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NASA's Lunar Communication and Navigation Architecture

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America's *Vision for Space Exploration* envisions the permanent return of humans to the moon and the expansion of human presence across the solar system. A major NASA effort to develop architectures for lunar exploration and science, called the Lunar Architecture Team (LAT), completed a multi-center, year long study in September 2007. The concepts of operations, analyses, requirements, and conceptual designs developed during the LAT study form the basis of the current effort to decide on the basic elements of the overall space transportation and lunar surface systems architecture. The elements of the Lunar Architecture include descent and ascent transportation, habitation, mobility, power generation and distribution, resource extraction and storage, Extra-Vehicular Activity (EVA), and communications and navigation. In this paper, an overview of the LAT Communication and Navigation (C&N) results will be described. This includes the architecture of the Lunar Network (LN), concepts of operations, spectrum utilization, traffic model, element design concepts (including lunar relay satellites, surface communication terminals, and user radios), and requisite technology improvements.

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

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A previous 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 sends 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 6 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-habs. 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.

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. The Outpost will consist of 1-5 habitable elements connected to form one pressurized Habitat with an internal Local Area Network (LAN). The Outpost will also include nearby Solar Power Units (SPU) and associated Makeup Power Units (MPU) to provide continuous power through day and night operations. A pair of Pressurized Rovers (PR) will enable four crew to conduct two or four person EVAs requiring communications and surface navigation for up to two PRs and four crew simultaneously. 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. Crewed operations build up from initial 7 day stays during early construction to 180 day stays with full logistics support.

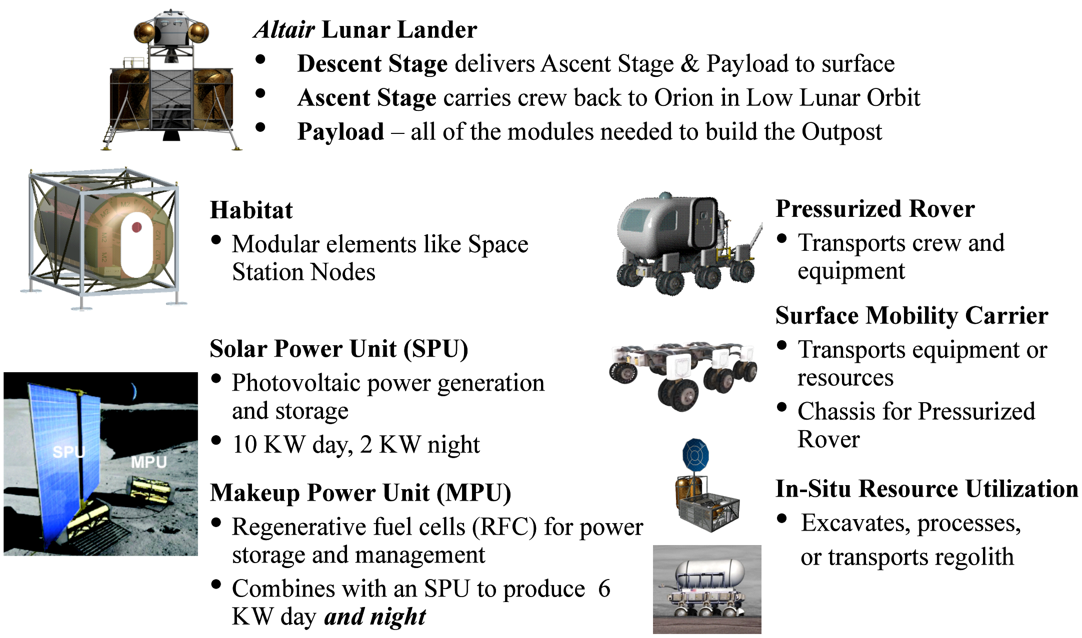

Figure 1. Typical Modular Components of Lunar Surface Architecture (Option 1)

At the Outpost and at sortie sites around the Moon, science packages similar to the Apollo Lunar Science Experiment Packages (ALSEP) would be deployed. Science packages may include any combination of instruments including passive, solar powered during lunar daytime only, solar powered during lunar daytime with 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 through the use of 12-15 Communications and Tracking (C&T) stations geographically dispersed to maintain 3-4 stations continuously tracking and monitoring the mission. 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 would use the Moon to prepare for eventual human missions to Mars where real-time Earth-based control would 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 technical 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 2 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.

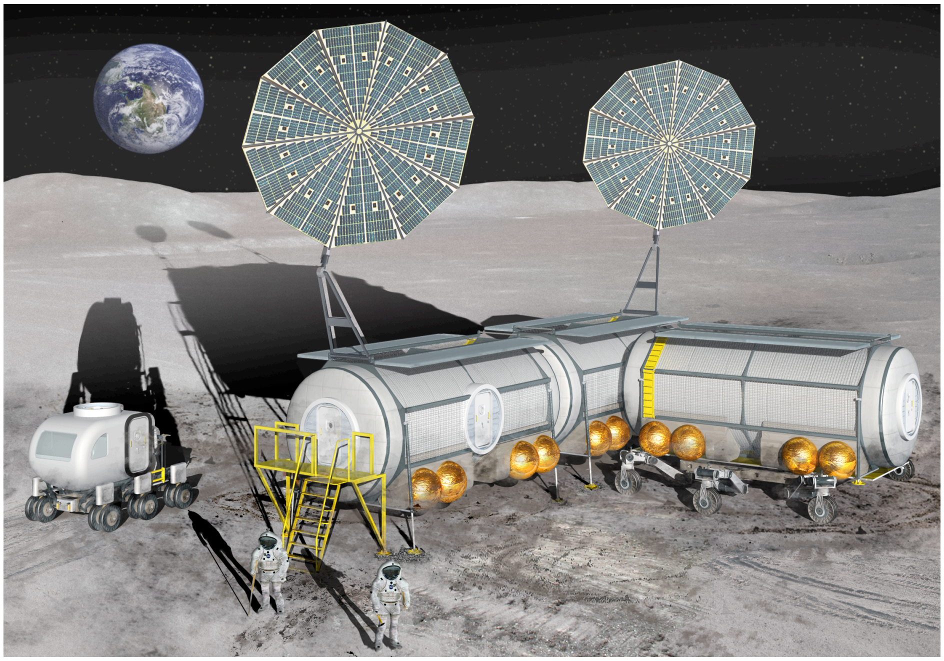

Figure 2. Final LAT Architecture Synthesizing the Best Features of All Options

This paper documents the results of the Communications and Navigation 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 LN design are covered in Section VI while Section VII delves into the ground system. Several of the technology advances required to make the C&N architecture work are identified in Section VIII. Preliminary studies always uncover additional work to be done which is discussed in Section IX.

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:

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 standards enabling full collaboration and coordination of operations, introduction of new technologies and capabilities, a low entry barrier for new participants, and preventing being held hostage by proprietary interfaces or equipment;
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 providing 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 direct line of sight to Earth 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 position, the communication availability for direct line of sight to the Earth 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 direct line of sight 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 Fig. 3:

- Lunar Relay Satellite (LRS): 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 Direct To Earth (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.

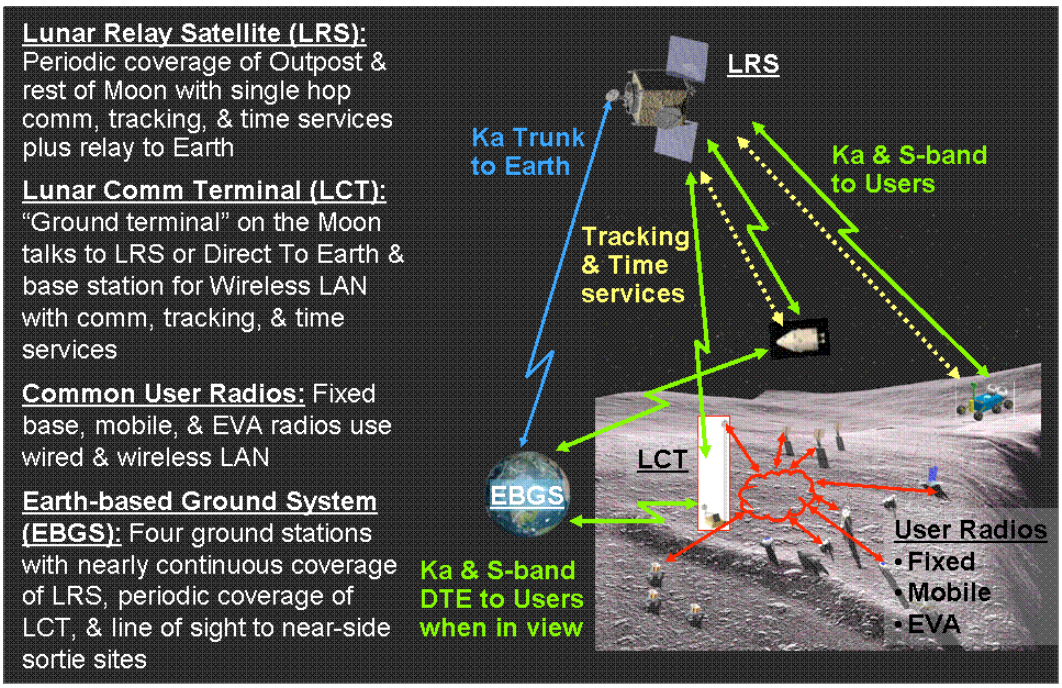

Figure 3. Major Elements of Lunar Communications and Navigation Architecture

- Lunar Communications Terminal (LCT): 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 directly to Earth when it 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 antennas operating from existing Deep Space Network (DSN) and Near Earth Network (NEN) ground stations. The LRS satellites are managed by an LRS Operations Center while the end-too-end Lunar Network is managed by the LN Mission Operations Center (LMOC).

A. Communications Architecture

Figure 4 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.

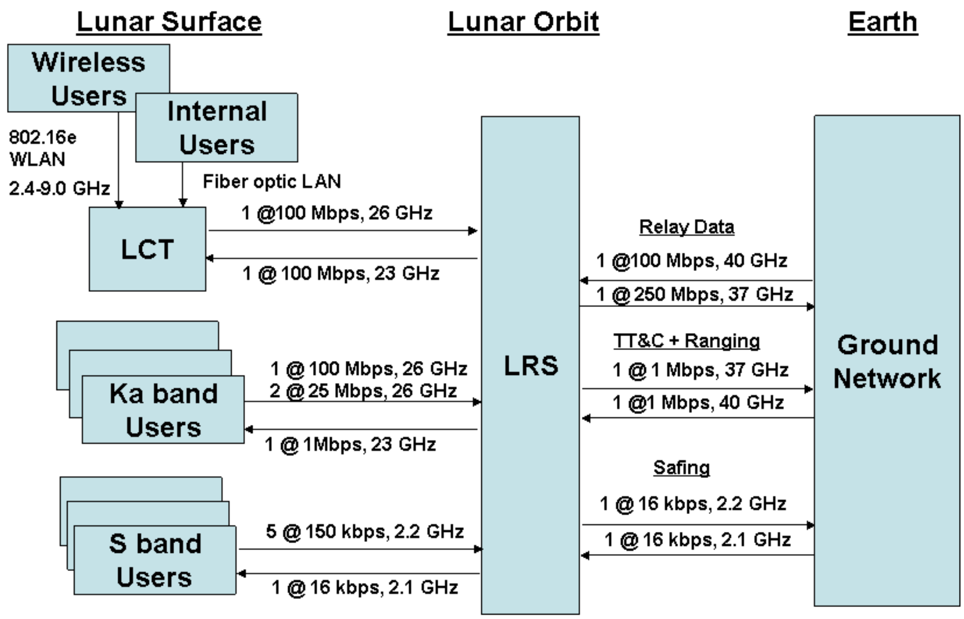

Figure 4. Link Capacities and Spectrum Usage

On the return links, the LCT multiplexes telemetry, voice, video, and science data into a 100 Mbps link to the LRS at 26 GHz. (Fig. 3 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 line of sight while resorting to its Ka-band link to the LRS when it is 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 Fig. 5. 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 Consultative Committee on Space Data Systems (CCSDS) Advance Orbiting Systems (AOS) protocol is used 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].

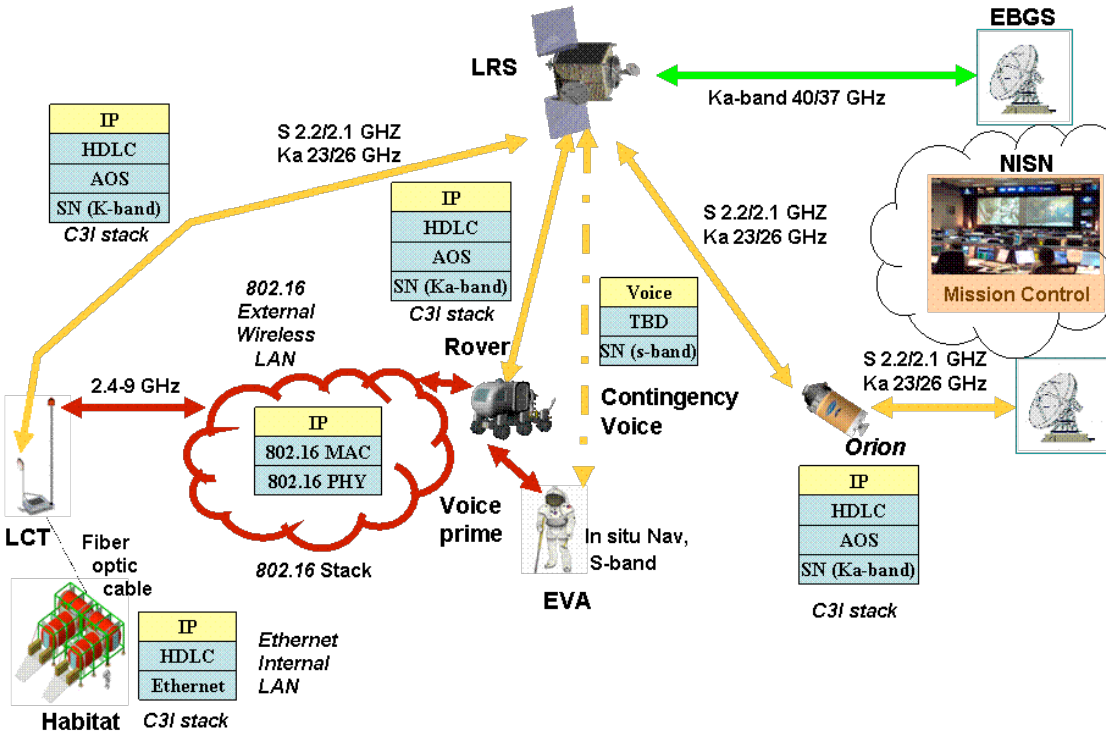

Figure 5. Lunar Network Protocols

B. Navigation Architecture

In developing a lunar navigation architecture that accommodates mission phases beginning with 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 (e.g., radiometric and optical) for all phases (e.g., cruise, landing, and roving).
- The navigation system should be fault tolerant with at least *two* independent navigation measurements for each mission phase.

Figure 6 illustrates the fundamental architecture as a function of mission phase, navigation data type/instruments, and the needed on-board processing. (In parallel to the on-board processing, there is a ground-based navigation process operating.) Key to the architecture is the ‘two independent navigation measurements in each mission phase’. Fundamentally these 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 exploration program) and nominally a site at White Sands, New Mexico. Augmenting the EBGS is radiometric tracking from a Lunar Network of 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 craters on the surface of the Moon) 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. Both are 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 sufficiently early in the development cycle;
- Maximizing multi-mission, multi-tasking and reliability of GN&C systems;
- Minimizing unnecessary redundancy of systems and techniques (i.e., if faced with the choice of multiple methods to do a job, use the one that shares systems, instruments, and software with other scenarios.), but at the same time, ensure 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.

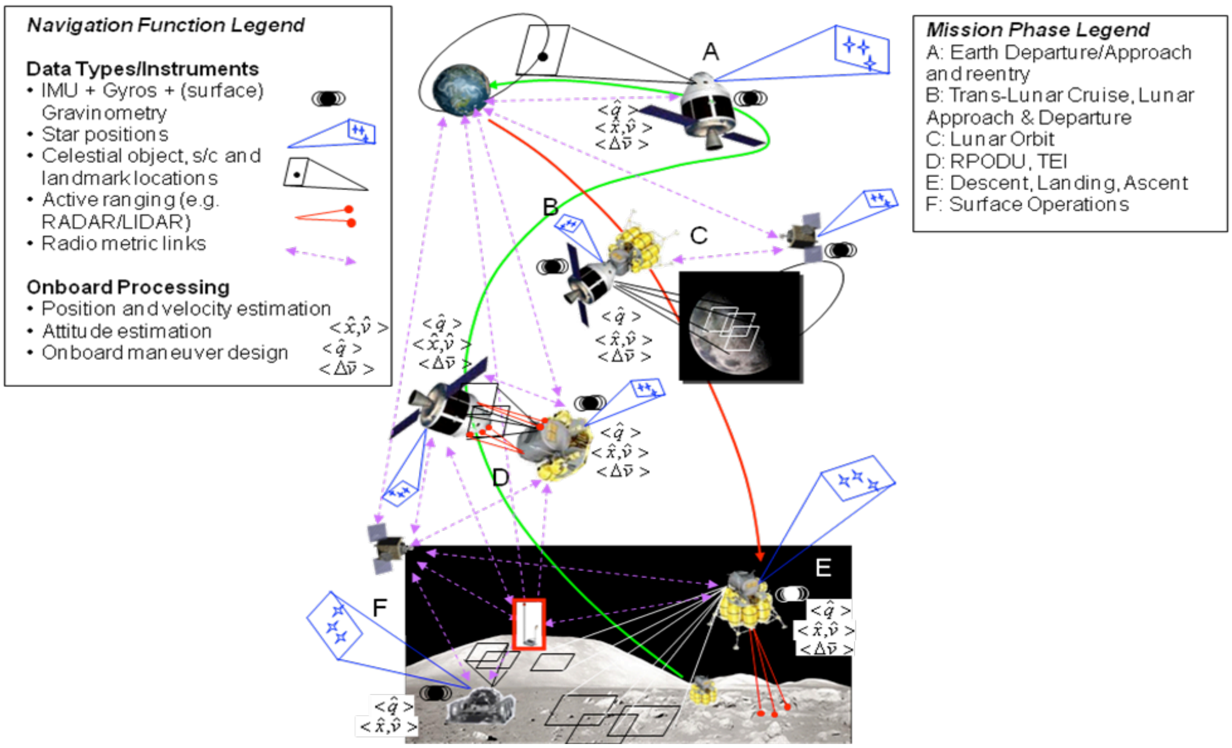

Figure 6. Lunar Navigation Architecture

It is believed by this team 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

In what follows is a brief description of the LN radiometric tracking service, the LN assets, and the radios (including both the LN and the user) used in generating the radiometric data. The LN, as envisioned by the LAT, includes up to two Lunar Relay Satellites (LRSs) currently in 12 hr elliptical/inclined orbits around the Moon and two Lunar Communications Terminals (LCTs) that are located at the lunar outpost site near the landing zone. These four elements comprise the Lunar Network. It should be noted that the composition and signal structure of the LN is under continuing study and may change; however, the fundamental data types that are defined in this document will remain the same regardless of the implementation and distribution of the LN assets.

On each LN asset there is a radio that can transmit/receive S-band spread spectrum signals and are used primarily for low data rate communications and radiometric tracking of lunar users. Each LN asset radio has a clock and frequency source that is derived from an 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.

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 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 and collects 2-Way range and tracks 2-Way phase for up to five users, simultaneously. This radio will be 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 pn-sequences that supports spread spectrum communications via 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 line-of-sight radiometric data types including 1-Way average Doppler and (pseudo) range and 2-Way average Doppler and range.

2. Optical Navigation System Architecture

As indicated earlier, passive optical navigation is available in all mission phases and augments radio-based navigation yielding robust fault tolerant system. A key requirement of the Constellation program is to be able to "get the crew home" when communications links are down. Though the precise meaning of "without com" is yet to be formally defined by Cx (Constellation program), Cx is considering a system-wide risk (Coronal Mass Ejection - CME) interference that will prevent radiometric-based navigation system from working implying the need for a radio-free navigation system on-board all Cx elements. The implications are powerful:

- Orion will require entirely complete and internal navigation capability, for all mission phases, with the possible exception of Lunar Orbit Insertion (LOI).
- Altair will require self-contained capability for ascent and rendezvous.
- Surface mobile systems will need to be able to determine their location relative to surface maps and return to base safely without mission support.

Passive optical data is a "radio-free" observable that can be made readily available in all mission phases. Depending on the mission phase, these observations can be of lunar landmarks, Earth/Moon limbs, and/or artificial satellites. This is depicted in Fig. 7.

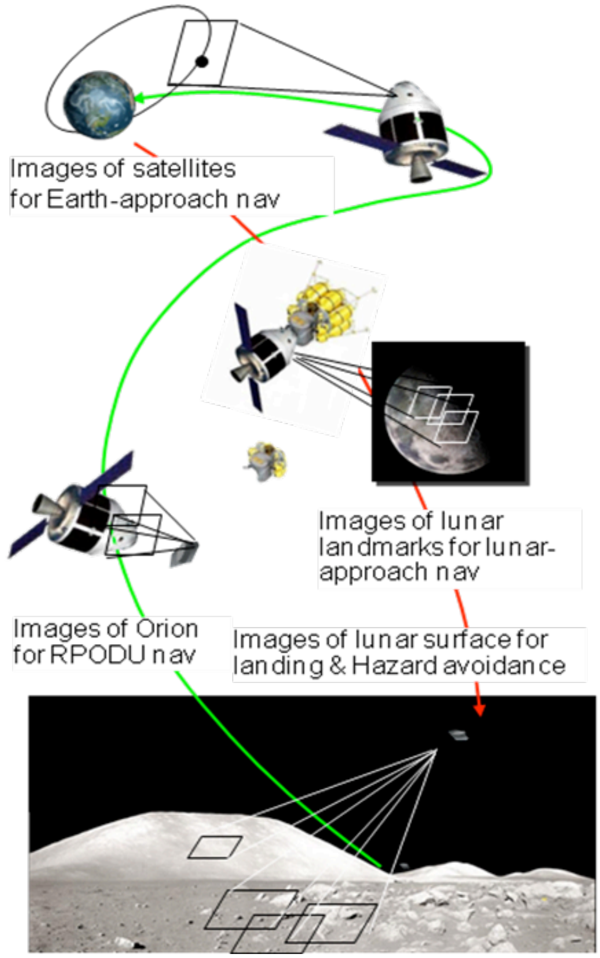

Figure 7. Optical Navigation System Architecture

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

- Precision camera, narrow angle, high performance (used for long range opnav, surface survey, precision surface Nav.)
- Wide angle camera (for star tracking, for Rendezvous, Proximity Operations, Docking and Undocking (RPODU), for landing, for low precision surface nav)
- Onboard navigation position, velocity (attitude) estimator (to also incorporate radiometrics, GPS, lidar, …)
- Onboard maneuver planner, estimator
- Gimbal (to make imager much more effective - allow dual OpNav/Tracker use)
- CPU - dedicated GN&C processor
- Landmark model and tracking software system (for both lunar surface and vehicles)
- Autonomy technology - fail proof planning, decision making, fault detection identification, and recovery.

The technology for these components exist and are flight proven, a challenge to the program is to develop a device that can efficiently and effectively integrate these instruments in a standalone package that is deployable on multiple elements whether it is a rover or lander.

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 an obstruction of LOS to Earth at times in the orbit. Descent operations occur out of sight of the Earth 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 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, Direct to Earth (DTE) communication will not be available.

For communication reasons, the use of a lunar relay is dictated by the need to service the South Pole for longer than 14 day habitation periods, covering expected terrain blockages, far side critical operations (descent) and far side science or excursions. From a navigation standpoint, there is a requirement to perform as well as was done during the Apollo era. To limit the number of ground stations and get the same performance also requires a relay.

On the lunar surface, the architecture uses a Lunar Communications Terminal (LCT) to provide for local communications over an 802.16 mesh network within a certain zone around the LCT located in the habitation zone. The LCT has limited LOS to Earth as well, 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 astronaut.

The result is that the operations concept for a user nominally depends on where they are located. Within the LCT coverage region, the user uses the LCT to communicate to other surface users and to Earth. Outside the LCT region, the user uses the LRS to communicate to other surface users or to Earth.

For CEV approaching (except for nav 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 near the equator.

Figure 8 shows the LRS service zones superimposed on the LCT service zone. These zones are displayed as concentric circles.

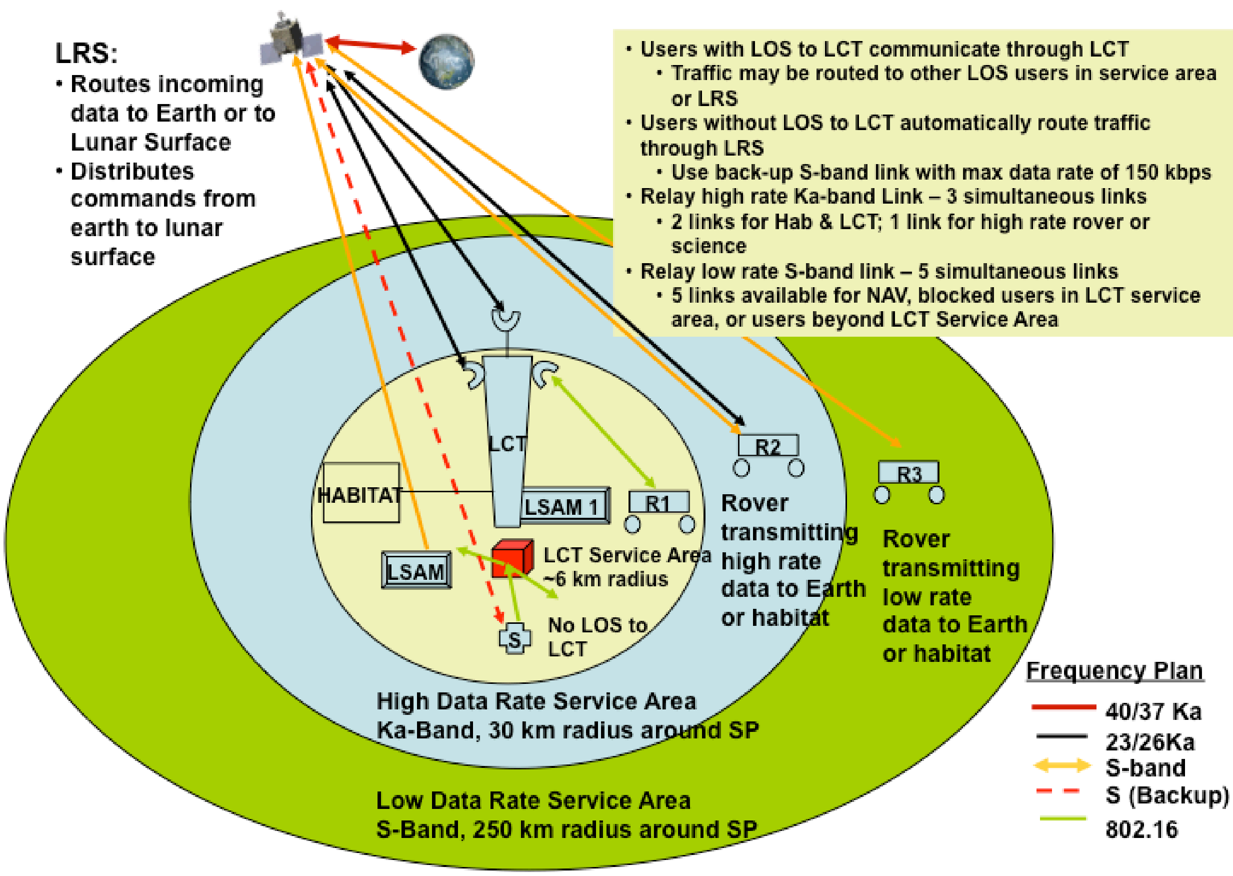

Figure 8. User Service Zones

However, the LRS zones can be moved independently of the LCT zone.

Users use the LCT when within the LOS range around the Outpost. The LCT service zone is a fixed region around the LCT with radius of around 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 LCT to save power. The LCT routes surface-surface data by wireless LAN and wired connections, such as the wired connection to the habitat. It routes surface-Earth data using LRS and/or DTE, when available, at K- 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.

On the surface the normal operations is that all the data to and from the astronauts radios are relayed initially from or to the LCT or when out outside of the habitation the rover.

When the missions or excursions from the habitat exceeds the area of the habitat zone then astronauts when outside of the rover will have their data relay through the rover to other astronauts in the vicinity, or through the rover to LRS or DTE as shown in Fig. 9. From there the data will be relayed to mission control or back to the surface of the Moon for other to communicate with the astronauts.

For rovers with attachment that are used to deliver raw materials to the processing plant and rovers to deliver the processed material (oxygen, hydrogen, water) to storage facilities near the habitat. When those rovers are near the ISRU then their data will be relayed by the ISRU back to the LCT or to the LRS depending on the location of the ISRU.

Outside of the LCT range, or behind an obstruction, the LRS is used. The service zone of the LRS 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.

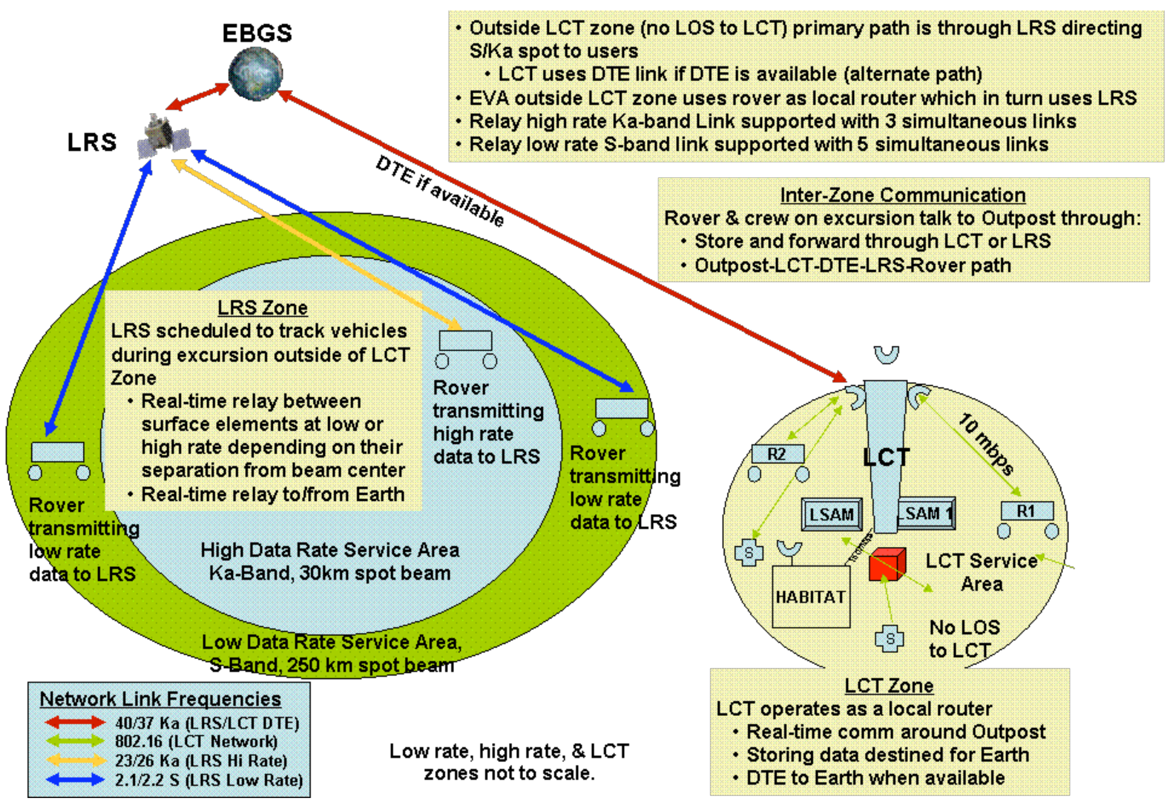

Figure 9. Outpost Coverage Zones for LRS and LCT when Roving outside of LCT Zone

With one satellite, normally the LRS service zones will stay 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.

The LRS zones are concentric S and Ka-band zones that move together as the antenna on the relay is pointed.

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 local router (LRS or LCT). 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 has a view to Earth simultaneously, then the link can be made with a few second delay through using a DTE link.

Contingency communication is the hardest part of the communication system requirement to meet for EVA astronauts. On the other hand, contingency communication using or relayed through mobile units, such as rovers, is straight forward.

To provide contingency communication whether for an astronaut or for a rover requires the use of a separate radio than normally used. In this architecture we chose to use the S-band radio up to LRS for contingency voiced communications. This is not a problem for rovers in term of mass or power. 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 that has yet to be firmly determined.

IV. Spectrum Utilization

The communication and navigation 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 meet both the data rates from the lunar outpost and allow exploration from the lunar outpost. Under the concepts of operations the system could only support communication with robots or rovers with astronauts exploring around the lunar outpost and the habitat zone simultaneously if the explorers and the habitat were within the same communication foot print of the satellite antennas. Longer explorations away from the habitat could be supported via the LRS on a periodic time table or, if the explorations were in the mid-latitudes (85 degree South to 85 degree North) and on the near side of the Moon, directly to Earth.

The following communication and navigational paths were used to form the communication network: Earth to LRS, Earth to lunar surface, Earth to CEV or Lander, LRS to lunar surface, Lander to lunar surface and lunar surface to lunar surface. From these paths we assigned what frequencies bands would be used and then the bandwidth or data rates between along the paths. The data rates came from our traffic models. Figures 10-12 give the frequency usage plan for three different cases.

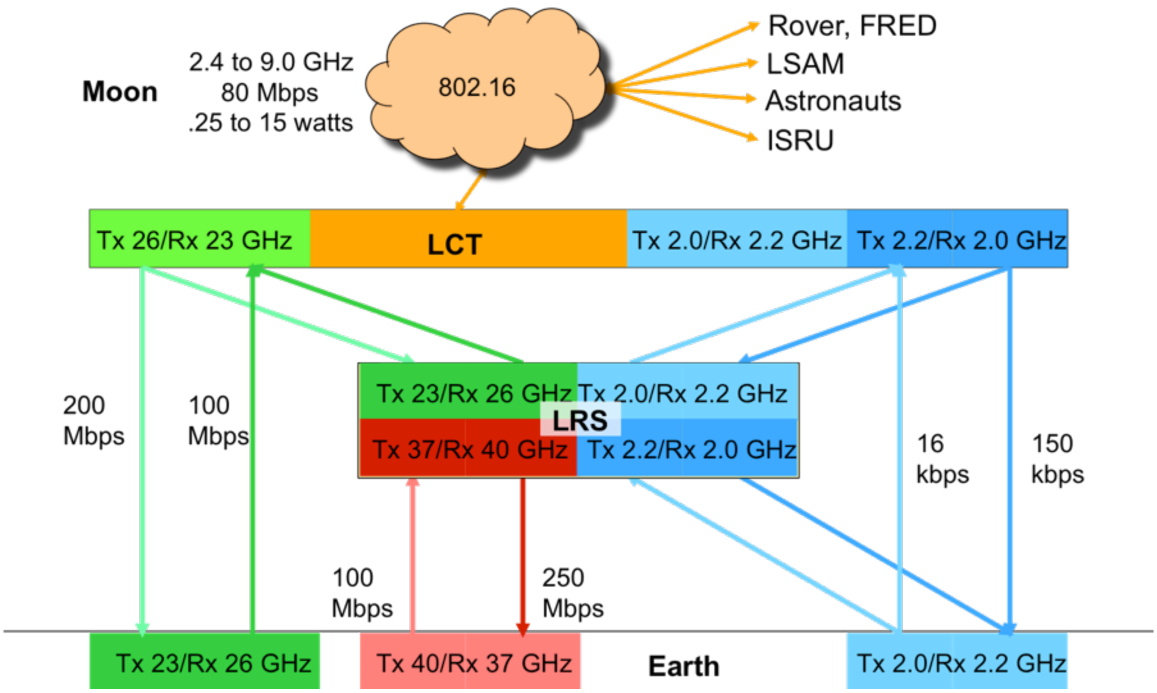

Figure 10. LAT Spectrum Plan: Normal operations around the habitat zone

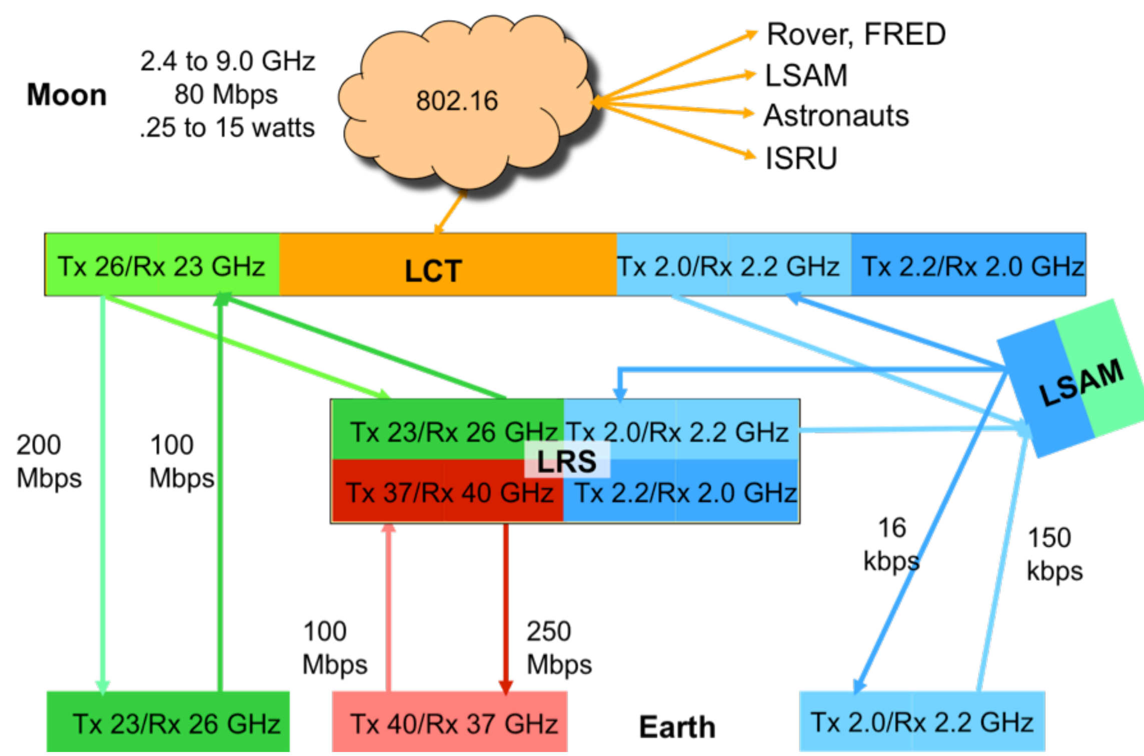

Figure 11. LAT Spectrum Plan: Landing of *Altair*

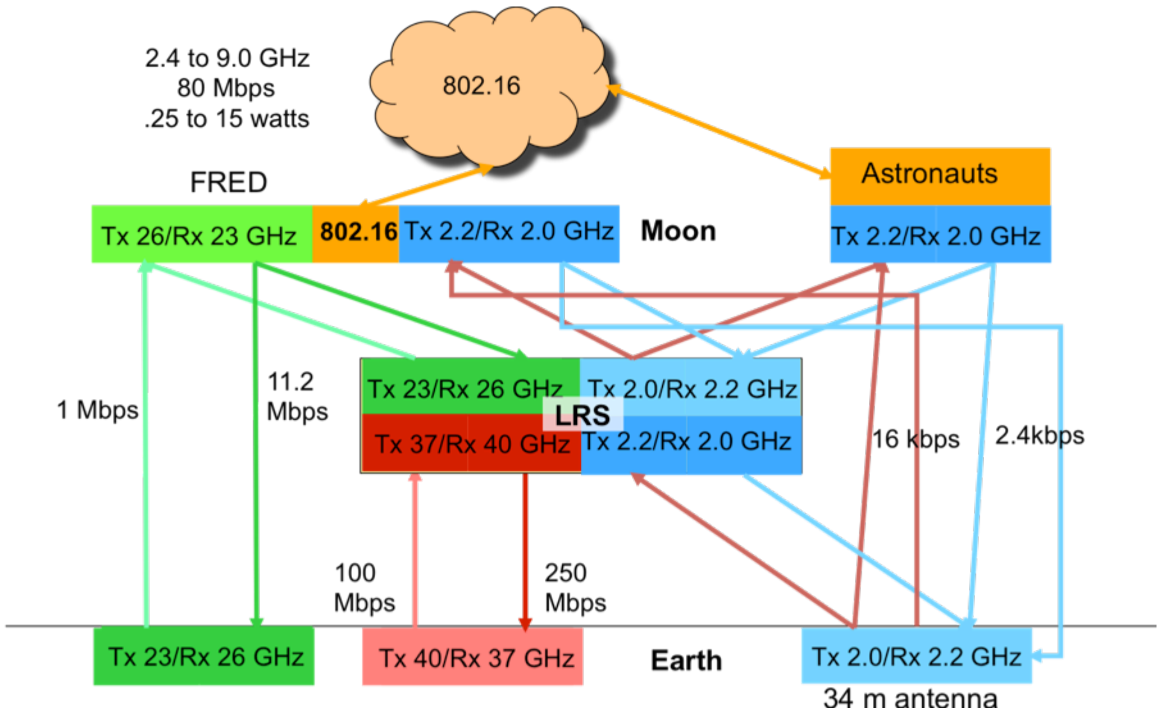

Figure12. LAT Spectrum Plan: Astronaut on EVA outside of Habitat walking back

The design of the LRS was chosen to make the LRS 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 we used current Earth assets and assets being developed for the lunar reconnaissance orbiter (LRO). This choice put limitations on some of the links but it allowed us to concentrate on the overall communication and navigation architecture that would not have been possible if different size Earth facilities were in the trade space.

An astronaut on EVA that is forced to walk from his or her rover back to the habitat presented a unique and serious problem. Because of the limitations on the transmit power on the EVA suit the 34 meter antennas on Earth must be used to maintain voice communication. This problem remains as one of the problems that need a better solution in future architectures.

1. EARTH

The Earth facilities had the following structure and communication spectrum. The antenna sizes were chosen to be 18 meters which is the same as for LRS. The frequency bands were S-band to and from the Lander, CEV, LRS, and the lunar surface; Ka-band (23/26 GHz) to and from the Lander 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 Space Network (SN) protocol. The protocol we chose limited us to 150 kbps using PN coding. This choice was made to allow two-way and Doppler ranging for navigation as current navigation methods utilizes the PN coding.

The Earth terminal on would transmit 100 Mbps of data up directly to the lunar surface or Lander at 23 GHz and receiver 250 Mbps down from the lunar surface at 26 GHz. The 250 Mbps was divided into 4 data channels. The channels were two 100 Mbps channels and two 25 Mbps channels. This channelization of the data rates allowed flexibility in designing missions. One of the two 100 Mbps channels allow a high rate data communication with the lander while it is landing and while the crew is inside the lander. After has left the lander then for the outpost then this channel can be used by outpost to support the mission. The other 100 Mbps channel is dedicated to the outpost. The two 25 Mbps channels were sized to support remote exploration of the lunar surface by robots, by human occupied rovers, or by a remote in-situ resource utilization (ISRU) plant.

At upper Ka-band (37/40 GHz) the Earth terminal would transmit up to 100 Mbps to lunar service via LRS at 40 GHz and would receive up to 250 Mbps at 37 GHz. In addition, there would be a small part of the bands allocated for navigation to allow two-ranger and Doppler shift 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 QPSK for modulation and Reed-Solomon with Viterbi code rate of ½ for forward error correction (FEC).

2. LRS

The LRS communicates to Earth and to the lunar surface primarily though it can support communications to the CEV and the Lander if needed and it is in the correct position. The LRS not only is a communication relay satellite it also provides navigation data to other spacecraft and to roving elements on the lunar surface. Also, the LRS along with the lunar communication terminal provides the local lunar clock.

The LRS communicates with Earth at 37/40 GHz and with the lunar surface at 23/26 GHz. The data rate and frequency going to Earth is 250 Mbps and 37 GHz, respectively. The 23/26 GHz band is divided the same way as on Earth so that users on the Moon has 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 and Earth, and LRS and the 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. Astronauts out on EVAs must be able to communicate with each other, communicate to other astronauts in the habitat or the lander, communicate with mission control, and communicate to the rover or habitat to send commands and to assess status. In addition, the astronauts on EVA may need to communicate with science packages, ISRU, or a power plant. Robots, rovers, habitats, power units and logistic units will need to be able to communicate back to Earth independently of astronauts for them to perform their needed tasks. An example would be a rover being directed from Earth to explore an area to be used as a landing site for astronauts on the next mission. To be able to devise a lunar communication network a surface to surface communication system must be established in addition to the previously describe links off of the lunar surface in the Earth and the LRS sections.

At the beginning of LAT2, before the traffic model, it was assumed that we might be able to us the S-band with SN format and/or the high frequency (HF) band to support low data rates and non-line-of-sight communication. But as the traffic models were being developed it became apparent the data rates needed exceed what either one method could support. That left us with using only high data rate surface to surface network. We chose to do our analyses at 2.4 GHz because it is an unallocated band, and at 3.8 GHz as that frequency is the down link frequency from commercial communication satellite to the Earth. The latter frequency band was felt that as there are no Earth sources pointing into Earth it would be a quiet band.

The lunar surface network was broken up into a wireless network and a dedicated wired line between the LCT and the habitat. The wired line 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 wireless network protocol that seems to be able handle the needed data rate from the traffic model is 802.16e. Though even that one would need to have a mesh capability added to it to allow astronauts to communicate between each other when not insight of a base station. Because to the maximum data rates (80 + Mbps) as identified in the traffic model 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 2 astronauts, and one high definition camera. Also smaller non-roving surface elements like ISRU plants and Landers would have smaller LCT on them sized to support 2 HDTV channels, 2 astronauts, and telemetry.

V. Traffic Model

The traffic model results are summarized in Table 2.

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 Earth Ground System	3.9	151.0	**154.9**
Aggregate Peak Rate from Earth	LRS and Earth Ground System	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**

The aggregate peak rate to and from Earth will occur between the LRS and the Earth Ground System 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 Comm

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

VI. Element Design Concepts

The LRS was initially designed to look like 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 ground antenna at 26 GHz that is being used for the lunar orbital reconnaissance (LRO) satellite. The orbit that was assumed was 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 receiver 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.

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

Since there are no frequencies allocations for lunar surface to surface communication, link analysis 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 was designed to be a space gateway, a surface to surface radio tower, a router, a time reference, and have store and forward capabilities. In the diagram Fig 13 the LCT major elements are shown. Under the LAT2 assumptions the LCT was supplied power from the power network. The LCT can be configured as a separate unit that is displace from the habitat or as an integrate unit on the habitat or another lunar asset.

From the link calculations the sub-systems of the LCT have the following properties. The link calculations assumed Reed-Solomon/Viterbi coding with rate ½ and QPSK and a bit error rate of 10^-8. There was a 3 dB margin used in the link calculations from the lunar surface to the satellite or Earth. The surface to surface link calculations between the LCT and other wireless users on the lunar surface assumed the other users were using an antenna with a 2 dB gain at either frequencies of 2.4 GHz or 3.8 GHz. The link margin used was 30 dB assuming a spherical moon. The 30 db margin was in place of surface to surface path loss as there was no lunar surface terrain data available.

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

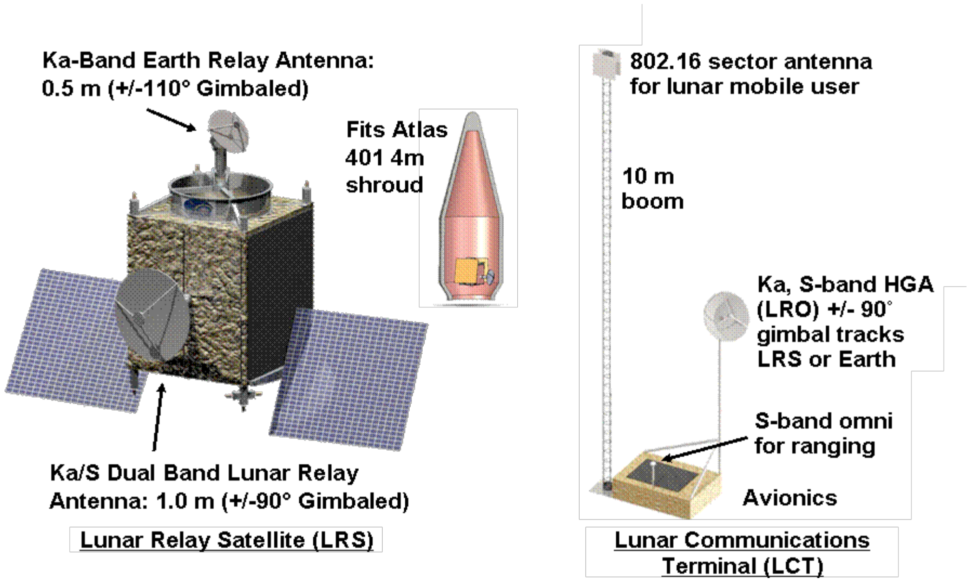

Figure 13. Key Features of LRS and LCT

A. LRS

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, as illustrated in Fig. 8. Coverage zones define the area over which satellite connectivity exists for a specified number of hours per orbit.

- The coverage requirement for S band was defined as 8 hours (out of 12) over a circular area with a radius of 250 km from the South Pole.
- The coverage requirement for Ka band was defined as 8 hours (out of 12) over a circular area with a radius of 30 km from the South Pole.
- Since the Ka band coverage area is relatively small, it may impact operations farther away from the South Pole. Further study is required on how to increase the coverage area or allow it to move relative to the Moon's surface to provide coverage for longer excursions.

Figure 8 also shows an approximately 6 km coverage area for an 802.16 network whose hub is in the LCT. The actual S band coverage, as seen from a perspective above the South Pole, is shown in Fig. 14.

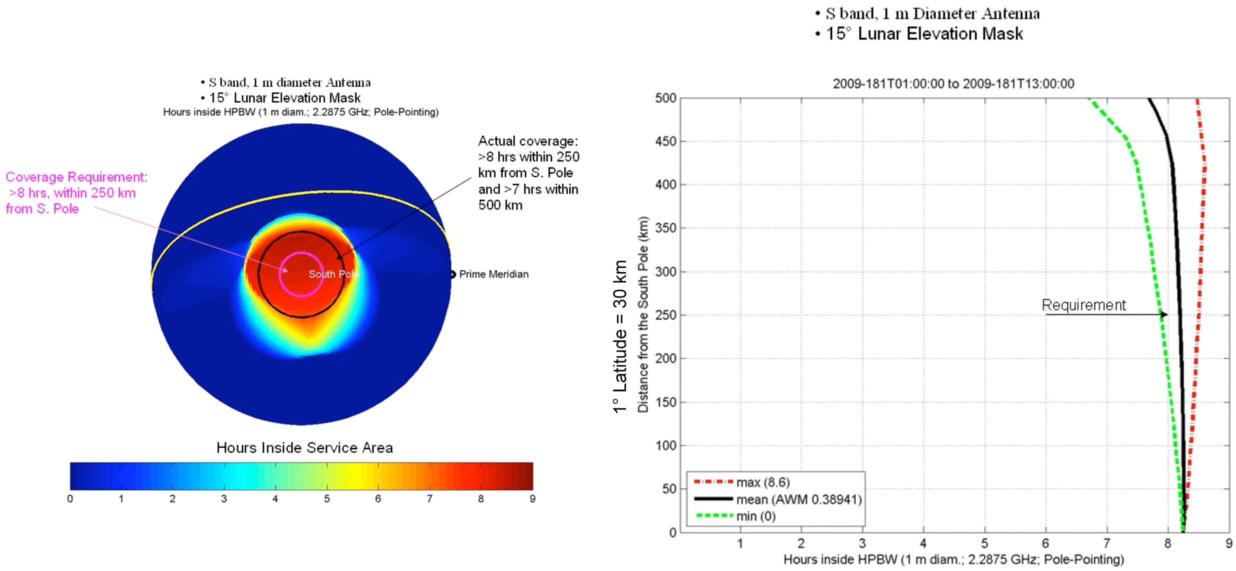

Figure 14. LRS S-band Coverage Patterns

Since the LRS Antenna beam is centered on the South Pole, the 3 curves represent minimum, mean, and maximum coverage time at a given latitude or distance from the South Pole.

- A degree of latitude represents approximately 30 km.
- The mean coverage time at a given latitude represents the average over all longitudes

It can be seen that an average of 8 hours of coverage is provided out to the required coverage area of 250 km radius

Similar plots, for Ka band coverage, are shown in Fig. 15.

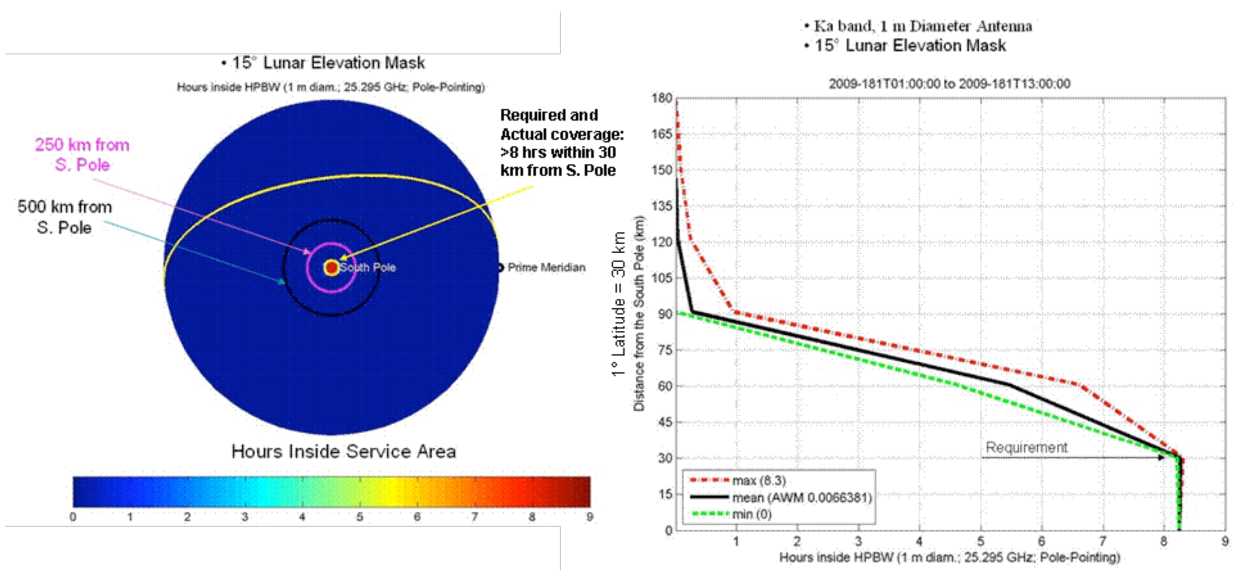

Figure 15. LRS Ka-band Coverage Patterns

It can be seen that an average of 8 hours of Ka band coverage is provided over the required coverage area of 30 km radius.

B. LCT

The LCT communications payload design contains the S-band, Ka-band and the 802.16 WLAN radios connected by a high speed router. The S-band and Ka-band radios share the same design as on the LRS. The design is single fault tolerant. The Ka-band radio has a 26 GHz transmitter and a 23 GHz receiver, two 100 Mbps modems, Frequency Division Multiple Access (FDMA) multiplexer at an Intermediate Frequency (IF), and shares a dual band Ka/S 1 m diameter dish antenna.

On the receive side, the system can switch between either the Low Noise Amplifier (LNA) or down-converter circuit. At the IF of that circuit, there is another switch that allows the signal to go into either input of the 100 Mbps modem. The output of the modem is to redundant 300 Mbps routers.

On the transmit side, data from the router goes into the two high speed modems. From the modems, the two signals are frequency multiplexed together into one signal at IF. Then that signal goes to the redundant up-converter/RF power amplifiers before the signal is routed to the antenna for transmission.

The maximum data rate that can be transmitted by a single LCT to the LRS or Earth is 200 Mbps and the maximum that can be received is 100 Mbps.

This radio uses the dual S/Ka-band antenna from LRO increased from the LRO's 0.75 m diameter to 1m. It also uses the TWTA power amplifier from LRO. No change in transmit power was made to the LRO TWTA so that there would be no development cost for a new tube.

The 23 GHz LNA/down-converter comes from the Orion CEV. The only item that needs development is the 100 Mbps modem. The data rate for these modems was determined from the Traffic Model and the reasonable expectation of being developed in time.

The S-band parts of the LCT consist of standard current day TDRSS radios organized in a single fault tolerant design. The transmitter, receiver, the modems, the PN circuit and the navigation all conform to current SN format. The high gain S-band antenna is part of the dual band S/Ka-band antenna. There is a low gain omni antenna for safe mode operations. The output of the radio goes into the 300 Mbps router. An atomic clock and timing circuits are used by the S-band radio for coherent ranging and one-way ranging measurement.

The WLAN radio is assumed to be an 802.16e base station. It consists of 3 base stations (2 active and 1 spare) and two sector antennas with a gain of ~15 dBi. The 802.16e sector antennas were placed 10 meters off the lunar surface on a boom to be able to allow LOS communication out to 5.8 km. This distance is the distance that will cover the anticipated outpost region consisting of the landing zone and outpost work area. A range of 10 km which would require a 40 m boom is under consideration to cover the EVA Walk back distance in case of a rover failure.

C. Communication Payload

Figure 16 provides a block diagram of the LRS communications payload. The left hand portion of the diagram including the 23/26 GHz Ka and 2.1/2.2 GHz S-band components and the on-board processing equipment (router, nav processor, Command and Data Handling, and Solid State Recorder) are all common on the LCT.

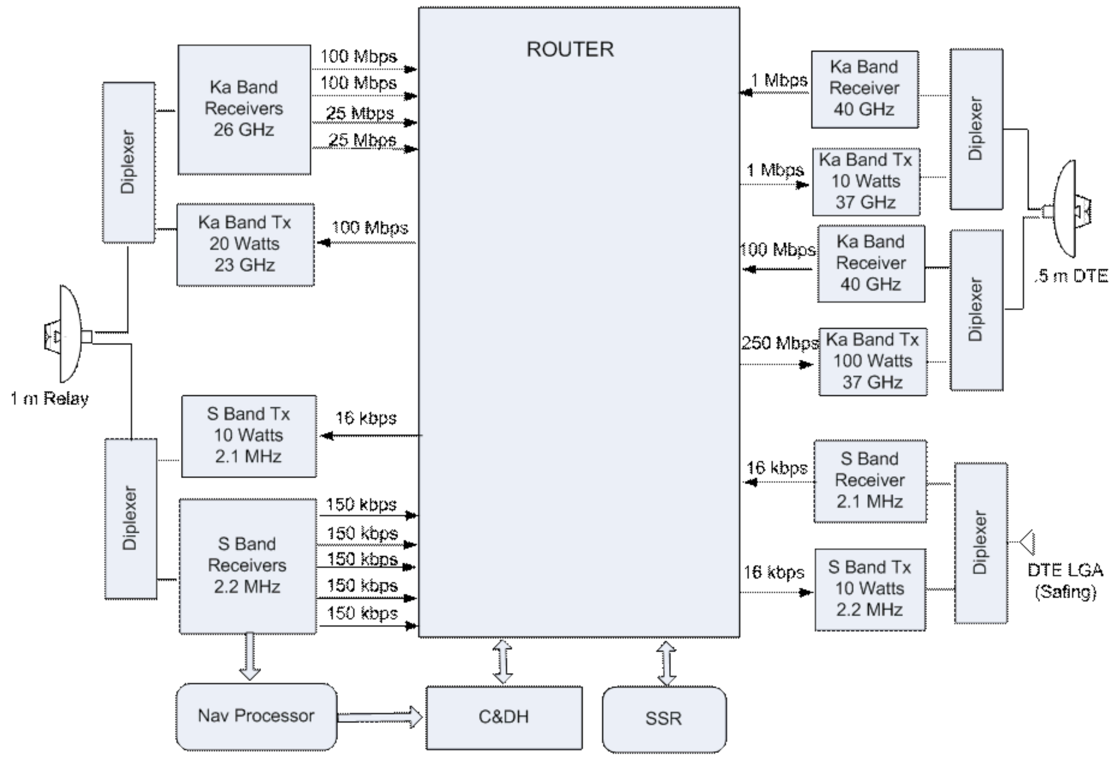

Figure 16. LRS Communications Payload Design

The LRS S band return Relay Link shall be capable of supporting [5] simultaneous access, [up to 150 kbps each] data rate links within the footprint of a given LRS orbiter.

The LRS S band forward Relay Link shall be capable of supporting 1 TDMA, 16 kbps data rate link within the footprint of a given LRS orbiter. (Assumes user has omni Rx antenna.)

The LRS Ka band return Relay Link shall be capable of supporting 4, [2@100 Mbps, 2@25 Mbps] data rate links within the footprint of a given LRS orbiter.

The LRS Ka band forward Relay Link shall be capable of supporting 1 [100 Mbps] data rate link within the footprint of a given LRS orbiter. (Worst Case Traffic Model needs 141 Mbps.)

After the Link and data rate requirements are established, the payload components can be defined and selected

The following slide shows the functional architecture of the Communications Payload, defining the antennas, receivers, transmitters, and other components such as the router and solid state recorder (SSR)

- The SSR is required because LRS operates in a store and forward mode
- The router is needed to set up all the required User to User and User-Earth data flow paths
- A reverse band S band transponder is needed during spacecraft safing for communication with Earth

D. 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 2.

· 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, PRs 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 for Rovers: 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 severe 1 kg and 0.25 W transmit power EVA Suit 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 2.4 kbps contingency voice to LRS on S-band as well as 2-way navigation.

Table 2. 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 TDRSS antenna	150 kbps navigation in Normal Mode or Safe Mode	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 TDRSS S band in SN	1-way and 2-way tracking (Doppler and ranging) via TDRSS S band in SN protocol	Relies on Rover in Normal Mode. 2-way tracking in Contingency Mode

VII. Ground System Design

1. Direct To Earth (DTE) Network

NASA will upgrade the communications network infrastructure to support missions for the manned lunar exploration in the 21st century. Earth-based direct communications support spacecrafts in transit and the lunar base when in view. Besides basic communications, higher data rates will be required, particularly for the manned lunar missions, including any lunar outposts. The current NASA plan is to increase the data rate to at least the 150 megabits per second (mbps) range using the Ka-band 26 GHz frequency. The Deep Space Network (DSN) is adding Ka-band 26 GHz to its 34-meter network in support of the James Webb Space Telescope (JWST). The Lunar Reconnaissance Orbiter (LRO) and Solar Dynamics Observatory (SDO) are constructing a Ka-band 26 GHz 18-meter antenna at the White Sands, NM facility. By 2014, two additional TDRSS (Tracking and Data Relay Satellite System) satellites (K and L) will be deployed to support the Crew Exploration Vehicle (CEV) mission to the International Space Station(ISS) using the Ka-band 26 GHz.

The first lunar outpost phase supports short duration missions. The plan calls for two missions per year. Short-stay missions will take place at the lunar vicinity, beyond the coverage of TDRSS. The primary method of supporting communications will be using Earth-based ground stations (DTE). These missions will be 7 days in duration and can be planned for periods of ground communications coverage of the Moon's South Pole to avoid the communication blockage periods between the lunar surface and the Earth.

NASA would like to maximize use of existing NASA sites and infrastructure (Fig 17). The most cost-effective choice to support short-stay missions is to use existing DSN sites [2]. Existing 34-meter Beam Wave Guide antennas will be upgraded with Ka-band 23 to 26 GHz and an S-band TDRSS compatible signal. The LRO 18-meter antenna, referred to as White Sands 1 (WS-1), will also be used for these missions. Once the frequency of the lunar missions is increased, 18-meter antennas will be deployed at DSN sites in Madrid, Spain and Canberra, Australia and, together with WS-1, will provide the lunar DTE network.The 18-meter antenna is used as a baseline for users to close their link margins. Rain attenuation for DTE will be provided by using the 34-meter as backup (additional 10 decibels compared to 18 meter) or by using S-band. An issue with the proposed approach is that the WS-1 DSN sites, as shown in Figure 3, provide 98.5% coverage of the Moon.

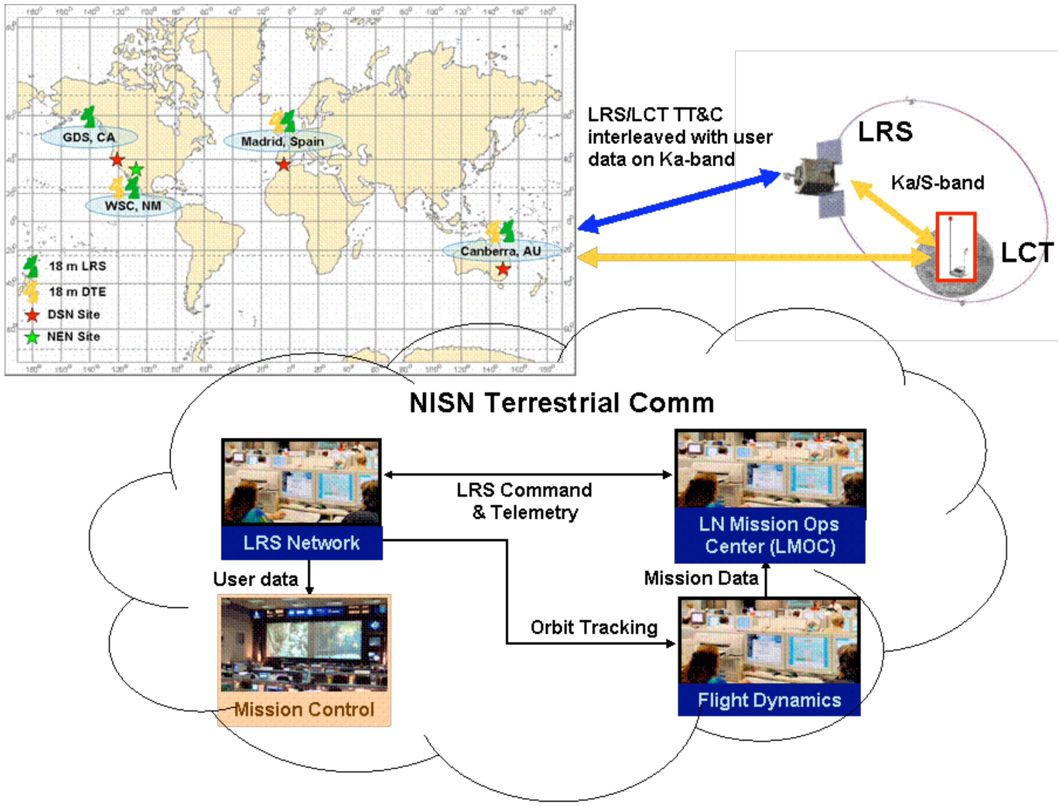

Figure 17. Earth-based Ground System Architecture extends existing NASA networks

2. The Lunar Network Architecture and Availability

The lunar outpost should be supported with a combination of Earth-based antennas, relay satellites, and lunar surface communication assets. The lunar surface network will be built around a commercially available standard, such as 802.16. The hub of the surface network is the Lunar Communication Tower (LCT) which serves as a gateway and communicates directly to the LRS. The LCT data rate is planned to be 200 Mbps. In addition to transferring LCT data to Earth, LRS provides rovers with*in-situ* navigation and voice. The architecture is depicted in Figure 4.

The availability of services to users is a combination of the three elements: LCT, LRS, and relay ground stations. The LCT availability is rather high at 99.5% due to the need to be self-contained on the surface with built-in redundancy and failovers. Each relay satellite's availability is 97%, from which 2.5% is allocated for housekeeping activities such as orbit maintenance, momentum dumps, and a spacecraft flipping maneuver that is required periodically to stay aligned with the Sun, Moon, and Earth. This fourth ground station increases the availability of the LRS element from 97% to 99.5%, thus significantly improving the overall availability of the lunar network.

3. Relay Ground Stations

The dedicated LRS ground stations provide a challenge in achieving high availability. The combination of geographical coverage, station downtime for maintenance, and rain attenuation, degrades the ground antenna availability to 90%. Unlike DTE, the LRS ground stations have no "elegant" options dealing with rain diversity.

- Unlike the Ka-band 26 GHz that is shared by other non-lunar missions, the Ka-band 37/40 GHz (Q-band) 18-meter antennas are dedicated to lunar relay satellites.
- LRS is required to use the same S-band frequency as its users. The LRS will need to shut down the S-band transmitter while serving its users. Use of X-band for LRS would alleviate this problem.
- Q-band is very susceptible to rain.

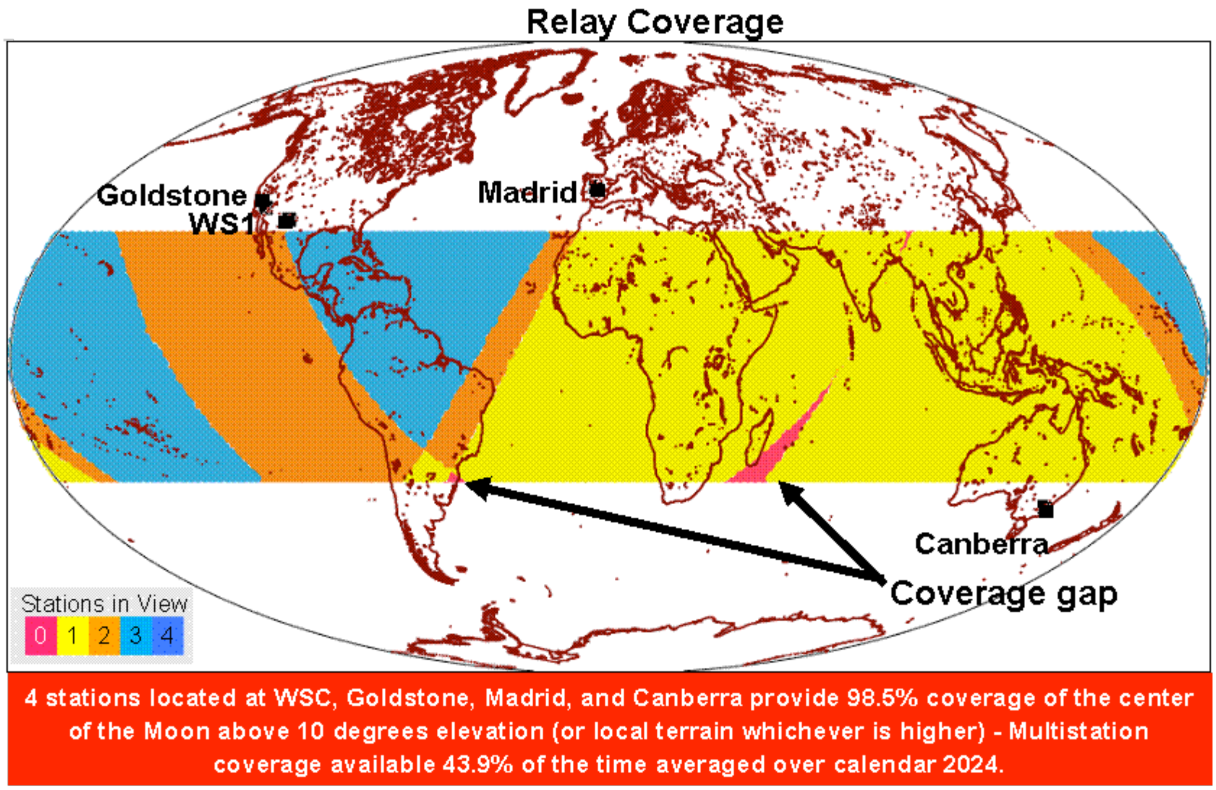

Figure 18. EBGS Coverage of the Lunar Network using four Ground Stations

There are two approaches to address the rain diversification problem; one is by reducing users' data rates and the other is to build more ground sites. Providing a high availability service with three planned ground stations requires a strategy of increasing the gain by reducing the data rates. For example, the Q-band for Canberra indicates that a gain of 3 dB can be achieved by reducing the data rate by half and will improve weather performance from 95% to 97.5% availability.

To provide 100% geographical coverage of the Moon and diversification to handle rain requires the use of six sites identified in the Exploration ground antenna study. The proposed approach is to have two sites in each geographical zone. These six proposed sites are listed below, namely:

- US: Goldstone and White Sands
- Africa/Europe: Madrid and Hartebeesthoek, South Africa
- Australia: Canberra and Dongara

The six site approach is rather expensive as it requires building antennas at two non-US sites. The use will only be 16% since they cannot be shared by other users unless they are upgraded to support multiple frequencies. Analyzing the coverage of the six sites shows that the system exceeds the requirement for double coverage and provides triple and even quadruple coverage in some areas.

4. LRS Fourth Site

As discussed earlier, the minimum number of sites required to support LRS is four and this increases the LRS availability from 97% to 99.5%. Three sites are needed to move users' data back to Earth and the fourth LRS site is used as overflow to perform spacecraft housekeeping for overflow dumping for the LRS recorder. The LAT recommended Goldstone (GDS) as the fourth site since deploying antennas at an existing US site is the most cost-effective. Goldstone and White Sands provide geographical diversification to handle rain attenuation of the US zone. However, GDS adds only 13% of double coverage area since the GDS coverage area overlaps with White Sands and Madrid. The total ground station system only has double coverage for half of the time and an outage in Canberra will significantly impact the total system. The proposed approach for deploying DTE and Relay antenna is shown in Figure 19.

			2018	2019	2020	2021	2022
USA	WSC	18m	LRS2	LRS2	LRS2	LRS2	LRS2
	WSC	18m		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM
	Goldstone	34m		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM
	Goldstone	18m				LRS3	LRS3
Aust.	Canberra	18m	LRS2	LRS2	LRS2	LRS2	LRS2
	Canberra	18m		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM
	Canberra	34m		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM
Europe	Madrid	18m	LRS2	LRS2	LRS2	LRS2	LRS2
	Madrid	18m		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM
	Madrid	34m		CEV/LSAM	CEV/LSAM	CEV/LSAM	CEV/LSAM

Legend
new antenna
Upgrade Ka 23
Q-Band
Ka-26/23
Ka-26/23 Backup

Figure 19. EBGS Extension Timeline

VIII. 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 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[10] in the 2012-2013 time 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 20. Very briefly, the technology advances used in the LN architecture include:

- **Navigation and Timing**
  - *Lightweight Atomic Clock*: Need a lightweight, liter-class 10e-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.

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

- **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 disruption tolerant networking techniques to successfully 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 (backbone and proximity). Need to support processing/routing at 350-500 Mbps for proximity and backbone links.
- **Advanced Antennas**
    - *Multi-beam High-gain Antenna*: 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 (Non-LOS) via a relay orbiter.
- **Optical Communications:** Need optical terminals to enable high bandwidth links to support surface-to-surface, surface-to-space, and DTE communications. Need to transmit up to 1 Gbps and receive 10 Mbps. Need photon counting detectors at 1.5 micron wavelength, two-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 humans, robots, habitat, power stations, ISRUs, rovers, and science packages together for line of sight applications. Support surface mesh networking using 802.16 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 one and possibly two way radiometric tracking.
    - *High Data Rate Modem*: Need to provide throughput of 100 Mbps interfacing to SN signaling side using Quadrature Phase Shift Keying (QPSK) and down-conversion to Intermediate Frequency (IF).
- **Integrated Wireless Technology**
    - *RFID Development*: Need space qualified interrogator that reads RFID tags for inventory management and also reads passive wireless sensors. Fundamental physics of interrogation are very similar, so 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.

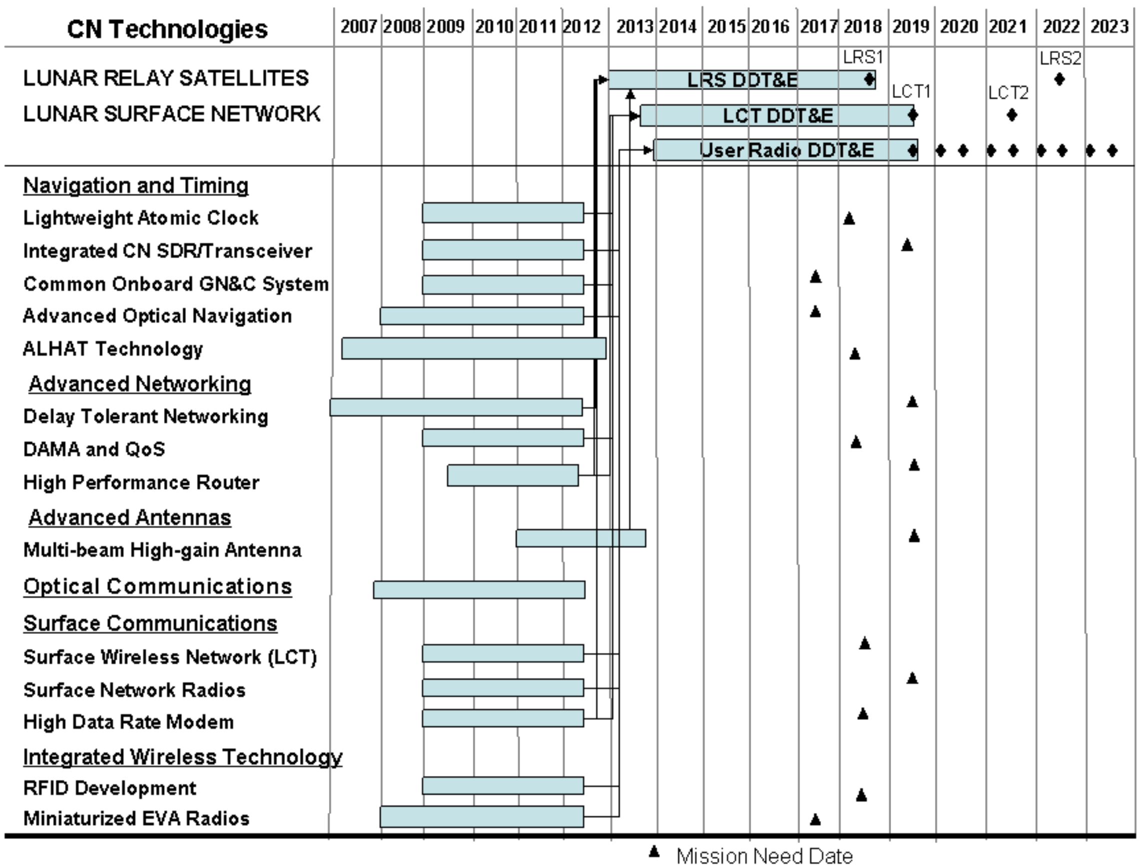

Figure 20. Technology Advances Incorporated into LAT Communications and Navigation Architecture

IX. 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 should 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 should 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 should 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 due to the use of reverse banding and use of S-band for both communications and navigation
  - Line Of Sight 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
- Define an integrated signal structure incorporating both communications and navigation.

- *Concepts of Operation*: Develop more detailed concepts of operation with other lunar elements (mobility, habitation, ISRU, power, *Altair*, *Orion*). For these scenarios, determine types of data required, data rates, latency limits, duty cycles, number of simultaneous users, nav accuracies needed, and in situ comm needs (e.g., during telerobotic operations & crew walk-back). Develop concepts for operating the LN including satellite handovers, operations during early Outpost construction, and management of the LN by the LMOC.
- *General:*
  - Study options for launching LRS on *alternative launch vehicles* such as emerging commercial vehicles
  - Study *commonality* of avionics across all orbiting and surface elements. Analyze commonality approaches considering programmatic implementation, cost, acquisition strategies, and risks.
  - *Model logistics and maintenance needs* for spares and repair operations.
  - *Assess the extensibility of the C&N Architecture to Mars*. This was planned to be part of the parallel Mars Architecture Team (MAT) study but was cancelled due to Congressional direction.
- *Navigation:*
  - To conduct mission design trades on LRS orbit, design, and control concepts, build a new mean element propagator application that works at the Moon with the requisite orbit stability analysis capabilities to design lunar constellations, assess orbital stability, and develop a constellation control strategy.
  - Study quantity and locations of EBGS site, radiometric data quality, and extent of tracking needed by the LN. Analyze the sensitivity of navigation performance on epochs (i.e., Earth/Moon geometry, arrival geometry). This was not addressed in LAT2 and is required for determining the sufficiency of the EBGS and LN in all tracking scenario assumptions/geometries.
  - Analyze LN clock stability and define mechanisms for synchronizing LN time with Earth time.
  - Develop a 3 Degree Of Freedom analysis capability for Rendezvous, Proximity Operations, Docking, and Undocking operations.
  - Conduct trades on 1-Way versus 2-Way ranging for surface roving navigation. This may result in signal redesign to accommodate the needed tracking data.
  - 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. RF Identification (RFID) standards need to be further explored for use in inventory tracking and management, asset location, and logistics.
  - Expand analysis of the network traffic behavior including throughput requirements and QoS under varying conditions driven by different modes of operation.
  - Investigate passive, wireless sensor (PWS) technology for potential dual-use SDRs that provide both RFID and PWS interrogation. Study how to extend sensor coverage with minimal size, weight, and power.

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