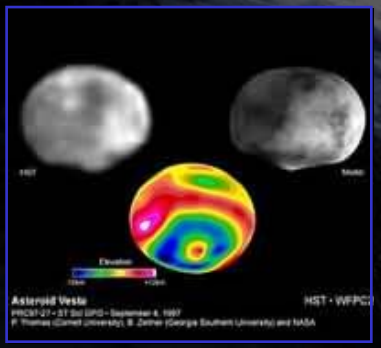
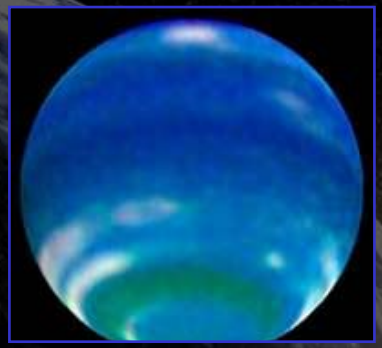
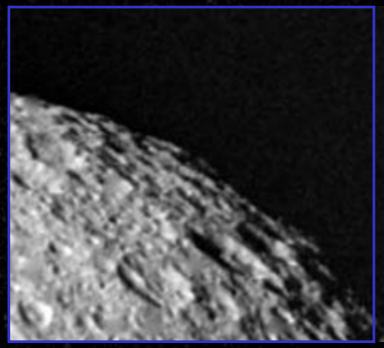
Space Communications Capability Roadmap Interim Review

March 24, 2005







NO COMMUNICATIONS

No Data

No Commands

No Pictures

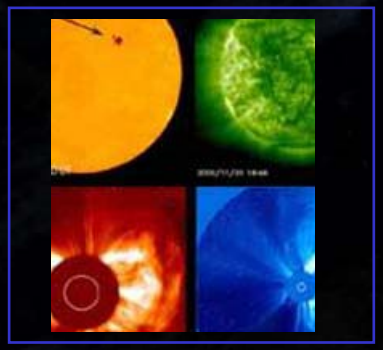
No Video

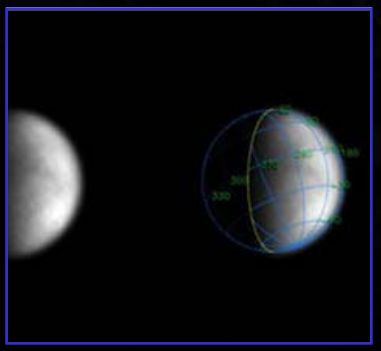
No Voice

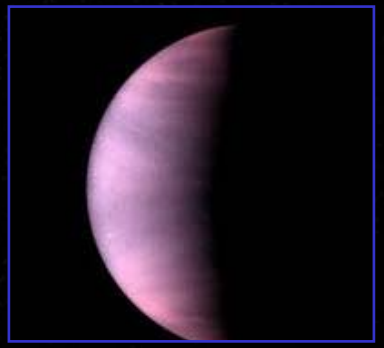
No Safety

NO SCIENCE

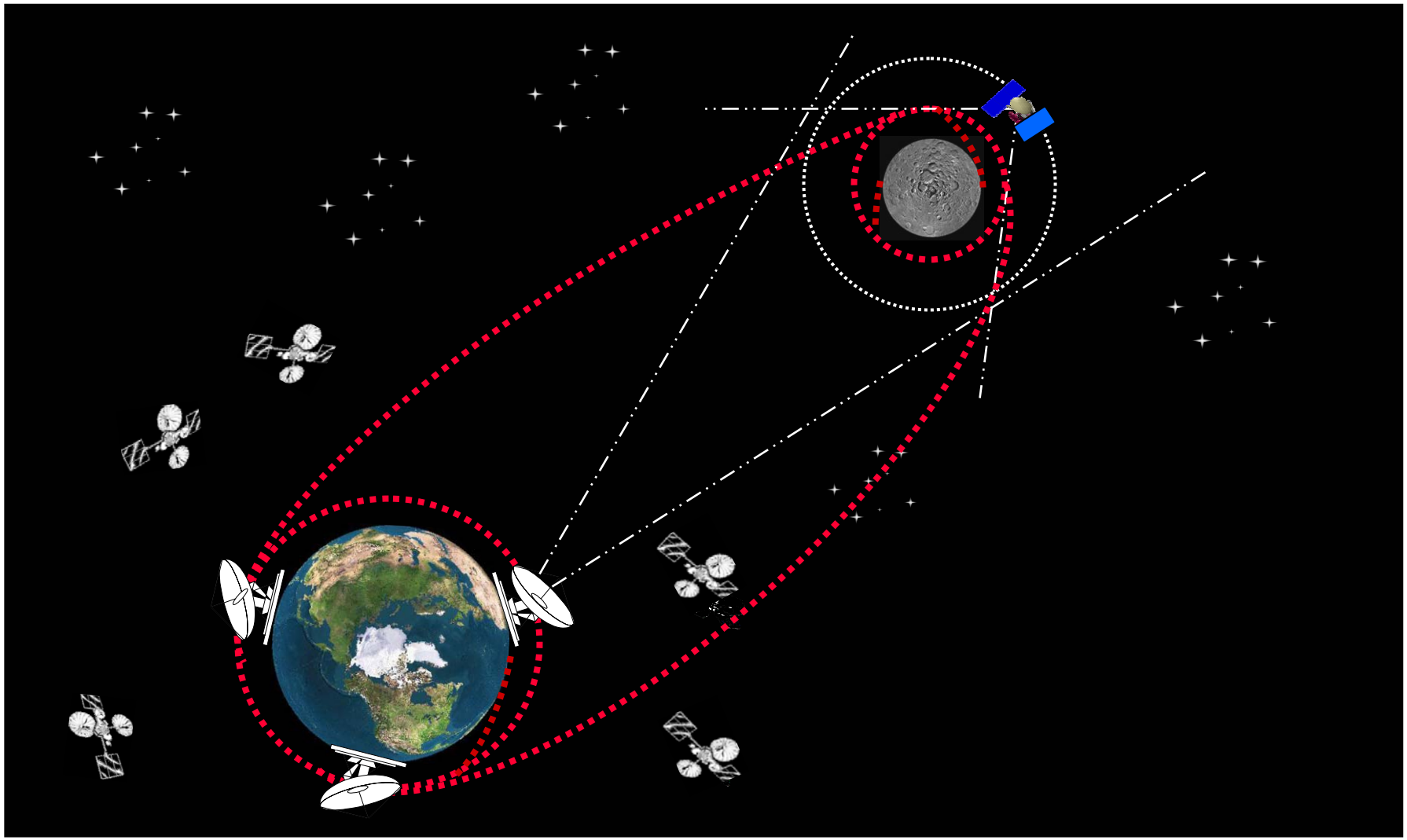
NO EXPLORATION





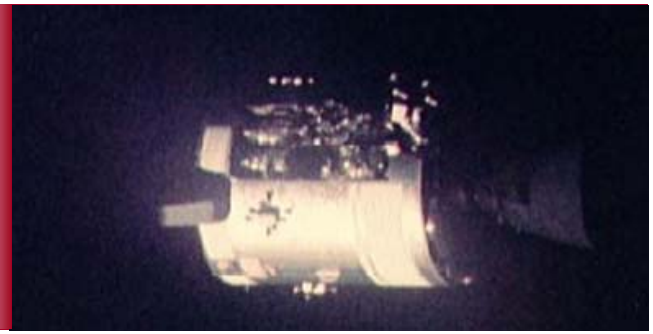


Comm Critical:
All Phases of Flight...



Comm-Critical Mission Safety: Apollo 13 Recovery

The Apollo 13 malfunction was caused by an explosion and rupture of an oxygen tank…All oxygen stores were lost within about 3 hours, along with loss of water, electrical power, and use of the propulsion system.



Communications with the ground support crew enabled dozens of engineers to work to find a solution

Mission Control devised a way to attach the CM canisters to the LM system by using plastic bags, cardboard, and tape- all materials carried on board.

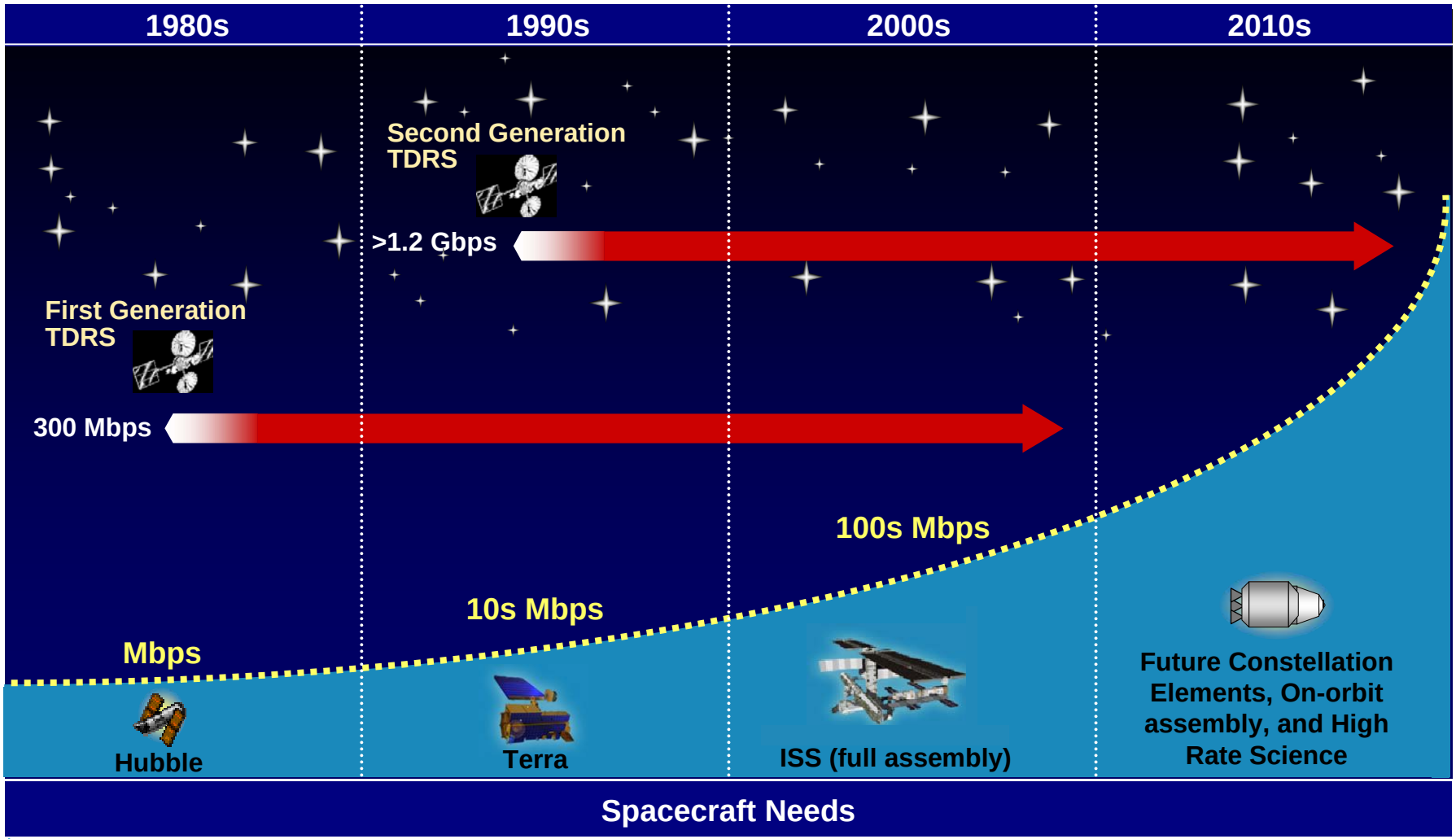
Communications resources should be enabling, not constraining

Photos: http://vesuvius.jsc.nasa.gov/er/seh/13index.htm

Timely Investment Remove Communications Constraints for Users

- **NASA has traditionally made strategic investments in communications capability ahead of user mission need**
  - **Must be available before mission operates**
  - **Long lead times to develop communication systems such as relays require advanced acquisition**
- **Goal for exploration and science communication capability: enable missions by providing ample, unconstraining capability**

Investing: The TDRSS Example



Executive Summary

- **Identify the need for a robust communications and navigation architecture for the success of exploration and science missions**
- **Describe an approach for specifying architecture alternatives and analyzing them**
- **Establish a top level architecture based on a network of networks**
- **Identify key enabling technologies**
- **Synthesize capability, architecture and technology into an initial capability roadmap**

Space Communication Capability Description

The space communication and navigation capability will fully enable evolution of the exploration and science programs.

- **connectivity to exploration and science program vehicles**
- **spacecraft position**
- **transferring mission data**
- **vehicle telemetry**
- **voice and commands**

Agenda

- Benefits of the Communications and Navigation Capability Roadmap
- Capability Roadmap Team
- Capability Description and Capability Breakdown Structure
- Roadmap Process and Approach
- Assumptions and Requirements, Current State-of-the-Art
- Communications and Navigation Capability Roadmap
- Sub-capability Descriptions and Relevant Technologies
- Description of Architecture Options and Recommendations
- Description of Technology Initiatives
  - Benefits
  - Current State of Art
  - Technology Roadmap
  - Technical Challenges
- Summary and Forward Work

Space Communications Working Group

- **Established prior to exploration program**
- **Goals:**
  - **Provide mission supporting communications & navigation system architectures for the agency**
  - **Identify key technologies needed to implement future architectures**
- **Architecture & technology recommended to Multi-Directorate Board**
- **Membership consists of representatives from both communication system providers (SN, GN, DSN) and consumers (All Space Missions)**
- **Approved architectures & technology initiatives provide guidance for budget formulation**

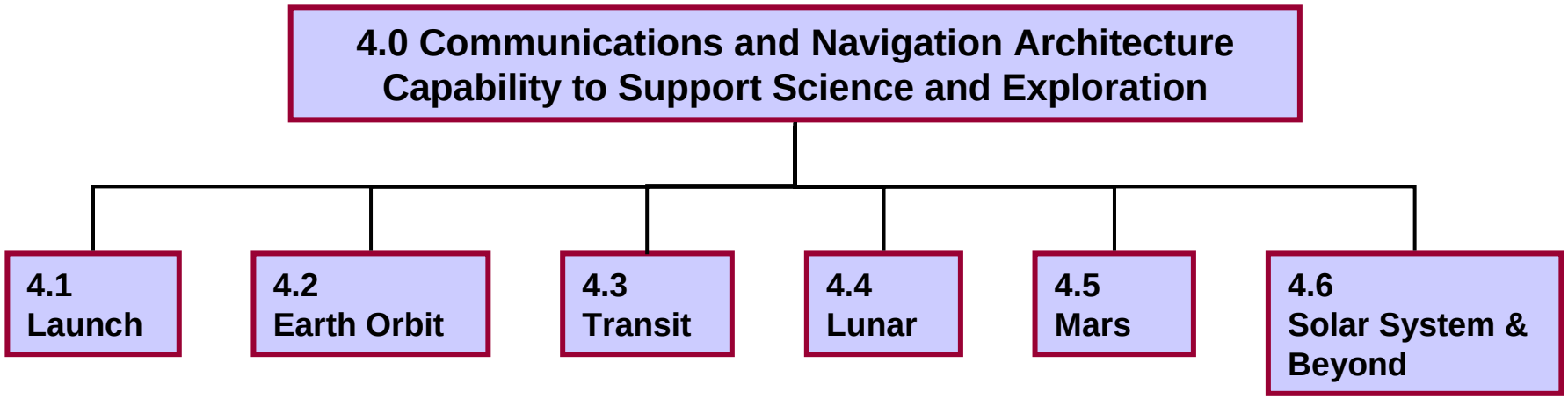
Space Communication Capability — Evolution

- **We have an architecture in place today; this distinguishes comm/nav from most other roadmaps**
- **Must evolve the architecture to meet the future needs of the exploration and science programs**
- **Developing communication/navigation capability requires analysis of architecture alternatives and the enabling technologies**

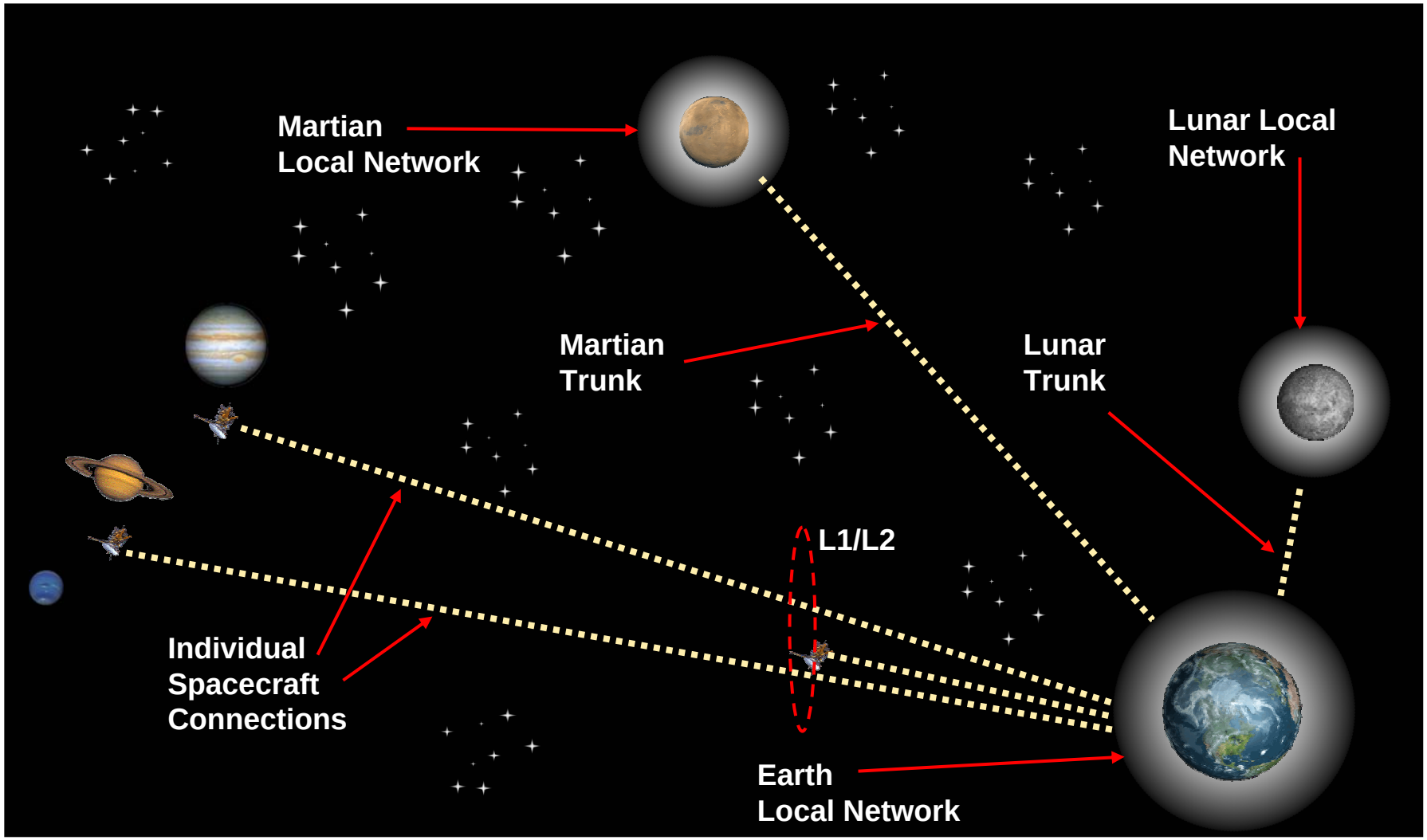
Comm/Nav Capability

Architecture | Technology

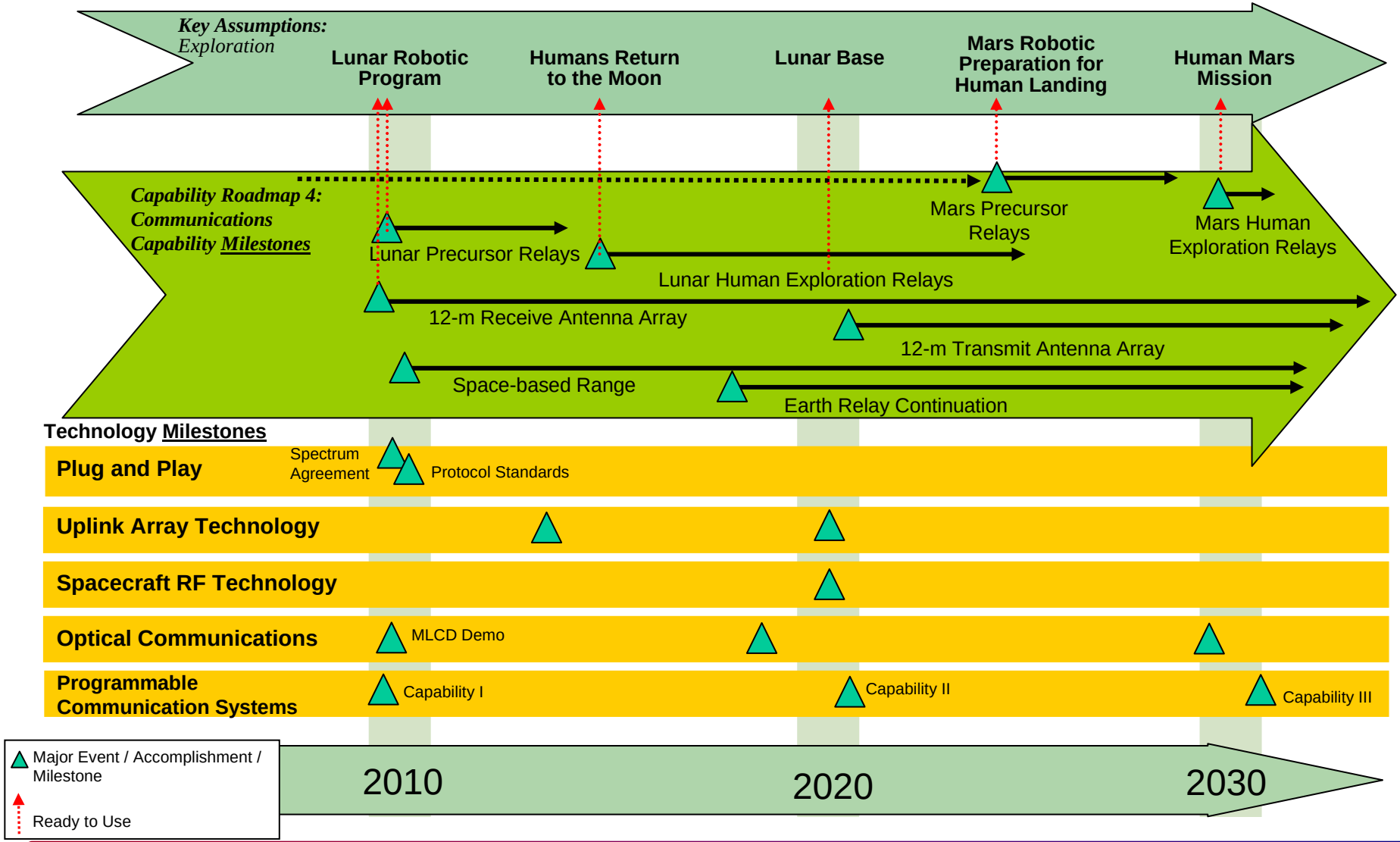
Capability Breakdown Structure: a Services Based Approach



Top Level Conceptual Communication Architecture ~2030



4.0 Communication Capability *Milestones* Roadmap

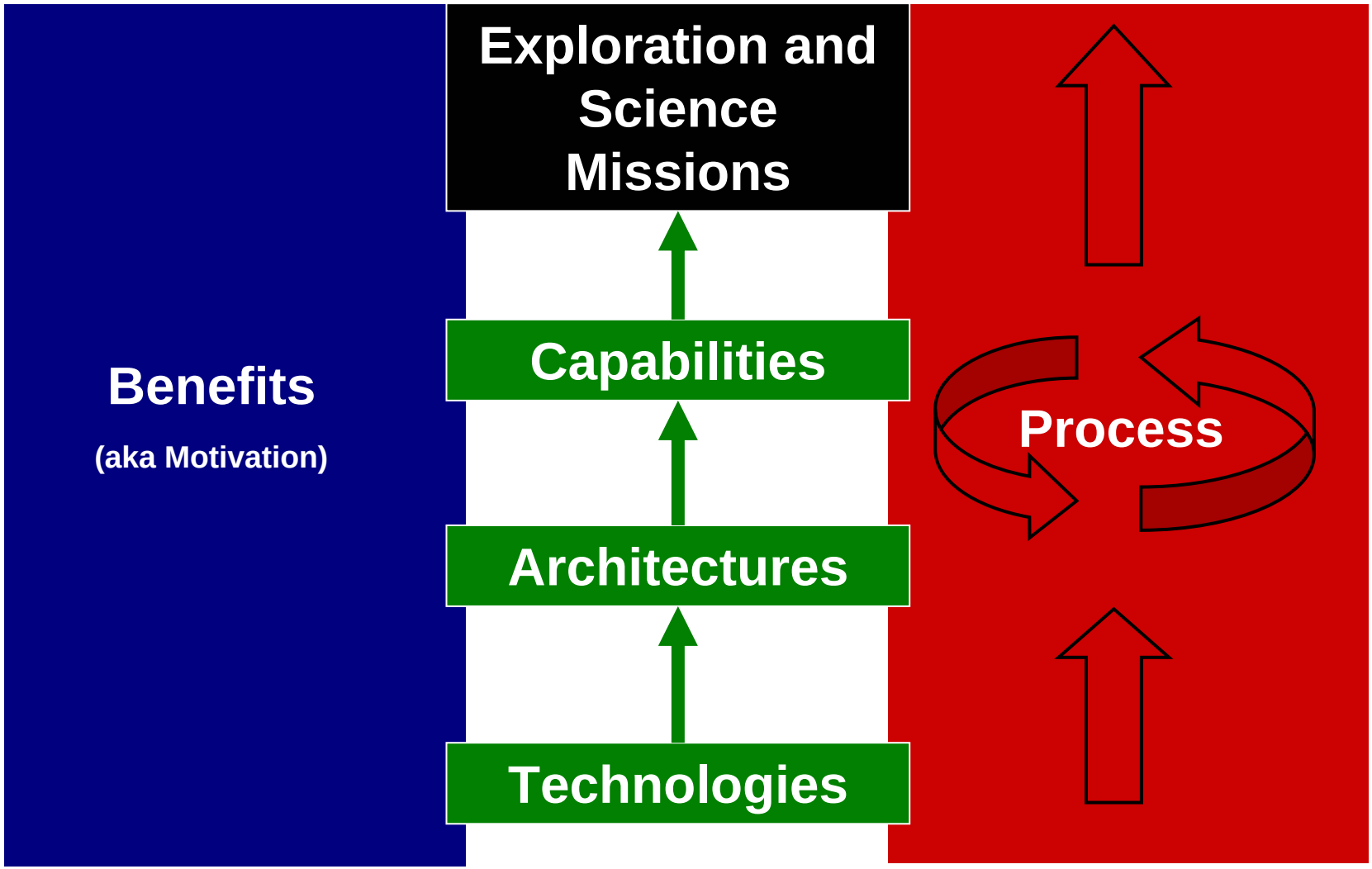


How to Make it Happen

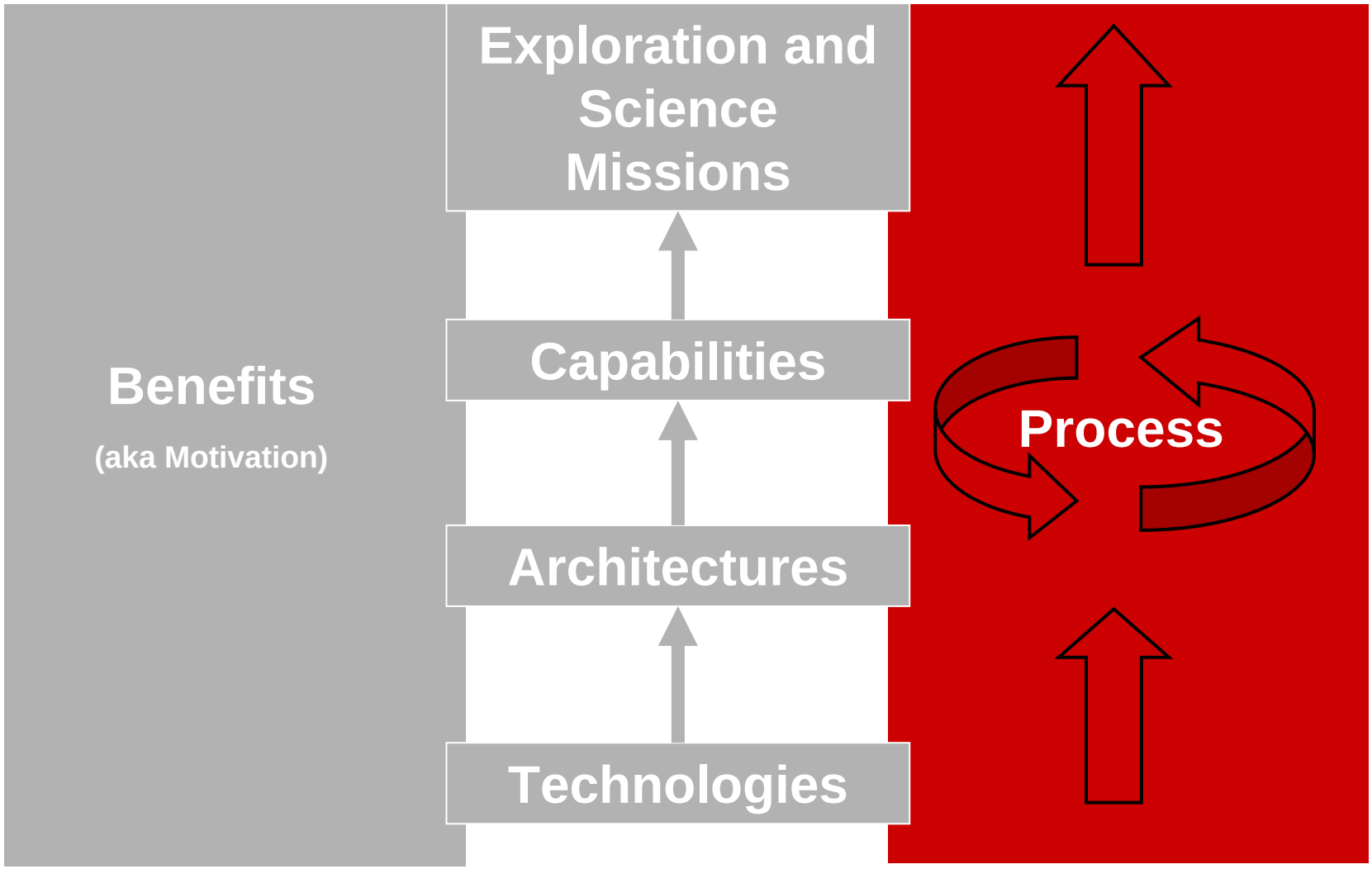
KEY ELEMENTS OF COMM/NAV CAPABILITY	FIGURES OF MERIT
Connectivity	Visibility
	Orbit Stability
	Failure Tolerance
	Navigation Utility
	Mission Evolvability
Bandwidth	Adaptability
	Link Capacity
	Scalability
Positioning	Sustainability
	User Burden

Quantitative technical assessments and qualitative judgments of comm/nav architecture options are a fundamental part of the roadmap process. Cost estimates, in addition to the FOMs, provide a means of assessing the cost-to-benefit of a given option.

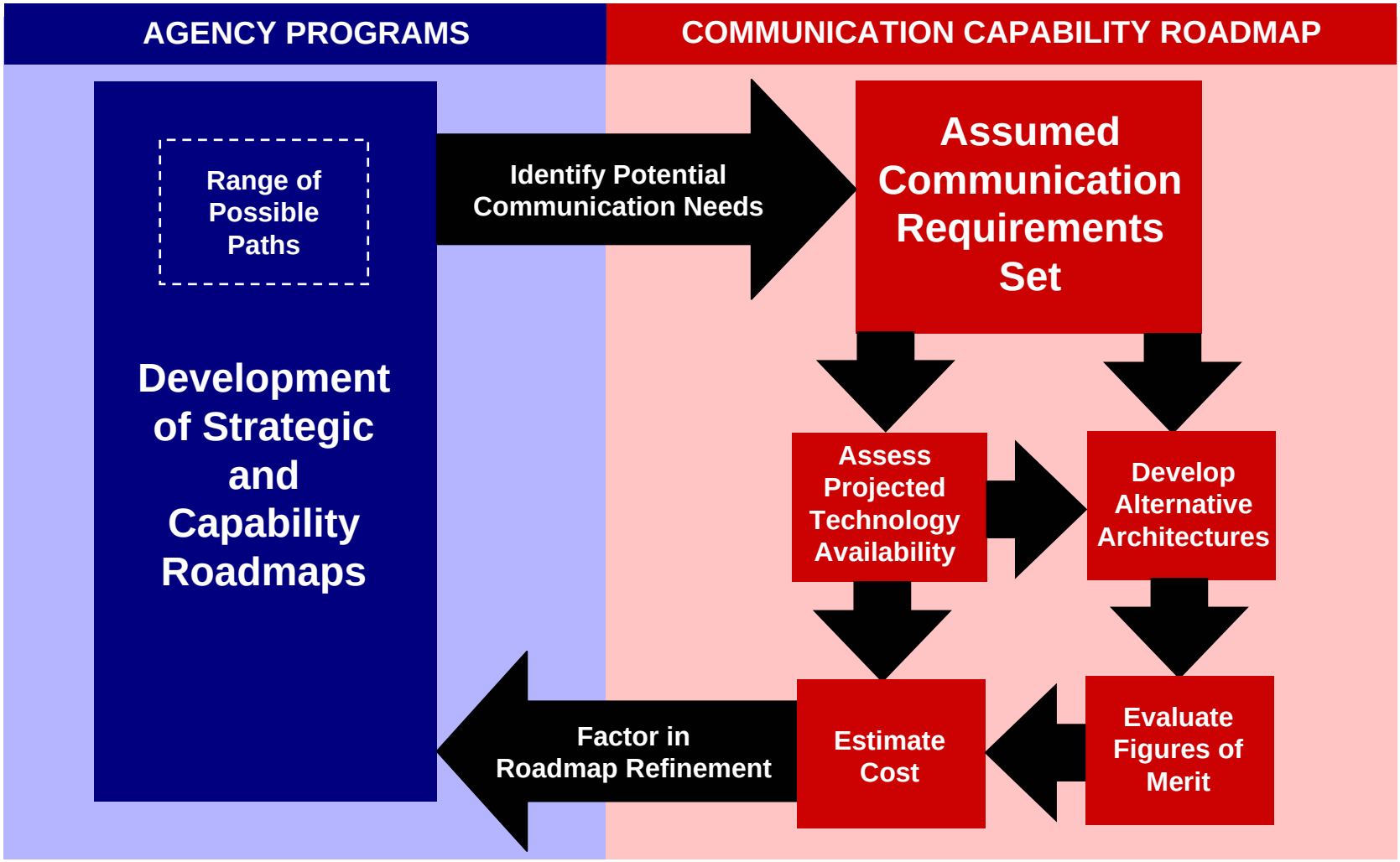
Comm Roadmap Elements



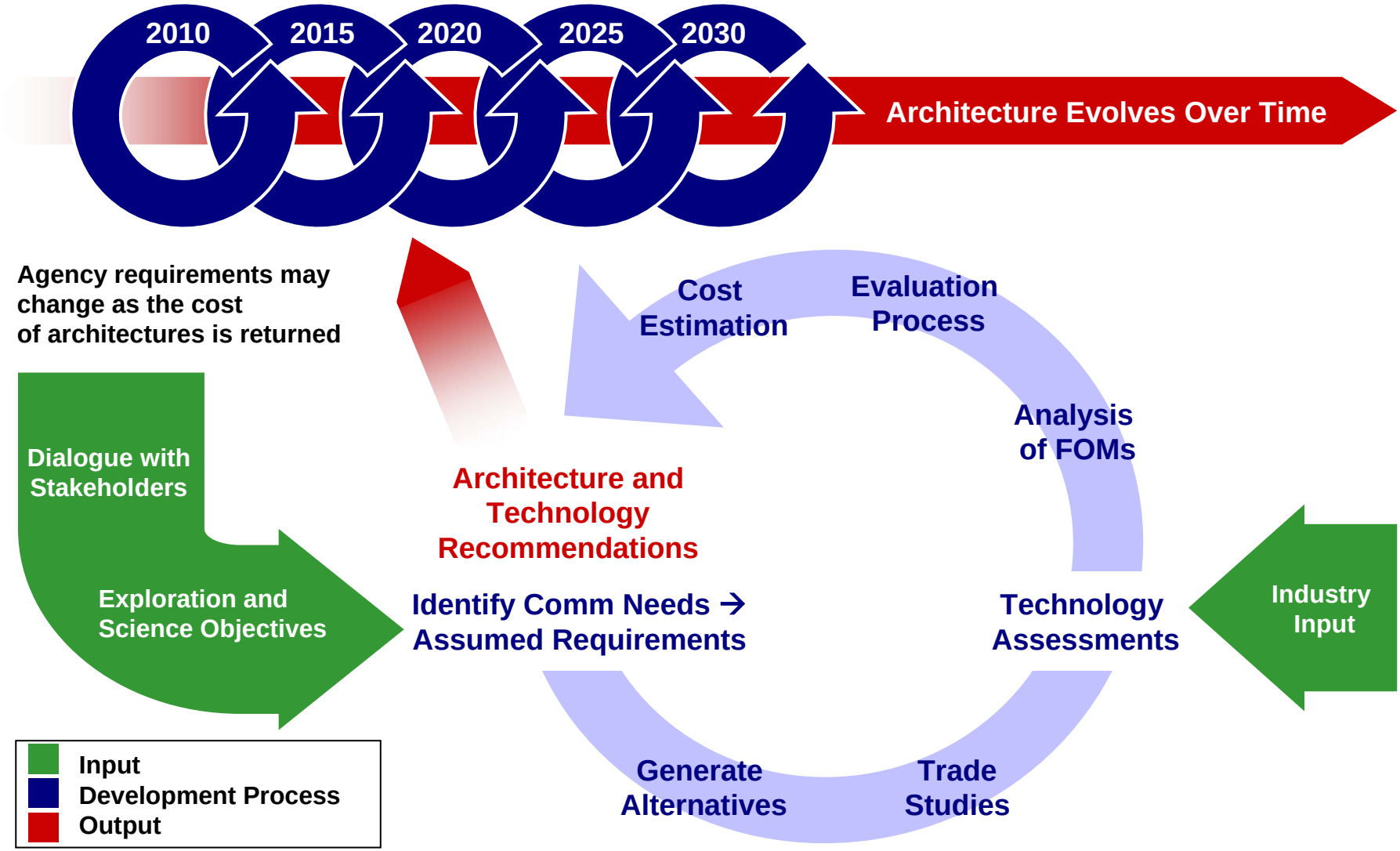
Comm Roadmap Elements



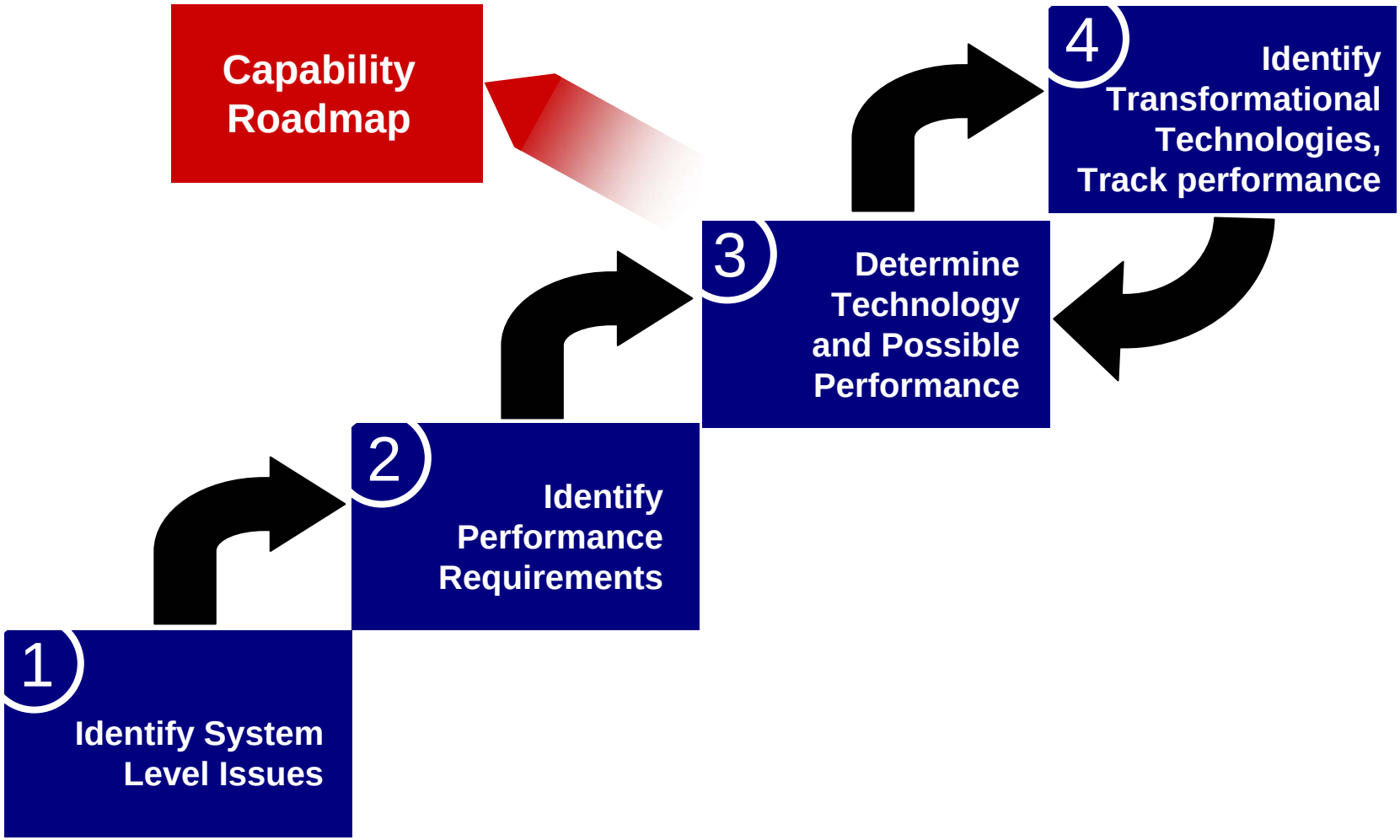
Dealing With Evolving Requirements



Architecture Development Process



Technology Assessment Process



Figures of Merit

FOM	Description
Visibility	Assets must have at least 1 visible relay back to Earth at all times (human missions). 10-degree minimum elevation angle
Orbit Stability	Measure of effort to maintain relay orbits: Delta-V for 5-yr period
Failure Tolerance	Percent visibility with 1 relay lost → % of data volume with 1 loss
Navigation Utility	Accuracy measured by Geometric Dilution of Precision; impact of spatial distribution of navigation data source errors
Mission Evolvability	Ability to modify assets by inserting technology * modifying design to meet changing exploration / science goals. Five criteria: programmability, pre-planned product improvement, open architecture, planned technology insertion, planned utilization
Adaptability	Ability to change operations in response to circumstance/environment change. Two criteria: programmability, operational flexibility
Link Capacity	Combination of aggregate data rate, data volume and latency
Scalability	Ability to expand capacity beyond initial deployment. 8 criteria, as ability to: add relays, add transponders, add frequencies, reuse spectrum, increase efficiency, increase locations served, increase data rates, improve other growth features
Sustainability	Cost to replace relay(s) to maintain a constellation for 5 years
User Burden	Effort required by users to use comm services provided. User burden is standardized, so this FOM is used to penalize options that fail to meet the standard or to reward options that reduce user burden

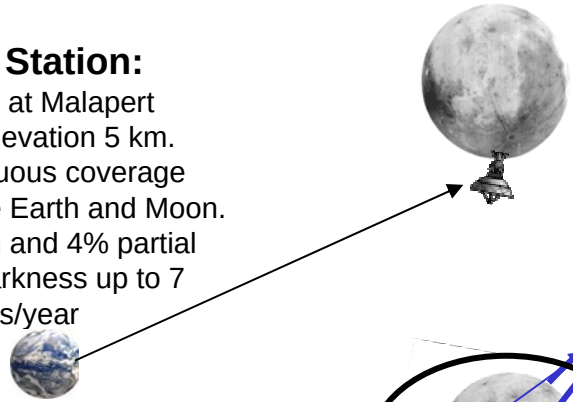
Example of How Process Applies to Evaluation of Lunar Relay Options

- **Scenario: First lunar human landing to be at lunar south pole where line of sight Earth-based communication resources not adequate**
- **Identified 50 candidate architectures**
- **Grouped 50 candidates Into 7 representative classes**
- **Analyzed each class and assessed Figures of Merit**
- **Estimated risk-adjusted cost**
- **Recommendation: Elliptical constellation of 2 satellites (Case 1) focused on lunar south polar coverage provides best overall cost & performance for given scenario**

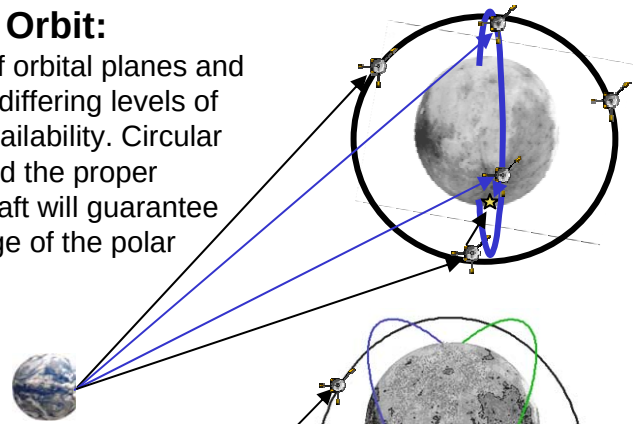
Candidate Architecture Classes: Lunar South Pole 2015

Advanced Planning & Integration Office

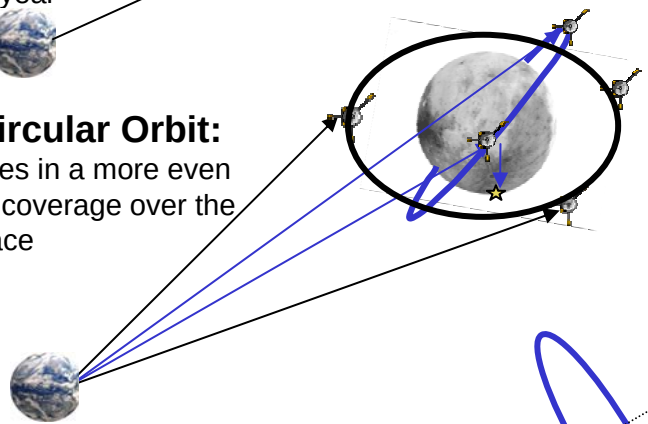
Malapert Station:
Comm base at Malapert Mountain, elevation 5 km. Near-continuous coverage between the Earth and Moon. 89% full sun and 4% partial sun, total darkness up to 7 days, 5 times/year



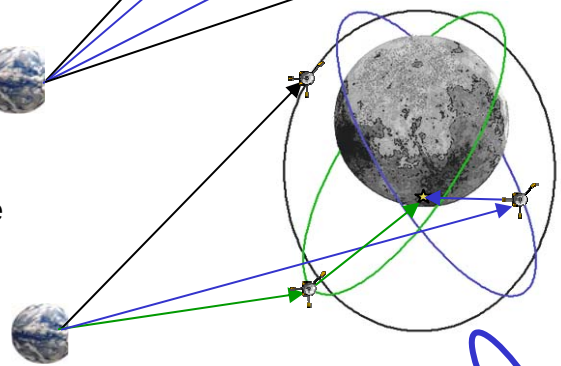
Polar Circular Orbit:
Varying numbers of orbital planes and spacecraft provide differing levels of redundancy and availability. Circular orbits are stable and the proper phasing of spacecraft will guarantee continuous coverage of the polar region.



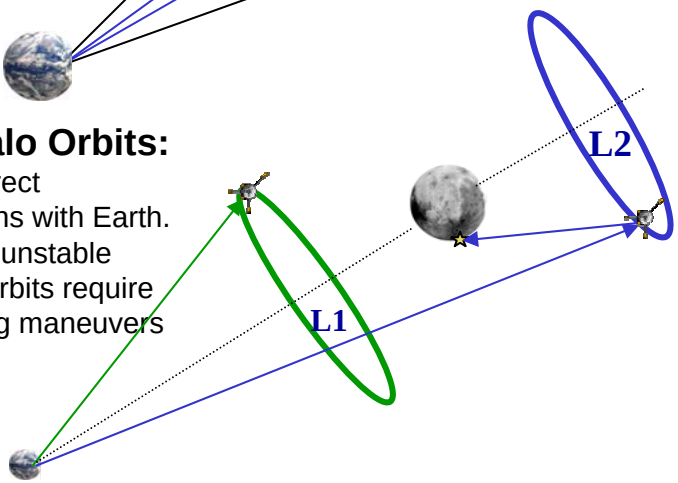
Inclined Circular Orbit:
Inclination aides in a more even distribution of coverage over the full lunar surface



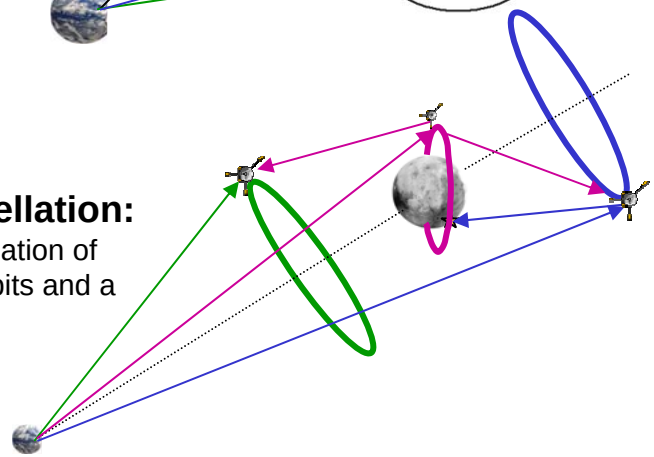
Elliptical Orbit:
Apoapsis beneath the South Pole increases dwell time above that region.



L1 & L2 Halo Orbits:
Continuous direct communications with Earth. L1 and L2 are unstable points, & the orbits require station-keeping maneuvers



Hybrid Constellation:
Example = combination of Lagrange point orbits and a polar orbit.

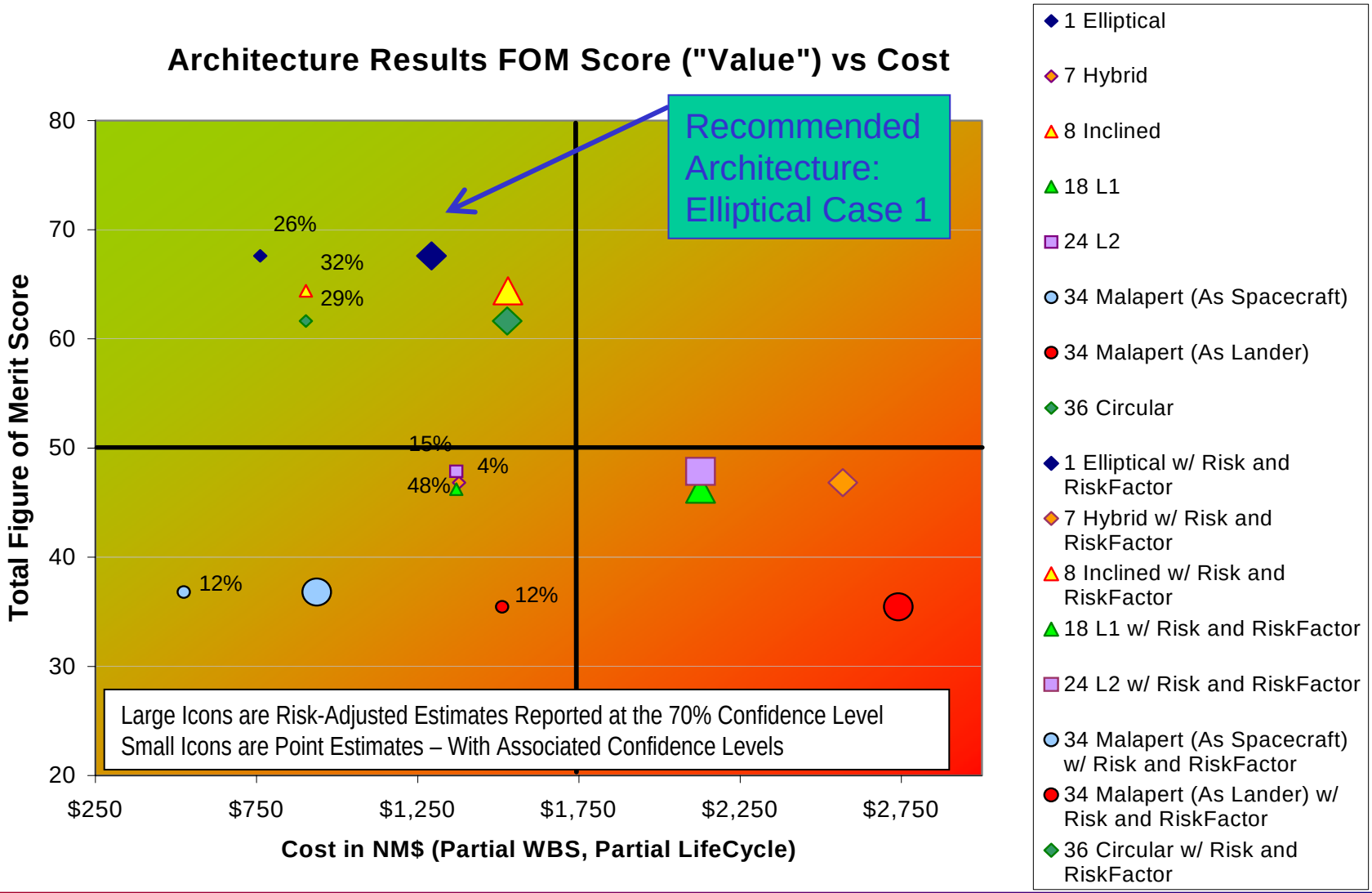


Example FOM Results

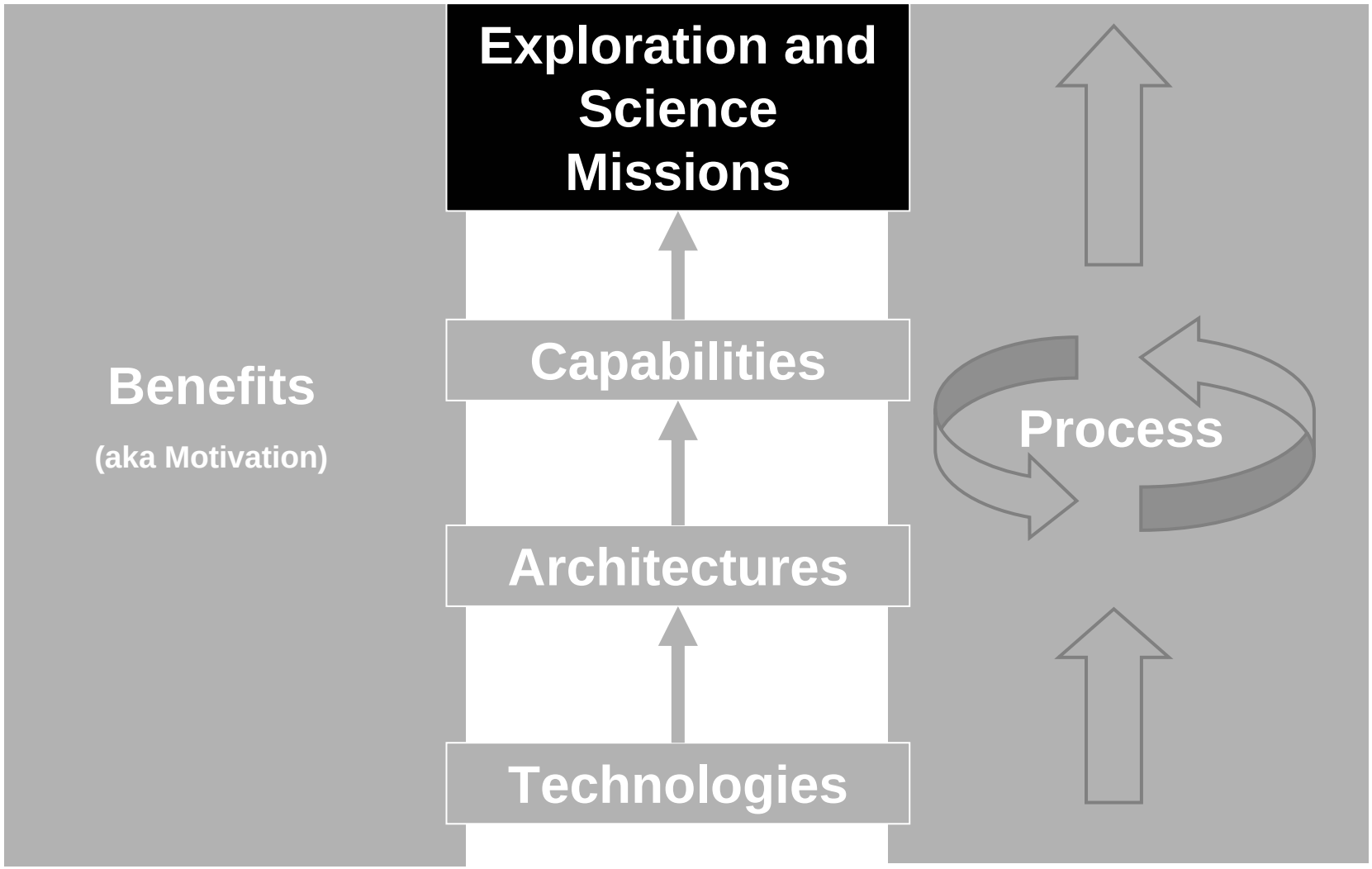
Case # / FOM	Visibility		Orbit Stability	Failure Tolerance	Navigation Utility	Initial Cost	Sustainability
	% of Time, 2+ Relays Visible[1]	% of Polar Cap Area Covered	5 Year Delta V Requirement (m/s)	With 1 Relay "Loss" : % of Time with Visible Relay	Max GDOP, 15 Minute Latency	NM$ for NRE & initial constellation	NM$ for RE replacements over 5 yrs if S/C has 3 yr life
Case 1 Elliptical Orbit: 2 Relays	46	100	0 to 30	73	125	761	313
Case 7 Hybrid Orbit (Polar +Equatorial): 6 Relays	15	100	898	72	2000	1378	863
Case 8 Inclined Circular Orbit: 3 Relays	3	100	81	68	60	903	452
Case 18 L1 Halo: 5 Relays	0	100	375	80	2100[3]	1370	799
Case 24 L2 Halo: 5 Relays	0	100	375	80	2100[3]	1370	799
Case 34 Malapert Lander: Lander = 1 Relay	0	20[2]	0	0	2100[3]	524-1512	157-326
Case 36 Polar Circular Orbit: 3 Relays	2	100	45	67	800	903	452

[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)

Composite FOM vs. Cost Results



Comm Roadmap Elements



First Challenge: Cope with Evolving Requirements

- **Communication capability depends upon answers to key programmatic questions:**
  - **Where in the Universe will communication capability be required?**
  - **When will the exploration program reach the planned destinations?**
  - **When exploration begins at the destination, what kinds of activities Will be executed ?**
- **The exploration program will be evolving over the next few years, and in some respects, over the life of the program**
  - **Final destinations will be determined after initial robotic exploration**
  - **Cost, including communication capability costs, will be a factor in making decisions**
- **At this point in time the initial communications capability architecture must be based on a set of <u>Assumed Requirements</u> to be validated and refined as the exploration program evolves**

Strategy

- **Developing communication capability must start with a base of assumed requirements to guide architecture development**
  - **Will change as exploration program matures**
  - **Must accommodate some decisions being built into exploration plan**
    - **Example: Lunar exploration with robots at South Pole**
    - **Won't know locations for human operations until analyze data from robotic missions**
- **Strategy:**
  - **Provide enough capability so exploration & science programs are not constrained**
  - Flexibility important Figure of Merit in analyzing lunar communication relay architecture alternatives
  - Evolvability/scalability Figure of Merit provides multiple potential paths

Assumed Mission Drivers

- **Continuous connectivity for crew**
- **Coverage of critical maneuvers**
  - **Back-side of the Moon**
  - **Earth orbit**
  - **Back-side of Mars**
- **Vehicle assembly, rendezvous/docking and continuous coverage of component vehicles prior to assembly**
- **Surface operations — connectivity between individual units on the surface must support over-the-horizon comm**
- **Increasing data rates will be required as exploration and science missions embrace new concepts and capabilities**

Assumed Requirements

- **Space-based Range**
  - **Relay telemetry from launch vehicles**
  - **Command destruct capability**
  - **Redundant paths for telemetry**
- **Human space flight in low Earth orbit during assembly of Constellation configuration**
  - **Continuous communication with vehicles and crew**
  - **Coverage of separate vehicles until rendezvous and docking**
  - **Communication services for assembly of second Constellation vehicle in Earth orbit**
  - **Re-entry communications with CEV and crew**
  - **Communication with crew on Earth ocean surface**
- **Robotic missions to the back side of the Moon**
  - **Communication during all critical events**
  - **Communication with lunar surface vehicles and probes that are out of view of Earth-based antennas**
  - **Moderate data rates (100's Mbps) return data from lunar science instruments**
  - **Tracking of low lunar orbiters when ever visible from Earth to address lack of lunar gravity field measurements**

Assumed Requirements (cont'd)

- **Human missions to the Moon**
  - **Continuous communication capability for vehicles and crew**
  - **Communications for critical flight events over the backside of the Moon**
  - **Human surface operations on the back side of the Moon South Pole region requiring voice and data transport services between elements as well as to and from Earth**
- **Robotic missions to Mars**
  - **Connectivity to vehicles during critical events**
  - **Connectivity to vehicles and probes on the Martian surface**
  - **High data rate instruments operating on the Martian surface and in orbit around Mars**
- **Human missions to Mars**
  - **Continuous connectivity supporting Human missions**
  - **Communication supporting operations on the Martian surface including communication between units on the surface and connections to and from Earth**

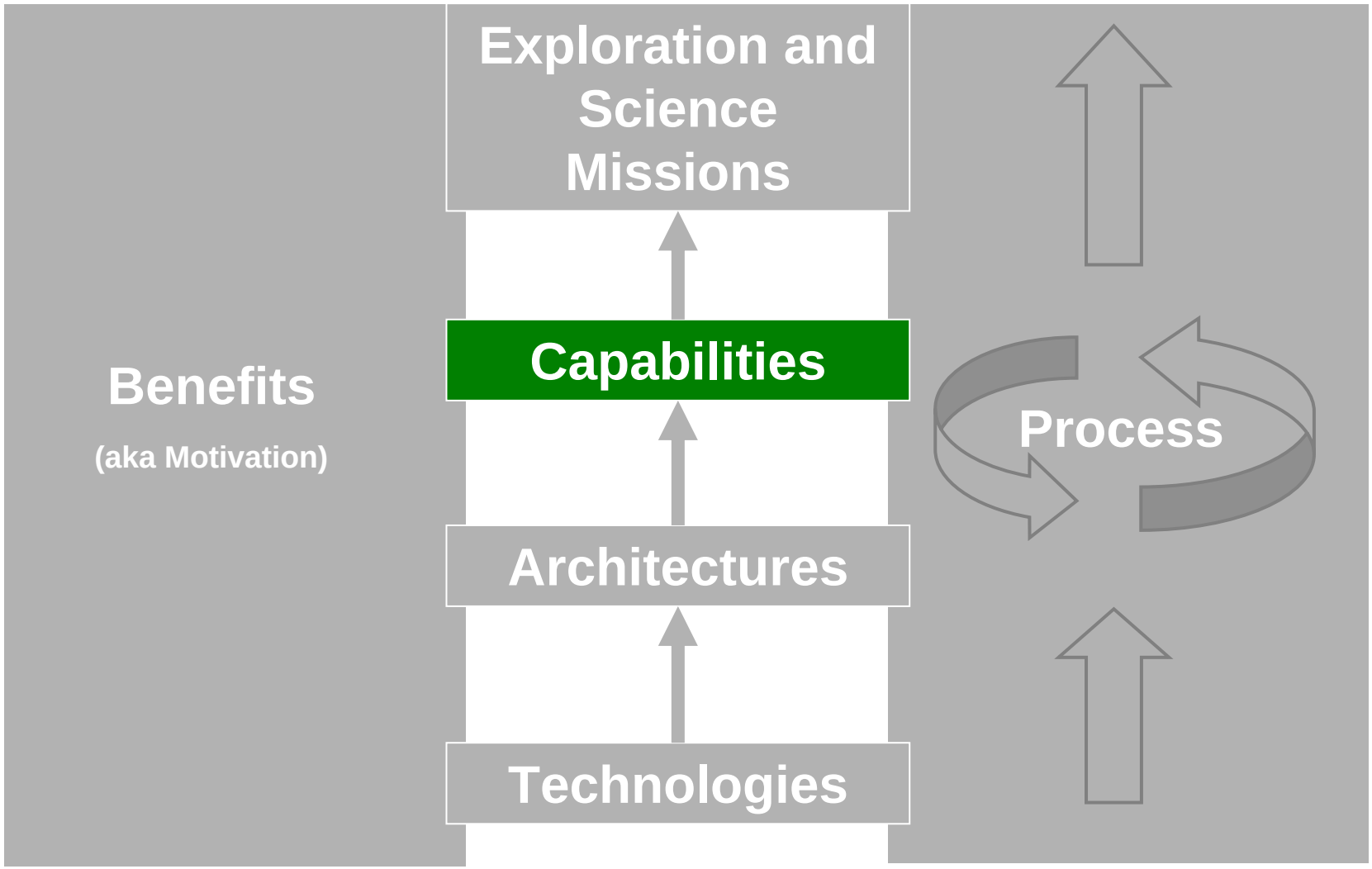
Assumed Data Rate Scenario

- **Data rates are major drivers**
- **Must be developed from assumed activities at destinations**
- **Developed set of characteristic data rates for typical data types (i.e. HDTV, Hyper-spectral imaging, Audio, etc)**
- **Apply data rates to activities**
- **Provides threshold data rates**

Example Service and Data Rate Scenario (Work in progress)

	User	Channel Content	Latency	# of Channels	Channel Rate	Total Rate
Operational	Base	Speech	NRT	2	10 kbps	20 kbps
		Engineering	NRT	1	100 kbps	100 kbps
	Astronauts	Speech	NRT	4	10 kbps	40 kbps
		Helmet camera	NRT	4	100 kbps	400 kbps
		Engineering	NRT	4	20 kbps	80 kbps
	Human Transports	Video	NRT	2	1.5 Mbps	3 Mbps
		Engineering	NRT	2	20 kbps	40 kbps
	Robotic Rovers	Video	NRT	8	1.5 Mbps	12 Mbps
		Engineering	NRT	8	20 kbps	160 kbps
	Science Orbiters	Quick Look	NRT	4	1 Mbps	4 Mbps
		Engineering	NRT	4	20 kbps	80 kbps
High Rate	Base	HDTV	1 day	1	20 Mbps	20 Mbps
	Human Transports	HDTV (PIO)	NRT	2	20 Mbps	40 Mbps
		Hyperspectral Imaging	1 day	1	150 Mbps	150 Mbps
	Robotic Rovers	Surface Radar	1 day	1	100 Mbps	100 Mbps
		Hyperspectral Imaging	1 day	1	150 Mbps	150 Mbps
	Science Orbiters	Orbiting Radar	1 day	2	100 Mbps	200 Mbps
		Hyperspectral Imaging	1 day	2	150 Mbps	300 Mbps
	Total					980 Mbps

Comm Roadmap Elements



Current State of the Art

- **Today NASA Operates Three Communication Networks**
  - **Space Network (SN): A system of Earth relay satellites covering low Earth orbit**
  - **Deep Space Network (DSN): Three global installations with large aperture antennas for communicating with missions operating in Deep Space**
  - **Ground Network (GN): A network of Earth-based ground communications stations primarily used for communicating with satellites in Earth orbit**
- **SN, DSN, and GN have evolved to support NASA's Current Science and Human Space Flight Mission Model**
- **<u>The Future Exploration and Science Mission Set will Require New Communication Capabilities</u>**

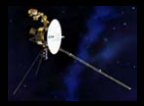
Deep Space Network Today

Inner Planet Missions

Missions Beyond Solar System

Accessible Planetary Surface Missions

Outer Planet Missions

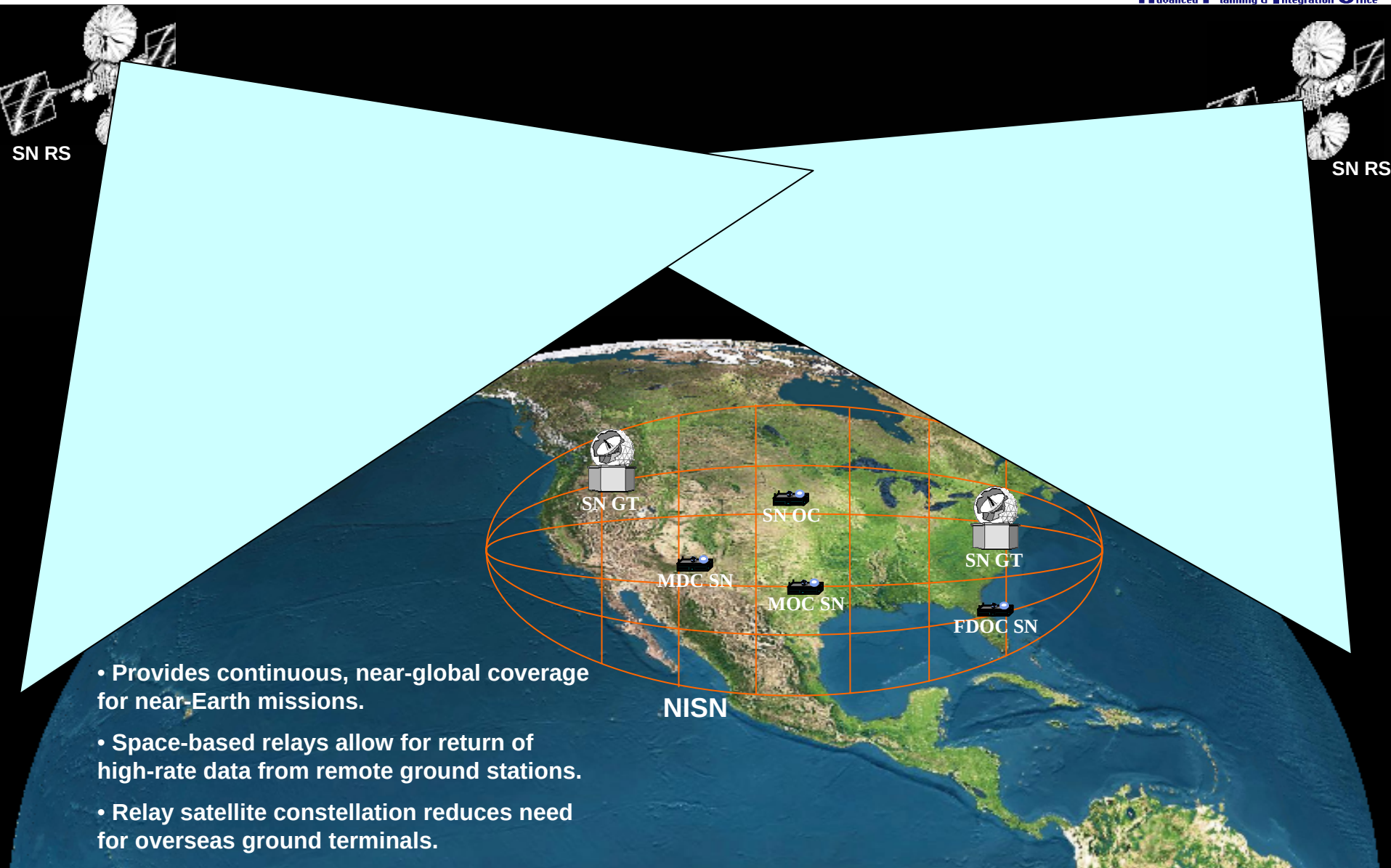


Earth & Earth Orbit Missions

Earth's Neighborhood Missions

- Supports interplanetary spacecraft missions and radio and radar astronomy observations for the exploration of the solar system and the universe.
- Supports selected Earth-orbiting missions (e.g., high Earth orbiting satellites).
- Provides emergency support

Space Network Today



- Provides continuous, near-global coverage for near-Earth missions.
- Space-based relays allow for return of high-rate data from remote ground stations.
- Relay satellite constellation reduces need for overseas ground terminals.

Ground Network Today

Current State-of-the-Art for Communication Capability

- **Current Earth-based Network:**
  - **Communication and tracking services are available for Earth orbiting satellites in any orbit.**
    - **Up to 300 Mbps in Ku-band for low Earth orbiters**
    - **Support for TT&C services in any Earth orbit in S-band**
    - **Ground-based antennas provide communication with satellites in S-, X-, and Ka-bands**
  - **Communication support is available for launch phase of space flight as well as for communication support for re-entry and landing of vehicles.**
    - **Example: Space Network currently provides telemetry support to launch vehicles such as Sea-launch during powered flight**
    - **Example: Space Network provides communication support with Space Shuttle during re-entry including communication through plasma period.**
  - **Communication support for deep space missions including connections with Mars network orbiting relays and surface robots.**

Current State-of-the-Art for Communication Capability

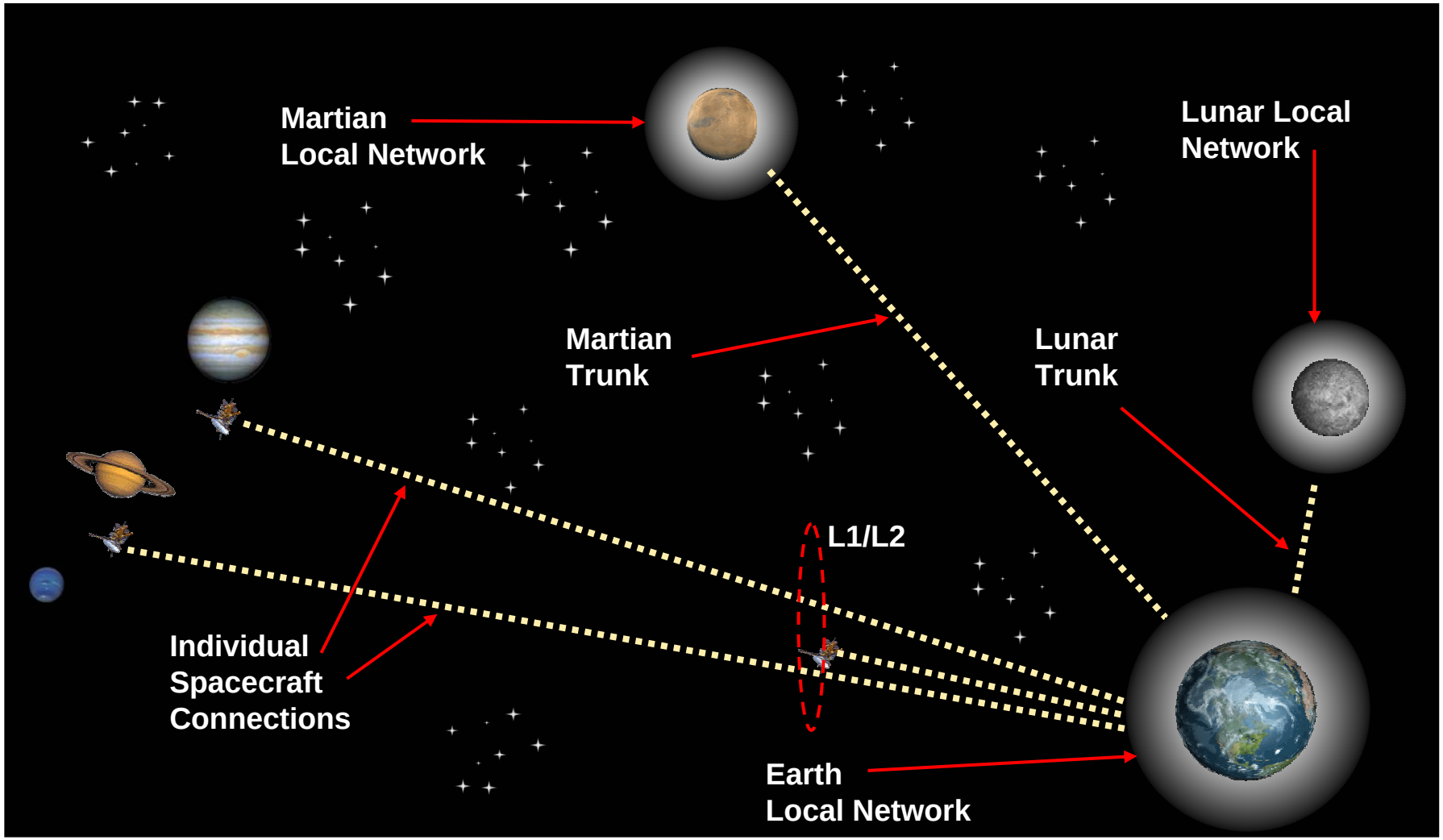
- **Current Lunar network:**
  - **Earth-based DSN antennas can currently provide S-band and X-band coverage of the near side of the moon.**
  - **No capability is in place that allows communication to the back side of the moon**

- **Current Mars Network:**
  - **Communication relay services for two Mars surface exploration robot connections with Earth**
    - **NASA Relay capability**
    - **One ESA Relay enabled by common frequency / communication protocols**
  - **Relay communications are conducted in UHF for proximity communications with robots on the surface of Mars and in X-band for high rate mission data relays back to Earth.**

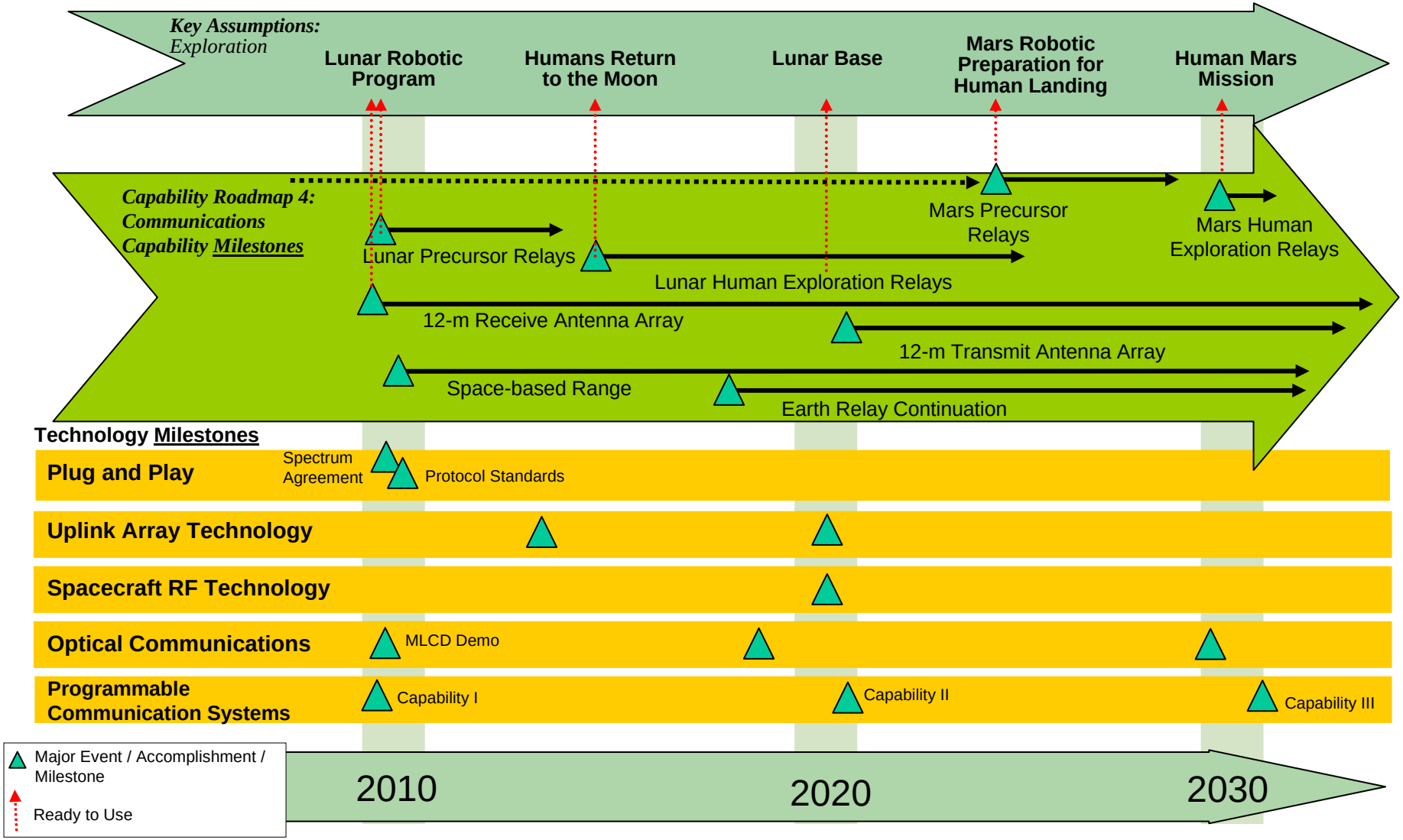
Existing Communication Capability Not Adequate for Future Exploration Program

- **No lunar backside capability**
- **Limited lunar pole coverage**
- **Limited Mars comm data rates and numbers of connections**
- **Option to include international spacecraft limited by no Spectrum, protocol, network agreement for Moon/Mars**
- **Limited precision lunar and Mars navigation capability**
- **Space-based range capability does not meet rigor required by DoD/NASA concept**
- **Existing Earth-based relay (TDRSS) will suffer attrition over next few years if not replenished**
- **Large aperture DSN antennas (26m, 70m, 34m) aging & must be maintained / replaced over next few years**

Top Level Communication Architecture ~2030



4.0 Communication Capability *Milestones* Roadmap



Capability Breakdown Structure

Advanced Planning & Integration Office

4.0 Communications and Navigation Architecture Capability to Support Science and Exploration

4.1 Launch

- 4.1.1 Global Coverage
- 4.1.2 Assured Comm
- 4.1.3 Tracking
- 4.1.4 Telemetry
- 4.1.5 Command Destruct

4.2 Earth Orbit

- 4.2.1 Tracking
- 4.2.2 Telemetry
- 4.2.3 Commanding
- 4.2.4 Mission Data
- 4.2.5 Spacecraft Anomaly Support

4.3 Transit

- 4.3.1 Tracking
- 4.3.2 Telemetry
- 4.3.3 Commanding
- 4.3.4 Mission Data
- 4.3.5 Spacecraft Anomaly Support

4.4 Lunar

- 4.4.1 Positioning
- 4.4.2 Telemetry
- 4.4.3 Commanding
- 4.4.4 Mission Data
- 4.4.5 Spacecraft Anomaly Support
- 4.4.6 Crew Support

4.5 Mars

- 4.5.1 Positioning
- 4.5.2 Telemetry
- 4.5.3 Commanding
- 4.5.4 Mission Data
- 4.5.5 Spacecraft Anomaly Support
- 4.5.6 Crew Support

4.6 Solar System & Beyond

- 4.6.1 Positioning
- 4.6.2 Telemetry
- 4.6.3 Commanding
- 4.6.4 Mission Data
- 4.6.5 Spacecraft Anomaly Support

Capability / System Relationships

High Level Capability *(Support & Service Provided to Operations)*	System of Systems					
	Terrestrial Network	Global Positioning System	Earth Stations	Earth Relays	Lunar Relays	Mars Relays
4.1 Launch	X	X	X	X		
4.2 Earth Orbit	X	X	X	X		
4.3 Transit	X		X	X	X	X
4.4 Lunar	X		X Near-side only		X	
4.5 Mars	X		X			X
4.6 Solar System & Beyond	X		X			

Capability / System Relationship: Milestones

High Level Capability *(Support & Service Provided to Operations)*	System of Systems								
	Terrestrial Network	Global Positioning System	Earth Stations		Earth Relays	Lunar Relays		Mars Relays	
	Milestone Developments								
			Ka-band Receive Antenna Array	Uplink Antenna Array	Earth Relay Cont.	Lunar Precursor Relays	Lunar Human Explor -ation Relays	Mars Precursor Relays	Mars Human Explor-ation Relays
Operational Period			2008 +	2025 +	2015 +	2008 to ~2012	2015 +	2025 to 2030	2030+
4.1 Launch					X				
4.2 Earth Orbit					X				
4.3 Transit			X**	X	X	X	X	X	X
4.4 Lunar			X			X	X		
4.5 Mars			X**	X				X	X
4.6 Solar System & Beyond			X**	X					

**** Scalability: Antennas added to the array in future years when needed**

4.1 Launch Support Capability

4.1 Launch			Technologies
Sub-Capability	*Description*	*Systems*	
4.1.1 Global Coverage	Comm must be available for launches from anywhere	Earth Relays	
4.1.2 Assured Comm	Redundant spacecraft for each launch site	Earth Relays	Low weight, low power, high reliability transceivers
4.1.3 Tracking	Launch Vehicle autonomous position determination	GPS	Autonomous position determination→ software algorithms
4.1.4 Telemetry	High and low rate telemetry data transfer from the launch vehicle	Earth Relays Earth Stations	High gain antennas for launch vehicles
4.1.5 Command Destruct	Manually initiated destruct command for anomalous launch vehicle operation	Earth Relays Earth Stations	

4.2 Earth Orbit Support Capability

4.2 Earth Orbit			Technologies
Sub-Capability	*Description*	*Systems*	
4.2.1 Tracking	Spacecraft position determination	GPS	Programmable Communication Systems
4.2.2 Telemetry	Transfer of spacecraft health and safety data to mission control centers	Earth Relays Earth Stations	
4.2.3 Commanding	Transfer of commands to spacecraft in Earth-orbit from mission control centers	Earth Relays Earth Stations	
4.2.4 Mission Data	Transfer of spacecraft science data from onboard instruments to mission data centers	Earth Relays Earth Stations	
4.2.5 Spacecraft Anomaly Support	Transfer of emergency telemetry and commanding to support recovery of anomalous spacecraft operations	Earth Relays Earth Stations	

4.3 Transit Support Capability

4.3 Transit			Technologies
Sub-Capability	*Description*	*Systems*	
4.3.1 Tracking	Spacecraft position determination	Earth Stations User Spacecraft (On-board autonomy)	Programmable Communication Systems Autonomous Navigation Technologies Spacecraft RF Technology
4.3.2 Telemetry	Transfer of spacecraft health and safety data to mission control centers	Earth Stations Lunar Relays Mars Relays	
4.3.3 Commanding	Transfer of commands to spacecraft in transit (to Moon, Mars, or outer planets) from mission control centers	Earth Stations Lunar Relays Mars Relays	
4.3.4 Mission Data	Transfer of spacecraft science data from onboard instruments to mission data centers	Earth Stations Lunar Relays Mars Relays	
4.3.5 Spacecraft Anomaly Support	Transfer of emergency telemetry and commanding to support recovery of anomalous spacecraft operations	Earth Stations Lunar Relays Mars Relays	

4.4 Lunar Support Capability

4.4 Lunar			Technologies
Sub-Capability	*Description*	*Systems*	
4.4.1 Positioning	Spacecraft position determination in Lunar orbit and on the surface	TBD	Programmable Communication Systems Autonomous Navigation Technologies Spacecraft RF Technology
4.4.2 Telemetry	Transfer of spacecraft health and safety data to mission control centers	Earth Stations Lunar Relays	
4.4.3 Commanding	Transfer of commands to spacecraft in Lunar-orbit and on the surface from mission control centers	Earth Stations Lunar Relays	
4.4.4 Mission Data	Transfer of spacecraft science data from on-orbit or surface-deployed instruments to mission data centers	Earth Stations Lunar Relays	
4.4.5 Spacecraft Anomaly Support	Transfer of emergency telemetry and commanding to support recovery of anomalous spacecraft operations	Earth Stations Lunar Relays	
4.4.6 Crew Support	Robust comm and nav support for human exploration vehicles and personnel during Lunar orbit and/or surface operations; includes two-way voice and video transfer	Earth Stations Lunar Relays	

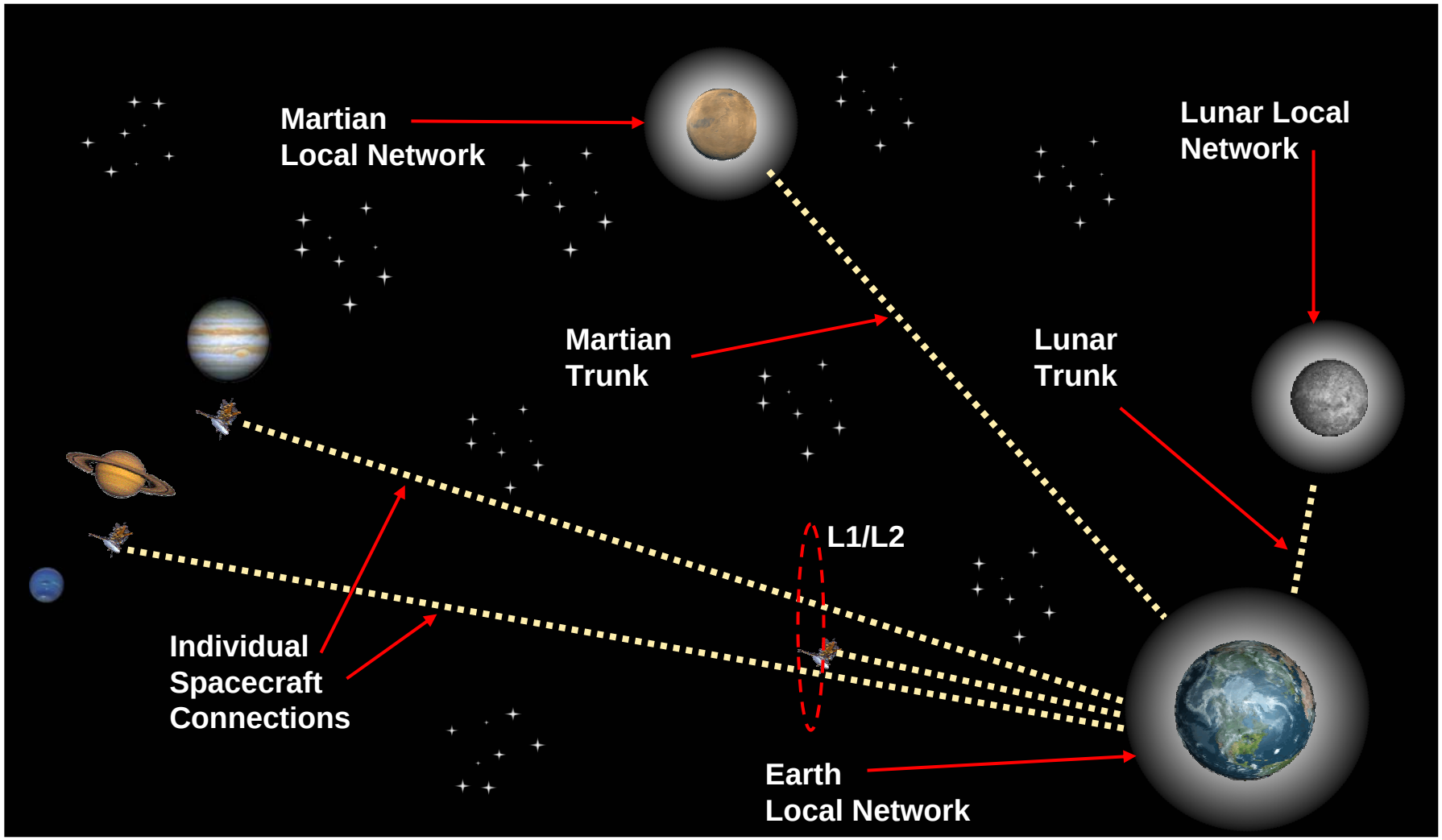
4.5 Mars Support Capability

4.5 Mars			Technologies
Sub-Capability	*Description*	*Systems*	
4.5.1 Positioning	Spacecraft position determination in Mars orbit and on the surface	TBD	Programmable Communication Systems Autonomous Navigation Technologies Spacecraft RF Technology Optical Comm Antenna Array Transmit Technology
4.5.2 Telemetry	Transfer of spacecraft health and safety data to mission control centers	Earth Stations Mars Relays	
4.5.3 Commanding	Transfer of commands to spacecraft in Mars-orbit and on the surface from mission control centers	Earth Stations Mars Precursor Relays Mars Human Exploration Relays	
4.5.4 Mission Data	Transfer of spacecraft science data from on-orbit or surface-deployed instruments to mission data centers	Earth Stations Mars Relays	
4.5.5 Spacecraft Anomaly Support	Transfer of emergency telemetry and commanding to support recovery of anomalous spacecraft operations	Earth Stations Mars Relays	
4.5.6 Crew Support	Robust comm and nav support for human exploration vehicles and personnel during Mars orbit and/or surface operations; includes two-way voice and video transfer	Earth Stations Mars Relays	

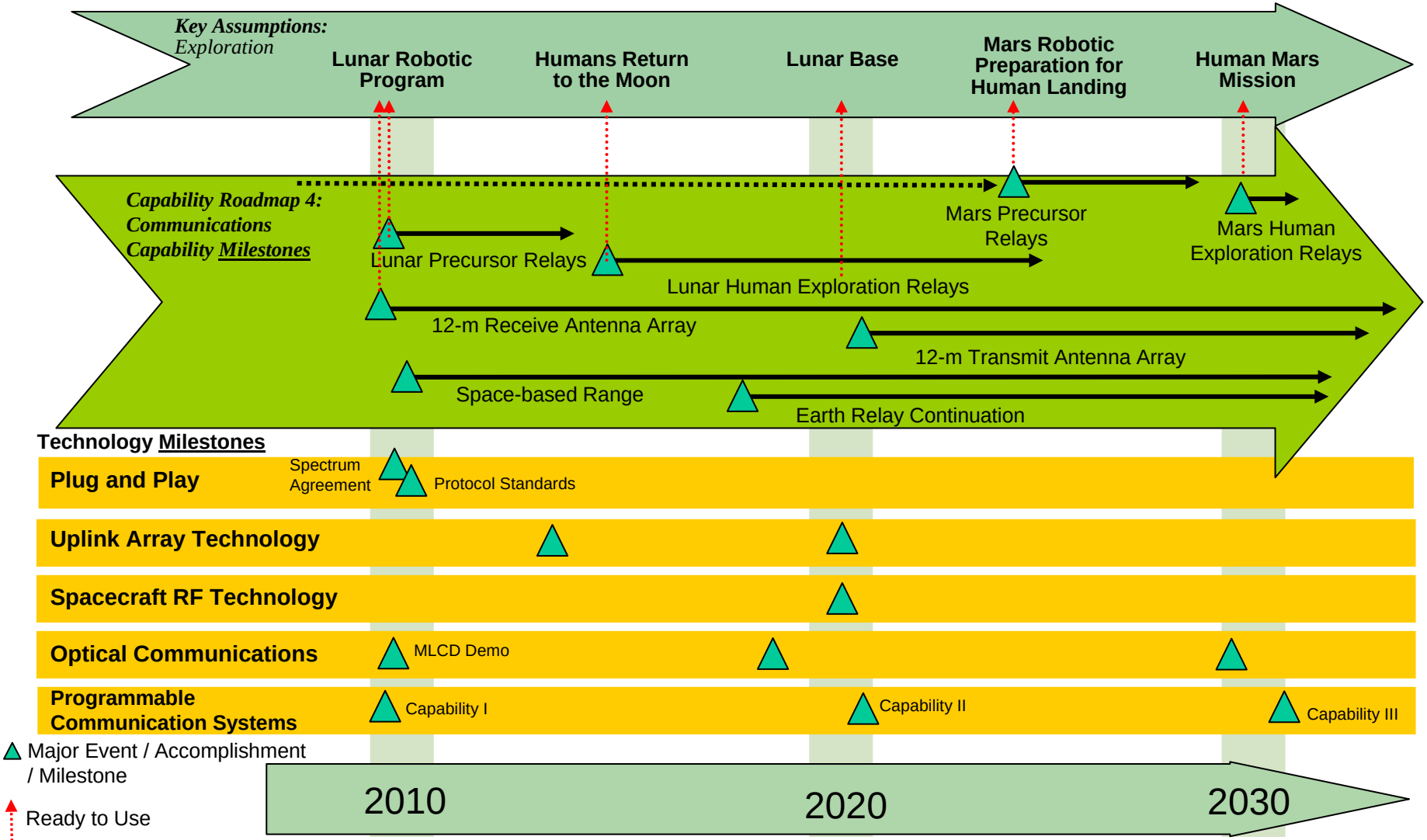
4.6 Solar System & Beyond Support Capability

4.6 Solar System & Beyond			Technologies
Sub-Capability	*Description*	*Systems*	
4.6.1 Positioning	Spacecraft position determination	TBD	Programmable Communication Systems Autonomous Navigation Technologies Spacecraft RF Technology Optical Comm Antenna Array Transmit Technology
4.6.2 Telemetry	Transfer of spacecraft health and safety data to mission control centers	Earth Stations	
4.6.3 Commanding	Transfer of commands to spacecraft at locations in and beyond the solar system from mission control centers	Earth Stations	
4.6.4 Mission Data	Transfer of spacecraft science data from on-orbit and surface-deployed instruments to mission data centers	Earth Stations	
4.6.5 Spacecraft Anomaly Support	Transfer of emergency telemetry and commanding to support recovery of anomalous spacecraft operations	Earth Stations	

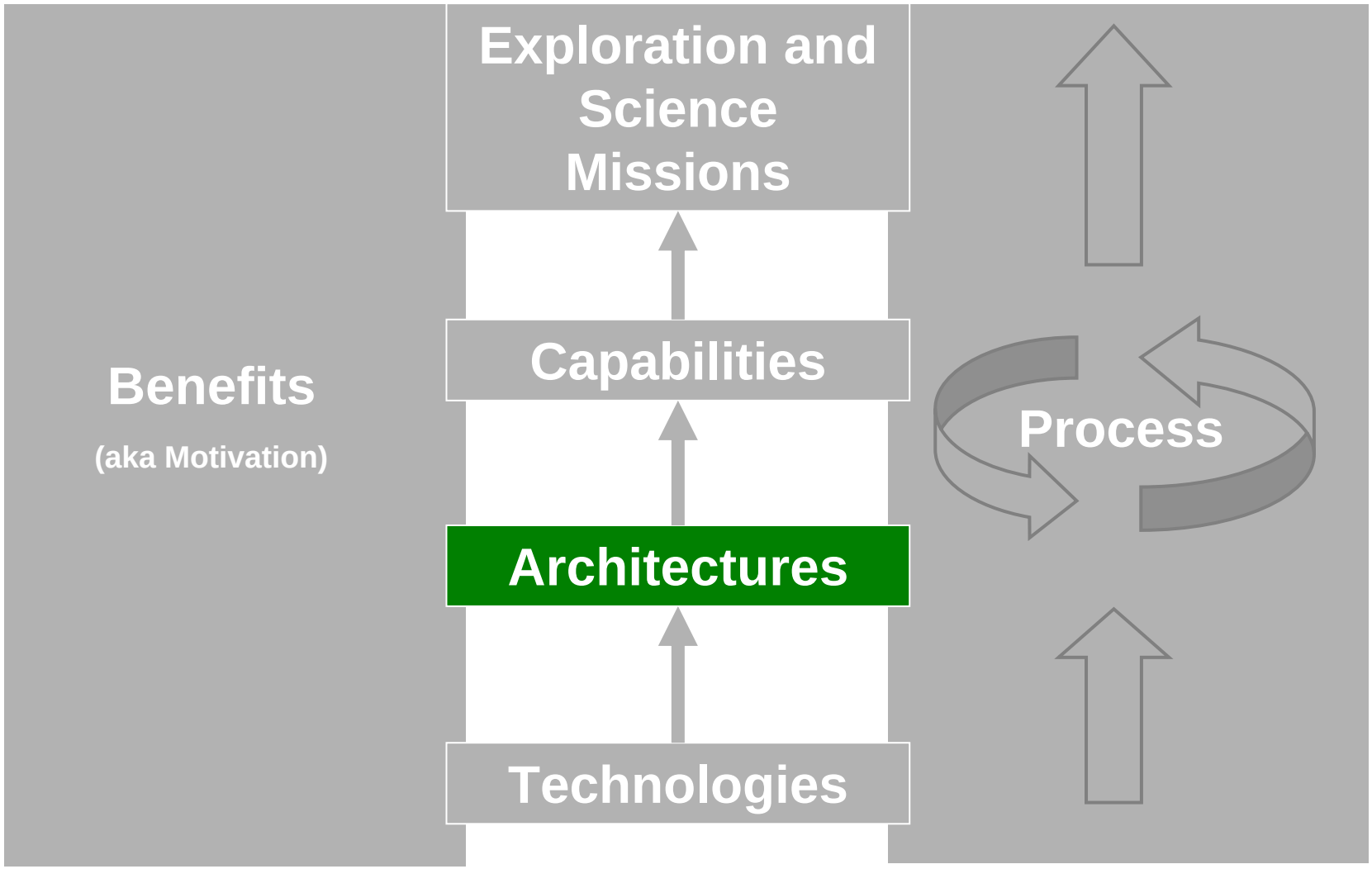
Top Level Communication Architecture ~2030



4.0 Communication Capability *Milestones* Roadmap

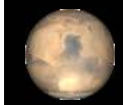


Comm Roadmap Elements



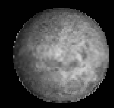
Space Communications Architecture: 2010

Mars Telecom Orbiter:
Relay: UHF & X-Band,CCSDS,Proximity-1, Electra, Steered MGAs



Mars

Moon



Lunar Recon Orbiter (Launch 2008/2009): Carrying S-band proximity comm package and fuel for insertion into comm relay orbit after completing the science mission objectives.
Follow-on RLEP missions will provide continuing relay proximity communications at S-band.

Science & Exploration in 2010

Return to the moon begins with robotic exploration initiatives- search for water, prepare for human landing

Robotic and fly-by exploration continues at Mars and other planets

Earth and Earth-sun system studies continue…

Mission-Direct-to-Earth:
X-band and Ka-Band
Comm Relay(s): Ka-Band and Optical

Comm Relay:
Ka-Band high rate,
S-band TT&C, ranging and Doppler

Solar System and Universe

Space Network: 4 TDRS available; F5, F6, F7, F10. One spacecraft with Ka-band antennas available, all four operate with S and Ku. Emergency TDRS S-band support available: F8 and F9

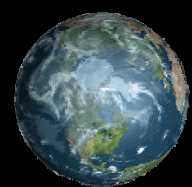
Deep Space Network:
Initial 12-m antenna array capability in place: 4 Ka-band and 2 S-band at 3 locations. Large antennas available: 34-m and 70-m. R&D optical stations.

Ground Network: Commercial S, X and Ka-band stations available. NASA and AFSCN ground stations available for S-band support.

Solar / Stellar Observatory Craft
Deep Space and Fly-by

Mission-Direct-to-Earth: S and X-band

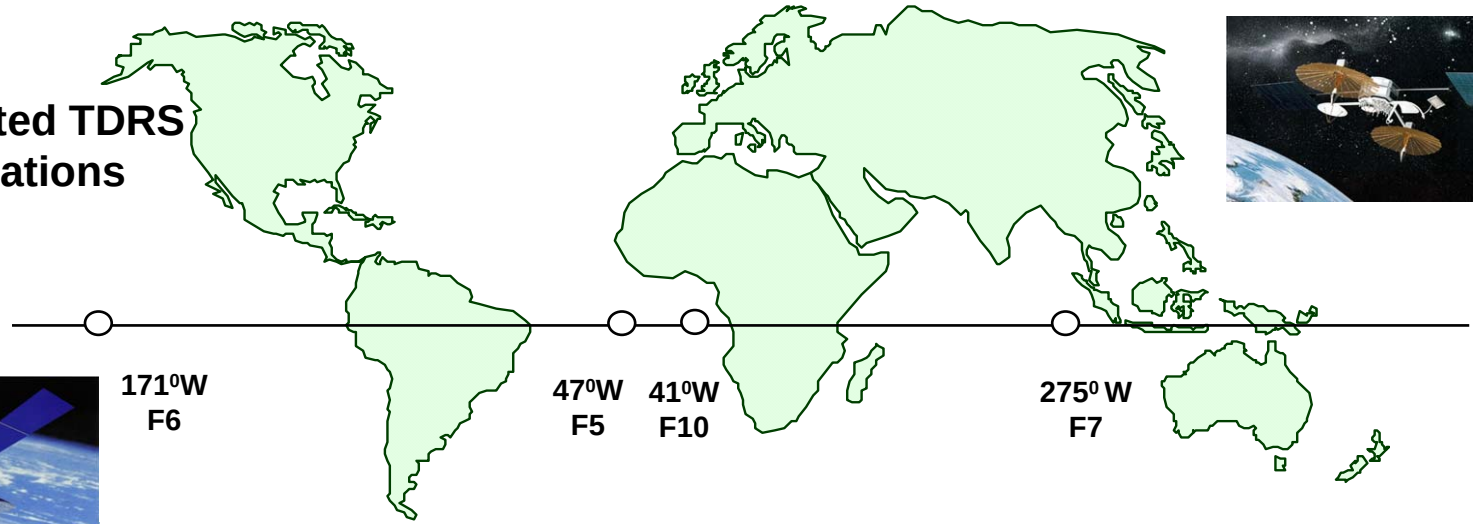
Earth



Space Network 2010
Tracking & Data Relay Satellite System (TDRSS)

Advanced Planning & Integration Office

Allocated TDRS Locations



Candidate Operational Constellation (Based on Reliability and Demand)

Timeframe Modeled	41 Degrees West Longitude		47 Degrees West Longitude		171 Degrees West Longitude		174 Degrees West Longitude		275 Degrees West Longitude		Total No. of SA's
4Q04-4Q06*	2	F10	2	F4	2	F5 **	2	F6	2	F3	10
1Q07-2Q07	2	F10	2	F4	2	F5 **	2	F6	2	F7	10
3Q07-2Q10	2	F10	2	F6	2	F5 **	0	--	2	F7	8
3Q10-2Q12	2	F10	2	F6	0	F5** (MA Only)	0	--	2	F7	6

** KSAF failure on F5 SA #1

Space Network 2010: TDRSS (cont'd)

Service			TDRS 1-7	TDRS 8-10	Notes
Single Access	S-band	FWD	7 Mbps	7 Mbps	No Change
		RTN	6 Mbps	6 Mbps	
	Ku-band	FWD	25 Mbps	25 Mbps	
		RTN	300 Mbps	300 Mbps	
	Ka-band	FWD	N/A	25 Mbps	>300 Mbps available via IF service
		RTN	N/A	300 Mbps/up to 1.2 Gbps*	
	Number of Links per Spacecraft		SSA: 2/TDRS; 10/WSC; 2/GRGT KuSA: 2/TDRS; 10 KuSA/WSC; 2/GRGT	SSA: 2/TDRS; 10/WSC; 2/GRGT KuSA: 2/TDRS; 10 KuSA/WSC; 2/GRGT KaSA: 2/TDRS; 8/WSC;	For TDRS H, I, J simultaneous operation of S & Ku and S & Ka services via a single SA antenna are required
Multiple Access	Number of Links per S/C	FWD	1/TDRS @ up to 300 kbps; 4/WSC; 1/GRGT	1/TDRS @ up to 300 kbps; 4/WSC (8 dB over TDRSS)	Anticipated SSA users < 3 Mbps off-loaded to TDRS H, I, J MA
		RTN	5/TDRS @ up to 300 kbps; 20/WSC; 2/GRGT (does not include DAS)	5/TDRS @ up to 3 Mbps; 20/WSC	
Customer Tracking			150 meters 3 sigma	150 meters 3 sigma	No Change

*Not all spacecraft capabilities (e.g., higher data rates) have been implemented at the ground stations.

Moon Reference Architecture: 2010

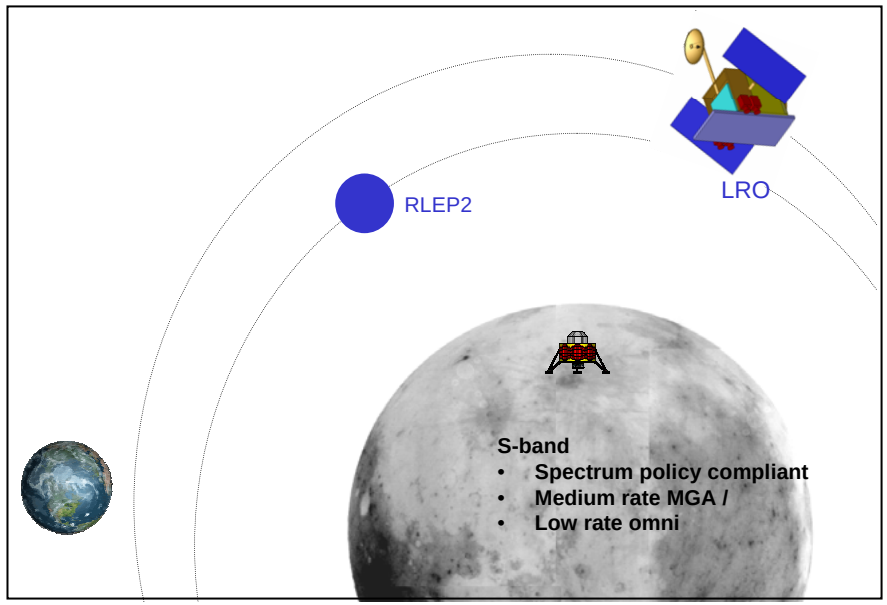
Architecture Elements

Number of spacecraft = LRO + 3 follow-on RLEP missions

Orbits: LRO- Polar Circular, science mission altitude 50 km, relay mission altitude 100 km. RLEP follow-on missions undefined

Spacecraft: Science mission spacecraft with added proximity comm package. Antennas:

- Up/downlink low rate S-band antenna,
- High rate downlink (100-300 Mbps) Ka-band antenna.
- Performance: South Pole coverage, relay connection times to polar surface ~5-10 minutes, sufficient connection for 900 Gb/day



*This architecture is based on the results of a study conducted by the SCAWG in **June/July of 2004** and relied on available mission data and assumptions current at that time.*

Moon Reference Architecture: 2010

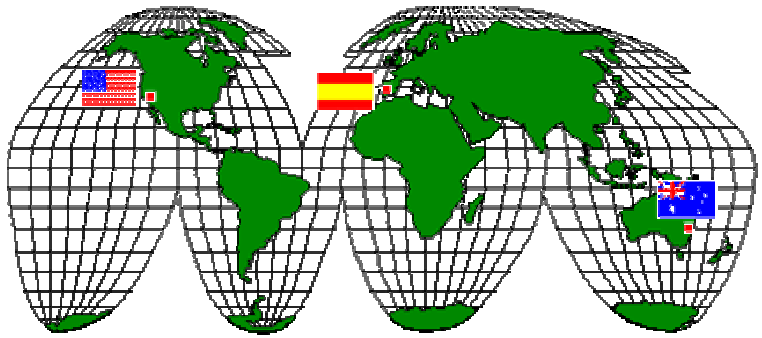
Relationships	Lunar Orbiter to Lunar Surface: S-band proximity link, low data rate to fixed or mobile science missions (penetrators, rovers…)
	Lunar Orbiter to Earth: S-band proximity link, low data rate, up and downlink to DSN Ka-band downlink, high data rate (100-300 Mbps) to DSN
	Standards: CCSDS Proximity-1 protocol for proximity link, DSN protocols for Earth link
Operations	LRO 2008 launch. Annual launches for follow-on RLEP missions. LRO performs 1-year science mission, then transfers to a higher orbit to perform relay mission supporting subsequent RLEP missions.
Assumptions	RLEP proximity comm 1 Mbps RLEP landers do not have LOS to Earth 10-degree min elevation angle Provide coverage for 80° to 90° South

DSN Antenna Array

- **Initial Array in 2010 consists of 4 Ka-band and 2 S-band 12-m antennas at each site**
- Use Arrays of Small Antennas to Build “Virtual” Large Aperture Antennas to Receive High Rate Science Data
  - Antenna Array Concept Used Successfully in the Past (Galileo)
  - Technology Available Now
- Locate Arrays In Three Global Locations for 24/7 Coverage of All Deep Space Missions (Assume DSN Sites but Final Location Requires Further Study)
- Antenna Sub-arrays Can be established to Form Virtual Antennas to Support Separate Missions
- Array Provides Graceful Degradation in Event of Failure

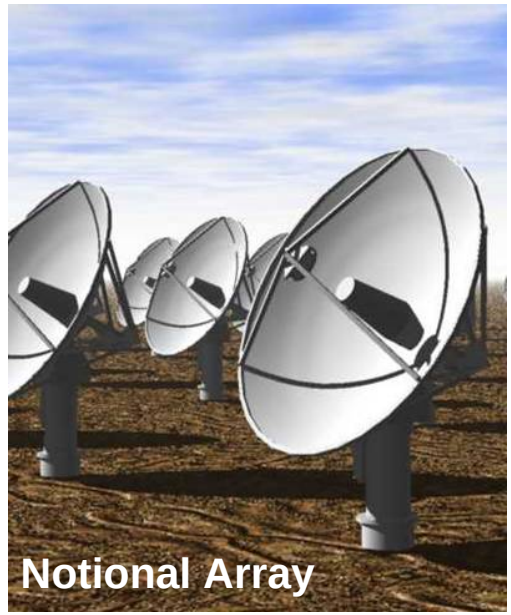
DSN Antenna Array (cont'd)

- Arrays Implement Ka-band Receive Capability Tunable Over All Three Allocated Bands
  - 26 GHz
  - 32 GHz
  - 38 GHz
- All Antennas Are the Same
  - 12 m is Optimum
  - Common Parts Pool / Maintenance Staff
  - 1 Shift Ops for Maintenance



DSN Antenna Array (cont'd)

- Very Scalable Architecture
  - Can Add Antennas in Small Increments
  - Spread Acquisition Over Years for As Needed Build Up
- Transmit of Commands Are Low Data Rate in X-band on Either Array Antennas or 34m
- Recommend Technology Development Effort for Long Term High Rate Transmission with Arrays



Space Communications Architecture: 2015

Mars Telecom Orbiter 2
Follow-on spacecraft to MTO provides relay to scout and large science missions.

Mars

Moon

Elliptical Orbit Relays:
2 TDRS-like spacecraft in a single elliptical orbit, a=6541 km, inclined to 63-deg with apoapsis aligned for South Pole coverage

Scenario:
Lander, 2 rovers, and science platform on lunar south pole surface- humans present.

Science & Exploration in 2015

During the 2015-2020 humans will make the return trip to the Moon. Robotic exploration and in-situ resource utilization and operations will continue.

The Mars Network will support numerous missions…science lab lander, scout missions, etc.

Earth science, astronomy, search for life/origins continues

Bi-directional Ka-band link
500 Mbps return service, 200 Mbps forward service

Solar System and Universe

JIMO and/or
Solar / Stellar Observatory Craft
(+ TBD)

Space Network: TDRSS continuation

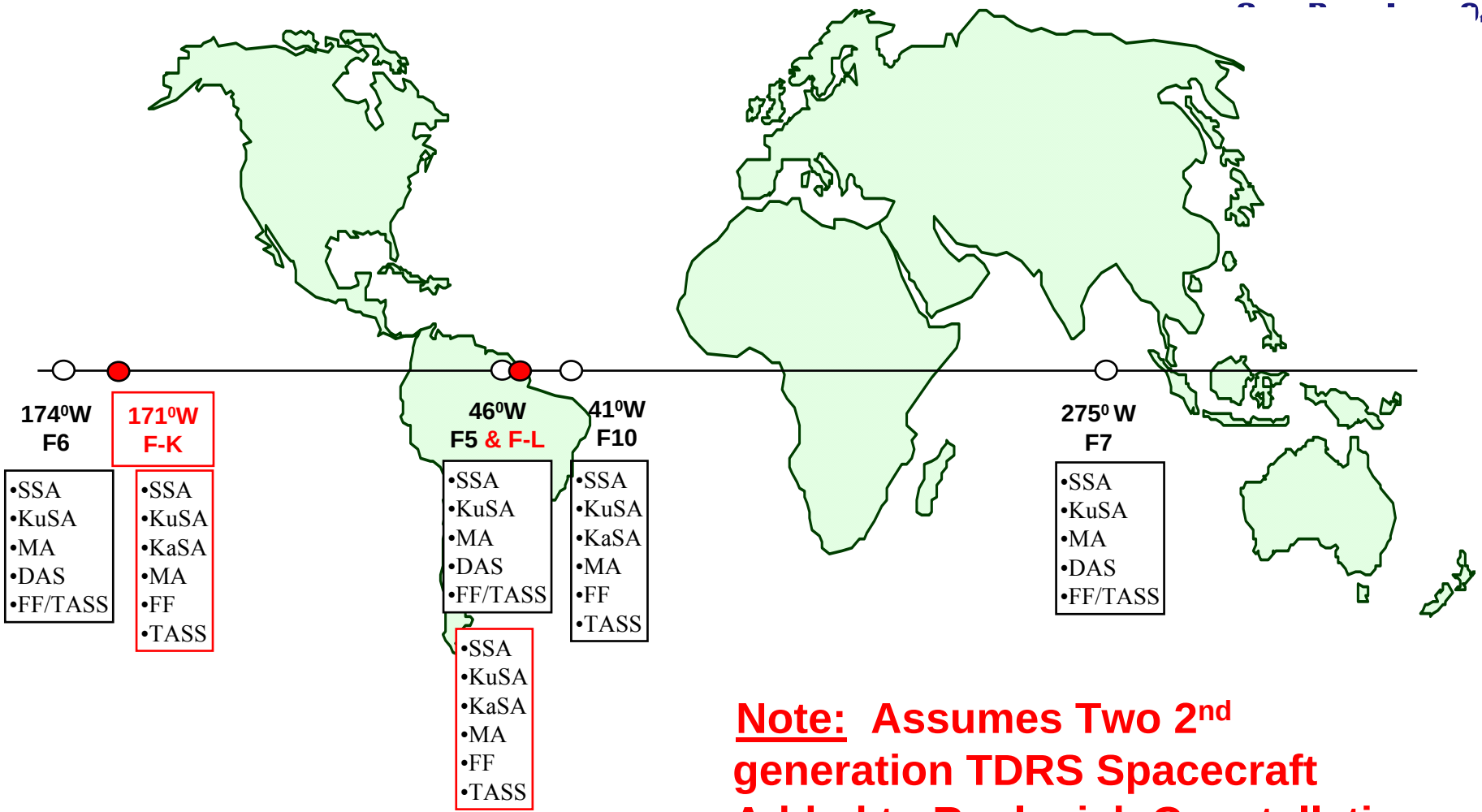
Deep Space Network:
How many Ka-band antennas?? Initial antenna array capability in place. Large antennas available: 34-m and 70-m. R&D optical stations.

Ground Network: Commercial S, X and Ka-band stations available. NASA and AFSCN ground stations available for S-band support.

Earth

Space Network 2015

Tracking & Data Relay Satellite System



Note: Assumes Two 2nd generation TDRS Spacecraft Added to Replenish Constellation

Moon Reference Architecture: 2015

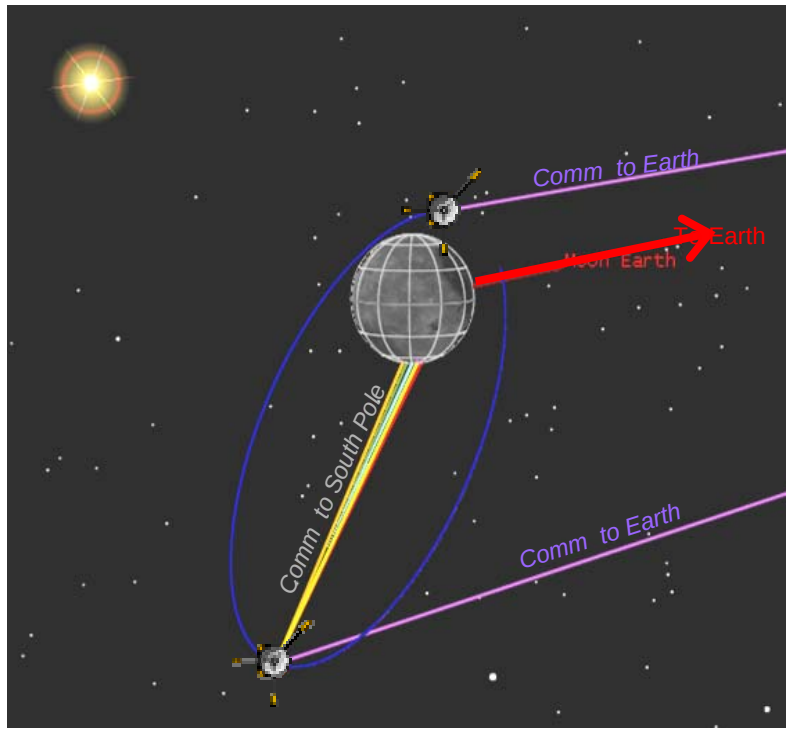
Architecture Elements

Number of spacecraft = 2 dedicated comm relays

Orbits: Inclined elliptical orbits, apoapsis adjusted to provide long dwell time over the south pole. The two spacecraft are spaced equally in the single orbital plane

Spacecraft: TDRS-derived spacecraft for dedicated comm capability. Antennas:

- Up/downlink high rate Ka-band antennas
- Up/downlink low rate UHF antenna, fixed
- S-band phased array, 2 GHz up/downlink
- Ka-band SGL Antenna, 26 GHz downlink, 40 GHz uplink
- S-band TT&C antennas
  - Performance: …



*This architecture is based on the results of a study conducted by the SCAWG in **September-November of 2004** and relied on available mission data and assumptions current at that time.*

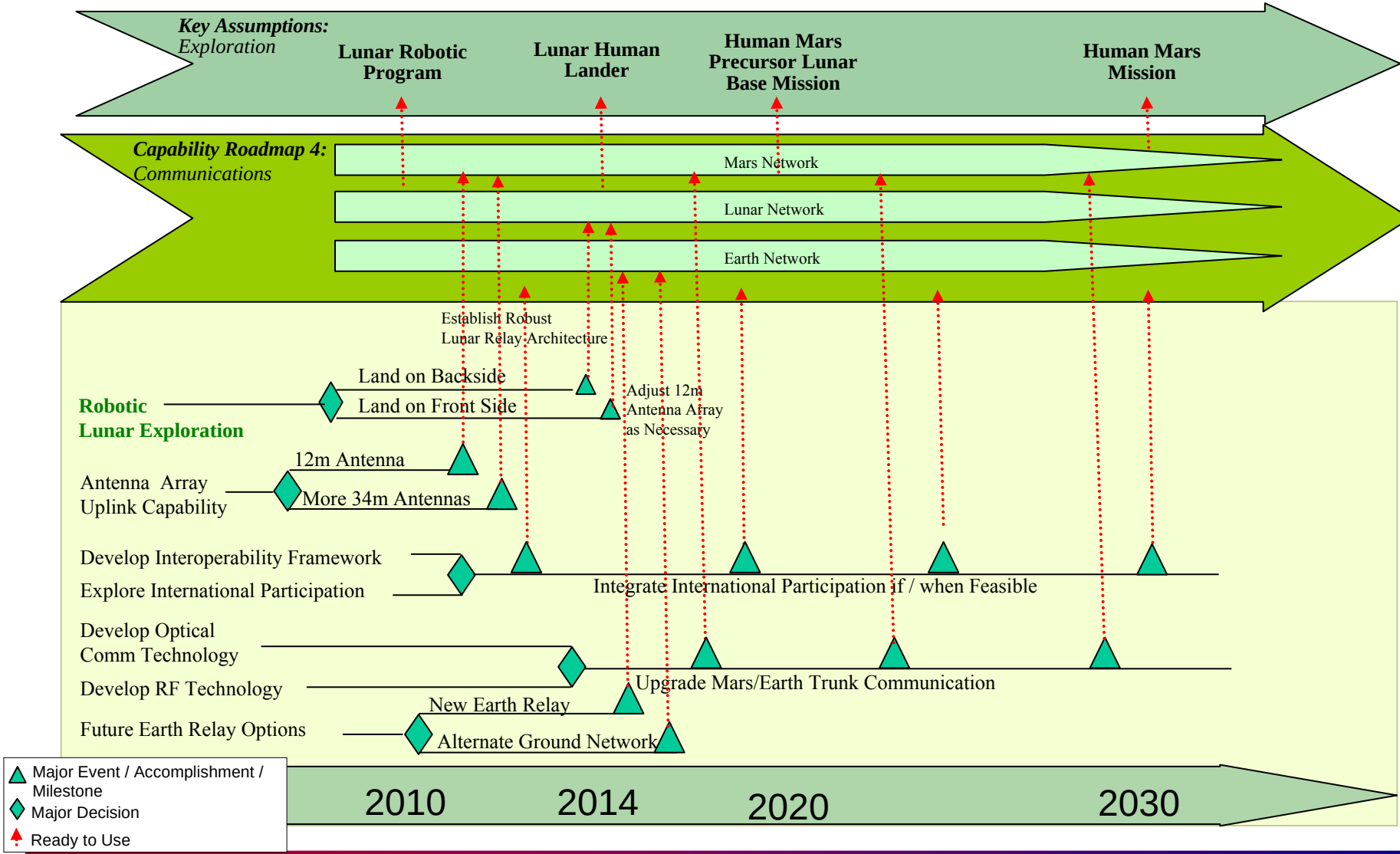
Features

Optimal south pole coverage – provides 100% visibility to at least one spacecraft from the polar region, 46% of the time with dual coverage

Moon Reference Architecture: 2015

Relationships	Lunar Orbit Relay (LOR) to Lunar Surface and Surface-to-Surface: S-band medium data rate proximity service for mission and ops data between rovers, CEV, lander, habitat, MCC UHF low data rate services- voice between crew locations, low rate mission data, and TT&C LOR to Earth: Ka-band high data rate service for mission data
Operations	Launch to support the 2015 to 2020 time period, during which the first human return mission will take place at the South Pole
Assumptions	Architecture is in support of South Pole missions only- optimized for south pole viewing / coverage 10-degree elevation angle requirement 24x7 coverage of polar cap Moon 2010 architecture is no longer available

4.0 Communication Capability Roadmap Decisions



Evolving the Lunar Architecture

An initial architecture recommendation is made based on an assumed human base at the <u>South Pole</u>

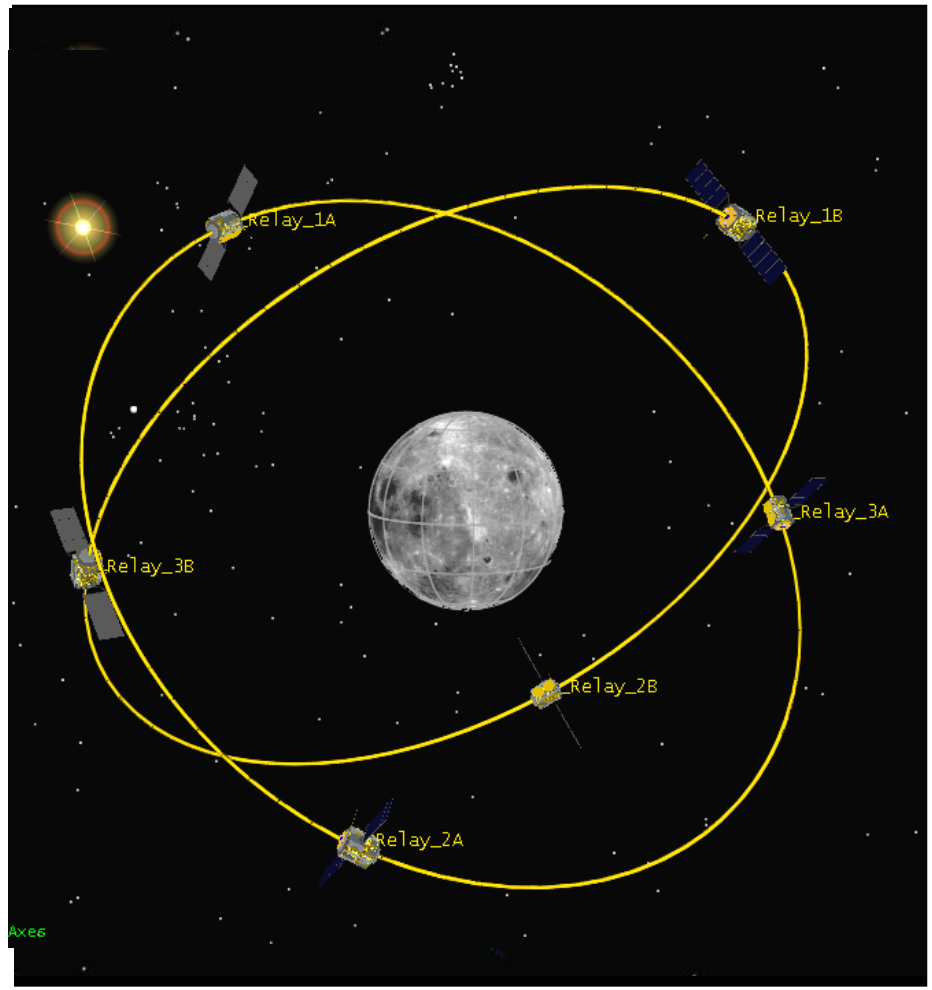
The 2 relays are moved to a circular orbit to support <u>South and North Pole</u> missions

A second plane of relays is added to <u>increase coverage</u> at the <u>South and North Poles</u>, and provide <u>global coverage</u>

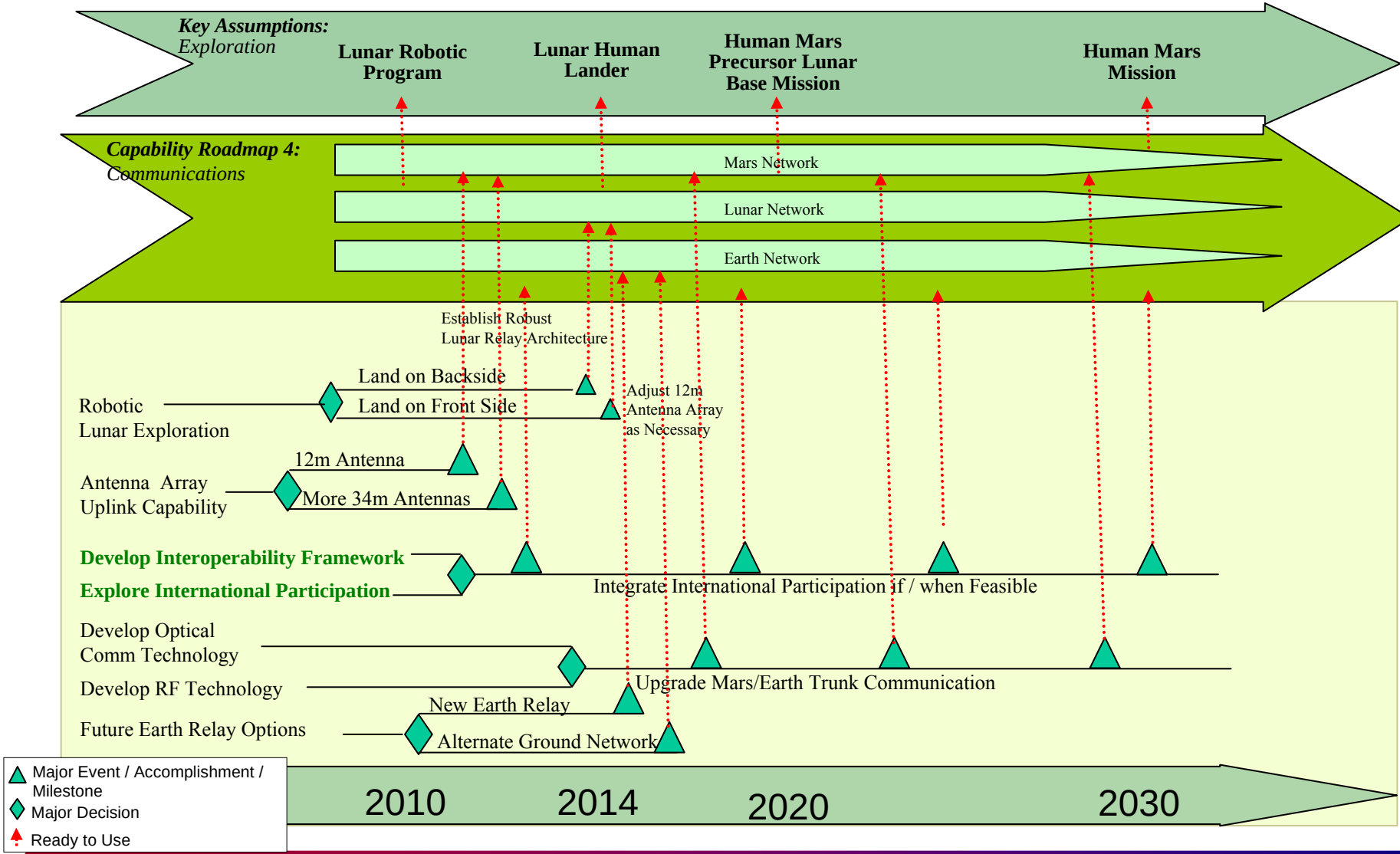
The orbital planes are inclined to support <u>global, far-side, and equatorial missions</u>

Final Configuration:
6 relay satellites
Two inclined circular orbits

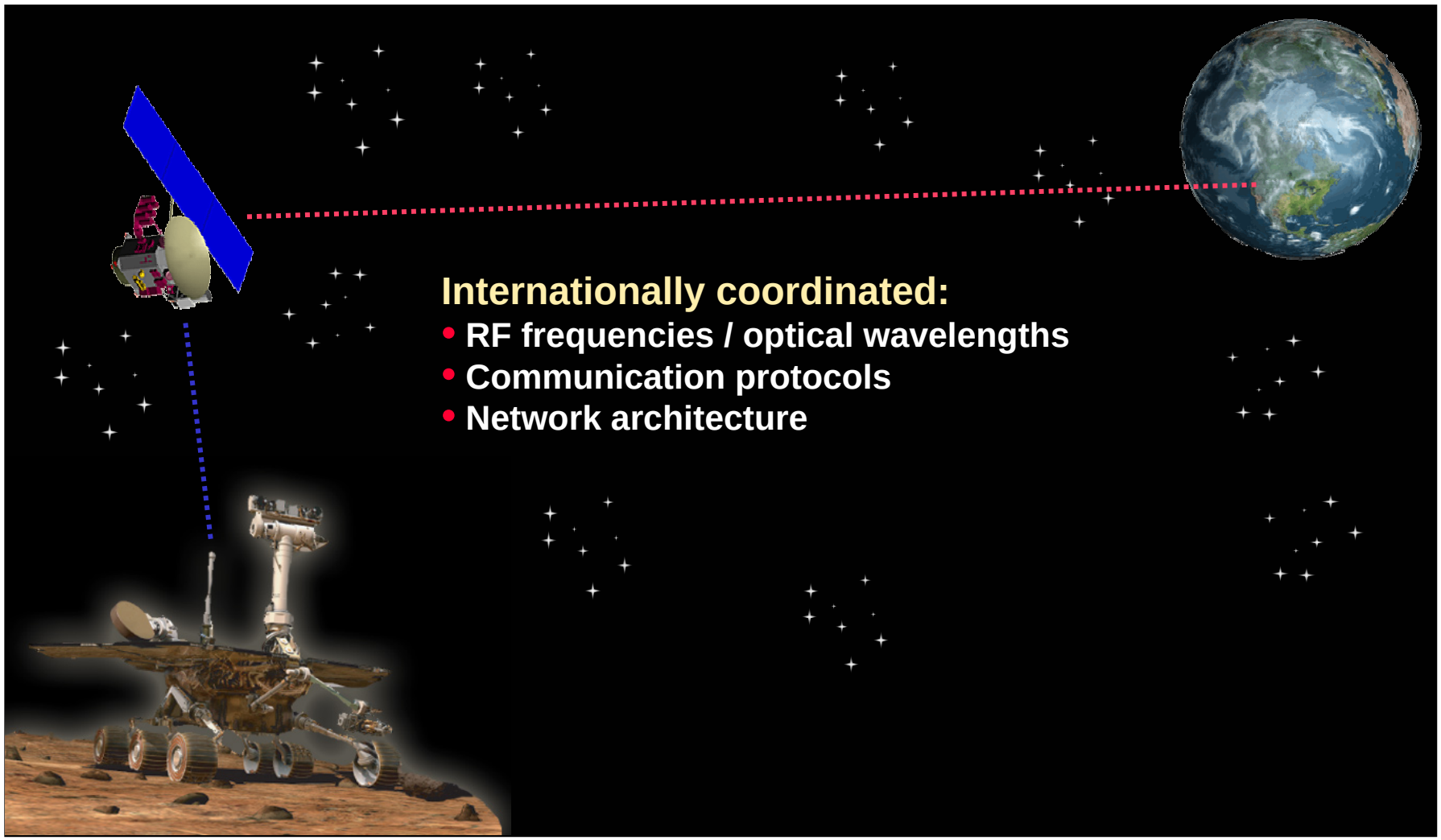
Advantage: global coverage, coverage is distributed more evenly than for polar orbits → better support to exploration at lower latitudes



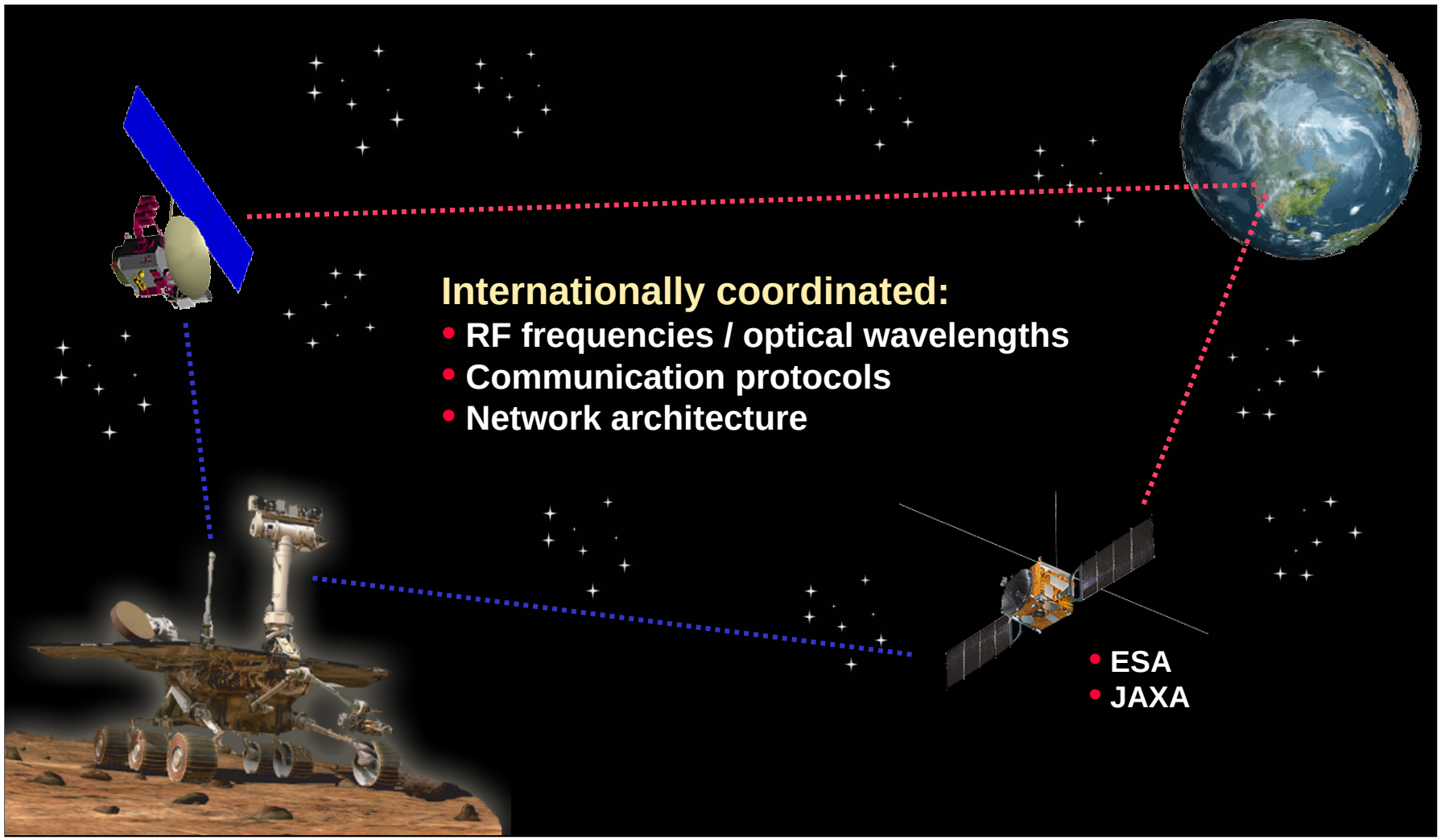
4.0 Communication Capability Roadmap Decisions



“Plug-and Play” Interoperable Framework



Interoperable Framework Enables Addition of International Assets



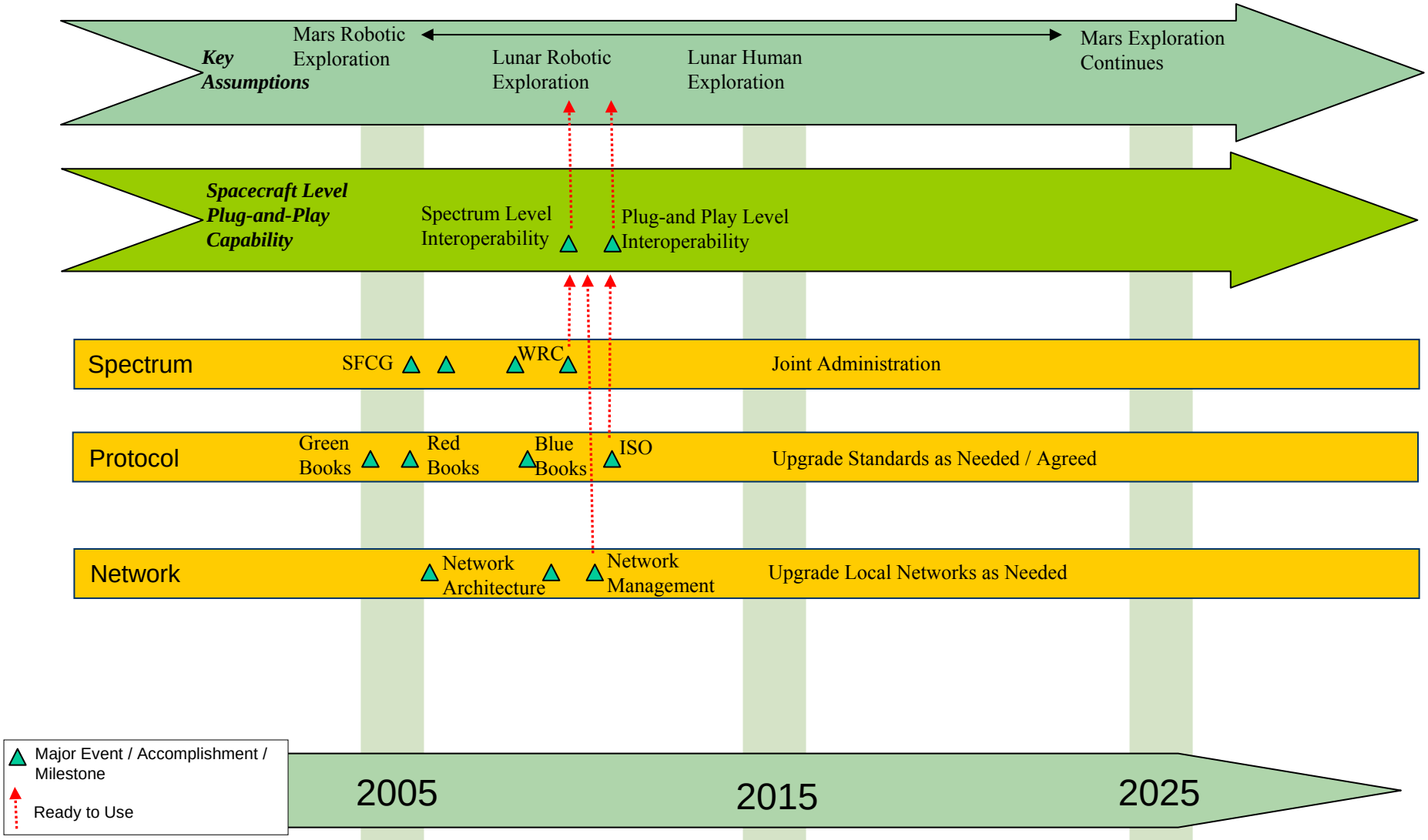
"Plug-and Play" Interoperable Framework

- **International participation in exploration program option must be retained**
  - **International participation part of Presidential Decision Directive**
    "Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests."
  - **No firm plans yet, <u>But Preserve Option for Future Consideration</u>**
- **Key factor is communication interoperability**
  - **Spectrum**
  - **Protocols**
  - **Network management & services**
- **Enables future leveraging of international investments**
  - **Communication assets (such as relays, antenna systems, etc)**
  - **Exploration & science vehicles (surface robots, human transport Vehicles, etc)**
- **Concept successfully demonstrated with current Mars relay spacecraft**

Objectives of Interoperable Framework

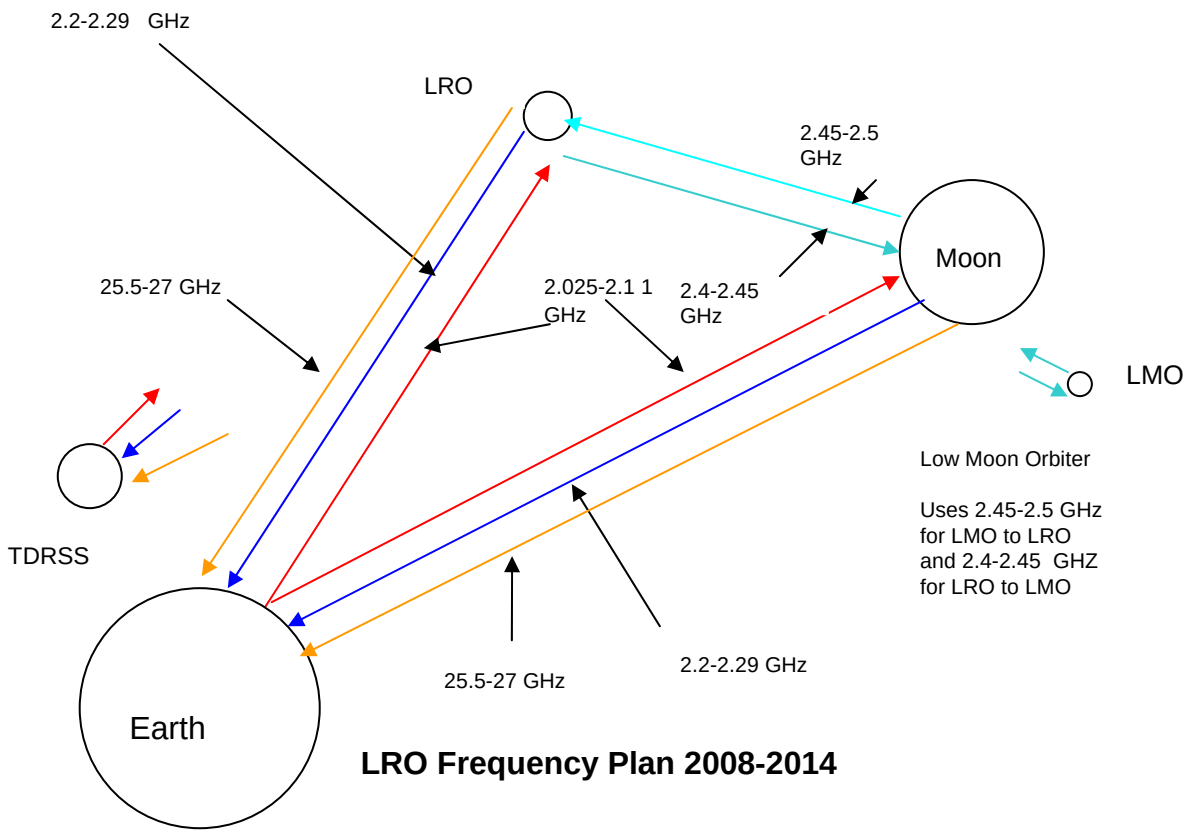
- **Enable use of international communication Resources to communicate with NASA exploration spacecraft**
  - **Relay satellites around Mars/Moon**
  - **Earth-based antenna Systems**
- **Enable international exploration vehicles to participate as part of NASA's exploration program through the use of NASA communication resources**
  - **Surface robots**
  - **Science spacecraft**
  - **Human exploration vehicles**

Spacecraft-level Plug-&-Play



Example Lunar Frequency Plan

In Development for Presentation to International Spectrum Community



LRO Frequency Plan 2008-2014

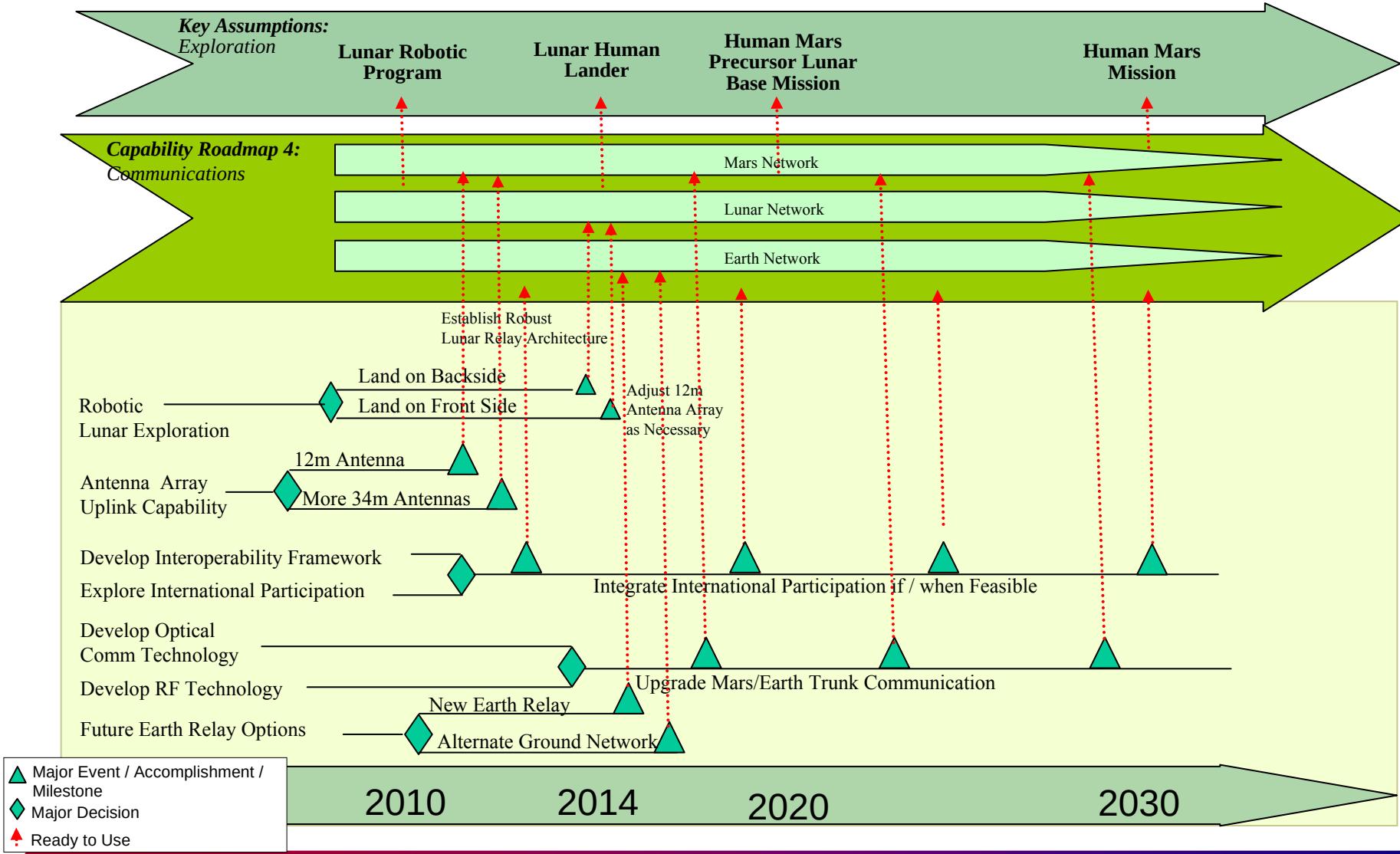
CCSDS Protocol Process

- **Consultative Committee for Space Data Systems (CCSDS) develops international standards for space communication protocols**
  - **Forum of representatives of international space agencies**
  - **Produces recommendations that are promoted to ISO standards**
  - **Operates on 6 month cycle discipline**
  - **Traditionally chaired by NASA**
- **“Green Book” is first stage of standards development – lays out concepts**
- **“Red Books” are working level recommendations rooted in Green Book concepts**
- **“Blue Books” are finished CCSDS recommendations which may be promoted to ISO standards**
- **Green Books being developed for Cis-Lunar operations and Space Link Extension (SLE) management function**

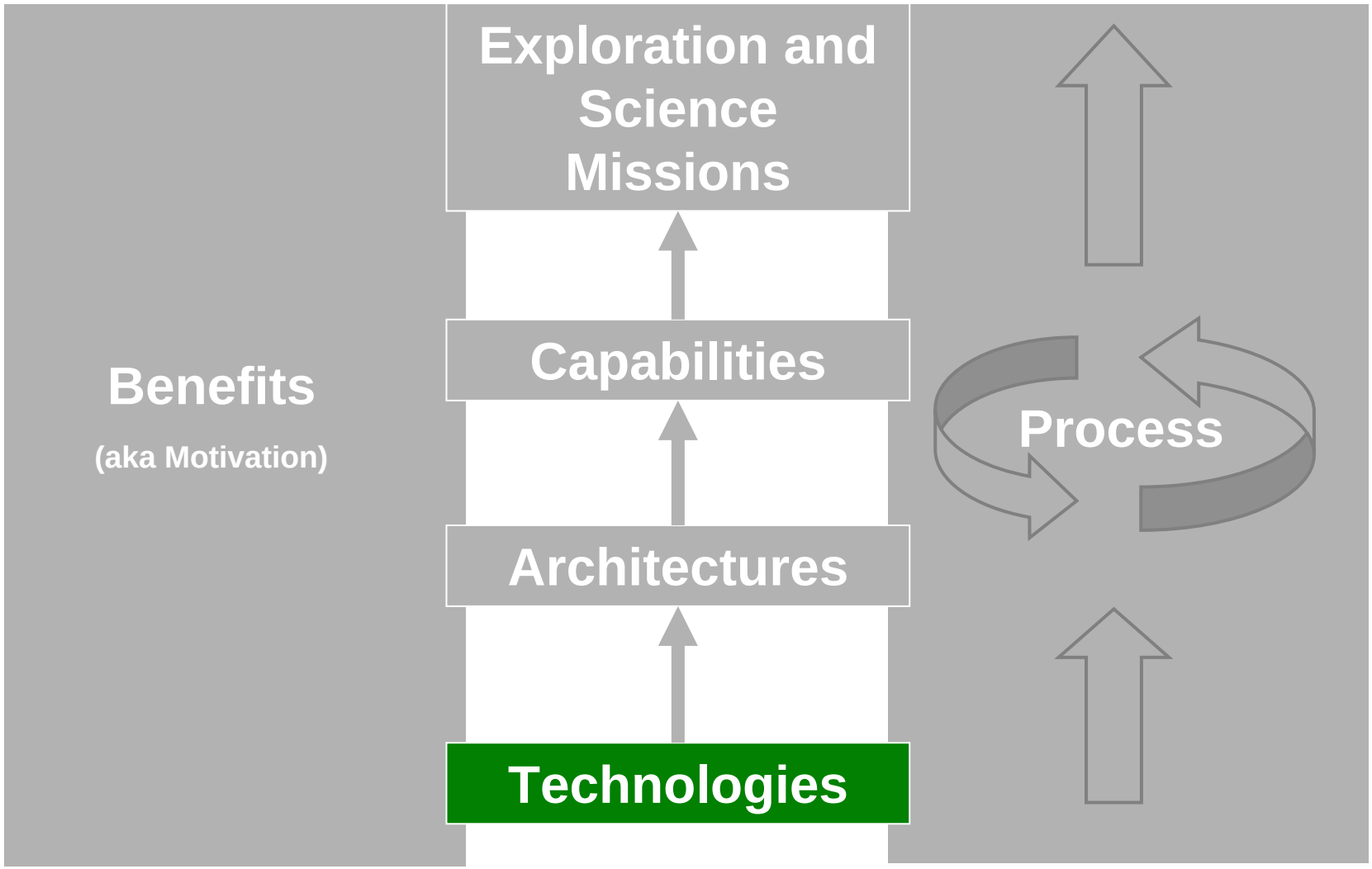
Network of Networks Plan

- **Develop Network Architecture**
  - **Build on Spectrum and Communication Protocol Interoperable "Plug-and-Play" Framework**
  - **Formulating overall architecture now ("Network of Networks")**
  - **Local network architectures developed as needed & plug Into "Network of Networks"**
- **Strategy: Make networks adaptable through use of programmable devices**
  - **Upgrade network protocols**
  - **Change network management rules**
- **Network management developed with participants**

4.0 Communication Capability Roadmap Decisions



Comm Roadmap Elements



Capability/Technology Relationships

High Level Capability *(Support & Service Provided to Operations)*	Technology Areas			
	Optical Comm	Spacecraft RF Technology	Uplink Arraying	Programmable Communication Systems
4.1 Launch		X		X
4.2 Earth Orbit		X		X
4.3 Transit	X	X	X	X
4.4 Lunar		X		X
4.5 Mars	X	X	X	X
4.6 Solar System & Beyond	X	X	X	X

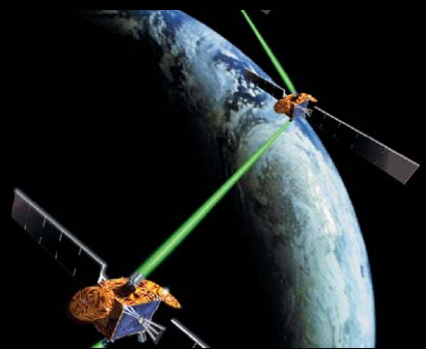
Optical Communications Capability

Space-based Optical Communications Comes in Two Forms

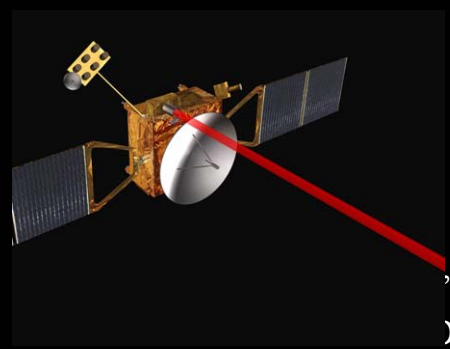
Optical Communications

Near Earth and Proximity

Dense Pl
Count at



Deep Space



Detector

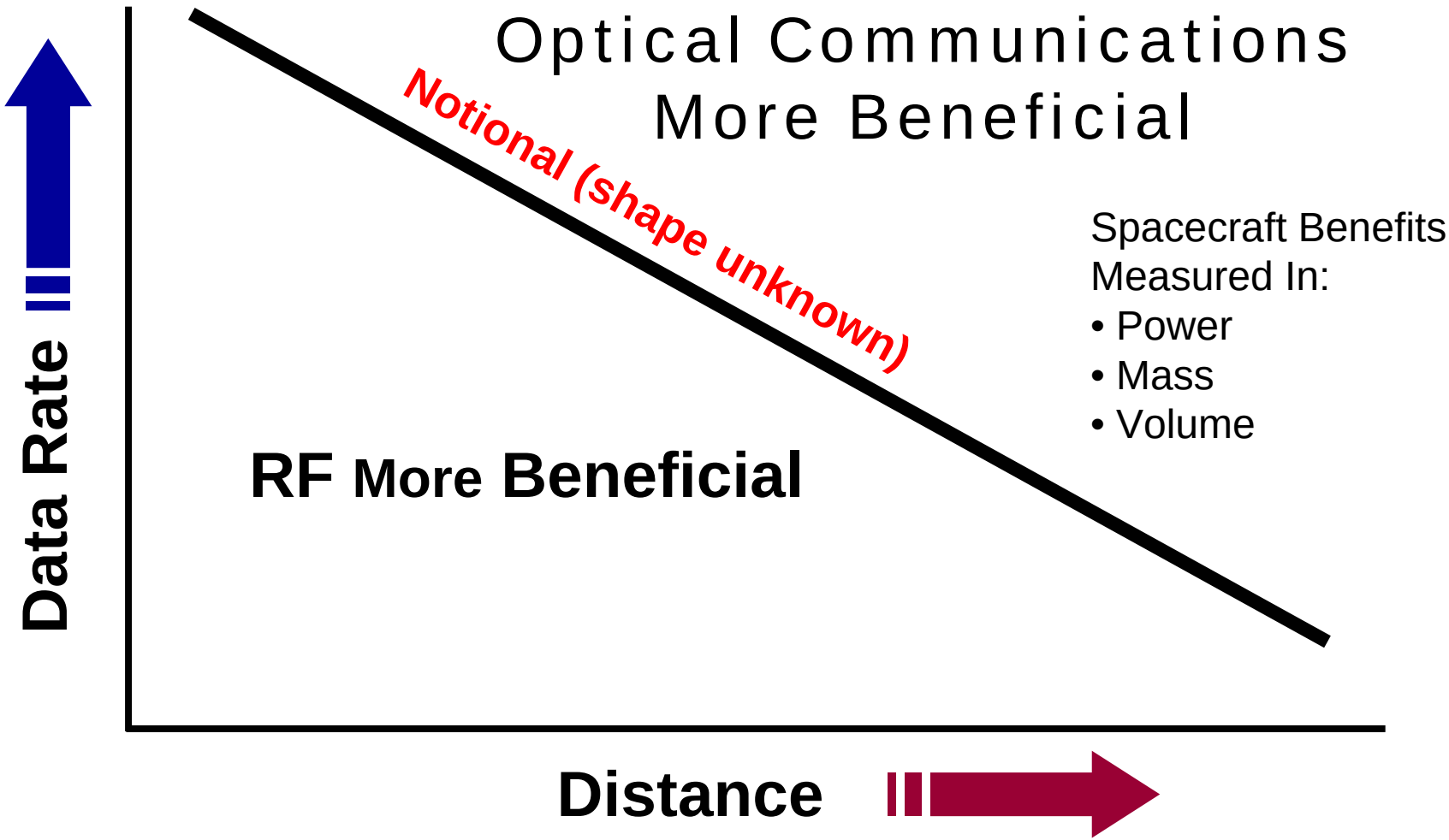
NASA's Needs

- **Earth orbit data rates are generally supportable with low cost RF technology**
  - **However, some high data rate applications such as Earth relay cross links may still benefit from optical communications**
  - **Capability being developed by other USG Agencies – does not require NASA investment**

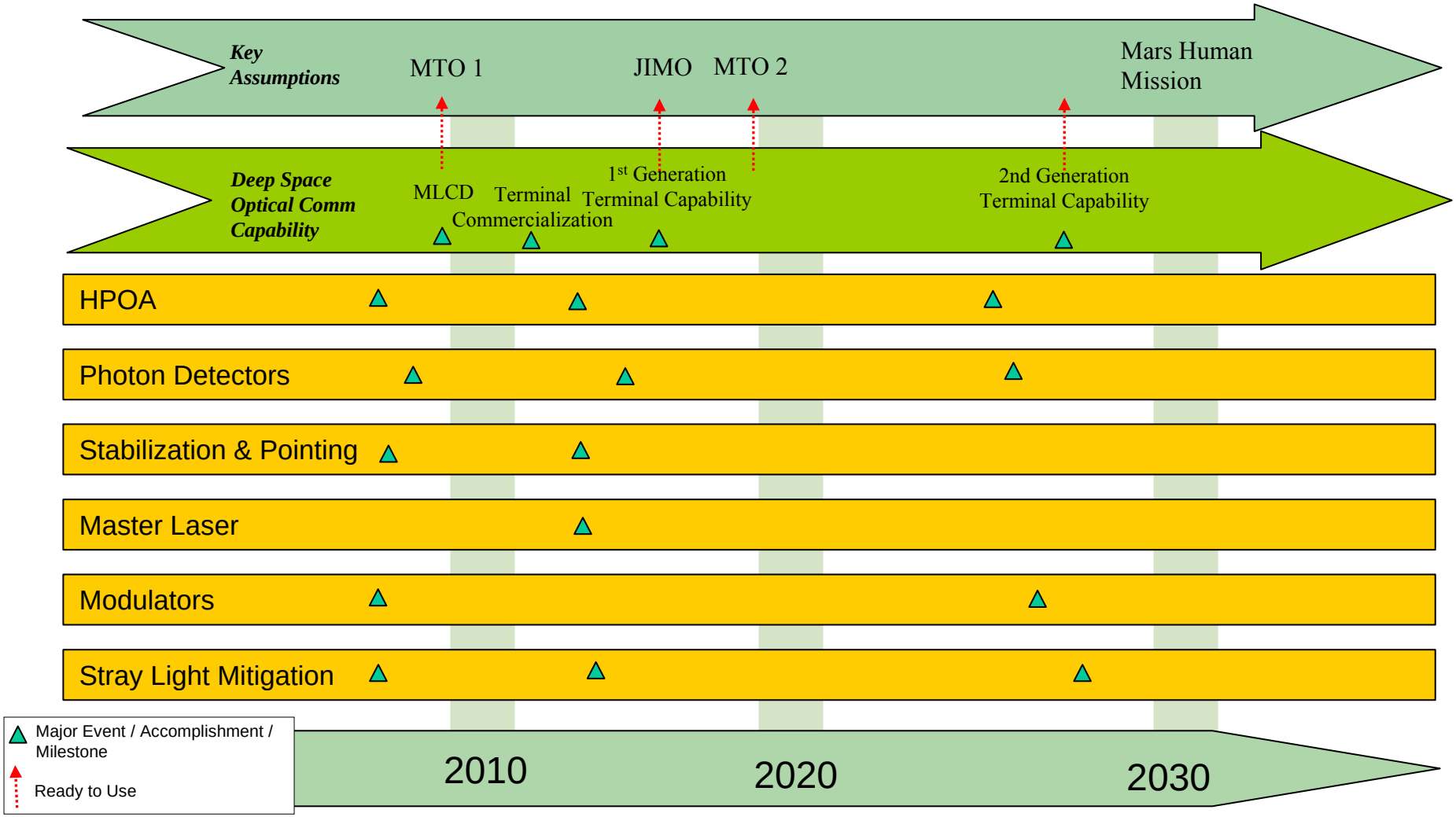
- **Projected data rates supporting Lunar exploration do not seem to warrant optical communications**

- **Exploration operations at Mars and beyond seem to indicate cross-over from potential RF to optical communication beneficial**
  - **Focus on high-rate data**
  - **However, Always Retain Trusted RF for TT&C, Emergencies**

Potential Benefits of Deep Space Optical Communications



Deep Space Optical Communication Technology



Technical Challenges of Deep Space Optical Communications (DSOC)

- **Link Availability — Ground-based detectors**
  - **Weather**
  - **Atmospheric turbulence**
- **Link Availability — Space-based detectors**
  - **Detector array size**
  - **Mass**
- **Pointing accuracy**
- **Efficiency**

Optical Communication Capability Goals

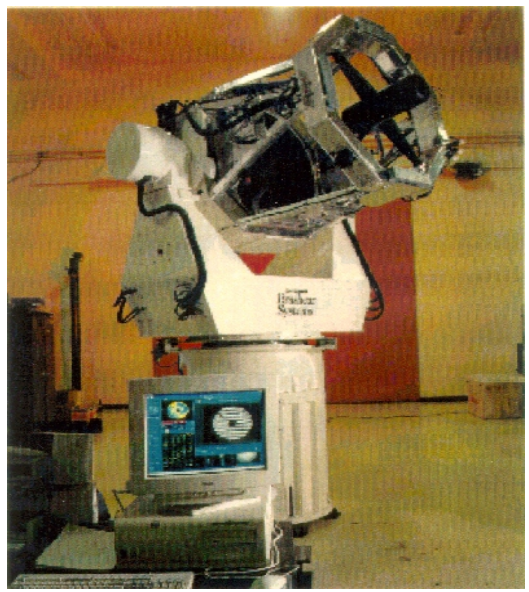
Parameter	MLCD	Capability I - 2018	Capability II - 2027
Data Rate at Mars (Min)	1 Mbps	200 Mbps	1 Gbps
Data Rate at Mars (Max)	50 Mbps	1 Gbps	2 Gbps
On-station Lifetime (Mars)	2 yrs	6 yrs	8 yrs

Critical Decisions:

- Detectors on Earth's surface or Space-based
- Need for optical uplink from Earth
- Beacon requirement
- Standard wavelength

OCTL (Optical Comm. Telescope Laboratory) (2005)

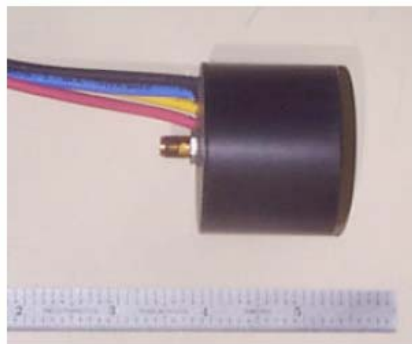
- **A 1-m uplink/downlink telescope facility dedicated to lasercomm**
- **Facilities dedicated 10/04**
- **Capable of tracking LEO spacecraft,**
- **Will be used as R&D station for deep-space link.**
- **Will be utilized in providing uplink beacon to MLCD**

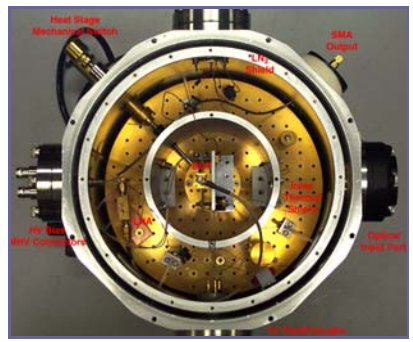


Photon Detectors (2007)

- **Deep-space optical links are in the photon-starved regime**
- **Photon counting detectors can yield a higher channel capacity than phase-sensitive detectors**
- **Deep Space Optical Communications requires data encodings that maximize the (bits/sec) per (Joule/sec) metric**
- **PPM Encoding with Photon Counting detection is an attractive solution**
- **Higher efficiency means a choice of lower transmitter lower, smaller receive aperture, and higher data-rate**

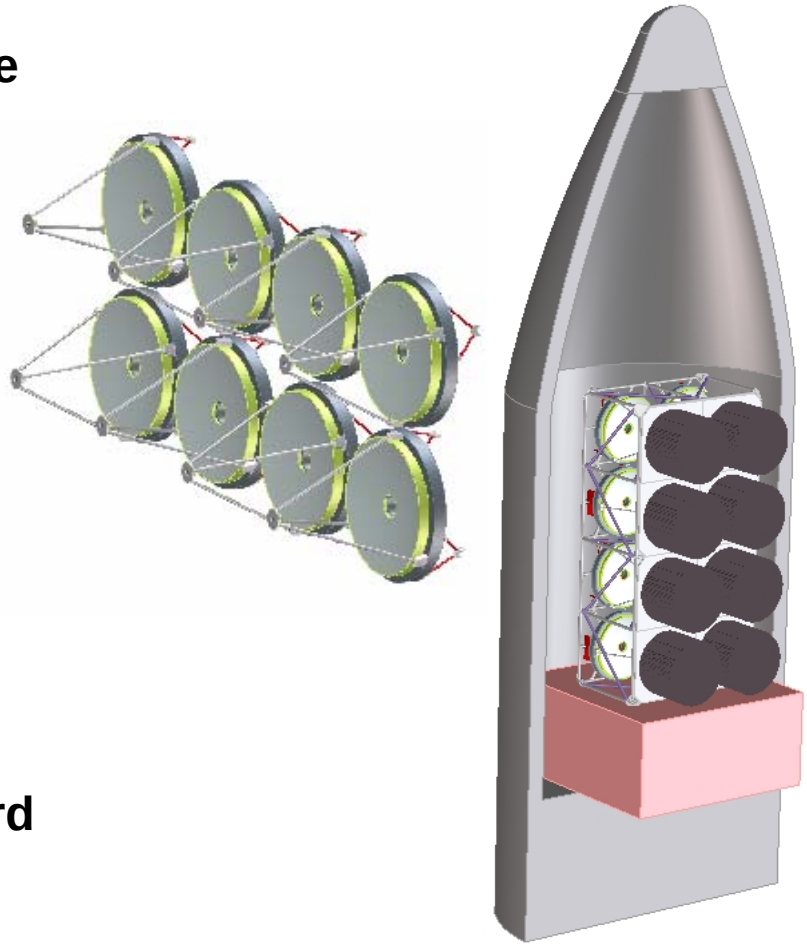
Detector Class	Examples	Photon Capacity Limit
phase insensitive amplifier	parametric amplifier, Raman amplifier, laser amplifier	1.44
dual quadrature sensitive	coherent heterodyne	1.44
single quadrature sensitive	coherent homodyne, degenerate parametric amplifier	(>5 photons/bit possible)
photon counting	photomultiplier tube, cooled avalanche photodiode, hot electron superconducting	$h\nu/2kT\ln 2$ (for instance, 69 bits /photon at 1μm & 150K)





Earth-Orbiting Terminal Options

- **Study various options for placing future optical relay terminals above Earth's clouds**
  - **LEO or GEO Orbits**
  - **Airborne (balloons, dirigibles, planes…)**
- **No atmospheric attenuation or turbulence**
- **Maintenance and upgrade issue**
- **3 Earth terminals provides ~95% availability**
  - **(GEO, 65° Inclination)**
- **Individual telescopes or arrays of telescopes**
- **Chose best options to carry forward to Earth infrastructure study**



Spacecraft RF Technology

Benefits of Spacecraft RF Technologies

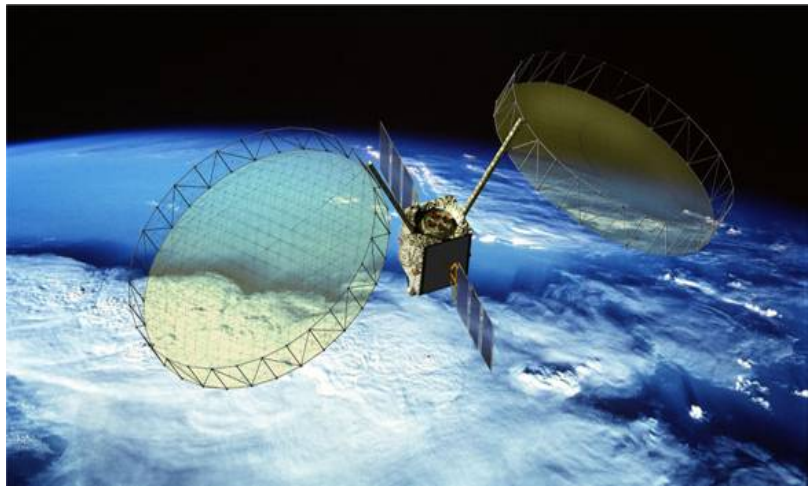
- **Proven technology**
  - **Experience with space environment**
  - **Well established industrial base**
  - **Cost to final product in the near-term is more reasonable than optical**
- **Continual product improvement**
  - **New material development reduces hardware mass and stowage volumes**
  - **Improved modeling and manufacturing process increases power efficiency**

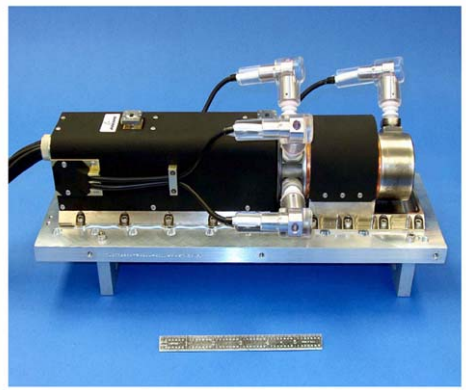
Desirable Features

- **Operational concepts are well understood**
- **Data rates can be increased with increasing antenna size, transmit power and improved bandwidth efficiency**
- **Utilization of existing and developing ground infrastructure**
- **Well understood integration with spacecraft – pointing requirements**

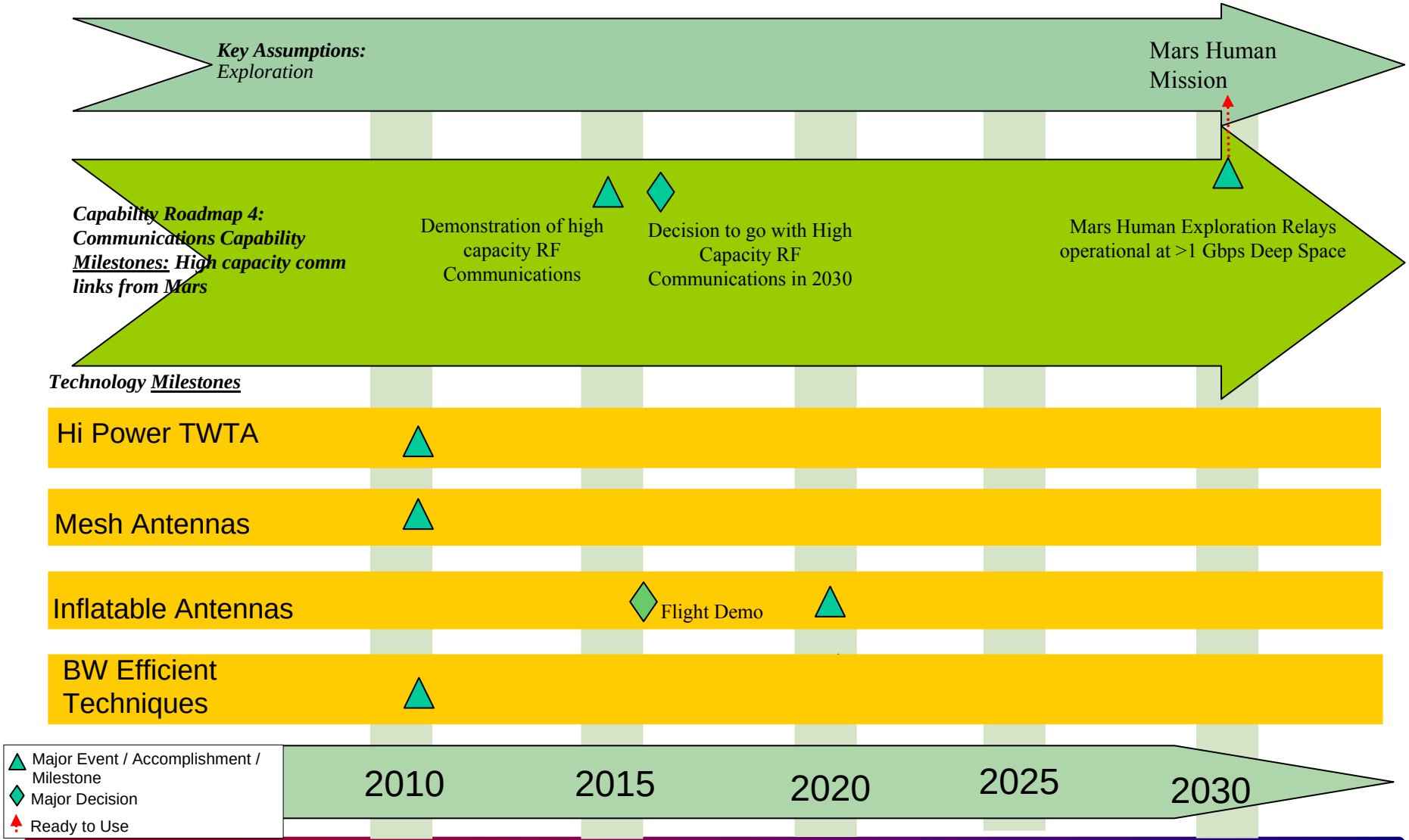
Potential Capabilities

- State of the Art:
  MTO ('09) planned for 1 Mbps from Mars with 100W TWTA and 3m SC antenna to 34 m ground station.
- Data rates up to 1 Gbps from Mars are possible with large antennas, high power transmitters, bandwidth efficient modulation and earth receive array.
- Mission challenges
  - Large Aperture mesh antennas are flying now — Thuraya 12m
  - Inflatable antenna technologies are being developed. May be available to 25m
  - Space qualified TWTAs are possible to 5kW or greater.
  - Bandwidth efficient techniques are presently available.





Spacecraft RF Technology Capability



Capabilities for Mars in 2030

1 Gbps with moderate user burden

- 10kW total power or 5kW radiated power, ¾ 8PSK, total RF system mass 250kg including 12m Spacecraft antenna
- Ground utilization of only 20 — 12m dishes.

Other trades include 2 polarizations, modulation schemes, 1000MHz bandwidth and could pre-distort and eliminate the 4dB back off used for linear PA operation.

- Example: At 1Gbps, 2kW, 2 polarizations,1GHz BW, 12m Spacecraft antenna, total RF mass 106kg with 45 – 12m dishes on ground.

Technical Challenges

- **Deployment mechanism for inflatables and mesh antennas**
- **Operating frequency to Ka-band for inflatables and mesh antennas**
- **Increase power for space qualified TWTAs**
  - **Ground already to 100kW in Ka-Band**
  - **Reliable operation**

Uplink Arraying

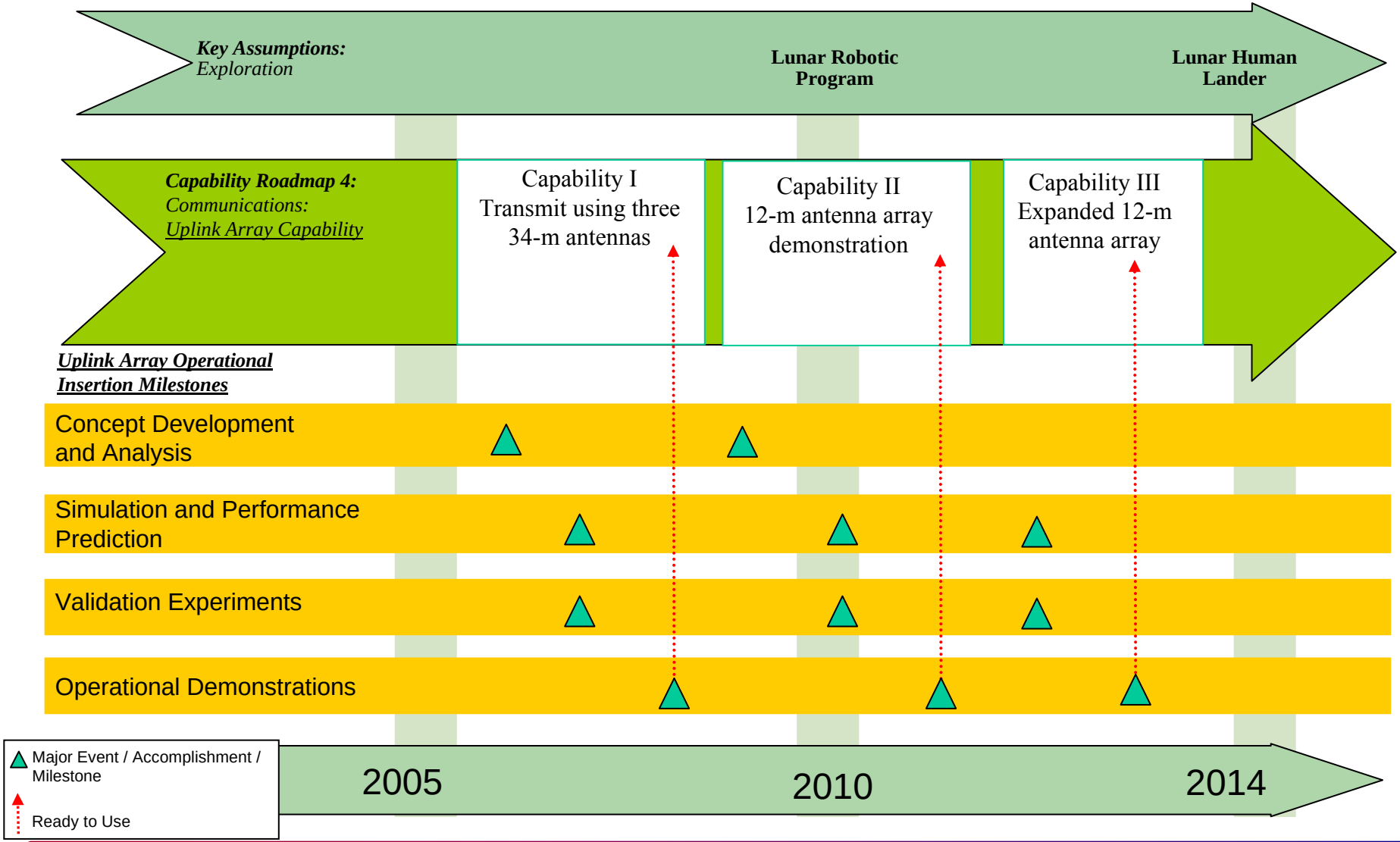
Benefits of Uplink Arraying

- **Reduce reliance on large aperture antennas**
  - **Maintainability — operations cost**
  - **Avoids single point of failure; inherently robust operation due to redundancy**
- **Scalable and evolvable**
  - **Dynamic modification of number of connections for a given mission or set of missions**
- **Flexibility for scheduling**
  - **Capability to form virtual large aperture antennas**
- **Emergency mode communications**
- **Enables greater data-rates or greater effective distance**
- **Reduces transmitter power requirements**

Technical Challenges — Uplink Arraying

- **Requires precise control of the phase in the far-field of each antenna**
  - **Alignment and Tracking**
  - **Measure or Infer accurately time-varying quantities**
  - **Maintain the required Signal-to-Noise ratios and bandwidths**
  - **Know angular relationship between receive and transmit directions well enough to meaningfully infer one from the other. (11º at max range)**
- **Not clear how good the blind-pointing accuracy of each antenna is in transmit mode.**
- **Phasing up the array through initial calibration prior to transmission**
- **Maintaining proper phasing as conditions change**
- **Implications of uncertainties and random variations due to tropospheric effects and equipment drift — implies limited distances between array elements**

Uplink Array Capability



Uplink Array Capabilities

Parameter	Capability I - 2006	Capability II - 2010	Capability III - 2013
Antenna Class	Three 34-m DSN DSS-13,24,25	12-m Array	Expanded 12-m Array
Activity	Concept Development and Analysis of Performance Characteristics	--	--
Simulation and Prediction	Yes	Yes	Maybe
Validation of Experiments	Moon bounce LEOS experiment Satellite experiment	Satellite Experiment Revisit Predictions and Simulations	Operational - Revisit Calculations and Simulations
Operational Demonstration with Satellite	--	--	Yes

Programmable Communication Systems
(aka Software Defined Radios)

Benefits of Programmable Communication Systems

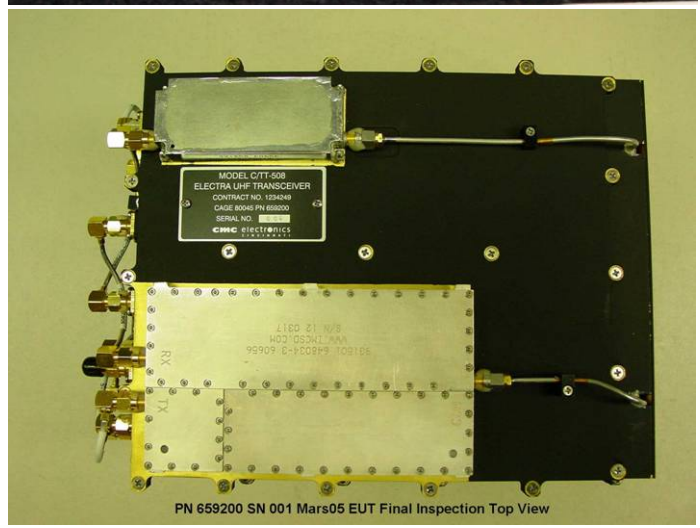
- **Provides a level of flexibility**
  - **Spacecraft reconfigurability**
  - **Dynamic frequency assignments**
  - **In-flight communication and protocol network architecture updates**
  - **Configure for various mission scenarios**
- **Savings in mass, power, volume**
  - **One box ←→ Multiple Operations**
  - **Need for separate, dedicated systems is eliminated**

Desirable Features

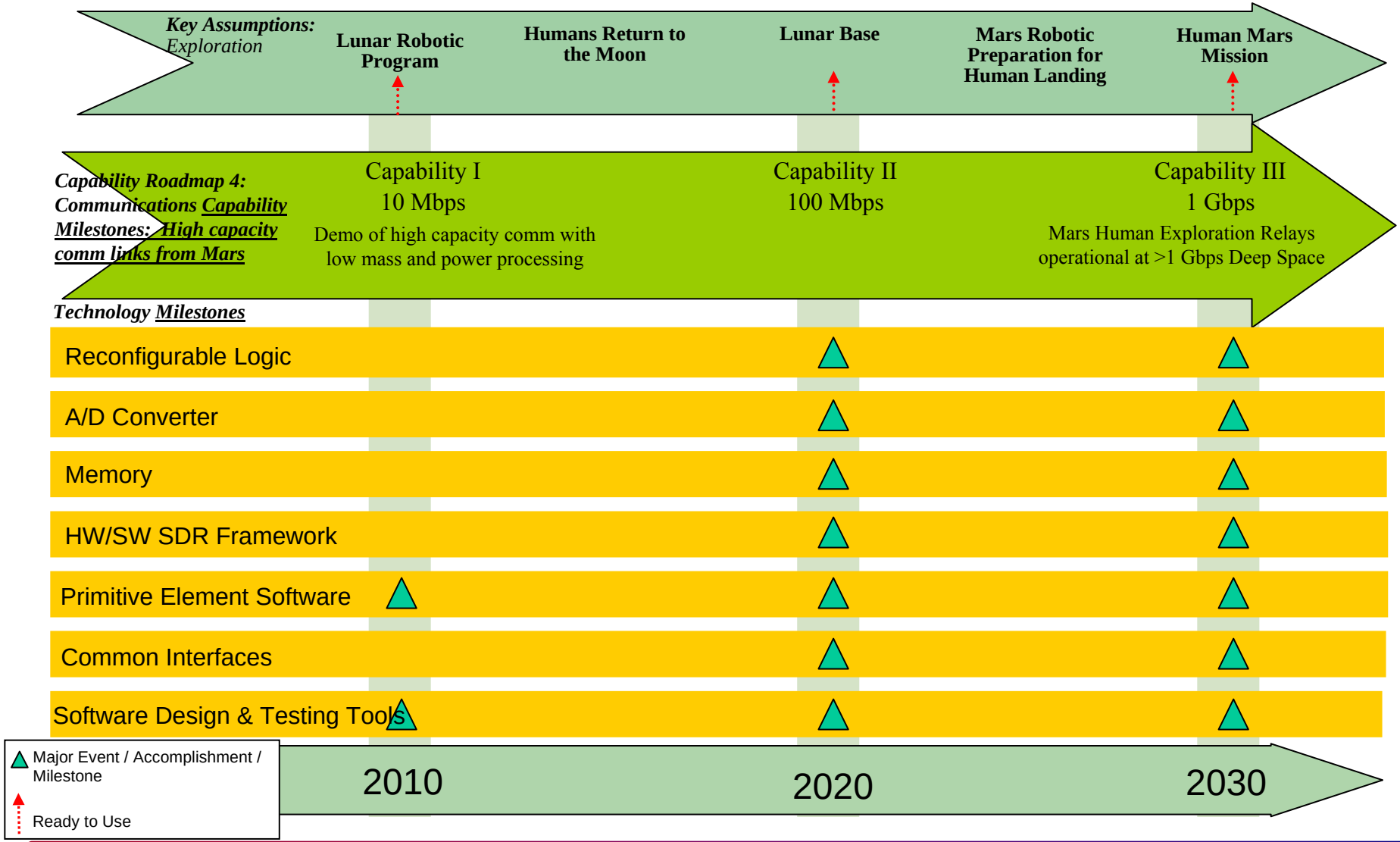
- Cost effective utilization of COTS (commercial off the shelf) technology
- Open system architecture
- Waveform portability
- Software reuse
- Technology insertion
- Interoperability — with legacy communications systems and across all JTR sets
- Hardware abstraction

Current State of the Art

- **Commercial**
  - **Vanu, Inc. (1st FCC Approval)**
  - **FlexRadio**
  - **ITT LPT**
  - **GD - Starlight**
  - **130 Companies**
- **Groups**
  - **SDR Forum**
- **Government**
  - **JTRS – DoD**
  - **NASA GRC, GSFC, JPL**
  - **Ex: L3 Com Electra**



Programmable Communication System Capability



Identified Capabilities of Programmable Communication Systems

Parameter	Capability I - 2010	Capability II - 2020	Capability III - 2030
Data Rates			
- Lander	10 MBPS	25 MBPS	25-100 MBPS
- Orbiter/CEV	10 MBPS	500 MPBS	1 GBS
Navigation			
- Range	10 m	1 m	1 m
- Doppler	1 mm/s	0.1 mm/s	0.1 mm/s
Mass			
- Lander	3 kg	2 kg	1 kg
- Orbiter/CEV	5 kg	<10 kg	<10 kg
Power (Baseband)			
- Lander	15 W	1-10 W	0.5 - 5W
- Orbiter/CEV	20 W	25 W	35 W
Volume			
- Lander			
- Orbiter/CEV			
RF Bands Supported	Slice	Slice/Digital (low f)	Slice/Digital (low RF)
Simultaneous Multiband Operatio	Limited	Several	All required links
Platform Specific Software	Partial	Independent	Independent
Autonomy (Scheduling /Link)	Semi	Semi/Full	Full

Technical Challenges — PCS

- **Closed vs. open architecture**
- **Potential for increased processing requirements**
- **Potential for unreliable operation from memory corruption, resource contention, and deadlock conditions**
- **Hardware limitation for logic and ADC**

Summary & Forward Work

Summary

- Identified the need for a robust communications and navigation architecture for the success of exploration and science missions
- Developed an approach for identifying architecture alternatives and analyzing them
- Established a top level, network of networks, flexible physical architecture based on the use of relays at Earth, Moon, and Mars
- Identified key enabling technologies
  - Optical Communication
  - Spacecraft RF Technology
  - Antenna Array Transmit Technology
  - Programmable Communication System
- Created an initial capability roadmap as a result of exploration & science inputs and assumptions, architecture analysis, and enabling technologies

Forward Work

- **Integrate with Strategic and Capability Roadmap Teams to firm up requirements**
- **Complete the architecture**
  - **By extending architecture definition to Mars and solar system based on maturing requirements**
  - **By developing navigation architecture as requirements become clear**
- **Continue to assess enabling technologies**
- **Define network architecture for complete network of networks**
- **Address communication protocols**
- **Complete cost estimates**
- **Refine technology metrics**

Acronyms

Acronyms

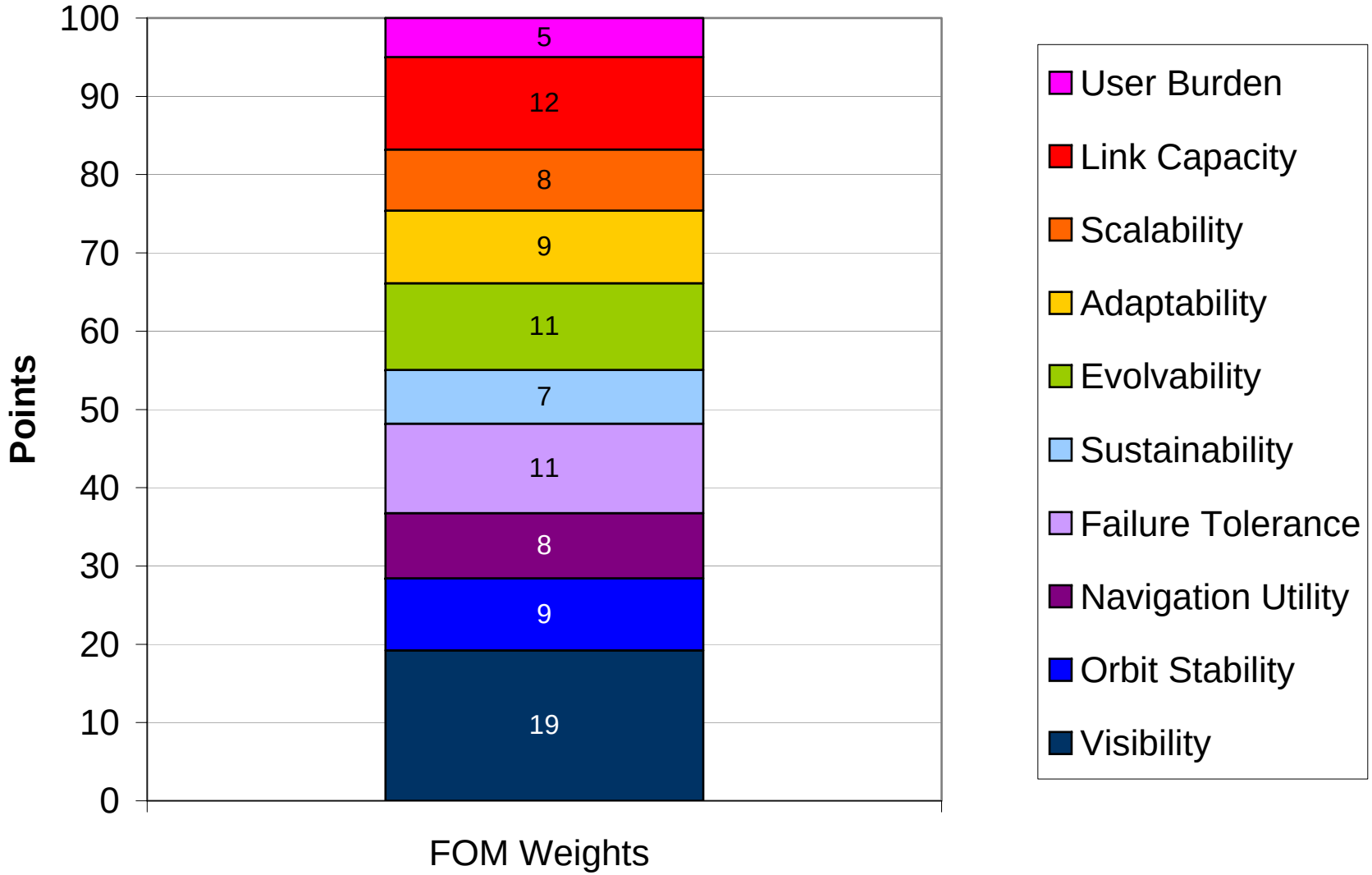
- A/D – Analog/Digital
- AFSCN – Air Force Satellite Control Network
- ARC – Ames Research Center
- BW – Bandwidth
- C&N - Communications and Navigation
- CCSDS — Consultative Committee for Space Data Systems
- CEV – Crew Exploration Vehicle
- CM – Command Module
- COMM – Communications
- COTS – Commercial Off the Shelf
- DAS – Demand Access Service
- DSN – Deep Space Network
- ESA – European Space Agency
- FCC – Federal Communications Commission
- FDOC – Flight Dynamics Operations Control
- FF – Fast Forward
- FOM – Figure of Merit
- FOM — Figures of Merit
- FWD – Forward Link
- Gbps – Gigabits per second
- GD – General Dynamics
- GDOP – Geodetic Dilution of Precision
- GEO – Geosynchronous Earth Orbit
- GN – Ground Network
- GPS – Global Positioning System
- GRC – Glenn Research Center
- GRGT – Guam Remote Ground Terminal
- GSFC – Goddard Space Flight Center
- GT – Ground Terminal
- HDTV – High Definition Television
- HGA – High Gain Antenna
- HPOA – High Power Optical Amplifier
- ISO – International Standards Organization
- ISS — International Space Station
- JAXA – Japan Aerospace Exploration Agency
- JIMO – Jupiter Icy Moons Orbiter
- JPL – Jet Propulsion Laboratory
- JTR – Joint Tactical Radio
- JTRS – Joint Tactical Radio System
- KSC – Kennedy Space Center
- KuSA – Ku-Band Single Access
- L&EO – Launch and Early Orbit
- L1 – LaGrange Point 1
- L2 – LaGrange Point 2
- LaRC – Langley Research Center
- LEO – Low Earth Orbit
- LGA – Low Gain Antenna
- LLO – Low Lunar Orbit
- LM – Lunar Module

Acronyms (cont'd)

- LMO – Low Moon Orbiter
- LOR – Lunar Orbit Relay
- LOS – Line of Sight
- LRO – Lunar Reconnaissance Orbiter
- MA – Multiple Access
- Mbps – Megabits per second
- MCC – Mission Control Center
- MGA – Medium Gain Antenna
- MLCD – Mars Lasercom Demonstrator
- MOC – Mission Operations Center
- MTO – Mars Telecom Orbiter
- NAFCOM – NASA Air Force Cost Model
- Nav – Navigation
- NISN – NASA Information System Network
- NM$ - NAFCOM Millions of Dollars
- NRE – Non Recurring Engineering
- NRT – Near Real Time
- NSF – National Science Foundation
- OC – Operations Center
- OPS – Operations
- PDD – Presidential Decision Directive
- PIO – Public Information Office
- R&D - Research and Development
- RE – Recurring Engineering
- RF – Radio Frequency
- RLEP – Robotic Lunar Exploration Program
- RS – Relay Satellite
- RTN – Return Link
- RTN – Return Link
- SA – Single Access
- SC – Spacecraft
- SDR – Software Defined Radio
- SFCG – Space Frequency Coordination Group
- SGL – Space Ground Link
- SLE – Space Link Extension
- SN – Space Network
- SSA – S-Band Single Access
- STS – Space Transportation System
- TASS – TDRSS Augmentation Satellite Service
- TDRSS — Tracking Data Relay Satellite System
- TRL – Technology Readiness Level
- TT&C – Tracking, Telemetry and Command
- TWTA – Traveling Wave Tube Amplifier
- UHF – Ultra High Frequency
- UMD – University of Maryland at College Park
- USG – United States Government
- WRC – World Radio Conference
- WSC – White Sands Complex

BACKUPS

FOM Weighting *Example*



Example of Data Rates from Mars

- **Mars Exploration Rovers**
  - **Direct to Earth transmission**
    - **3.5 to 12 kbps (1/3 as fast as a home modem)**
    - **Transmit for up to 3 hours = 60 Mb**
    - **Limitation is visible time to Earth + power and thermal limitations**
  - **Relay to Orbiters**
    - **128 kbps (4x faster than a home modem)**
    - **Transmit for 8 minutes per orbit = 60 Mb**
    - **Relays have up to 16 hours of visibility to Earth**
- **Mars Relay Spacecraft Direct to Earth**
  - **Mars Global Surveyor (1996) – 33 kbps**
  - **Mars Odyssey (2001) – 14 kbps**
  - **Mars Express (2003, ESA) – 97 kbps**
  - **Mars Reconnaissance Orbiter (2005) – 526 kbps**
  - **Mars Telecommunications Orbiter (2009)– 350 kbps (1 Gbps Lasercomm)**
- **Compare to *example* projection for total peak data rates from human Mars base in ~2030 = 980 Mbps**