NASA's Lunar Space Communication and Navigation Architecture

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NASA has completed a preliminary study of the U.S. lunar architecture. The space transportation systems deliver crew (*Ares I* launch vehicle and *Orion* crew vehicle) and cargo (*Ares V* launch vehicle and *Altair* lander) to the Moon. A polar Outpost will be capable of sustaining four crewmembers for long duration habitation. Unpressurized and pressurized rovers will enable the crew to construct the Outpost and explore the Moon. Mining equipment will extract and process resources from lunar regolith. Scientific instruments will be deployed to conduct scientific studies. Sortie missions can be conducted to any location on the Moon for specific scientific research. This paper describes the Communications and Navigation (C&N) system of this lunar architecture. Communications: NASA's Deep Space Network (DSN) will be modified to meet new performance and interoperability requirements. A small constellation of Lunar Relay Satellites (LRS) will be placed into orbits with long term stability that provide periodic coverage of the entire surface of the Moon as well as Low Lunar Orbit (LLO). Two LRSs provide periodic coverage of the entire Moon for sortie support. Medium and high rate links will be provided between the LRS and Lunar Communication Terminals (LCT) at the Outpost. Lunar surface communications will leverage commercial network technologies running Internet Protocol (IP) for seamless interplanetary communications based on an open, standards-based architecture. S- and Ka-bands are employed for both the Earth-Moon long haul links and the lunar orbit-to-surface links. S-, K- and Ka- bands are used for primary surface-to-surface links while S-band is used for contingency voice channels. Standards will be coordinated with other national space agencies through the Consultative Committee for Space Data Systems (CCSDS) international interoperability. A product line approach is used to provide common radios for fixed, mobile, and crew spacesuit systems. Navigation: The DSN tracks space vehicles in transit to and from the Moon and in lunar orbit as well as to surface assets on the near side. The LRS constellation provides satellite-based tracking and timing to lunar orbiting vehicles, the Outpost, and rovers and crew performing sorties anywhere on the surface including the far side. Due to the small quantity of lunar assets, a GPS-like solution for position determination is inappropriate. Instead, a TRANSIT-like approach is adopted which integrates satellite position over time relative to the tracked asset. LRS satellites and surface LCTs contain compact atomic clocks to provide highly accurate time and position. Standard tracking methods are used including 1- and 2-way range and Doppler. Autonomous Landing and Hazard Avoidance Technology (ALHAT) enables unaided landings to be performed with 100m accuracy, for example, into a permanently shadowed crater. LCTs and smaller surface beacons to enhance accuracy to <10m at improved sites like the Outpost.

I. Introduction

The *Vision for Space Exploration*, proposed by President Bush in 2004 and authorized by Congress in 2005, directs the National Aeronautics and Space Administration (NASA) to accomplish the following goals:

- Return to the Moon no later than 2020
- Extend human presence across the solar system and beyond
- Implement a sustained and affordable human and robotic program

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- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration

The Exploration Systems Architecture Study[1] selected the space transportation approach. This consists of two launch vehicles and two in-space systems. *Ares I* is the partially reusable launch vehicle that places the crew into Low Earth Orbit (LEO) in the *Orion* Crew Exploration Vehicle (CEV). *Ares V* is the partially reusable launch vehicle that places the Earth Departure Stage (EDS) and *Altair* Lunar Lander into LEO for rendezvous with *Orion*. The EDS propels the mated *Orion/Altair* stack to the Moon where they enter a Low Lunar Orbit (LLO) of 100 km. *Altair* separates from *Orion* and descends to the lunar surface. If *Altair* carries crew, upon completion of surface operations, the *Altair* Ascent Stage launches for a rendezvous with *Orion* in LLO. *Altair* is jettisoned and *Orion* returns the crew to Earth. These systems are now being developed by the Constellation Program.

A second major study, termed the Lunar Architecture Team (LAT), was conducted in 2006-2007 to recommend the reference architecture for initial lunar surface systems. Conducted in two phases, LAT Phase 1 resulted in a point-of-departure architecture directly traceable to the specific themes and objectives identified in a series of workshops held with international space agencies, interested commercial parties, and space advocacy groups. The team analyzed two approaches to human lunar exploration: short *sortie missions* prior to any permanent outpost and a second approach dubbed "*outpost first*." LAT Phase 1 concluded that the "outpost first" approach, coupled with the flexibility to conduct lunar sorties, best addresses the entire portfolio of strategic themes and objectives.

LAT Phase 2 refined LAT Phase 1 concepts, considered alternative approaches, and examined the options in greater design detail. Table 1 summarizes the six architecture approaches studied while Figure 1 illustrates sample configurations of the basic surface elements. Option 1 retained the LAT Phase 1 point-of-departure architecture. Options 2-4 looked at the range of habitation choices. Option 2 explored smaller habitable elements while Option 3 explored a single, large habitable element and Option 4 gave the habitat wheels making it a large pressurized rover. Option 5 studied the strategy of flying the pressurized rovers earlier in the outpost assembly sequence than the Phase 1 approach. Early in the Phase 2 analysis, the advantages of having early pressurized rovers became so apparent that a decision was made to incorporate this feature into all of the other options, thus eliminating the need for a distinct Option 5. While Options 1-5 employed conventional photovoltaic solar power sources, Option 6 studied the use of a fission reactor to supply larger amounts of power independent of the lunar day/night cycle. To allow effective comparison with the solar powered options, Option 6 utilized the architectures of Options 2 and 3 substituting only fission power for solar power.

Table 1. LAT Phase 2 Architecture Options Studied

Option	Description/Distinguishing Characteristics
Option 1— LAT Phase 1	A stationary polar outpost with a crew-assembled four-module habitat and solar power generation. After an initial uncrewed mission, all other missions include four crew.
Option 2— Mini-Habitats	A modular habitat consisting of 5 mini-habitats. Given enough transportation performance, any element can be brought with the crew, but a significant portion of the surface elements are also delivered on uncrewed landers.
Option 3— Monolithic Habitat	An outfitted, complete habitat element is delivered in a single uncrewed cargo flight, early in the campaign, simplifying surface operations.
Option 4— Mobile Habitat	A fully functioning crew lander/habitat is able to traverse the lunar surface. Employs a modular, integrated design for simplicity of operations, flexibility and wide-ranging capabilities.
Option 5—Early Pressurized Rovers	Provide long-range surface exploration as early as logically possible in the campaign. Option 5 was cancelled as this capability was incorporated into all other Options.
Option 6— Nuclear Power	Includes variants of Options 2 and 3 that replace solar power units with a fission reactor for continuous day/night, long term, primary outpost power generation. Two sub-options included a fully shielded reactor left on the surface and a buried reactor using regolith shielding.

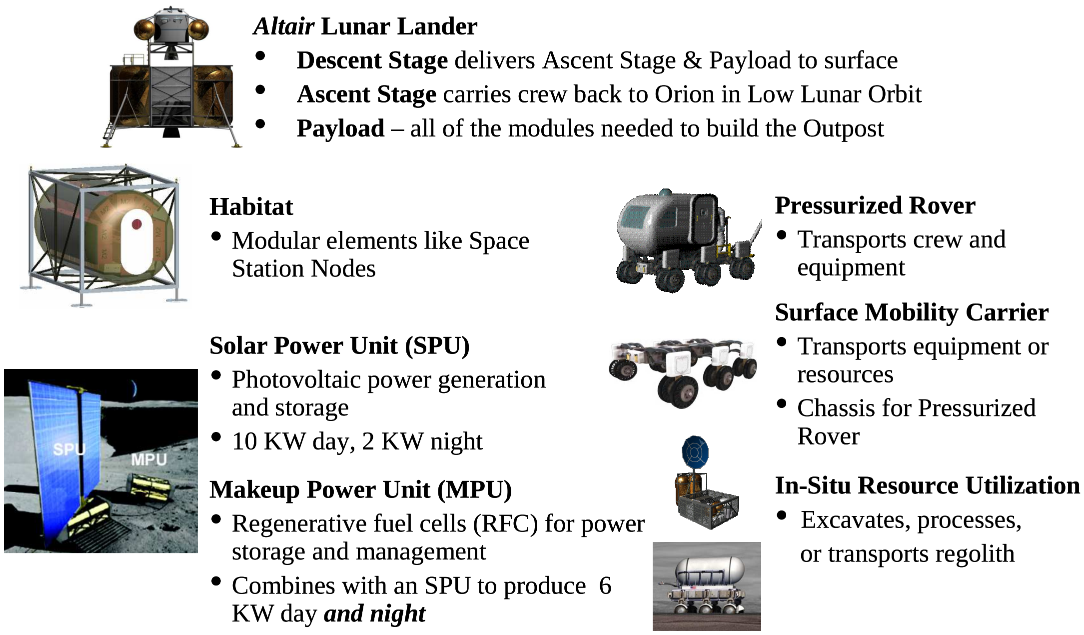

Figure 1. Typical Modular Components of Lunar Surface Architecture (Option 1)

As an example, Figure 2 provides a synopsis of the assembly sequence for missions 1-9 of Option 2 with five mini-Habitats.

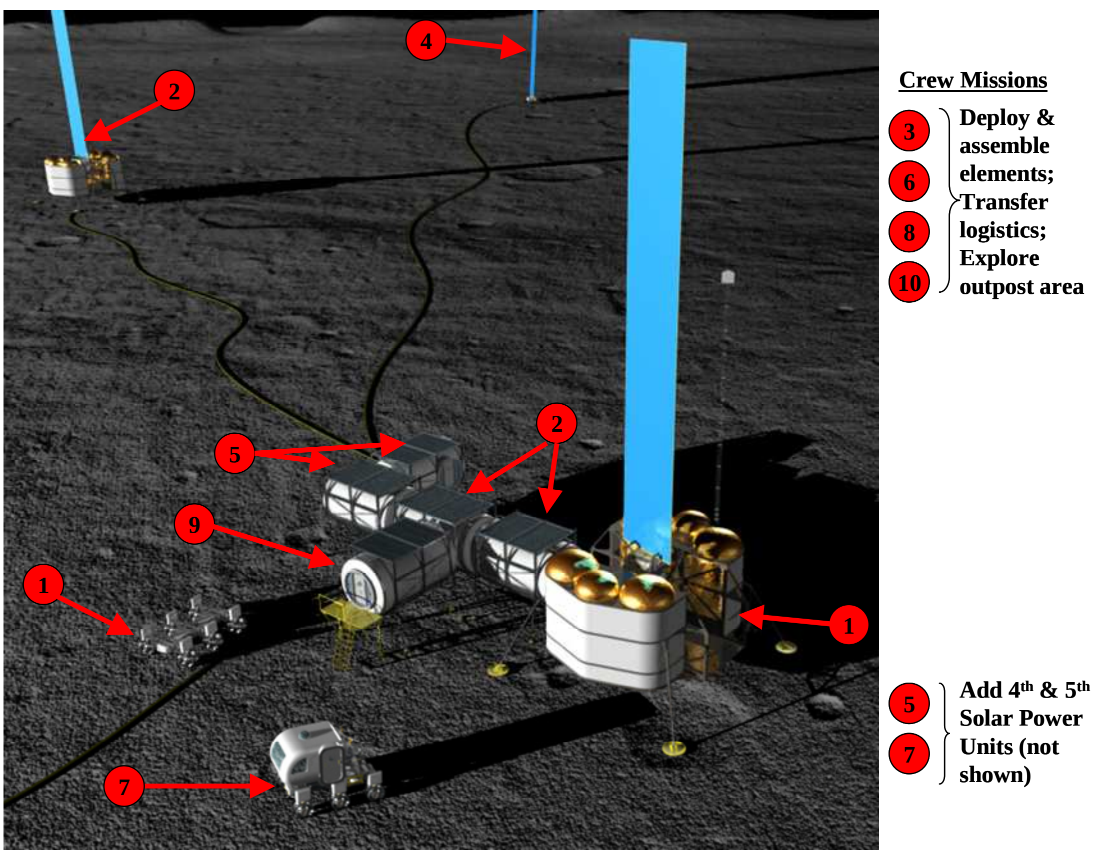

Figure 2. Assembly Sequence for Option 2 Combining Crew and Cargo Missions

The C&N architecture serves the needs of the completed initial Outpost as well as an arbitrary number of sortie locations anywhere on the Moon with communications, tracking, and time services on a largely unscheduled (i.e., on-demand) basis. Based on a number of criteria, preliminary site selection places the Outpost at a north or south polar location. The LAT study selected the rim of Shackleton Crater at the South Pole for the reference architecture. Habitable elements connect to form one internal Local Area Network (LAN). A pair of Pressurized Rovers (PR) will enable four crew to conduct two or four person Extra-Vehicular Activities (EVA) requiring communications and surface navigation. Excursions up to hundreds of kilometers are envisioned placing far greater need on precise surface navigation than was required on Apollo. Several robotic Surface Mobility Carriers (SMC) may also be used in cooperative operations with the crew. In-Situ Resource Utilization (ISRU) will require a combination of regolith excavation using SMCs equipped with digging attachments, regolith transportation using SMCs equipped with holding bins, regolith processing using small processing plants, and product (e.g., oxygen) transportation using SMCs carrying tanks in order to replenish storage tanks. These robotic ISRU elements require continuous command and control as well as surface tracking either from Mission Control on Earth or from the crew on the surface. Crewed operations build up from initial 7 day stays during early construction to 180 day stays with full logistics, communications, and navigation support.

At the Outpost and at sortie sites around the Moon, science packages similar to the Apollo Lunar Science Experiment Packages (ALSEP) will be deployed. Science packages may include any combination of instruments including passive, solar powered during lunar daytime only, solar powered during lunar daytime with keep-alive battery power during nighttime, or Radioisotope Thermoelectric Generator (RTG) powered continuously for years. At the planned rate of two missions per year during the 2020s, this may result in building up a set of 5-20 science packages spread around the entire lunar surface to establish a geophysical science network for seismic, thermal, surface environment, and other measurements.

Apollo missions required complete planning of every mission detail prior to launch plus continuous monitoring by hundreds of experts throughout each flight. Continuous communications were maintained with the flight systems and crew except on the far side in lunar orbit through the use of 12-15 Communications and Tracking (C&T) stations geographically dispersed to maintain 3-4 stations with continuous coverage. The next lunar generation needs to allow the crew much more opportunity to do their own planning and to perform exploration and scientific operations with limited oversight from Mission Control on Earth. Continuous Earth-based coverage for real-time control is not required as we use the Moon to prepare for eventual human missions to Mars where real-time Earth-based control will not be possible.

The LAT study concluded that none of the individual options studied offered decisive advantages over the others although solar power was preferred over nuclear due to cost and risk. Consequently, the overall result was to identify the best features that emerged across all options and generate a new option that integrates these features into an architecture that will be further studied in the next analysis cycle. Figure 3 shows this arrangement with one habitat element being positioned for connection to two others by a SMC. Three medium sized habitat elements carry their own solar power arrays, top-mounted thermal radiators, and communications. The modules can be connected in flexible arrangements and one or more modules can be relocated to new outpost sites by the SMC. Consumable tanks are mounted low on the sides to allow replenishment by ISRU-produced material or supplies delivered from Earth. Small PRs provide the crew transportation in a shirt-sleeve environment with the ability to easily don EVA suits through a suit port rather than an airlock preventing the lunar dust from being tracked inside.

This paper documents the results of the C&N element of the LAT Phase 2 study. Section II gives an overview of the C&N Architecture. Section III discusses concepts of operation. Section IV addresses the spectrum. The initial traffic model built to size the system capacity is discussed in Section V. Additional details on the LRS and LCT elements of the Lunar Network (LN) design are covered in Section VI. Several of the technology advances required to make the C&N architecture work are identified in Section VII. Preliminary studies always uncover additional work to be done which is discussed in Section VII.

II. Communications and Navigation Architecture of the Lunar Network

The lunar environment described above does not address the desired international and commercial participation which will extend greatly the lunar capabilities and need for communications in ways that have not been studied. Thus, the communications environment will be dynamic on both a short term basis as EVA crew operations briefly increase the number of nodes and traffic volume and on a long term basis as the Outpost is built and science packages are deployed. The LN architecture developed to address the environment described above is based on several fundamental tenets. The LN architecture must be:

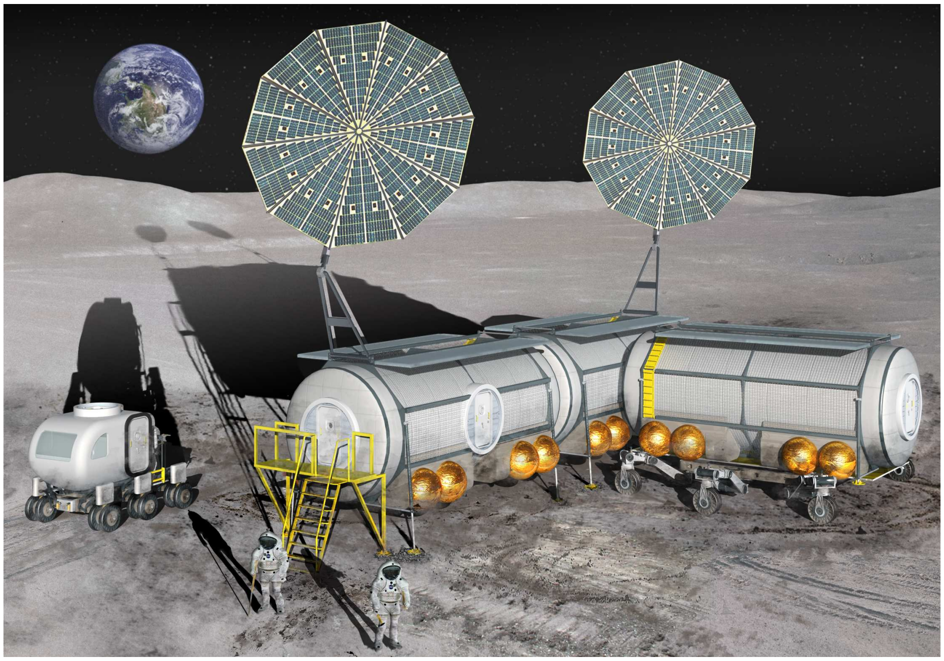

Figure 3. Final LAT Architecture Synthesizing the Best Features of All Options

1. *Functionally independent* from the architecture of other systems to prevent continuous design changes inherent in tightly coupled systems;
2. *Extensible and open* to inserting new services, adding capacity, increasing performance, inserting new technology, and adding new partners;
3. *Interoperable* based on the use of international spectrum and standards for fully collaborating and coordinating operations, introducing new technologies and capabilities, and lowering the entry barrier for new participants;
4. *Compatible with terrestrial communication infrastructure* to reduce risk and cost by providing seamless communications from Earth to the Moon leveraging the enormous investments already made in existing communication infrastructure inside and outside of NASA as well as new investments being made in global telecommunications technologies; and,
5. *Robust* in the face of anticipated and unanticipated failures by providing diverse communication paths and at least two independent navigation data types in each mission phase.

Initially, the LAT established one C&N groundrule: "An overhead C&N asset is required for the outpost location to provide roughly 8 hours coverage every 12 hours exclusive of Line Of Sight (LOS) Direct To Earth (DTE) availability from the surface, beginning with the first mission. A backup capability shall also be provided prior to human return." The rationale is that at the polar site, the communication availability for LOS DTE is less than 50%. Therefore, it is necessary that one overhead asset be provided to support human operations with a backup. Since 24 hour coverage is not required, even with a loss of a single asset, the mission can still be accomplished, since a second backup still exists through periodic direct LOS to the Earth. Further, a stable, elliptical "frozen" orbit exists that provides excellent coverage for roughly 8 out of 12 hours, which is adequate to support human operations. The backup capability requirement was relaxed by not insisting that it be in place prior to human return.

The resulting reference C&N architecture consists of four segments as shown in Figure 4:

- <u>Lunar Relay Satellite (LRS)</u>: The relay provides connectivity to lunar far side systems such as the *Altair* lander on sortie missions and remotely deployed science packages. It provides the principal link for the Outpost since its polar location provides DTE capability typically 14 days per lunar month. It provides on-board processing, storage, and data routing using the Internet Protocol (IP). Since the LN cannot afford a Global Positioning System (GPS) sized constellation, LRS uses the approach successfully used by the Navy's *Transit* system[2] to provide precise position determination to surface users when only one LRS is in view. In all of the LAT2 options studied, one LRS is launched prior to the first Altair landing to provide communications including coverage of critical events such as Lunar Orbit Insertion (LOI) burn and navigation including descent and landing assistance at the polar Outpost side. A 12 hour frozen orbit (Figure 5) was selected to provide 8 hours of coverage per orbit with no ΔV requirement for orbit maintenance and the flexibility to cover one or both hemispheres driven by future selection of mission types and sites.

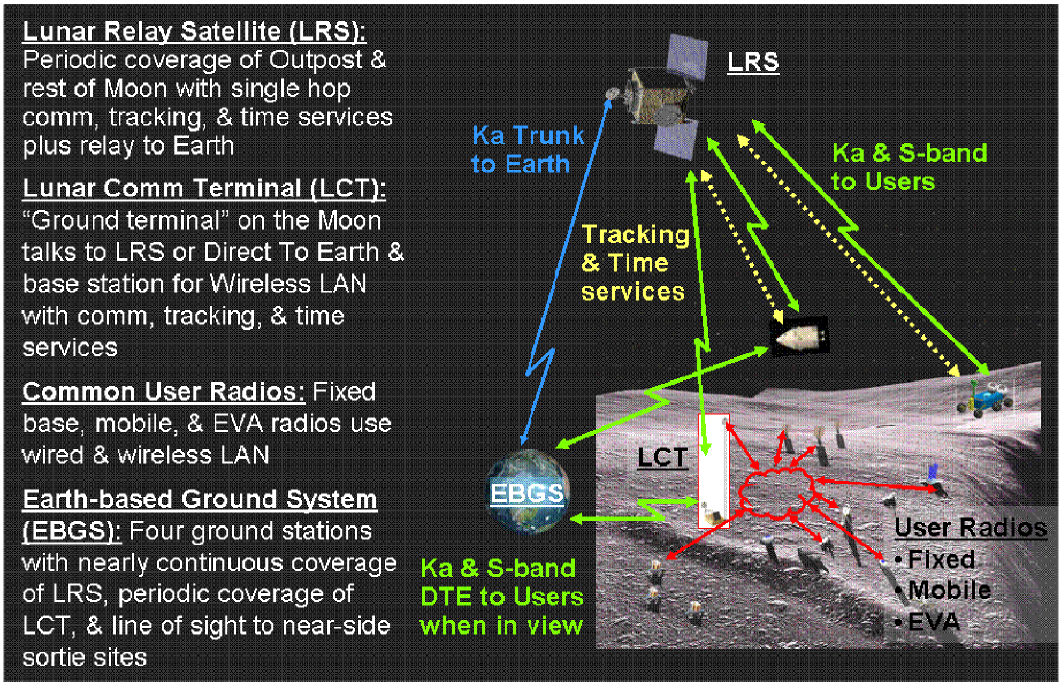

Figure 4. Major Elements of Lunar C&N Architecture

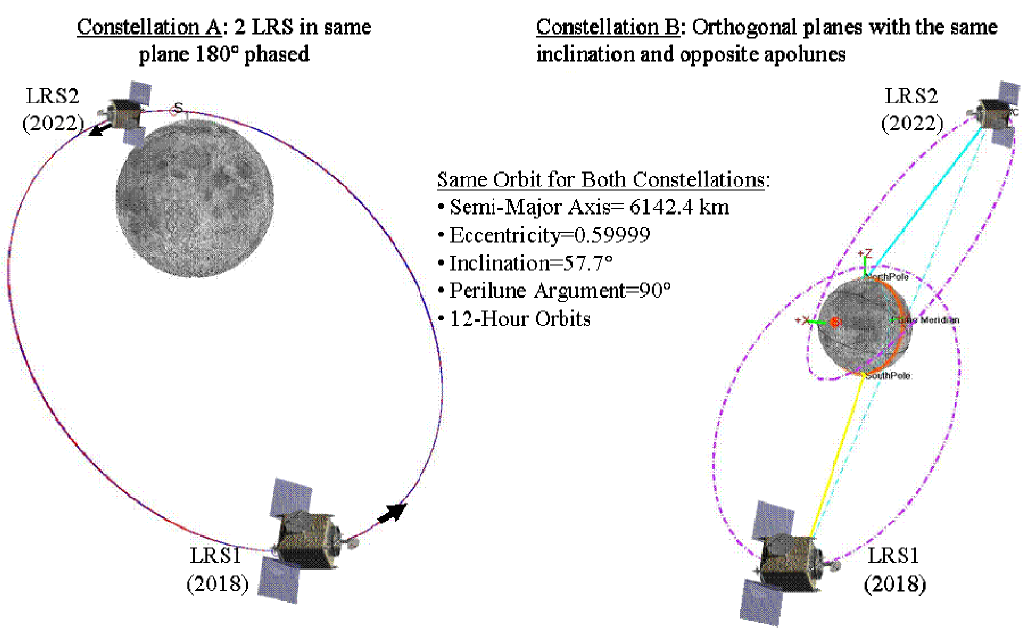

Figure 5. Use of the Same Orbit Gives Flexibility to Cover One or Both Hemispheres

- Lunar Communications Terminal (LCT): As part of the Outpost, the LCT has three primary functions:
  - It acts as a communications relay literally as if it were a "low flying LRS". It multiplexes data from lunar sources into a broadband signal up to the LRS or DTE when Earth is in view. It demultiplexes data from Earth received either from the LRS or directly from Earth and routes data to surface destinations.
  - It also acts as the base station for the surface Wireless LAN (WLAN) using a commercial standard such as IEEE 802.16e[3-4] (although selection of a specific standard is not recommended until ~2012).
  - The LCT provides the same tracking and time services as the LRS.

- User Radios: Adopting a commonality approach, all of the radios used by other surface systems are based on a family or product line of interoperable units. Three basic types with decreasing levels of capability are *fixed base radios* for large elements like the Habitat, *mobile user radios* for rovers, and *EVA radios* for EVA suits.
- Earth-based Ground System (EBGS): The ground system employs new and existing antennas operating from existing DSN and Near Earth Network (NEN) ground stations. The LRS satellites are managed by an LRS Operations Center while the end-to-end LN is managed by the LN Mission Operations Center (LMOC). The term EBGS was used to abstract the architecture of the terrestrial stations away from the lunar architecture.

A. Communications Architecture

Figure 6 captures the top level communications architecture in terms of number of channels, bandwidth, and spectrum used between the elements. The forward link is capable of sending 100 Mbps to the LRS at 40 GHz while returning 250 Mbps at 37 GHz. The LRS in turn forwards up to 100 Mbps to the LCT at 23 GHz or distributes smaller individual data streams of 1 Mbps at 23 GHz to medium rate users or 16 kbps at 2.1 GHz to low rate users. The LCT demultiplexes data and distributes it via the Ethernet LAN or 802.16 WLAN. The 802.16 protocol allows a wide range of frequency choices in the 2.4-9.0 GHz range. Since there is no interference in this entire range at the Moon, no determination was made about what portion of the range to use.

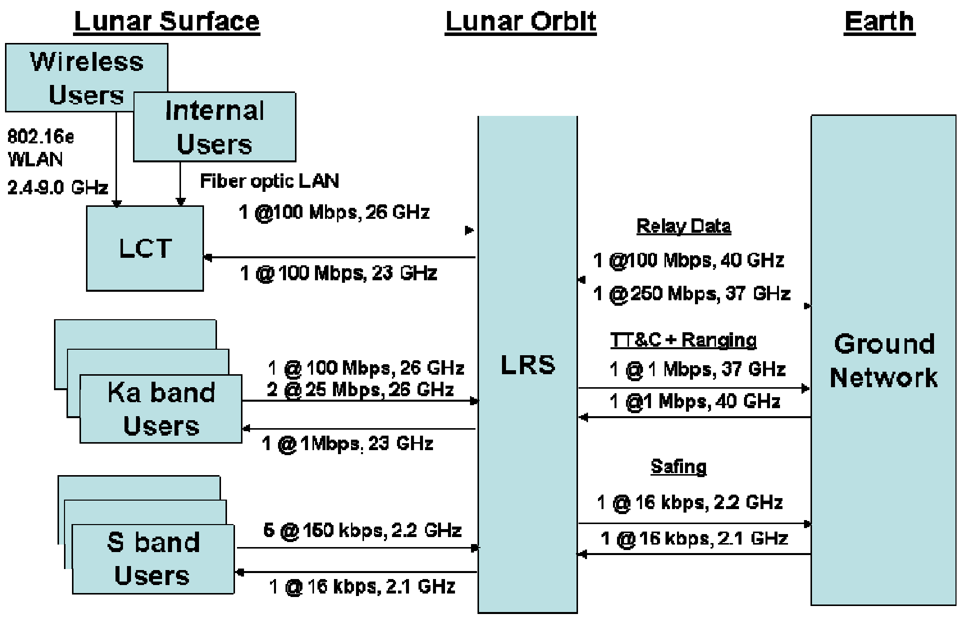

Figure 6. Link Capacities and Spectrum Usage

On the return links, the LCT multiplexes telemetry, voice, video, and science data into a 100 Mbps link to the LRS at 26 GHz. (Figure 6 does not show the use of the same LCT forward and return links directly to the EBGS.) Ka-band users are also able to send up to 100 Mbps on a high rate channel at 26 GHz or two medium rate 25 Mbps channels to the LRS. Low rate telemetry is sent via S-band at 150 kbps. The LRS is able to receive five users simultaneously. All of the return data is multiplexed into a 250 Mbps high rate stream to the ground at 37 GHz.

Surface systems typically contain more than one radio. For example, a rover uses both 802.16 WLAN for direct surface-to-surface communication to systems within LOS while resorting to its Ka-band link to the LRS on long-range excursions. It also uses an S-band radio for navigation. The EVA suit which uses 802.16 for all of its normal operations has a contingency S-band voice-only link to the LRS or to a 34m EBGS antenna. In-band commanding at Ka-band is used to control the LRS while S-band commanding is available for emergency use.

The LRS demodulates and decodes incoming data and uses IP routing to distribute data according to the protocol stack shown in Figure 7. NASA Space Network (SN) signaling is used at the physical layer in accordance with the Space Network Users Guide (SNUG)[5] modified to accept Low Density Parity Check (LDPC) error correcting code. The CCSDS Advance Orbiting Systems (AOS) protocol is proposed at the link layer in combination with High-level Data Link Control (HDLC). The protocol stack used by LRS is the same as the interface that will be used by *Orion* to NASA's Tracking and Data Relay Satellite System (TDRSS) in LEO enabling *Orion* to use one radio all the way from Earth to the Moon. This protocol stack is defined in the Constellation Program's Command, Control, Communication, and Information (C3I) Interoperability Standards Book[6].

B. Navigation Architecture

In developing a lunar navigation architecture that accommodates mission phases including trans-lunar cruise, lunar orbital and surface operations, and return to Earth, the following goals were established:

- All mission phases should be serviced by an integrated set of navigation methods.
- Navigation sensors are reused in all mission phases and on all vehicles.
- The navigation system integrates multiple sensors for all phases (e.g., cruise, landing, and roving).
- The navigation system is fault tolerant with at least *two* independent measurement types per mission phase.

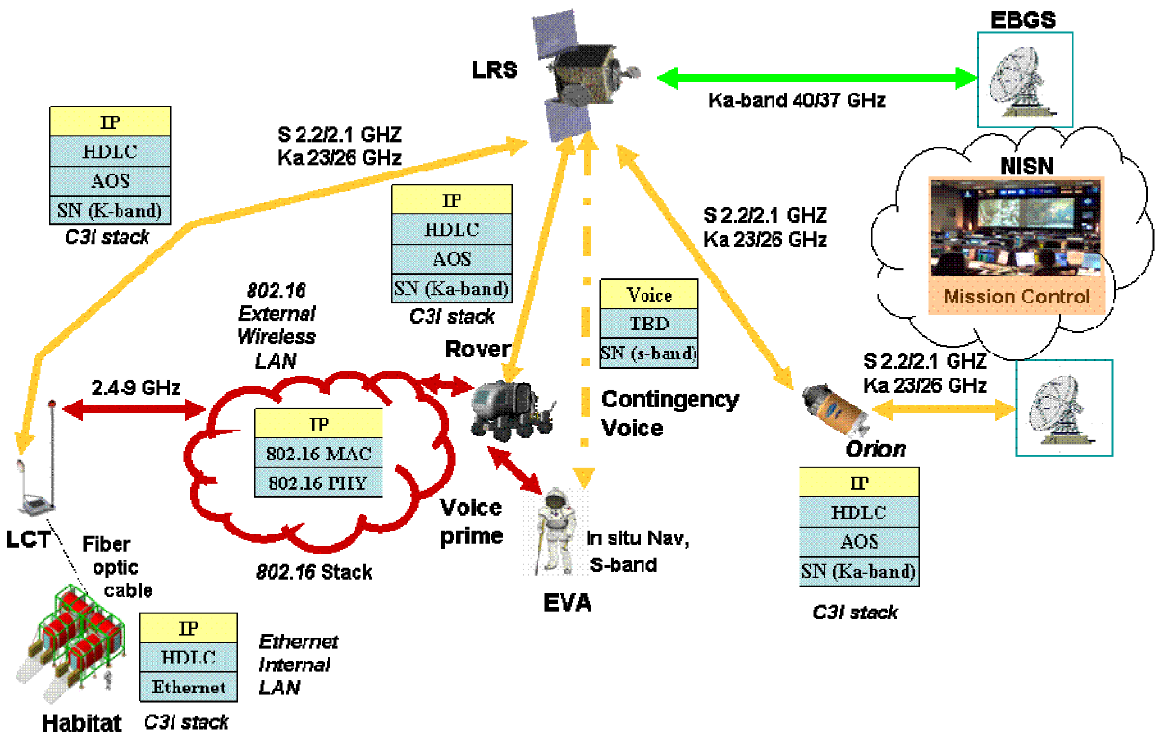

Figure 7. Lunar Network Protocols

Figure 8 illustrates the architecture as a function of mission phase, navigation data type/instruments, and on-board processing. In parallel to the on-board processing, there is a ground-based navigation process. Key to the architecture is the 'two independent navigation measurements in each mission phase'. These methods include radiometric, inertial, and optical techniques. Radiometric data will be collected via a combination of Earth-based tracking from the existing DSN (updated to support the lunar program) and a site at White Sands, New Mexico. Augmenting the EBGS is radiometric tracking from the LN's orbiting spacecraft and lunar surface terminals. Complimentary to these RF-based measurements are on-board cameras for taking pictures of near-field celestial objects/landmarks (such as the lunar craters) relative to a star-filled background. The two data types are dissimilar in that RF techniques measure line-of-sight quantities such as range and range-rate while the optical techniques measure plane-of-sky quantities such as angular separation of sited features. Each method is sufficient to uniquely solve for position and velocity using data spaced over time, but together they yield a solution that is robust in the presence of data outages or loss of observability. The challenges to implementing such an approach include:

- Insuring that Guidance, Navigation, and Control (GN&C) risks and associated technology needs are addressed early in the development cycle to establish an integrated approach;
- Maximizing multi-mission, multi-tasking and reliability of GN&C systems;
- Minimizing redundancy of systems and techniques (i.e., with multiple methods to do a job, use the one that shares equipment), while ensuring at least two independent measurements for each mission phase;
- Ensuring that across lunar surface elements, a cohesive, consistent, and shared GN&C system is implemented;

- Coordinating across technology and development projects to create the minimum system that is easiest to integrate and does the maximum GN&C work for lunar systems; and
- Using precursor lunar robotic missions for testing to validate technology, mitigate risks, and contain cost by having similar GN&C for robotics and crewed elements.

If these challenges are addressed, the result will be a cost-effective, robust navigation architecture that supports lunar exploration and paves the way to developing a Mars-forward exploration strategy.

1. Lunar Network Radiometric Tracking Service

The LN includes up to two LRSs in 12 hr elliptical, inclined orbits around the Moon and two LCTs located at the lunar outpost site near the landing zone. On each LN asset, a radio transmits and receives S-band spread spectrum signals used for low data rate communications and radiometric tracking of lunar users. Each LN radio has a clock and frequency source derived from an onboard atomic clock that guarantees a spectrally pure signal yielding better than 10^{-13} stability over a day. Fundamentally, this enables pseudo-noise sequence transmission that is synchronous with an established local LN time (also correlated with the Constellation-specified standard Earth time) such that individual LN clocks differ in knowledge by no more than 10 nanoseconds from each other. Such a capability is necessary to enable a usable 1-Way radiometric service, and provides for a precision 2-Way radiometric service.

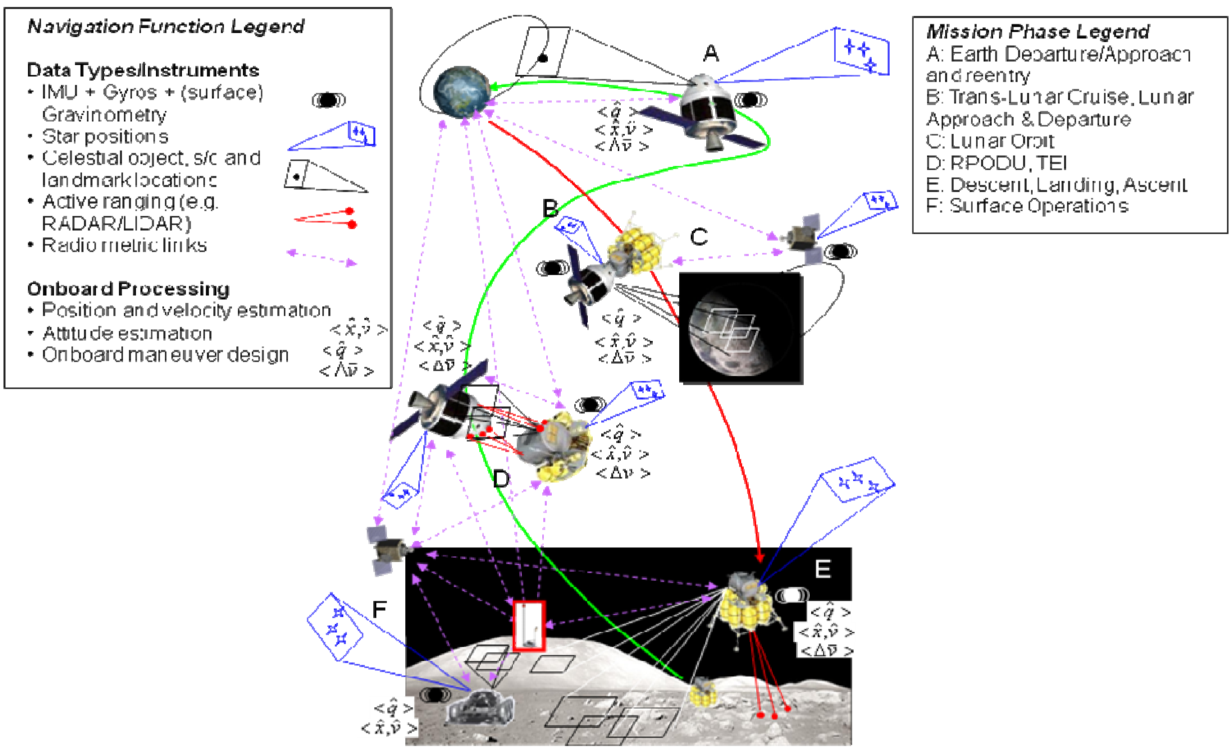

Figure 8. Lunar Navigation Architecture

The LN and user radios will be designed to enable a multiple access radiometric tracking service for each user that possesses the following design elements:

1. 2-Way signal path: A LN asset originates the forward link. The user transponds the signal onto the return link. The same LN asset collects the 2-Way radiometric measurements and telemeters them back to the user on the forward link (and back to the Earth for post-processing).
2. 1-Way signal path: All of the LN assets originate the forward links, and the user receives and tracks the signals from any LN asset in view. From these in-view links, the user collects 1-Way radiometric measurements for its own navigation processing (and telemeters back to the Earth for post-processing).
3. The LN radio supports transmission and reception of coherently transponded signals, collects 2-Way range, and tracks 2-Way phase for up to five users, simultaneously. This radio is referred to as the *LN transceiver*.
4. The user radios support 2-Way coherent transponding on a selected single link with simultaneous receive of 1-Way signals from multiple LN assets. This implies that the user can simultaneously correlate, track, and collect *up to* 4 pairs (range and phase) of 1-Way radiometric data (when four assets are in-view), and 1 pair (range and phase) of 2-Way radiometric data (from one of the in-view assets). Note that the 2-Way data

combined with the 1-Way data from the selected LN asset can be used to resolve the user's clock and frequency offset relative to the LN assets. This radio will be referred to as the *user transponder/receiver*.

5. Ranging is via Pseudo-random Noise (PN) sequences that supports spread spectrum communications via Code Division Multiple Access (CDMA).
6. Coherent carrier phase tracking is via suppressed carrier on the spread signal.
7. Each link involves only 2 elements – user and network asset (orbiting relays or ground terminal). There is no multi-leg transponding like TDRSS.
8. Near real time processing of the tracking data is enabled via each LN asset continuously broadcasting a low-rate navigation message containing LN asset ephemerides, locations, clock models, and other ancillary data required to process the radiometric tracking.

The above signal design model is one implementation that provides four distinct LOS radiometric data types including 1-Way average Doppler and (pseudo) range and 2-Way average Doppler and range.

2. Optical Navigation System Architecture

Passive optical navigation is available in all mission phases to augment radio-based navigation yielding a robust fault tolerant system (Figure 9). The Constellation Program is required to "get the crew home" when communications links are down. A system-wide risk such as Coronal Mass Ejection (CME) is being considered as a credible hazard that could cause interference preventing the radiometric-based navigation system from working. The need for a radio-free navigation system on-board all Constellation Program space elements implies that:

- *Orion* requires complete internal navigation capability for all mission phases.
- *Altair* requires a self-contained capability for ascent and rendezvous.
- Surface mobile systems need to be able to determine their location relative with sufficient accuracy to return to base safely without mission support.

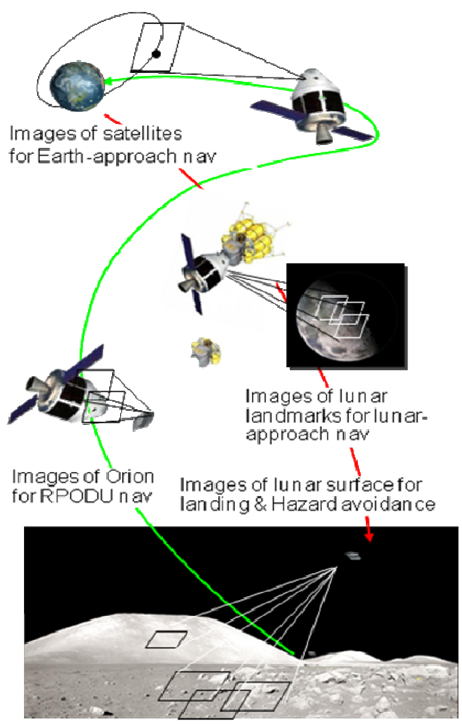

Figure 9. Optical Navigation System Architecture

The overall optical navigation system spans a space of instruments and software that overlaps the needs of a generalized GN&C system. This consists of the following components:

- Narrow angle precision camera (used for long range optical navigation, surface survey, and precision surface navigation)
- Wide angle camera (for star tracking; Rendezvous, Proximity Operations, Docking and Undocking (RPODU); landing; and low precision surface navigation)
- Onboard navigation position, velocity (attitude) estimator (to also incorporate radiometrics or lidar)

- Onboard maneuver planner and estimator
- Gimbal (to make the imager much more effective allowing dual optical navigation/tracker use)
- Dedicated GN&C processor
- Landmark model and tracking software system (for both lunar surface and orbiting vehicles)
- Autonomy technology focusing on autonomous fault detection, isolation, and recovery.

The technologies for these components exist and are flight proven. A challenge is to integrate these instruments in a stand-alone package that is deployable on multiple elements from rovers to landers.

III. Concepts of Operation

Providing communication services to the user involves Earth based, lunar orbiting, and lunar surface elements. Various considerations play into the partitioning of the communication services along these lines.

During cruise to the moon, the link is through antennas at DSN sites which will maintain LOS to the vehicle. However, once the vehicle attains lunar orbit, the moon itself provides a periodic obstruction to LOS to Earth. Descent operations are initiated on the far side of the moon. Other assets are required to close these gaps.

Users on the surface will have Earth LOS coverage depending on their location. Missions to the habitation zone around the South Pole will be blocked for roughly 14 days out of every 28 due to the orientation of the moon with respect to the Earth. In addition, the surface terrain of the area around the South Pole is not well enough known, but likely will introduce additional impediments. Users away from the poles and on the near side of the moon will have better DTE coverage, maximally at the equator. For operations on the far side of the moon, such as descent, or for science instruments left in that location, DTE communication will not be available.

The use of a lunar relay is dictated by the need to service the South Pole for longer than 14 day habitation periods, expected terrain blockages, far side critical operations (RPODU) and far side science or excursions. From a navigation standpoint, there is a requirement to aid surface navigation without employing a large GPS-like constellation. To limit the number of ground stations and get the same performance also requires a relay.

On the lunar surface, the LCT provides local communications over an 802.16 mesh network (or equivalent) within a certain zone around the Outpost LCT. The LCT has limited LOS to Earth, so it uses the LRS when it communicates back to Earth. When outside this zone, a rover can act as a relay to the LRS for the EVA crew. The result is that the operations concept for users depends on where they are located. Within the LCT coverage region, the user employs the LCT to communicate to other surface users and to Earth. Outside the LCT region, the user interfaces with the LRS to communicate to other surface users or to Earth.

For an approaching *Orion* (except for navigation considerations discussed later) and in orbit, DTE is used. DTE can also be used by the users, including the LCT, but is limited in coverage unless they are on the near side with DTE service. Figure 10 shows the LRS service zones (green low rate and blue high rate) superimposed on the LCT service zone. These zones are displayed as concentric circles. The LRS zones can be moved independently of the LCT zone by pointing the dual S/Ka-band LRS antenna.

Users talk to the LCT when within the LOS range around the Outpost. The LCT service zone is a fixed region around the LCT with a radius of ~6 km based on LOS over a smooth moon surface. Within this zone, the user receives continuous communications coverage over WLAN links. The effects of a real moon surface terrain will likely reduce this LOS range. In addition, if the user is behind an obstruction within the zone, they will link to the LRS using an S-band or Ka-band radio. Surface elements like EVA suits communicate to the LCT to save power. The LCT routes surface-surface data by WLAN and wired connections, such as the fiber optic connection to the habitat. It routes surface-Earth data using LRS and/or DTE, when available, at Ka-band. Radiometric tracking services are provided at S-band for orbiting and landing users, and for surface navigation by surface elements.

The zones are co-centered so that the Ka zone always falls within the S-band zone. Intra-zone communication is accomplished using S-band or Ka-band radios through the relay. Five S-band users and four Ka-band users can simultaneously use this LRS centered network. Surface elements, like EVA suits and rovers, communicate to LRS through S-band (low-medium rate data) or Ka-band for higher data rates. For robotic ISRU rovers near the ISRU fixed based processing plant, their data will be relayed by the ISRU processing plant back to the LCT or to the LRS depending on the location of the ISRU.

Normal EVA operation is that data to/from the astronauts' radios are relayed initially from/to the LCT or the rover. When excursions leave the LCT zone, astronauts conducting EVAs will have their data relayed through the rover to other astronauts in the vicinity, or through the rover to LRS or Earth as shown in Figure 11. From there the data will be relayed to Mission Control or back to the surface of the Moon to communicate with other astronauts.

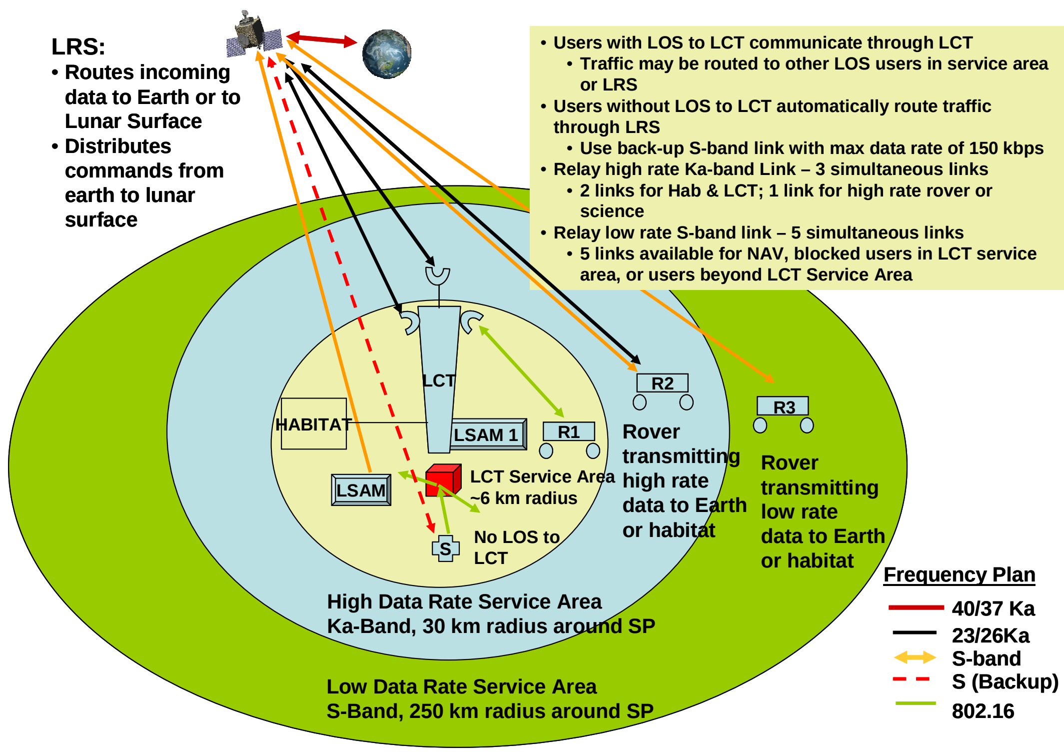

Figure 10. User Service Zones

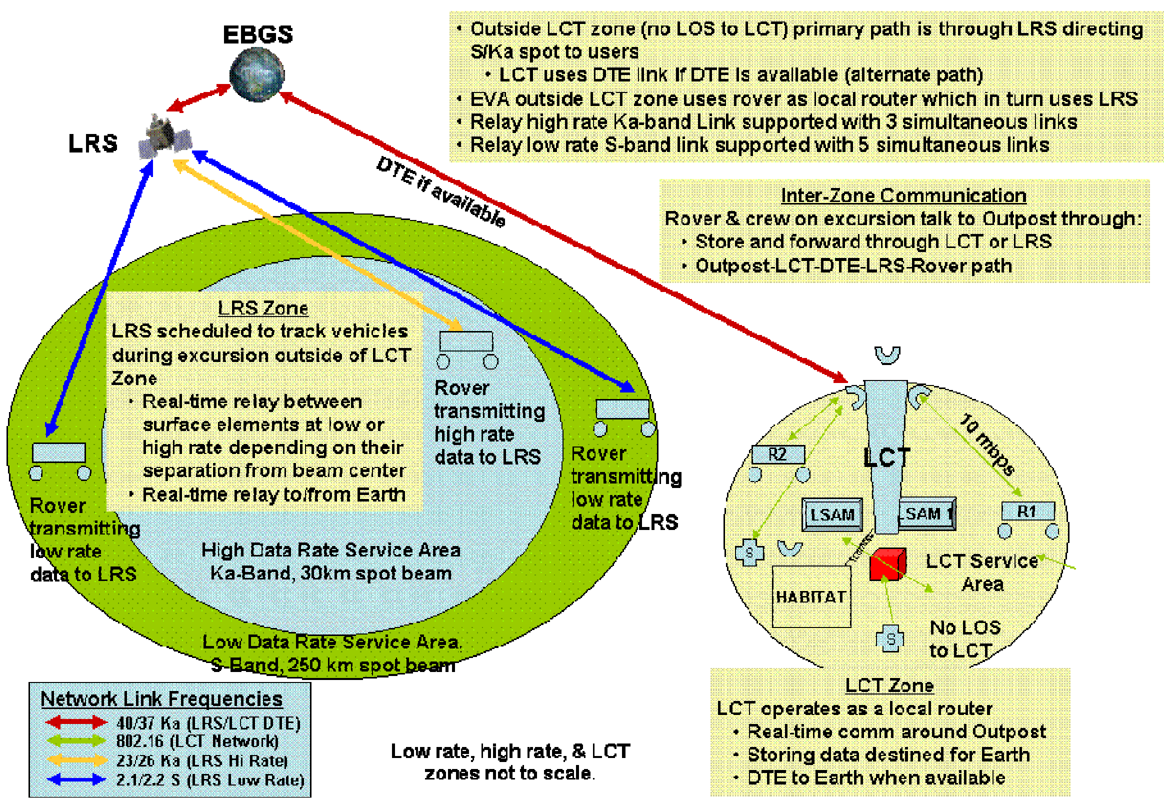

Figure 11. Coverage Zones for LRS and LCT when Roving outside of LCT Zone

Outside of the LCT range, or behind an obstructing hill, the LRS is used. The LRS service zone is 250 km in radius for S-band and 30 km for Ka-band. The S-band and Ka-band zones represent the lunar surface area which receives at least 8 hours of coverage by any part of the beam from the satellite.

With one satellite, normally the LRS service zones will be focused around the Outpost. However, the LRS service zones are not fixed in location like the LCT zone. The location of the relay in orbit and the pointing of the antenna determine the location of the LRS zones. Thus the LRS zones can move to cover other areas of the moon to track extended excursions, interface with remote science packages, or track inbound and outbound *Orion* vehicles.

Users in the LCT service zone can still communicate to other users within the LCT service zone through the LCT directly. Similarly, the users within the LRS service zones can communicate with users within a given LRS zone (S or Ka) through the LRS directly. These intra-zone communications links can be accomplished through the local router (LRS or LCT).

Inter-zone communication begins at the LRS and LCT routers. The (local) LCT or LRS stores the data for later forwarding to the recipient when the (remote) LCT or LRS is in view. If the local router and recipient have a view to Earth simultaneously, then the link can be made with a few second delay through a DTE link.

EVA contingency communication is the hardest part of the communication system requirement to meet and drives the LRS S-band link budget due to the low power available on the EVA suit. For the astronauts' EVA suits the power allowed for transmission is limited because of exposure limits for humans. Also, there is a mass limitation for the communication system such that both the surface wireless radio and the S-band radio must fit within that mass limit. On the other hand, contingency communication relayed through mobile units, such as rovers, is straight forward.

IV. Spectrum Utilization

The C&N network involves multiple frequencies and communication techniques. The network designed under LAT2 used the allocated frequencies from NASA except for the surface to surface communication on the lunar surface. The bandwidth of the communication channels and the number of channels were designed to traffic model (see next section).

The C&N paths were used to form the communication network: Earth to LRS, Earth to lunar surface, Earth to orbiting vehicle, LRS to lunar surface, orbiting vehicle to lunar surface, and lunar surface to surface. From these paths we assigned frequency bands and bandwidth for each path. Figures 11-13 give the frequency usage plan for three different operational scenarios.

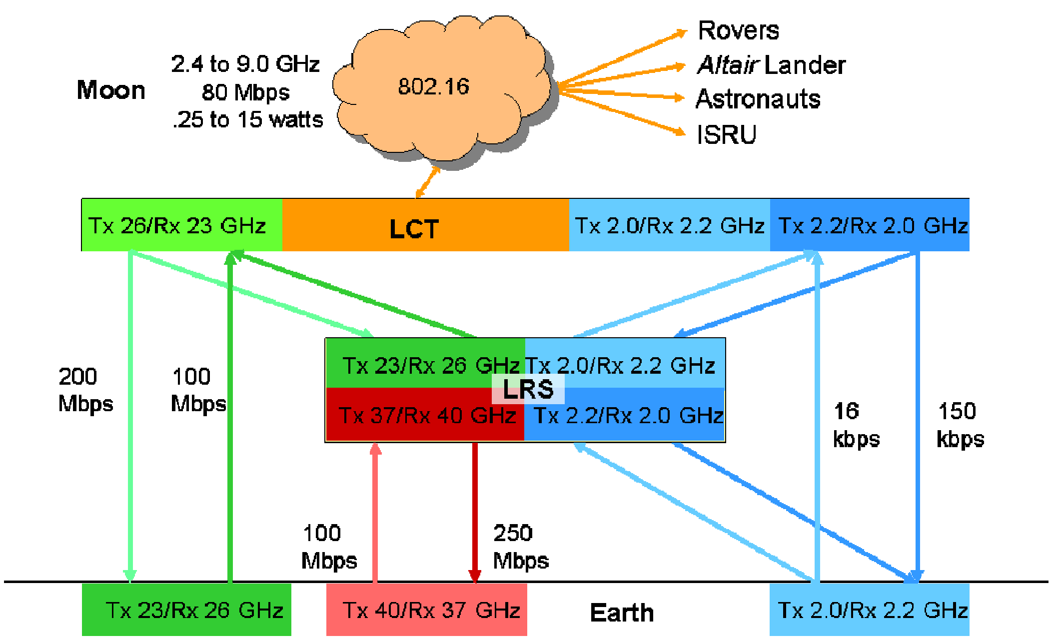

Figure 12. LAT Spectrum Plan: Normal operations around the habitat zone

The LRS was designed to look like an Earth ground terminal from the surface of the Moon, except for when an astronaut is walking without a rover outside of the habitat zone. The concept is that the lunar user would have the same communication capability whether they were communicating directly to Earth or via LRS. To minimize cost, current Earth assets and assets being developed for the Lunar Reconnaissance Orbiter (LRO) were used. This choice put limitations on some of the links but allowed concentration on the overall C&N architecture that would not have been possible if different size Earth facilities were in the trade space.

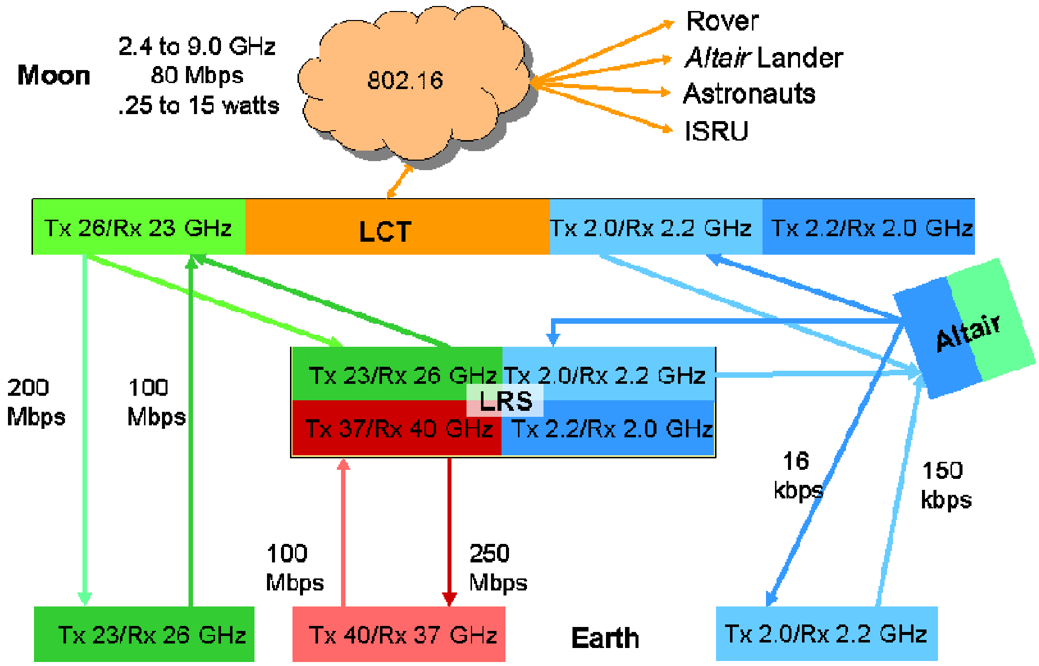

Figure 13. LAT Spectrum Plan: Landing of *Altair*

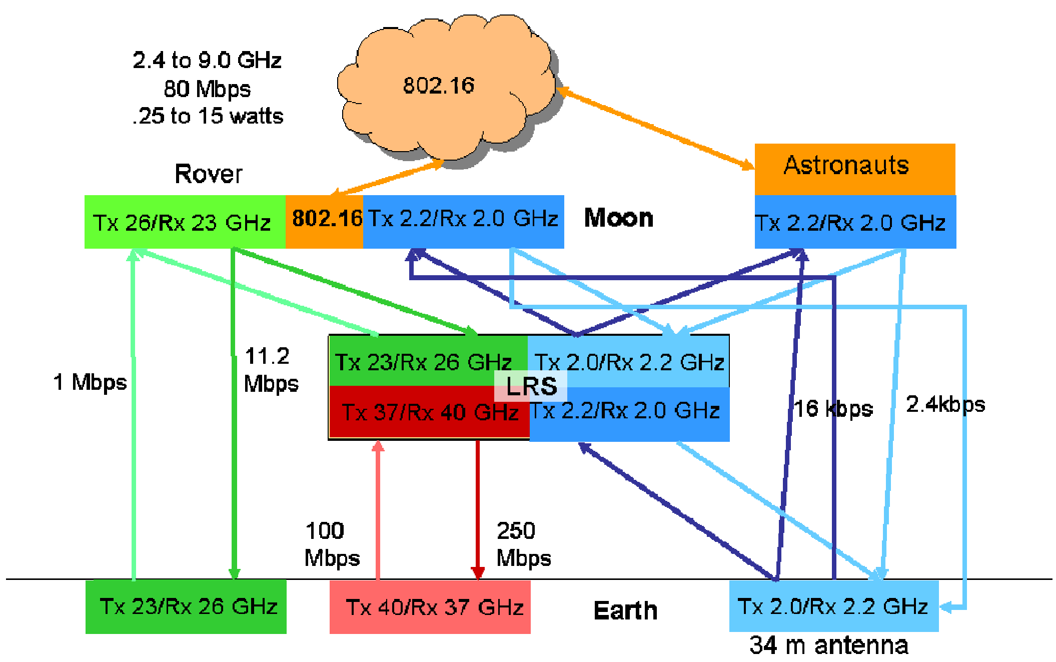

Figure 14. LAT Spectrum Plan: Astronaut on EVA outside of Habitat walking back

1. EBGS

The Earth antennas were chosen to be 18 meters which is the same as for LRS and LRO. The frequency bands were S-band to and from *Altair*, *Orion*, LRS, and the lunar surface; Ka-band (23/26 GHz) to and from *Altair* and the lunar surface; and upper Ka-band (Q-band or 37/40 GHz) to LRS.

The S-band communication and navigation is compliant with SN (TDRSS) protocol. The protocol is limited to 150 kbps using PN coding. This choice was made to allow two-way and Doppler ranging for navigation using current navigation methods.

The Earth terminal transmits 100 Mbps of data forward to the lunar surface or *Altair* at 23 GHz and receives 250 Mbps return from the lunar surface at 26 GHz. The 250 Mbps is divided into 4 data channels: two 100 Mbps channels and two 25 Mbps channels. This channelization allows flexibility in designing missions. One of the two 100 Mbps channels allows a high rate data communication with the *Altair* while it is landing. After landing, this channel can be used to support the Outpost. The other 100 Mbps channel is allocated to the Outpost except when the crew goes on extended excursions when the channel must be switched between the Outpost and the rovers. The two 25 Mbps channels were sized to support remote exploration of the lunar surface by robots, human occupied rovers, or remote ISRU plant(s).

For communications via the LRS at the upper Ka-band (37/40 GHz), the Earth terminal would transmit up to 100 Mbps forward to the LRS at 40 GHz and would receive up to 250 Mbps at 37 GHz. The return link is a single channel since the LRS router bundles all Earth-bound data into one data stream. A small part of the bands is allocated for navigation to allow 2-way ranging and Doppler measurements.

The protocols at Ka-band and upper Ka-band were not determined and were left open. The modulation and encoding assumed in any link calculations were assumed to be Quadrature Phase Shift Keying (QPSK) for modulation and Reed-Solomon with Viterbi code rate of ½ for forward error correction (FEC).

2. LRS

The LRS primarily communicates to Earth and to the lunar surface; however, it can support communications to the *Orion* and *Altair* if needed. The LRS is not only a communication relay satellite; it also provides navigation data to cislunar spacecraft and to surface roving. Also, the LRS along with the LCT provide the local lunar clock.

The LRS communicates with Earth at 37/40 GHz and with the lunar surface at 23/26 GHz. The 23/26 GHz band is divided the same way as on Earth so that users on the Moon have the same performance as if they went directly back to Earth. The LRS uses the navigation signals in the 37/40 GHz bands to determine its location from Earth. The LRS provides navigation data to other spacecraft or lunar elements at S-band using the PN-channels. Separating the navigation signals in frequency between the LRS-Earth, and LRS-lunar surface eliminates self-interference.

3. Lunar Surface

The lunar surface is made up of many elements that need to communicate between themselves and Earth. The initial approach attempted to use S-band with SN format and/or the high frequency (HF) band to support low data rates and non-line-of-sight communication. However, the traffic model exceeded what either one method could support. Consequently, only a high data rate surface to surface network is employed. Two frequencies were selected for analysis: 2.4 GHz and 3.8 GHz.

The lunar surface network was broken up into a WLAN and a dedicated wired LAN between the LCT and the habitat. The wired LAN would be either an optical line if the LCT was remote from the habitat and got its power from the habitat, or would be a typical Ethernet CAT5 cable if integrated with the habitat. One WLAN protocol that seems to be able handle the needed data rate from the traffic model is 802.16e. It would need to have a mesh capability added to it to allow astronauts to communicate between each other when not in sight of a base station. Because of the maximum data rates identified in the traffic model (80+ Mbps), there may need to be two base stations with closely spaced channels. Communication nodes could be put on roving elements like robots and rovers. These nodes were sized to support two astronauts and one high definition television (HDTV) camera. Also, smaller fixed surface elements like ISRU plants and Landers would have mini-LCTs sized to support two HDTV channels, two astronauts, and telemetry.

V. Traffic Model

A simple traffic model was built by estimating the deterministic, nominal data flows between all sources and destinations in the Earth-Moon network including surface to/from surface and Earth to/from surface. Detailed models based on specific scenarios or operational modes have not been constructed yet. The traffic model results are summarized in Table 2.

The aggregate peak rate to and from Earth will occur between the LRS and the EBGS in the 37/40 GHz band. The aggregate peak rate up to LRS and down from LRS relative to the lunar surface will have to be apportioned between the S-band and 26/23 GHz band links occurring between:

- LRS and LCT (when all surface elements are in sight of LCT)
- LRS and LCT + mini-LCT + Mobile User Radios + EVA Suit Contingency Communications

The aggregate peak rate across the lunar surface pertains to the 802.16 capacity of the LCT when all surface elements are in sight.

Based on the Aggregate Peak Rate from Earth of 67 Mbps, the forward link to the LRS was sized at 100 Mbps providing 49% margin. Based on the worst case return traffic (Aggregate Peak Rate Up to LRS from Lunar Surface) of 222 Mbps, the LRS return link was sized 250 Mbps providing 12% margin. The low margin on the return link is considered sufficient due to the ability to operationally constrain the large amount of video data included in the 222 Mbps estimate.

Table 2. LN Traffic Model Summary

Description	Applicable System(s)	Data Rates (without explicit margin added)		
		Low Rate (Mbps)	High Rate (Mbps)	Total Rate (Mbps)
Aggregate Peak Rate to Earth	LRS and EBGS	3.9	151.0	**154.9**
Aggregate Peak Rate from Earth	LRS and EBGS	1.1	66.0	**67.1**
Aggregate Peak Rate Up to LRS from Lunar Surface	LRS and LCT	6.4	216.0	**222.4**
Aggregate Peak Rate Down from LRS to Lunar Surface	LRS and LCT	6.1	141.0	**147.1**
Aggregate Peak Rate Across Lunar Surface	LCT	8.7	143.0	**151.7**

VI. Element Design Concepts

The major elements of the LRS and LCT designs are shown in Figure 15. The LRS is designed to be equivalent to an 18 meter diameter Earth terminal to the users on the lunar surface. The 18 meter diameter dish was chosen because that is the size of the new ground antenna at 26 GHz that is being used for the LRO satellite. The orbit that was selected is a “frozen” orbit with a maximum range of 9000 km from the lunar South Pole. A frozen orbit is an orbit that meanders within an envelope but does not require thrust from the satellite to stay within that envelope.

The LCT and the LRS communication systems at Ka-band were designed to be mirror images of each other. The LCT would transmit at 26 GHz and receive at 23 GHz while the LRS would transmit at 23 GHz and receive at 26 GHz. Both of them would have store and forward capability, a high speed router, and an atomic clock. The atomic clocks would be synchronized against each other to provide a local time reference with extremely low drift.

At S-band the LCT and LRS would use complimentary radios that adhere to the SN protocol.

Since there are no frequency allocations for surface to surface communication, link analyses were done at two frequencies: 2.4 GHz and 3.8 GHz. The frequency of 2.4 GHz was chosen as this is the unlicensed band that is used for WiFi. The frequency of 3.8 GHz was chosen as this is within the band for Geo-satellite to Earth and was felt that there would not be an issue of interference. It is recognized that other frequencies could be used but would not change the qualitative results of the study.

The LCT is designed to be a space gateway, a surface to surface radio tower, a router, a time reference, and have store and forward capabilities. The LCT can be integrated into the *Altair* or Habitat elements or relocated to operate as a stand-alone unit to take advantage of local terrain to extend the LCT’s WLAN range.

The LCT link calculations assume Reed-Solomon/Viterbi coding with rate ½ and QPSK and a bit error rate (BER) of 10^{-8}. There is a 3 dB margin used in the link calculations from the lunar surface to the LRS or Earth. The surface to surface link calculations between the LCT and other wireless users on the lunar surface assume that the other users are using an antenna with a 2 dB gain at either frequencies of 2.4 GHz or 3.8 GHz. The link margin used is 30 dB assuming a spherical moon. The 30 db margin is in place of surface to surface path loss as there was no lunar surface terrain data available.

The protocol selected for analysis of the WLAN link is 802.16e. This assumption was made to be able to estimate the power and mass requirements for the LCT. The study did not try to recommend a selection of WLAN implementation. Two wireless base stations were needed to meet the data rates identified in the traffic model.

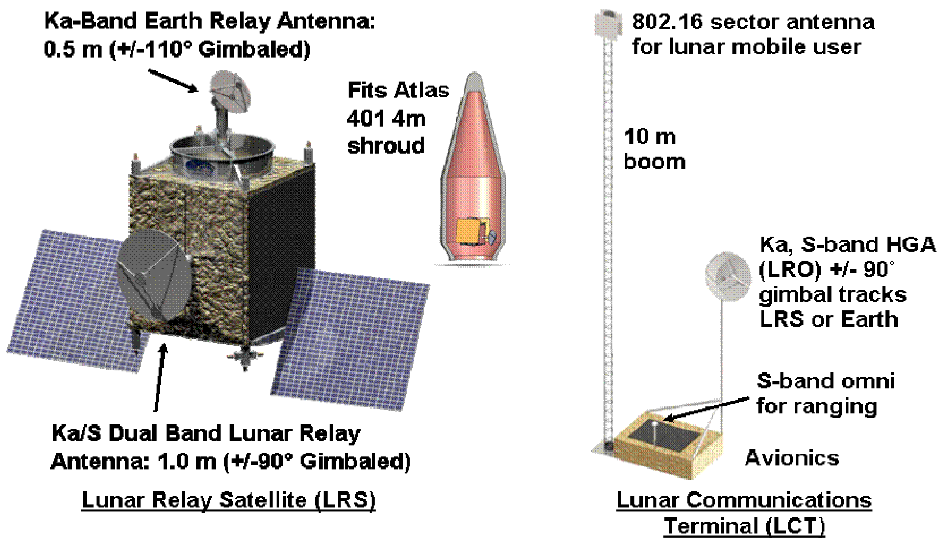

Figure 15. Key Features of LRS and LCT

A. LRS Communications Payload

The LRS Communications Payload is the collection of communications equipment, including Receivers, Transmitters, Antennas and passive components, which are configured to support a communication network between the Earth and the Moon. The LRS S band and Ka band Relay Antennas (both 1 meter diameter) are co-located on the bottom of the spacecraft deck which points to the South Pole. This results in roughly circular coverage zones around the South Pole. Figure 16 provides a block diagram of the LRS communications payload. The left hand portion of the diagram including the 23/26 GHz Ka components, 2.1/2.2 GHz S-band components, and the on-board processing equipment (router, navigation processor, Command and Data Handling, and Solid State Recorder) are all common on the LCT.

B. User Radios

A common set of radios was designed to meet the needs of all other lunar surface elements. To minimize recurring unit cost, all radios use common technology and components wherever possible. Three types were defined as part of a family or product line. Key characteristics of the user radios are compared in Table 3.

- Fixed Base User Radio: This radio is a power-efficient mini-LCT sized for five simultaneous users. It supports operations remote from the LCT anywhere on the Moon. For example, it could be used in an ISRU plant in a crater, a nuclear power source behind a hill, a PR used for long range sorties, a mobile Lander, or a human-tended science experiment cluster. It creates a WLAN sub-node fully connected to the LN providing Ka and S-band antennas to close links to the LRS or Earth.
- Mobile User Radio: In the normal mode when in line-of-sight of an LCT or Fixed Base Radio, the Mobile User Radio provides high rate data via 802.16e connections plus 2-way navigation using an omni S-band antenna. In the self-sufficient mode for remote operations, it provides Ka and S-band antennas for a Rover to communicate via the LRS or Earth and forwards data from EVA crew members.
- EVA Suit Radio: This radio is designed to meet challenging 1 kg and 0.25 W transmit power limits. It provides high rate 802.16e cell phone service to an LCT or Rover while the Rover provides navigation. In contingency walk-back scenarios, the suit radio supports a 2.4 kbps S-band contingency voice link to the LRS as well as 2-way navigation.

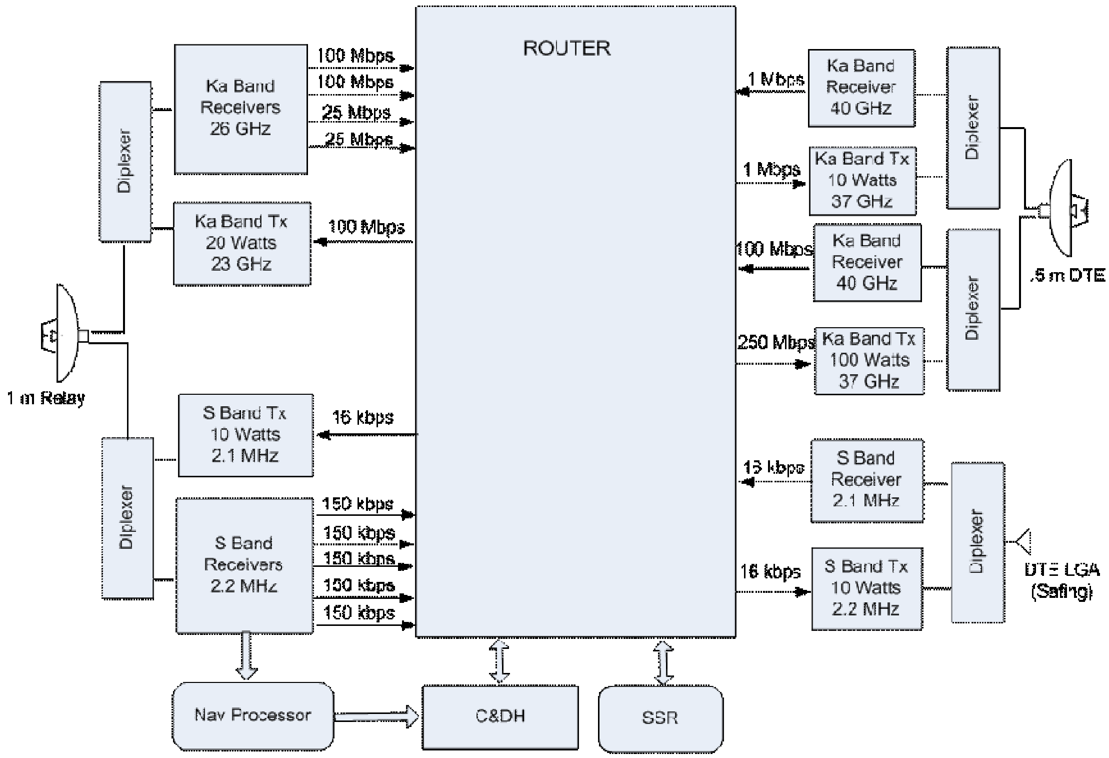

Figure 16. LRS Communications Payload Design

Table 3. User Radios: Key Features of the Product Line

Capability	Fixed Base User Radio	Mobile User Radio	EVA Suit Radio
802.16 Wireless LAN on lunar surface	Base station, 11.2 Mbps to LCT to create remote WLAN or back up LCT	Cell phone & 11.2 Mbps video in Normal Mode; 2 Mbps from EVA Suit in Self Sufficient Mode	Cell phone: 2 Mbps to LCT, Rover, or portable Fixed Base Radio in Normal Mode.
Ka/S band dual feed antenna for high rate data to LRS or Earth	20 Mbps Ka and 150 kbps S band in Self-Sufficient Mode or to back up LCT	Folded up to protect from dust in Normal Mode; 9.5 Mbps Ka & 150 kbps S band in Self Sufficient Mode	N/A. Astronaut relies on LCT, Rover, or portable Fixed Base Radio.
S band antenna	150 kbps navigation in Normal or Safe Modes	150 kbps nav in Normal Mode 19 kbps nav/voice in Safe Mode	Contingency Mode: 8 kbps voice & 2-way nav
Navigation	1- way and 2-way tracking (Doppler & ranging) via S band in SN protocol	1-way and 2-way tracking (Doppler and ranging) via S band in SN protocol	Relies on Rover in Normal Mode. 2-way tracking in Contingency Mode

VII. Technology

Some of the key decisions made in the trade studies leading to the reference C&N architecture were associated with the degree of new technology to be incorporated. Concepts utilized technology efforts currently funded but were not constrained to the funded set. Instead the team identified functional capabilities needed to achieve the objectives of NASA's overarching Exploration Architecture that were defined in LAT Phase 1 and then identified technologies that would fit into a design concept that implements those objectives. The one real constraint is that the selected technologies have to be able to reach Technology Readiness Level (TRL) 6[2] in the 2012-2013 time

[2] TRL 6 is defined as demonstrating a system/subsystem model or prototype in a relevant environment (ground or space).

frame to be realistically capable of use in the design of the C&N systems. The technologies selected and the roadmap for their development are shown in Figure 17. The technologies used in the LN architecture include:

- **Navigation and Timing**
  - *Lightweight Atomic Clock*: Need a lightweight, liter-class 10^{-13} drift/day stable ion clock for synchronous transmission of PN-sequences by multiple relays and ground stations (LRS and LCT). GPS-level accuracy is key to supporting autonomous navigation and tracking and associated crew safety and surface mobility.
  - *Integrated C&N Software Defined Radio (SDR)/Transceiver*: Need integrated C&N transceiver with functions that are easily reprogrammable through software uploads that works in S, L, K, and Ka bands.
  - *Common Onboard GN&C System*: Need a modular and interoperable navigation system so common navigation technologies and software can be leveraged across platforms and missions infusing capabilities into the *Altair* lander, surface mobility, EVA suits, & ISRU elements.
  - *Advanced Optical Navigation*: Need to provide autonomous and comm-link-independent navigation and attitude estimation services using optical observables for *Orion*, *Altair*, surface rovers, and robotic orbiters. The system should operate cooperatively with a radiometric-based navigation subsystem (dependent on Earth, GPS and/or lunar relay links) or operate independently using celestial/optical observations only.
  - *Autonomous Landing and Hazard Avoidance Technology (ALHAT)*: Need autonomous landing and hazard avoidance system including terrain relative navigation that operates in all lighting conditions including a permanently shadowed crater. Need 100m landing position accuracy unaided at 3σ certainty and <10m accuracy aided by LRS, surface beacons, or EBGS. Need 0.5 meter hazard recognition and avoidance.

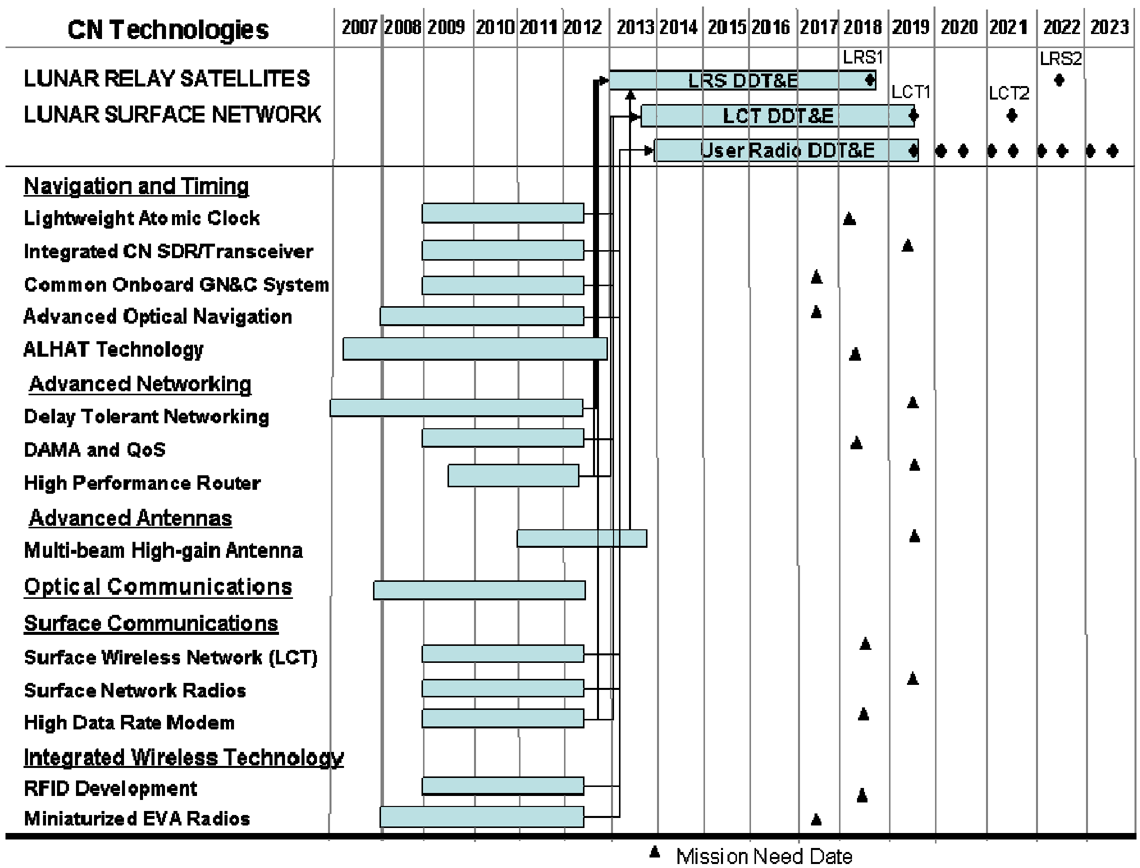

Figure 17. Technology Advances Incorporated into LAT C&N Architecture

- **Advanced Networking**
  - *Delay Tolerant Networking (DTN):* Need a large number of space systems to automatically intercommunicate using techniques (based on IPv6) that broadly parallel those used in the terrestrial Internet, but in a space communication large delay environment. Need techniques to bridge islands of connectivity (i.e., lunar network and terrestrial network).

- *Demand Assigned Multiple Access (DAMA) and Quality of Service (QoS):* Need QoS protocols to support traffic prioritization and DAMA schemes to enable auto discovery of the network load for self-managed, autonomously reconfiguring networks.
- *High Performance Router:* Need to support multiple 100 Mbps network interfaces to terminate high speed RF links. Need to support processing/routing at 350-500 Mbps for proximity and backbone links.

- **Advanced Antennas:** Need a lightweight two-beam S-/Ka-band (2 GHz/40 GHz) High-Gain Antenna (HGA) to enable communications with both a habitat and rover separated by 250 km distances via LRS.
- **Optical Communications:** Need optical terminals for high bandwidth surface-to-surface, surface-to-space, and DTE links. Need to transmit up to 1 Gbps and receive 10 Mbps. Need photon counting detectors at 1.5 micron wavelength, 2-way ranging with centimeter class precision, and clock synchronization.
- **Surface Communications**
  - *Surface Wireless Network*: Need to support $\geq$15 simultaneous users with aggregate bandwidth of 80 Mbps at ranges of 6-10 km and data rates from 16 kbps to 20 Mbps. Convert conventional IP stacks to SN and C3I stacks. Support time synchronization service to all surface elements.
  - *Surface Network Radios*: Need IP-based radios to link surface elements together for LOS applications. Support surface mesh networking using 802.16-like protocols. User network radios need to have MAC layer protocol support for both SN signaling at high rate Ka-band and 802.16 protocols on the lunar surface to the LRS. Radios need to support 1- and 2- way radiometric tracking.
  - *High Data Rate Modem*: Need to provide throughput of 100 Mbps interfacing to SN signaling side using QPSK and down-conversion to Intermediate Frequency.
- **Integrated Wireless Technology**
  - *RFID Development*: Need space qualified interrogator that reads RFID tags for inventory management and also reads passive wireless sensors. Physics of interrogation are very similar, so an SDR for interrogator should reduce cost and permit re-use. Need interoperability of spectrum with international and commercial partners, as well as inventory management commonality between multiple Constellation Program elements.
  - *Miniaturized EVA Radios*: Need a miniaturized lunar EVA suit radio that integrates an 802.16e WLAN radio and S-band voice/navigation radio. The EVA suit radio must fit within a difficult-to-achieve two pound weight limit for the radios, avionics, radiation protection and cooling. Need to provide two-way navigation to enable relay of crew position back through the voice channel. Need a new antenna system, combining the S-band and 802.16e dipole antennas which are comparable in wavelength.

VIII. Future Work

While a tremendous amount of work was done in all areas of the Exploration Architecture on the LAT study, it still represents a preliminary study with a vast amount of additional work required to establish a baseline architecture that is technically feasible, affordable in terms of NASA's anticipated budget, prudent in balancing risk with aggressiveness, and that achieves as many of the 180+ specific objectives that were identified by the stakeholders. A few of the most significant tasks that need to be accomplished in the next year follow:

- *Commercial and International Participation*: LAT2 was not able to study potential commercial and international participation resulting in an architecture that does not meet the *Vision's* goal to "Promote international and commercial participation in exploration". A study will be performed in collaboration with interested industrial and international entities to solicit input and ideas for broader participation. Barriers and enablers to private investment need to be identified with options to mitigate the barriers and implement the enablers. An analysis will determine which capabilities need to be retained by NASA and which could be done by other partners. Business case analysis is needed to identify opportunities with sufficient Return On Investment to attract industrial commitment. International agencies need to evaluate the benefits of pooling their national investments with America's to multiply the overall gain.
- *Cost*: While the cost of the lunar architecture was estimated during LAT, no trades were performed driven by cost. Candidate trades for C&N have been identified and will be performed to consider alternate architectures that reduce cost either with or without sacrificing performance.
- *Spectrum Analysis*: The LAT study assumed the use of the spectrum architecture recommended by earlier studies [7, 8]. Issues that remain include:
  - Spectrum for contingency communications
  - Radio Frequency Interference (RFI) including self-interference on the LRS and LCT
  - LOS limitation for surface communication due to use of S-band and realistic terrain

    - Sharing International Telecommunications Union bands allocated for space use with commercial and international partners
    - Scalability of C&N beyond the initial Outpost
    - Definition of an integrated signal structure incorporating both communications and navigation.
- *Commonality* and *extensibility:* Study commonality of avionics across all orbiting and surface elements. Analyze commonality approaches considering programmatic implementation, cost, acquisition strategies, and risks. Assess the extensibility of the C&N Architecture to Mars.
- *Navigation:*
    - Study quantity and locations of EBGS sites, radiometric data quality, and extent of tracking needed. Analyze navigation performance sensitivity on epochs for Earth/Moon geometry and arrival geometry.
    - Analyze LN clock stability and define mechanisms for synchronizing LN time with Earth time.
    - Study passive and active surface navigation aids to determine the most cost effective mix.
- *Networking:* Continue to study standards and industry trends in mobile ad hoc networking such as the IEEE 802.16 family, delay/disruption tolerant networking, and implications of IPv6 including security. Determine whether NASA has unique requirements in the lunar environment that necessitate investing in the development or modification of industry standards.

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