realistic conditions, no attempt has been made to reduce algorithm complexity; the design and evaluation of less complex algorithms with similar capabilities will be addressed in a future article. The performances of the candidate algorithms discussed in this article have been evaluated in terms of the number of symbols needed to achieve a given level of combining loss for different numbers of array elements, and compared on this common basis. It is shown that even the best algorithm requires approximately 25,000 symbols to achieve a combining loss of less than 0.5 dB when 128 antenna elements are employed, but generally 50,000 or more symbols are needed. This is not a serious impediment to successful arraying with high data-rate transmission, but may be of some concern with missions exploring near the edge of our solar system or beyond, where lower data rates may be required.

B.6.2. SCAWG Web Documents for the GEE

[61] 11-19-04 Antenna Array Brief, Nov 2004 Overview, John Rush.
This presentation describes how investments in communications support equipment are evolvable to support future NASA deep space missions in scalable, and low cost increments of capability for supporting simultaneous

missions by assignment of sub-array segments to meet individual spacecraft link requirements.

[62] 2010 Earth-Moon Comm Recommendation rev1, Options Studied with comments from Telecon, John Rush.
This report identifies options for the Earth-based communications architecture to support RLEP between 2008 and 2013. Evaluation of the options is considered based on: estimated cost, link performance, reliability, scalability, evolvability and sustainability.

[63] 70m-34m_phaseout, Feb 2005, Wallace Tai.
This report outlines the action item for phase-out of 70m and 34m antennas such as identifying sustainable life time of the 70m and 34m networks and if they are to be replaced, to what degree the 12m antenna network can be used to take over legacy and future mission support from the 70m and 34m networks. The phaseout timeline is also provided.

[64] Array network status 10-20-05, Earth-based Array Network status Oct 2005, Les Deutsch, Frank Stocklin, and WallaceTai.
This report provides status of Earth Based Array Network with brief functional description of the proposed architecture. Also includes an outline of the final report in progress including a list of FOMS.

[65] Draft_2 23 05, Uplink Arraying, February 2005, Jim Lesh.
This presentation described the technical challenges of uplink arraying and technologies and solutions to the problems.

[66] EarthArray2010_11_19_04, Ka-band antenna array recommendation (Nov 2004), John Rush
The SCAWG assessed 6 options for implementing the antenna array and recommends that NASA's long term Deep Space communications needs would be best handled with new 12m stations using S-band for engineering TT&C and an array of 12m antennas using Ka-band for high-rate data return. Construction of the antenna array could be started in the near term instead of upgrading the 26m network. Sufficient Ka-band 12m antennas could be installed at three global locations, along with two 12m S-band antennas at each site, in time to service the LRO mission in 2008.

[67] Ka 12M-HGA Opt3, 5 October 2004.
This spreadsheet details the Option 3 link budget analysis using the Ka-band 12 meter high gain antenna.

[68] Ka 34M-HGA Opt1-2, 5 October 2004.
This spreadsheet details the Options 1 & 2 link budget analyses using the Ka-band 34 meter high gain antenna.

[69] Ka 4-12M-HGA Opt5, 5 October 2004.
This spreadsheet details the Option 5 link budget analysis using the Ka-band 4-12 meter high gain antenna.

[70] Lev1_Reqmts for 12m array_3_15_05, 15 March 2005.

The level-1 Requirements for the 12m array define the space communications and tracking support to missions and extravehicular activities on the lunar surface, the scalability into varying sub-networks, array scheduling, interoperability with other space agencies, and the ability to evolve into new capabilities.

[71] LN Options – 0929041, Earth Ground Network for Lunar Support, 29 September 2004, Jason Soloff, Frank Stocklin, Wallace Tai, and Les Deutsch.
This study presented the 12m array support requirements and the proposed the site locations. The study identified the advantages of using arrayed antennas and described how the array is able to continue to grow in support of future deep space missions. The costs for operating and maintaining S-band and X/Ka-band arrayed antennas are estimated. Risk and risk mitigation are also examined.

[72] LRO Ground Comm Options 9-15-04, List of Options for LRO Ground Support, 15 September 2004.
A Listing of the 7 options for the 2010 Lunar Reconnaissance Orbiter ground communications network operating at S-band and Ka-band using the new 12m, 18m and the existing DSN 34m Beam Wave Guide (BWG) and refurbished 26m antennas.

[73] LRO_Margin_Comparison.
A spreadsheet that shows the link margins of Lunar Reconnaissance Orbiter S-band telemetry, S-band command, and Ka-band science data relative to 5 ground antenna options.

[74] LRO-DSN update, DSN Support for LRO, August 2004, Wallace Tai.
This report provides an update on the DSN potential support for the Lunar Reconnaissance Orbiter. The report gives a summary of DSN services to LRO, antenna options considered, a summary of telecom link analysis, a summary of ranging link analysis, and cost estimate of the DSN services. The report concludes that supporting high-rate data return at Ka-band using the 34m BWG is not a problem, existing 26m subnet meets LRO requirements at S-band for engineering TT&C, and the new 12m subnet will be able to meet LRO requirements, if X-band is used, for engineering TT&C.

[75] Lunar_network_options1, Update to GEE Options for Lunar Support, October 2004, Jason Soloff, Frank Stocklin, Les Deutsch, and Wallace Tai.
This study presented Lunar support requirements and considered 5 options for the ground network. The study compared the pros and cons of each option and described the advantages of using 12m arrayed antennas. The costs for operating and maintaining S-band and Ka-band arrays are estimated. Risk and risk mitigation are also examined.

[76] NGDSN_30min talk, Next Gen DSN, 4 October 2004, Barry Geldzahler
This presentation provides a overview of the proposed next generation architecture for the DSN.

[77] Revised Rec. SCCIB 11-2-04 Lunar 2010, 2010 Recommendations Update- LRO Support and 12m Rationale, January 2005, John Rush.

This presentation explores the vision of the next-generation DSN as being comprised of a balanced optical and RF capability. Optical communication alone will not meet all of NASA's future needs, but will provide key advantages (e.g., high data rates to Mars and selected missions). Deep space missions carrying large RF communications systems are planned for launch over the next 20 years – hence we will need to support RF at much higher data rates for at least 30 years. RF ground arrays have extremely high reliability, could operate with no new spacecraft technology, and will benefit all NASA spacecraft, large or small, new or old. Ground arrays of small antennas are significantly less costly to operate and maintain than large antennas with equivalent sensitivity.

[78] RLEPArchitecture-GSFRcmmndtn (v4), RLEP Spectrum and Ground Site Options, September 2004, GSFC.
This presents GSFC's recommendation for the RLEP communication architecture, assuming LRO plus three additional RLEP missions, and potential evolution to support CEV.

[79] S 12M HGA-HGA Opt2-3-5, 5 October 2005.
This spreadsheet details the Lunar Reconnaissance Orbiter link budget analysis using the S-band 12m high gain antenna for options 2, 3 and 5.

[80] S 12M LGA-LGA Opt2-3-5, 5 October 2005.
This spreadsheet details the Lunar Reconnaissance Orbiter link budget analysis using the S-band 12m low gain antenna for options 2, 3, and 5.

[81] S 26M HGA-HGA Opt1, 5 October 2005.
This spreadsheet details the Lunar Reconnaissance Orbiter link budget analysis using the S-band 26m high gain antenna for option 1.

[82] SCAWG_Array_Tutorial, November 2005, Les Deutsch.
This report presents a basic tutorial on antenna arraying in the uplink and the downlink. Some historical background is provided on what has already been accomplished with arrays since the 1970's. The separation of the uplink and downlink antennas and the resulting impact on performance degradation is discussed. Relative cost estimate vs antenna diameter is presented graphically and indicates that the 12m antenna would minimize cost.

[83] SCAWG_EGA_CONOPs_and_Alts, Antenna Array CONOPS and Alternatives, November 2005, Les Deutsch.
The Concept of Operations describes the basic characteristics and functions of the antenna array. A matrix shows qualitatively 5 identified ground network architecture options and the associated figures of merit. The key characteristics of the antenna array are summed up as follows: (a) Earth stations will be located at a minimum of three sites; (b) Downlink will be provided through arrays of moderate sized antennas; (c) Antenna sites will be automated and have maintenance staff only; (d) The array will support Demand Access.

[84] SCAWG_S-band_Question, November 2005, Les Deutsch.
This presentation deals with post 2008 and the question of needed EIRP at S-band for missions that normally use the 26m antenna. The EIRP for near-Earth

missions will be tracked by a single 12m antenna and others requiring higher EIRP and normally tracked by the 26m antenna will be tracked using the 34m antennas until the array is completed.

[85] SCCIB 11-2-04 Lunar 2010, 2010 Recommendation, November 2004, John Rush.
This presentation discusses the proposed merits of the Ka-band for the Lunar Reconnaissance Orbiter and compares ranked options to figures of merit. The cost for providing the G/T equivalent of 12 34m antennas or 100 12m antennas vs the antenna diameter is also estimated.

[86] Soloff - Lunar Network Options - SCAWG 092204, September 2004, Jason Soloff, Frank Stocklin, and Ronna Brockdorff.
This presentation provides a link analysis comparison of 12m vs 18m systems for S/X/Ka bands & provides the basis of the 18m as the minimum acceptable.

[87] U L_Follow-On, Uplink Arraying Follow-up question/answers, February 2005, Bob Cesarone.
This report examines the some of the concerns involved with 34m antenna arraying to add 3 receive capabilities to 34m BWG antennas will require Ka-band, Cryogenic equipment and 8.4 MHz reception. Cost-benefit trade-off is still TBD. If existing 34m BWG's are used in the Array Ka-band receive mode, the concerns are: (a) At X-band, the antennas have rather relaxed requirements on blind pointing and on surface accuracy (these antennas use monopulse for accurate pointing - they do not have the blind pointing accuracy needed for Ka-band); (b) There may be a steep cost difference between an X-band antenna and a Ka-band antenna, under blind pointing conditions; (c) Analysis is needed to determine if monopulse will degrade under weak signal conditions.

[88] U L_for_SCAWG, Future Uplink in the DSN, February 2005, Bob Cesarone.
The report discusses future uplink capabilities, which include: (a) Number of links, data rates & volumes, emergency U/L, and high B/W U/L for eventual human missions that are still being investigated; (b) Options have been identified to increase the routine & emergency U/L EIRP capability: very high power on 34m, U/L arraying on 34m or 12m antenna, and high power on the 70m antenna; and (c) Methods have been identified to reduce the required routine & emergency U/L EIRP lowered loop B/W, U/L coding, reduced microwave losses, and reduced noise temperature.

[89] Uplink Arraying Concepts 20050609, 9 June 2005, Dan Williams.
The uplink arraying concept described in this report outlines the benefits of uplink arraying, the implementation approach, and the technical challenges of performing uplink calibration and managing atmospheric effects. A sample phase error budget is provided that shows less than 1.0 dB loss at X-band.

[90] Uplink-SCAWG, November 2005, Joe Statman.
This report describes the basic principles and reasons for using uplink arraying. The technical challenges in implementing an uplink array are identified and

discussed. The approach described for developing a prototype uplink array is conducted in 4 phases that lead to final validation tests with a cooperating spacecraft.

[91] SCAWG30 Final Presentation to SCCIB, 25 May 2005.
The interim NER Recommendation is that Near-Earth missions will be best supported by a network of arrayed antennas of small to moderate size similar to the SCAWG Recommendation for the DSN. Background discussion for this recommendation is included.

[92] SCAWG45 aug1 LJD, 2 August 05.
This presentation contains the results of the 45-Day Study from August of 2005. This study reviewed two ground network options in detail: (1) A single network that would be capable of supporting all missions assuming the additional existence of the SN and polar LEO tracking stations, and (2) Two distinct networks- one for the deep space robotic and human (category B) and one for Near Earth robotic and human (Category A).

[93] Deep Space Array Network Re-Validation Study, M.J. Hard (Mar 1, 2006) (Set of 5 Files)
Provides an independent assessment on the cost estimates of the relative costs of a number of DSN architecture options: new 34m antennas with array capability, new arrays of 6m, 12m 18m, and 24m antennas, for downlink. Addressed required uplink antennas (not arrayed). A cost model is described. The life cycle cost estimate for the period 2005-2030 is provided. The study assumes existing DSN assets are retired at the start of 2015 and is based on the SCAWG IMS for Deep Space missions, and Near Earth plus Deep Space.

[Disclaimer: Information presented in this material is work-in-progress and has not been endorsed by the SCAWG.]

[94] CoveageCheck_rev5_070705_sy_rbb_Mod400k_0713051.ppt, 13 July 2005.
This presentation provides an analysis for the coverage of Lunar mission for both SN and proposed Ground stations & defines coverage gaps for the assumed Lunar trajectory.

[95] Ground Network Brief_042104_v2.ppt, 21 April 2004.
This presentation provides an overview of the GN architecture, including an overview of NASA facilities at Fairbanks, McMurdo, KSC, Santiago, and Wallops as well as commercial facilities at Kongsberg, Poker Flat and USN. It describes SafetyNet and the Air Force Satellite Control Network (AFSCN). It also describes the upgrade in progress for the Space Link Extension.

[96] Link Margins_051804_rs.ppt, 18 May 2004.
This presents a strawman signal design for the LRO, assuming DSN 26m and 34m ground terminals.

[97] classaw.ppt, March 2006.

Communications Link Analysis and Simulation System (CLASS) – An overview of CLASS capabilities to model and analyze communications links. Examples are included.

[98] Atm_loss.ppt
LRO Signal Design: This file contains atmospheric attenuation calculations based upon the ITU models at 26.25 GHz for the 3 DSN locations. These do not include the increased system temperature due to atmospherics, but these will be considered when performing the link analysis.

[99] CoverageCheck_rev2.ppt
SN coverage plots for the following altitudes: 20,000 km, 30,000 km (max altitude with 100% coverage at +/- 28.7 deg latitude), 60,000 km, 70,000 km, and 270,000 km

[100] site trade data (4)1-fs (unequal Weighting).xls
This spreadsheet evaluates a variety of existing sites, including NASA, DoD, and commercial sites, in terms of their logistics, operations, facilities, political, data security, communications, weather and commercialization factors. This file treats all factors with proposed unequal weights.

[101] site trade data (4)1-fs (equal Weighting).xls
This spreadsheet evaluates a variety of existing sites, including NASA, DoD, and commercial sites, in terms of their logistics, operations, facilities, political, data security, communications, weather and commercialization factors. This file treats all factors with equal weights.

[102] RatingResults.ppt
This briefing provides integrated results of the ground site evaluation trade study.

[103] SCAWG Presentation_rev2.ppt
This report documents the S-Band Near Earth Network Code Division Multiple Access (CDMA) Capacity Study. Its objectives were to: (1) Identify the maximum S-band Command and Telemetry data rates which can be supported for a parametrically increasing number of lunar platforms using CDMA and a single 6 MHz S-band uplink frequency allocation and a single 6 MHz S-band downlink frequency allocation; and (2) Compare CDMA capacity results with a Frequency Division Multiple Access (FDMA) approach. The scope was limited to an emphasis on TDRSS-compatible S-band Pseudo-random Noise (PN) spread signal format.

[104] update_analytical_max_DR.ppt
Two charts on analytical uplink results showing both polarizations at rate ½ convolution coding. Number of lunar users is varied.

[105] SCAWGPresentation(V13)_0825044.ppt, 25 August 2004.
This report provides a summary of RLEP Communication Architecture Definition Study including requirements, assumptions, and constraints for the RLEP mission taking into consideration requirements for the LRO. It presents status on the supporting studies including: Geometric study, TT&C signal design, K-band

signal design, DSN cost/issues, and build new ground terminals. The study included various ground station options for Lunar support as well as signal design options with coding recommendations.

B.7. Near-Earth Relay References

[106] SCAWG Near-Earth Relay Architecture Study Report, NER Team, February 2006.

This report presents the background for the NER recommendation. This includes the operations concept overview, driving functional and performance requirements, an overview of the options considered, characterization of the options in terms of user burden, summary of architecture sizing and costing, figures of merit, excursions on reducing user burden, additional services and capabilities for consideration, and review of an optical communications option. Appendices are also provided: (a) operations concept; (b) on-board processing; (c) space segment design and sizing; (d) ground segment design and sizing; (e) space segment refinements and sizing.

B.8. Lunar Relay References

[107] SCAWG Lunar South Pole and Full Coverage Studies Report: September 2004-March 2005, Lunar Relay Team, Published March 2006.

Full Coverage: This report compiles the results of several studies conducted by the SCAWG at the request of ESMD that developed concepts of operation, preliminary requirements, candidate relay satellite constellations and designs, and cost estimates for the two basic scenarios of: (1) human sortie missions anywhere on the Moon requiring full coverage; and (2) human outpost missions to the South Pole. The purposes of the full coverage study were to: (1) Provide a program development timeline; (2) Provide top level architecture concepts; and (3) Estimate the program's Life Cycle Cost (LCC). Driven by ESS requirements, a total of 18 constellation configurations were analyzed using three different design options (small, medium, and large satellites). The study concluded that continuous 100% lunar global coverage can be achieved with 5 or more satellites. Several good candidates exist for global lunar coverage with 6 satellites in polar or inclined orbits. A small communication payload can meet the requirements. the study recommended that the architecture for full lunar coverage consist of 6 dedicated relay satellites in 2 planes and that the development timeline for the program should be 10 years to minimize schedule risk and limit annual funding. The cost in the initial study (December 2004) was estimated at up to $2.3B (in FY2004 $). After enhancing the completeness and depth of the cost model, an updated estimate recommended that ESMD budget $2.55B (in Then Year $ including agency overhead) to cover development and operation through 2030.

South Pole: The outpost phase assumed that continuous coverage was required for the South Polar region from 80-90°S. The purpose of the outpost phase study was to recommend an architecture for lunar communications relay in 2015 time period. It assumed that continuous coverage was required for each individual mission with residual assets accreting over the campaign until continuous global coverage is required. Out of 50 candidate constellations, seven were selected for detailed analysis. FOMs were defined to assess performance in terms of visibility, orbit stability, navigation utility, failure tolerance, and robustness. Overall benefit was assessed resulting in a recommendation that an elliptical constellation of 2 satellites provides the best overall cost and performance.

[108] Ely, T., Lieb E. "Constellations of Elliptical Inclined Lunar Orbits Providing Polar and Global Coverage," American Astronautics Society (AAS)/AIAA Astrodynamics Specialists Conference, 7-11 August, 2005. AAS 05-343

A method has been developed for designing a high altitude lunar constellation that provides stable and redundant coverage to a selected pole at the Moon. The approach is guided by analytical techniques for initial orbit selection, and then a numerical procedure for tuning the coverage of the constellation to achieve a final design. The resulting constellation design yields stable orbits with lifetimes in excess of 10 years, and a stable 'formation'. Under the influence of only gravity effects, the constellation requires no additional orbit control in order to maintain its formation. It is anticipated that a small amount of control will be required to accommodate other perturbations, such as solar radiation pressure.

[109] A Five-Satellite Constellation for "Cover Where You Go" Lunar Exploration, Richard Orr/SATEL LLC, Erica Lieb/ASRC, 31 October 2005.

A study was performed to identify reduced constellations that provide coverage of any lunar site during a mission with an emphasis (not exclusive) on the "Top Ten Sites" identified by the ESAS but do not require continuous global coverage. The six-satellite, two orthogonal polar orbit constellation recommended for full coverage was the baseline for departure. A constellation of five satellites was identified that provides coverage of 8-9 sites with operational flexibility to reposition satellites if the polar target changes to the other pole. The effect of crosslinks was considered in the study concluding that the constellation cannot function without crosslinks.

[110] Trade Study Report: Recommended Lunar Data Relay Configuration for the Robotic Lunar Exploration Program, Lunar Relay Team, 24 September 2004.

The SCAWG conducted a study of options to provide lunar data relay support for missions in the RLEP. The purpose of the study was to identify options for data relay from lunar surface landers and recommend the most cost and performance effective approach. Analysis of mission requirements identified the need for a PCC providing data relay from lunar landers to Earth at up to 1 Mbps. The study considered multiple options including dedicated communications missions of a Lunar Data Relay System (LDRS), combined communications and science missions on LRO and RLEP2, and various LV options. High-level mission concepts were formulated for LRO, LDRS, and the second RLEP mission, RLEP2, based on potential mission and communication requirements to support all other missions in the RLEP series. For each option, a set of performance levels was modeled. Partial LCC models were developed for each concept to allow discrimination between the candidate concepts. Results showed that the lowest cost and performance option was approximately $12M (in FY2004$) to add the PCC to the LRO with more robust performance options requiring up to $63M. Adding the PCC to the RLEP2 required from $48-95M while the dedicated LDRS required $110-231M, depending on the performance level. The SCAWG recommended incorporating a PCC on both LRO and RLEP2 with best efforts towards a 5 year life with a 100-600 km circular polar relay orbit to provide the best performance with acceptable risk for approximately $60M.

ALECAN Studies (next three references):

[111] Status of Lunar C&N Studies_SCAWG_6.9.05.ppt, SCAWG Presentation, 9 June 2005, Jim Schier, Rich Orr, Lenny Schuchman, Bob Nelson, Erica Lieb.

The Affordable Lunar Evolvable Communication And Navigation (ALECAN) study was divided into two phases. The Phase 1 study responded to the concern that prior approaches were too costly, thus a lower cost option needs to be developed. The study objective was to evaluate the feasibility of a low cost comm package that only covers critical far-side maneuvers. The goals were to limit the solution to one relay only with a design life on par with the human mission duration. The study used ESMD's Exploration System of Systems (ESS) Point of Departure (POD) architecture. It concluded that the relay should be placed in the highest inclination and highest altitude orbit consistent with any restrictions on fuel mass required for orbit insertion. The optimum orbit is approximately a 9000 km SMA polar orbit. A single relay meeting the conops and requirements for far side critical maneuver coverage is feasible based on a design that is low-moderate risk based on an off-the-shelf bus.

The Phase 2 study was to develop a concept for providing lunar C&N infrastructure that optimizes there criteria: (1) Low Cost –low initial cost, a low operating cost, & a low cost to evolve as exploration needs change; (2) Evolvable –Start with minimal initial capability & add minimal additional capability as required to meet Exploration Spirals and driving Science missions; and (3) Flexible –Provide significant flexibility in planning lunar campaigns. It investigated a spiral approach to development of Communication and Navigation Sats (CANsat) using the ESS POD architecture and developed multiple scenarios for deployment of constellations based on different exploration strategies. It concluded that the approach appears to be feasible & can achieve goals of: (1) Reducing and/or deferring cost beyond Phase 1 approach; (2) Integrating communication & navigation architectures; and (3) Providing high degree of evolvability & flexibility. Many options and paths are feasible. The approach appears to offer major improvements in flexibility.

[112] ALECAN Study Status_SCAWG_7.14.05.ppt, SCAWG Presentation, 14 July 2005, Jim Schier, Rich Orr, Lenny Schuchman, Erica Lieb.

This presentation continued to develop the ALECAN study. Three "reasonable" campaign scenarios are developed based on ESMD Spiral definitions varied over the threshold-to-objective range in Spiral 2 to 3 performance. The campaigns are based on picking decision paths based on lunar "discoveries" &/or changes in strategies. The 3 strategies are: (1) Discover H2O at the S. Pole; Build permanent SP Base; (2) Find several useful sites; Build 3 Outposts; and (3)

Conduct human and robotic missions for tech R&D; On to Mars. Results show the initial build-up of assets followed by sustaining operations or tapering off as emphasis shifts to Mars. The study addresses the trade between deploying CANsats on dedicated ELVs, shared launch as a secondary payload, or on an Earth Departure Stage. Design feasibility is studied using General Dynamics SA-200 buses with a trade study on single vs. dual string designs. A cost model and estimated costs based on the design concept are presented.

[113] Lunar Relay Network Report 9-29-05.ppt, SCAWG Presentation, 29 September 2005, Jim Schier, Erica Lieb, Lenny Schuchman.
This report shows the first results of shifting to the Constellation requirements from the prior ESS requirements. FOMs and design results are updated from the July report. Requirements differences in coverage for 85-90°S latitude are addressed. The marginal utility of crosslinks is assessed. The cost model and cost estimate are revised for a 6 satellite constellation trading 3 year and 10 year design life (single vs. dual string). Results show that the ALECAN approach emphasizing Evolvability & Scalability is now obsolete. A revised approach with no product line but greater flexibility is proposed.

[114] "Application Data Rates - Example Scenarios: CEV in Earth Orbit & CEV in L1", Hugh LaMaster & Ken Freeman, presentation to SCAWG, August 2004.
This study defined scenarios for the CEV in LEO and lunar environment that were used to identify types of data and data rates for uplink, downlink, and crosslink. Simulation of various design options especially concerning TV were conducted to show the impact on aggregate data rates.

[115] "High-Level Lunar Trade Space Definition and Analysis: Final Presentation", RFT - 0002.04 LARC, presentation to SCAWG, 23 July 2004.
A multi-center team was established to assess potential mission concept trade options around two broad Lunar Mission Scenarios: (1) global access with 7-day surface stays; and (2) South Pole access with 30-90 day surface stays. A trade tree was defined and a down-selection of major trade tree branches was performed. The study concluded that staging from Lunar Orbit is preferable to staging from Earth-Moon L1 for both scenarios. Detailed results are provided for both scenarios.

[116] "A Survey Of Earth-Moon Libration Orbits: Stationkeeping Strategies And Intra-Orbit Transfers", David Folta and Frank Vaughn, AIAA paper, August 2004.
Cislunar space is a readily accessible region that may well develop into a prime staging area in the effort to colonize space near Earth or to colonize the Moon. While there have been statements made by various NASA programs regarding placement of resources in orbit about the Earth-Moon Lagrangian locations, there is no survey of the total cost associated with attaining and maintaining these unique orbits in an operational fashion. Transfer trajectories between these orbits required for assembly, servicing, and positioning of these resources have not been extensively investigated. These orbits are dynamically similar to those used for the Sun-Earth missions, but differences in governing gravitational ratios and perturbation sources result in unique characteristics. We implement numerical

computations using high fidelity models and linear and non-linear targeting techniques to compute the various maneuver ∆V and temporal costs associated with orbits about each of the Earth-Moon Lagrangian locations (L1, L2, L3, L4, and L5). From a dynamical system standpoint, we speak to the nature of these orbits and their stability. We address the cost of transfers between each pair of Lagrangian locations.

[117] "Libration Point Navigation Concepts Supporting the Vision for Space Exploration", J. Russell Carpenter, David C. Folta, Michael C. Moreau, and David A. Quinn, AIAA paper, August 2004.
This work examines the autonomous navigation accuracy achievable for a lunar exploration trajectory from a translunar libration point lunar navigation relay satellite, augmented by signals from the GPS. We also provide a brief analysis comparing the libration point relay to lunar orbit relay architectures, and discuss some issues of GPS usage for cis-lunar trajectories.

[118] "Stable Constellations of Frozen Elliptical Inclined Lunar Orbits," T.A. Ely, Jet Propulsion Laboratory Engineering Memorandum, 12 March 2004.
This memo presents a class of stable altitude orbits at the Moon. The orbits are elliptical with their line of apsides librating in the polar region (a.k.a. 'frozen' orbits), and exhibit lifetimes in excess of 10 years. This paper will describe the processes for selecting the orbital parameters for the constellation, and the mechanisms behind its subsequent stable, long-term evolution. It will also be shown that, with appropriate selection of initial semi-major axis values, satellites in the same orbital plane can maintain a relatively stable mean separation between them with little or no orbit maintenance costs.

[119] "Viking '75 Spacecraft Design and Test Summary Volume I: Lander Design", Neil A. Holmberg, Robert P. Faust, and H. Milton Holt, NASA Reference Publication 1027, Langley Research Center, November 1980.
This publication, Volume 1 of 3 volumes, discusses the design of the Viking Lander and the engineering test program to verify it. It includes a summary of the Viking mission and detailed design data by subsystem.

[120] "Malapert Station Lander", J. Soloff, J. Schier, SCAWG Presentation, 13 October 2004.
This presentation contains additional details on the concept of the Malapert Station Lander design including mass and power estimates, rationale for design concepts from Viking and Surveyor missions, advanced technology concepts and rationale, and risks.

[121] 15. "ESMD Exploration Communications and Navigation Systems (ECANS) Architecture; Interim Status Briefing" Jason Soloff, 26 January 2006.
This presentation provides a status of ECANS architecture development effort. It addresses organizational representation, operational scenarios, internal and external interfaces. It decomposes ECANS into an overall C3I architecture, constituent communications and navigation portions, and provides an overview of the Lunar Communications and Navigation System (LCNS).

[122] 16. Vol I 060307 LCNS Arch Overview SCAWG.ppt, 7 March 2006.
This Volume I presentation contains the plans, architecting process and background material for the Lunar Communications and Navigation System. Detailed architecture views are in Volume II.

[123] 17. Vol II 060307 LCNS Arch Status SCAWG.ppt, 7 March 2006.
A continuation of Volume I, this presentation covers the operational, systems, and technical views in greater detail.

B.9. Mars Relay References

[124] Mars Mission Set, 14 December 2005.
The Mars mission set presented here is an extract from the overall SCAWG Mission Model (Ref. [1]), including all missions that orbit or land on Mars. It is included for convenience in order to provide a focused view of the Mars subset of the overall SCAWG Mission Model.

[125] Telecom Analysis, Charles H. Lee, Mars Relay Team, March 2006.
In this document you will find the detailed analysis of how the visibility /coverage and the telecom capability for the Mars Network are computed. For each surface user on Mars, the access link to the orbiters and trunk-line link direct to Earth are considered. Assumptions such as orbital elements, telecom configurations including the resulting metrics and their definitions, for both the robotic and human exploration eras, are also provided. The procedure for calculation the scores for assessing the Mars Network elements are described.

[126] Mars Telecom Strategy, 6 December 2005.
This presentation represents the results of a study chartered by the Mars Program Director, SMD. The study objectives included understanding the telecommunications needs of Mars robotic exploration through the 2020 time frame, evaluating options for meeting those needs, assessing the overall robustness of the planned relay communications strategy, and providing specific recommendations regarding the Mars telecommunications infrastructure. The study involved participants from NASA HQ, JPL, and SAIC.

[127] Figure of Merit Analysis, Mars Relay Team, March 2006.
This briefing provides a full explanation of the approach used to evaluate the various Mars Relay Element architecture options which were considered. Specific FOMs are identified and evaluated for each architectural option, with supporting rationale for any qualitative or subjective FOM assessments. The algorithms used to combine these FOMs are defined, leading to an integrated FOM for each architecture option. Cost estimates were performed for a representative subset of the architecture options to also provide some insight into relative cost-benefit ratios for the various architecture options.

[128] Mars Relay Operations Concept, Kar-Ming Cheung and Charles Lee, Mars Relay Team, 25 January 2006.
This presentation details the current MRE operation experience to support the near-term robotic missions, and describes the operation scenarios and

challenges of the long-term human outpost missions. It is envisioned that the MRE operation must be automated to the extend that it can support rapid turn-around re-allocation of communication and navigation resources to support unforeseen variations in spacecraft and external conditions in the human outpost era.

[129] Mars Relay Element Requirements Document, Chad Edwards and Jim Schier, Mars Relay Team, 15 December 2006.
This document contains Mars Relay Element requirements, including requirements related to geometric coverage, telecommunications services, navigation services, and timing services. Functional capabilities and performance requirements are tagged with need dates based on the specific mission requirements of the integrated SCAWG mission set.

[130] Optical Communications for Mars Relay Element Applications, A. Biswas, Mars Relay Team, 24 February 2006.
This presentation examines the application of optical communications technology to Mars trunk line and access link scenarios. Reference link designs are presented for data rate capabilities of 1, 10, 100, and 1000 Mbps, and resource requirements (mass, power) are derived for each of these performance points. While the baseline Mars Relay Element strategy utilizes RF technologies, the long-term Mars telecommunications roadmap will consider infusion opportunities for optical communications where appropriate.

[131] Rationale for Mars Relay, C. Edwards, Mars Relay Team, 15 December 2005.
The fundamental rationale for a Martian relay infrastructure is presented in terms of key metrics related to Mars exploration, such as returned data volume, coverage and communications contact opportunities, mass and energy considerations, and telemetry support for critical events. Recent experience with UHF relay support tot he Spirit and Opportunity rovers is reviewed to illustrate the benefits of relay communications.

[132] The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities, NASA/TP—2001–209371, December 2001, Stephen J. Hoffman, editor.
This document, originally published as Johnson Space Center document EX13-98-065, describes representative activities that will be carried out by humans and robots as they explore the surface of Mars. The Mars Surface Reference Mission is a tool used by the Exploration Team and the exploration community to compare and evaluate approaches to surface activities. Intended to identify and clarify system drivers, or significant sources of cost, performance, risk, and schedule variation, it does not represent a final or recommended approach. This document represents a “snapshot” of work in progress in support of planning through October 1998 for future human exploration of the Martian surface.

[133] Relay Communications Strategies For Mars Exploration Through 2020, IAC-05-A3.3.06, C. D. Edwards, Jr, B. Arnold, R. DePaula, G. Kazz, C. Lee, G.

Noreen, 54th International Astronautical Congress, Vancouver, Canada, 4-8 October 2004.
Mars exploration poses significant telecommunications challenges, including the return of large data volumes from high-resolution surface instruments, highly constrained mass, power, and energy for surface spacecraft, frequent telemetry and command sessions for supporting complex surface operations, and high-risk mission events such as entry, descent, and landing for which the capture of engineering telemetry is deemed critical. Relay telecommunication via Mars-orbiting spacecraft offers significant advantages in meeting these challenges, relative to conventional direct-to-Earth communications. NASA's Mars Global Surveyor and Mars Odyssey orbiters, along with ESA's Mars Express orbiter, represent an initial relay telecommunications infrastructure that has successfully supported the Spirit and Opportunity rovers. With the arrival of the Mars Reconnaissance Orbiter in 2006, this expanded relay network will provide key support to the 2007 Phoenix Lander and 2009 Mars Science Laboratory missions later this decade. Second decade mission concepts will introduce new communications challenges; the provision of relay science orbiters provides a cost-effective means to sustain and evolve the Mars relay network.

[134] A Martian Telecommunications Network: UHF Relay Support of the Mars Exploration Rovers by the Mars Global Surveyor, Mars Odyssey, and Mars Express Orbiters, IAC-04-M.5.07, C. D. Edwards, Jr., A. Barbieri, E. Brower, P. Estabrook, R. Gibbs, R. Horttor, J. Ludwinski, R. Mase, C. McCarthy, R. Schmidt, P. Theisinger, T. Thorpe, B. Waggoner, 55th International Astronautical Congress, Fukuoka, Japan, 17-21 Oct 2005.
NASA and ESA have established an international network of Mars orbiters, outfitted with relay communications payloads, to support robotic exploration of the red planet. Starting in January, 2004, this network has provided the Mars Exploration Rovers with telecommunications relay services, significantly increasing rover engineering and science data return while enhancing mission robustness and operability. Augmenting the data return capabilities of their X-band direct-to-Earth links, the rovers are equipped with UHF transceivers allowing data to be relayed at high rate to the MGS, Mars Odyssey, and Mars Express orbiters. As of 21 July, 2004, over 50 Gbits of MER data have been obtained, with nearly 95% of that data returned via the MGS and Odyssey UHF relay paths, allowing a large increase in science return from the Martian surface relative to the X-band DTE. The MGS spacecraft also supported high-rate UHF communications of MER engineering telemetry during the critical period of EDL, augmenting the very low-rate EDL data collected on the X-band direct-to-Earth link. Through adoption of the new CCSDS Proximity-1 Link Protocol, NASA and ESA have achieved interoperability among Mars assets, as validated by a successful relay demonstration between Spirit and Mars Express, enabling future interagency cross-support and establishing a truly international relay network at Mars.

B.10. Technology References

B.10.1. General Overview

[135] “NASA Communication and Navigation Technology Capability Portfolio”, J. Rush and W.D. Williams, 19 August 2005.
This file provides an overview of the technologies (as of 8/05) important for the agency’s future space communication and navigation system. Material included in this portfolio is based on the work done by the SCAWG Technology Assessment Team. Technology for the Science Mission Directorate is emphasized but relevant to other space mission directorate’s needs.

B.10.2. Navigation

[136] XNAV_NASA_24_October_05 – NASA Use Only.ppt, Darryll J. Pines/DARPA, 24 October 2005.
An introduction to the concept of X-ray navigation, pulsars as celestial beacons, sensitivity etc for autonomous navigation. XNAV is planned to fly on ISS in FY08/09.

[137] SCAWG Oct 21 2005 XNAV Presentaiton HANDOUT – NASA Use Only.pdf, Suneel Sheikh/Univ. of Maryland, 21 October 2005.
A technical introduction to the use of variable celestial X-ray sources for spacecraft navigation. Includes discussion of celestial X-ray sources, pulse identification and modeling, time transformation, navigation methods, absolute and relative position, and delta-correction to position.

B.10.3. Networking – Disruption Tolerant Networks (DTN)

[138] Cerf-In-Space Routing-29Sep05.pdf, Vinton Cerf/Google, 29 September 2005.
This paper provides an elegant discussion of in-space routing and DTN.

[139] DraperLabs-050819.ppt, Draper/MIT Team, 19 August 2005.
This paper provides an excellent discussion of Information Architecture, a least expensive design that satisfies requirements, validate of Mars plans, operations and equipment on the Moon. The Information Architecture discussion includes information flows, requirements imposed for information provisioning an proposes the use of DTN communication protocols.

[140] DTN overview.ppt, Scott Burleigh, 8 February 2006.
This briefing provides a basic description of Disruption Tolerant Networks, what they are and a possible solution for disruption.

[141] SCAWG-HQ-hooke-14Jul05.pdf, Adrian Hooke, 14 July 2005.
Limited discussion of DARPA’s Delay Tolerant Networks and possible relationship with ASA’s Disruption Tolerant Networks.

B.10.4. Optical - RF Crossover

[142] Optical and RF Comm Comparison 20060303, Optical - RF Crossover Team, 3 March 2006.
This draft report compares optical and RF technologies. Assumptions are based on similar costs of Ground Stations, allowing for advances in technologies through 2015 for a deployable system by 2020. Analysis of technologies based on complexities and likelihood of success is described. The backup charts include discussion of: 1) RF Fine Beam Pointing Systems; 2) Optical Receive System; and 3) Additional mass for higher power for various years of availability.

B.10.5. Optical Communications

[143] Tutorial-1.pdf, Don Boroson/MIT/LL, February 2006.
This presentation provide a tutorial introduction to free-space lasercom, brief history, optical basics, basic optical communication theory, technology overviews, MLCD, and possible uses of lasercom for NASA missions.

[144] Optical Study 02-17-05, Optical Team Report, February 2005.
This repot looks at cost, mass, power, and data rate over varying and fixed parameters for lasercom. Some varying parameters include ground and space-based platforms, data rates, launch dates, and spacecraft available power. It gives detailed calculations and results. This is a companion study to Reference [147].

[145] Development Table.ppt, Don Boroson/MIT/LL.
This chart shows proposed demonstrations for optical communications. It shows various types of demonstrations and distances from which those demonstrations can be achieved.

B.10.6. RF Studies

[146] High Capacity Comm from Mars Distances 03032006.pdf, RF Team Report, 3 March 2006.
This is a thorough discussion on ways to enable high data rates (1 Gbps) from Mars to earth using RF communications with maturing technology; suggest conceptual designs of spacecraft subsystems; and suggest strategic, high-payoff investment in technologies.

[147] RF Study 20050217.ppt, RF Team Report, February 2005.
Early report on an RF and optical study. Includes approach, study parameters, process, downlink analysis, uplink analysis, and discussion of solar conjunction outages for both optical and RF. This is a companion study to Reference [144].

B.10.7. Software-Defined Radio

[148] SDR Report – Ver 12 – 12.12.05.doc, SDR Architecture Team (SAT) Report, 12 December 2005.

This document summarizes work of the SAT for the first of three phases in the development of an open SDR architecture and standard. Final recommendations are expected to be completed by May 2006.

[149] SAT to red Team dec briefing-rev4(PI) & P(PII)RevB.ppt – 2 parts.SAT Team Report (multi center) - Part 1 and Part 2, December 2005.
This document discusses the open architecture format for SDR. It delves into mission applications, different agency perspectives, roles, and responsibilities, current SDR architectures, and long term evolution and usage.

B.10.8. Uplink Arraying

[150] Sig Event-2.doc, Jim Lesh/JPL, February 2006.
This document gives a one page description of the February 2006 uplink arraying demonstration.

[151] uplink_arraying_description.doc, Victor Vilnrotter/JPL, January 2005.
An excellent description by of the phasing, electronic delay, atmospheric effects, space delay, scattering from lunar or other reflecting surfaces and other phenomenon effecting operation of a ground based array.

[152] Uplink-SCAWG.ppt, Joe Statman/JPL, 21 October 2005.
This is an overview presentation including why we should use uplink arraying, some technical challenges, and plans.

[153] Uplink-SCAWG-v2.ppt, Joe Statman/JPL, 21 October 2005.
Two actions were given by the SCAWG and answered by this presentation. They were: 1. What are the cost components of an antenna? Can you show comparable data for 12m and 34m antennas? 2. You've shown the error budget for X-band uplink arraying. What is the error budget for other bands?

Appendix C. SCAWG Membership

The SCAWG has many participants from across all of the centers as well as NASA Headquarters. The following list includes SCAWG participants in alphabetical order followed by lists of the participants on each of the individual SCAWG study teams. Note that the individuals with an asterisk (*) next to their names represent the study/team lead.

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Appendix D. SCAWG Charter

1. PURPOSE

The purpose of the Space Communications Architecture Working Group (SCAWG) is to develop a future space communication architecture, and identify associated technology investments necessary, to support all future NASA Exploration, Science, and human-tended missions.

2. AUTHORITY

The SCAWG reports to the Space Communications Systems Engineering Working Group (SEWG), which operates under the guidance of the Space Communications Coordination and Integration Board (SCCIB) and in accordance with the Space Communications Memorandum of Agreement (MOA).

3. SCOPE

The WG recommends to the Space Communications SEWG coordinated space communications architecture solutions and corresponding strategic investments. The WG will:

- Investigate and report to the SEWG on results of communication architecture and technology studies conducted by the SCAWG;
- Develop and maintain a plan and road map for getting to future architecture for SCCIB concurrence;
- Collect current and future mission needs as well as program visions and roadmaps from the Mission Directorates for use in architecture formulation;
- Formulate future communications and navigation architecture describing interface areas of commonality between Mission Directorate networks;
- Develop Transition Plans to go from present to future architecture;
- Identify key technology initiatives necessary to realize future architecture;
- Identify architecture boundaries both in ground systems and onboard spacecraft;
- Identify areas where compatibility among Mission Directorate technology and upgrades initiatives are required to promote common interfaces;
- Document future architectures at “overarching” level, building on individual network architecture documentation;
- Develop cost estimates for architecture alternatives and changes;
- Coordinate with the Frequency Management Liaison Group;
- Verify that future architectures implement appropriate spectrum usage consistent with international, National and NASA Spectrum Policy;
- Coordinate with the Data Standards Working Group;
- Identify interface standards and standards initiatives that need to support future architecture recommendations;
- Determine the degree of interoperability/integration feasible with other Agencies and service providers;
- Assess user burden resulting from architecture for suitability with regard to each class of user;

- Identify shortcomings of existing and proposed architectures, which will include consideration of lessons learned from current and past systems and consideration of technical and programmatic barriers to implementation of future space communications architectures.

Space Communication architecture actions agreed upon by the SCAWG will be taken to the SCCIB for approval upon concurrence of the SEWG.

4. MEMBERSHIP

The membership of the SCAWG will include representatives from both the communications networks and the user community:

- A representative from each of the Mission Directorates;
- A representative from the Strategic Investment Division of the CFO;
- Two Representatives for each of the space communication networks;
- Center Representatives for major space communication user systems.

In addition, subject matter experts will be invited to participate in specific study areas on an as-needed basis.

5. PROCESS OVERVIEW

The SCAWG will be chaired by the Office of Space Operations (Space Communications). Since the communications architecture is a supporting architecture for NASA's future space exploration efforts, the communications needs in terms of locations, data rates, numbers of locations, and the time frames in which the various exploration and science initiatives are planned will be developed in coordination with the Mission Directorates.

Studies and analyses identified by the SCAWG will be performed by focus teams established with the appropriate expertise to address the various questions. Detailed studies will be presented to the SCAWG for consideration in evaluating the various architecture trades.

A technology assessment team will provide technology assessments and gap analyses that will be factored into the Working Group's communications architectures. Communication architecture concepts developed by the SCAWG will include the flow of new technology into the architecture as it evolves.

An important part of the Working Group's efforts will be to assure that cost trades are conducted to help evaluate architecture options. This task will be take advantage of the cost estimation techniques provided by the Office of the Chief Financial Officer (CFO). Expertise and cost estimation tools from the Cost Analysis Division of the CFO will form the core of this effort.

Appendix E. Mission Model Description

E.1. Purpose

The purposes of the SCAWG Mission Model are to: (1) assemble and track information about the space communications needs of the currently flying, planned, and predicted flight missions on a rolling 25 year planning window; (2) provide a controlled baseline of such information to all SCAWG studies for related analyses; and (3) identify and analyze trends in communication needs that will drive the space communications architecture.

E.2. Overview

The SCAWG Mission Model began in May 2005 when JPL and GSFC were asked by the SCCIB to produce an Integrated Mission Set (IMS) for the 2005-2020 time frame to support ongoing SCAWG studies. After an initial May delivery, this Integrated Mission Set was further refined and updated through SCAWG-sponsored weekly telecons with GSFC and JPL. In October, the SCCIB expanded the scope of this modeling effort, tasking the SCAWG to develop a model (database) of all approved, planned, and predicted NASA missions and their communications needs through 2030. At the recommendation of the SCAWG, NASA's Program Analysis & Evaluation (PA&E) Office established a simplified version of the mission model called the Agency Mission Planning Model (AMPM). The AMPM was coordinated with inputs of the baseline missions of the Exploration Systems, Science, and Space Operations Mission Directorates producing a NASA baseline on December 9th. The SCAWG Mission Model was synchronized with the baseline AMPM. On December 14, 2005, the SCAWG Mission Model was baselined for use in the final SCAWG studies for the analysis cycle that ended in February 2006.

E.3. Approach

E.3.1. Overview

Development of the SCAWG Mission Model has involved three key steps:

- Identifying the mission set,
- Collecting key mission and spacecraft communications parameters, and
- Analyzing these parameters as a function of time.

Identification of the mission set began with efforts to develop a "strawman" mission set through examination of the latest Exploration and Science mission launch manifests, NASA strategic roadmaps, associated National Research Council reviews of these roadmaps, and communications with NASA's advanced planners and program/project managers. These initial efforts were then refined through ongoing weekly telecons and the use of PA&E-supplied inputs from the NASA Headquarters mission directorates.

Collection of key mission and spacecraft communications parameters relied on data collected for JPL and GSFC loading and planning analyses. These data were gleaned from a combination of mission requirements documents, mission concept studies, discussions with program/project personnel, and extrapolation of past and current spacecraft and technology trends. The specific data source for any given mission or spacecraft depended upon its concept maturity.

Analysis of these parameters as a function of time involved both qualitative and quantitative assessments of the data. The qualitative assessments characterized fundamental changes occurring in the space exploration and science picture over the next 25 years. The quantitative assessments analyzed trends in the key parameters by plotting their values at 5-year intervals from 2005 to 2030. Correlations were drawn between the identified qualitative fundamental changes and the observed quantitative trends.

E.3.2. Initial Mission Model

The initial IMS was started by integrating the GSFC Space Communications IMS and the JPL Data Systems Mission Set. Since the two databases had very different information models, development of the SCAWG Mission Model required designing an integrated information model. Attributes were identified to be used from each database along with the changes needed to normalize the data in the two sets. Once the revised database structure was implemented, data from the two sets was imported. The core Mission Model was then augmented and extended to 2025 with the GSFC Planning Set, which included study missions, extrapolations from historical data and science/technology trends, and results of the GN Architecture Study. Similarly, the DSN User/Future Mission Planning Set was extended by incorporating the JPL DSMS Architecture & Strategic Planning Office model and information from the Deep Space Roadmap.

E.3.3. PA&E AMPM

This mission model is used by the PA&E Office to conduct studies and support budget analysis and scheduling. It can be used as a reference to conduct sensitivity studies, which assume future missions and capabilities, so that Agency management can be informed concerning the value and robustness of alternate investments and development activities. The AMPM was initiated on the recommendation of the SCAWG and the initial SCAWG Mission Model was used as a starting point by PA&E.

The AMPM validates the set of missions that NASA plans to execute, or is considering for the future. The AMPM reflects the Agency's recent architecture decisions and identifies and characterizes the missions in NASA's budget, short and long term through 2025. It includes missions at different levels of development and approval, including:

- Congressionally-approved missions in the Program Operating Plan for 2006-2010 or under definition;
- Internal pre-decisional missions for long-term planning from 2011-2025.

E.3.4. Predicted Mission Model

From October to December 2005, the SCAWG Mission Model was updated to be consistent with the missions identified in the AMPM, extend the AMPM from 2025 to 2030, and modify dates for common missions. The updated model was reconciled with the results of the Exploration Systems Architecture Study (ESAS) when it was provided. The model was also adjusted to account for recent mission cancellations and deferrals.

The predicted Mission Model includes information that is not in the AMPM including several categories of data that are important for doing communications capacity analysis:

- Information about missions other than new flights. The Mission Model includes information about communications support for:
    - Missions currently in operation,
    - Launch Vehicle support
    - Payload support for Launch and Early Orbit Phase (for missions not routinely supported)
    - International missions where NASA provides instruments, participates in scientific research, or provides support for mission communications,
    - Anomaly and contingency support for NASA and non-NASA missions,
    - University missions, and
    - Missions beyond 2025.
- Information about mission communications including data rates, spectrum bands, frequency and duration of contacts, and ground terminal sites used.

In addition, the SCAWG Mission Model incorporated a new set of predicted missions, primarily in the 2020-2030 time frame. While the mission set in the 2005-2020 period was believed to be mature and accurate, planning beyond 15 years is incomplete. A gap was noticed between the missions identified as being in Directorates plans and the probable quantity of missions based on historical trends. To avoid underestimating the communication capacity likely to be required and consequent under-sizing of the Space Communication Architecture, an analysis of the growth rates in number of missions, communication data rates and data volumes, and number of uplinks and downlinks was performed. An estimate was created of the most likely or “predicted” quantity of missions and their communication attributes. The difference between actual missions in the Mission Model and the predicted quantity was defined as the “predicted mission set”. Representative entries were created in the Mission Model for these missions. The database information model was extended to differentiate between the planned and predicted missions so that database queries and reports can be performed on either subset or the full set. This predictive version of the SCAWG Mission Model was approved by the SCAWG and baselined for use by the SCAWG studies on December 15, 2005.

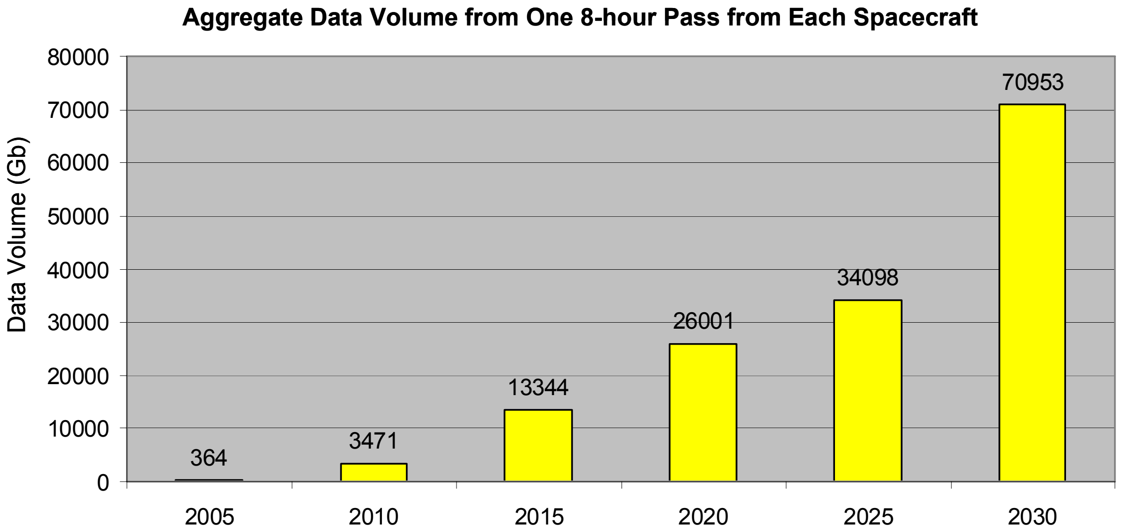
E.4. Results

Trends in both the deep space and near Earth missions were analyzed. In the deep space region, eight trends were identified. The “low hanging fruit” within the solar system, Sun-Earth connection, and astrophysical exploration realms has already been “picked.” Getting to the “higher hanging fruit” requires much more capable remote sensing using *in situ* robotic, human, and observatory-class missions. Achieving this greater exploration capability by 2030 translates into supporting:

- Roughly 3 times as many links with the majority occurring in Category A space.
- Several frequency band ranges that have not received much prior use (e.g., all Ka-bands and Category A use of X-band)
- Downlink rates at least 2 orders of magnitude greater than today's, as well as human-exploration-driven uplink rates some 4 orders of magnitude greater
- Data volumes 2-to-3 orders of magnitude greater than today's
- End-to-end link difficulties (i.e., data rate times the square of the maximum distance) 2-to-3 orders of magnitude more challenging than today's
- Effective Isotropic Radiated Power (EIRP) for emergency uplink 3 to 6 times today's capability (subject to validation)
- Roughly 3 times as many multi-spacecraft missions and coordinated activities between spacecraft, necessitating roughly 4 times as many proximity links
- Navigation, guidance, and control in at least 8 environments not commonly encountered in past exploration.

GSFC also made many predictions based on the SCAWG Mission Model. Current trends in near Earth missions show an increase in data rate requirements, moving into the hundreds of Mbps and even Gbps as well as a shift to Ka-band and potentially optical communications. Mission planning shows an increasing number of constellation missions (i.e., clusters of spacecraft), with as many as 50 spacecraft in a single constellation. A trend of Space Science missions moving out of Earth orbit and into Lagrange, Earth trailing and leading, and lunar orbits is also evident. An increase in autonomy, which assumes more reliable spacecraft requiring occasional software updates, will lead to an increase in uplink requirements.

Figure 58 shows one example of the trend analysis. The remainder can be studied in more depth in the full report on DSMS Mission Set Trends (Section E.5, Reference [1]). The full SCAWG Mission Model was exported from its Microsoft Access database into an Excel file (Section E.5, Reference [2]).



Significantly larger aggregate data volumes

By 2030, a single 8-hour pass for each spacecraft will yield an aggregate data volume almost the same size as the entire 30-year data collection currently in the Planetary Data System!!!

Similarly shaped trends apply to the uplink

Future mission uplink volumes will be driven more by software & data uploads than by simple commanding. Human missions drive the downlink & uplink to become more symmetric.

Figure 58. Mission Model Trend Analysis Example

E.5. References

[1] Mission Model Update, presentation to SCAWG, 12 Dec 2006.
[2] SCAWG Current Baseline Mission Model, 14 Dec 2006.