Section 4H
Lunar Surface Outpost Communications Strategy

Appendix 4H - Lunar Surface Outpost Communications Strategy

Introduction

This section summarizes the effort to support the 60-day Exploration Systems Architecture Study (ESAS) with an initial look at the communications architectures required for lunar surface communications. The work considered lunar outpost deployment and sortie mission scenarios as described in the main report. This appendix presents a communications concept and architecture, with sections addressing frequency band and data rate analysis, lunar communications constellation considerations, reconfigurable transceiver assessment, microwave antenna selection, and a Rough Order of Magnitude (ROM) estimate of the costs associated with providing the lunar communications architecture. Some information is also provided on the architecture for the sortie missions. Principle contacts for this information include Mr. Lawrence Wald at NASA/Glenn Research Center (GRC) and Mr. Fred Stillwagen at NASA/Langley Research Center (LaRC).

Outpost Communications

The Lunar surface communications concept centered around the need for communications to and from the different lunar surface elements, including the Lunar Surface Access Module (LSAM), the habitat, In-Situ Resource Utilization (ISRU) equipment, personnel on External Vehicular Activities (EVAs), rovers (both unpressurized and pressurized), science instruments, and power elements. Also included in the analysis was consideration of the communication needs for LSAM separation from the Crew Exploration Vehicle (CEV) and descent to the lunar surface and ascent stages from the lunar surface back to the CEV.

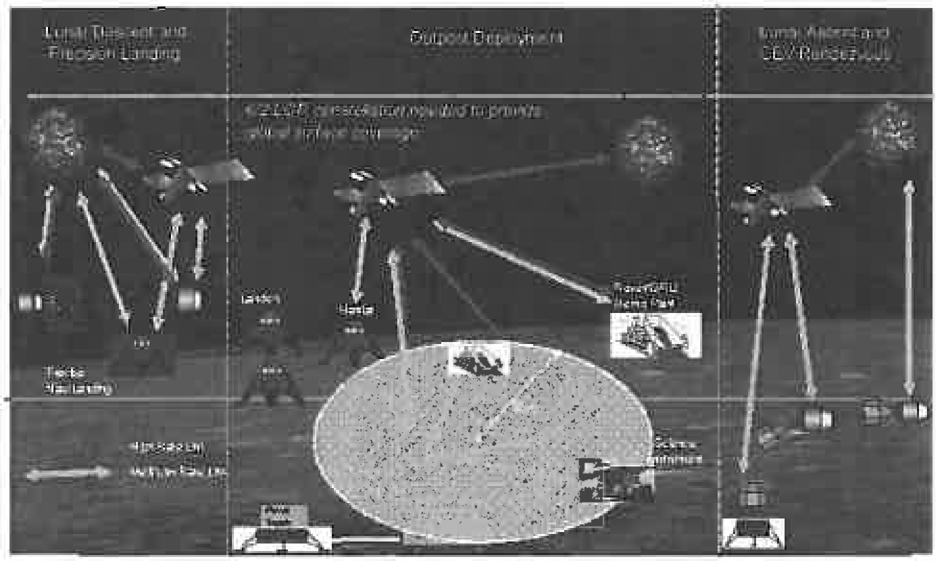


Figure 4H-1. Lunar Surface Communications Concept

Figure 4H-1 illustrates the three phases for the outpost deployment. Phase I represents the CEV separation and lunar descent stage. Phase II represents the outpost deployment scenario including habitat deployment, ISRU and EVA activities, and science experiments. Phase III represents the ascent stage and CEV rendezvous. Only the communications aspects were considered in the analysis.

The concept considers a surface network, star topology architecture for surface communications. A gateway or surface local area network enables line-of-sight coverage out to the 15 km range for local EVA excursions. The gateway function aggregates the surface communications for lunar-to-Earth communications, implying a need for a high-rate link from the gateway to Earth (via relay satellite or direct-to-Earth link). The alternative architecture considered using relay satellites or Earth relay for element-to-element communications. These two alternatives were rejected for local excursions due to higher complexity and cost for larger-surface radio requirements. For excursions beyond 15 km, a lunar relay satellite, Earth relay, or surface repeaters are required because of limited line-of-sight connectivity due to the Moon's curvature. Relay satellites are preferred over an Earth relay due to the size, mass, and power impact to surface radios to close the link to Earth at high-data rates. Surface repeaters are not favored due to the anticipated increase in operations cost to deploy and maintain surface communications infrastructure. A more complete trade is required to properly asses the different architecture trades between lunar relay satellites, direct-to-Earth relay, and surface network infrastructure based upon refined data requirements.

The lines connecting different communication elements represent anticipated data link requirements. For the descent and ascent stages, low to moderate data rates (< 40 Mbps) are expected to satisfy communications requirements. Data requirements are expected to be driven by video requirements during critical maneuvers. A high-rate link between the lunar relay and Earth is shown, as the relay satellite may aggregate moderate data rate links into a single high-rate return link. This would reduce the complexity and number of different links on the satellite. For the outpost stage, high-rate links are expected between the gateway function and the lunar relay satellite and between certain surface science payloads, ISRU assets, and the lunar relay satellite. These applications require high-rate links to transmit high-data volumes generated by instruments such as hyperspectral imagers or ISRU data collection and processing requirements. Lower data rate links are also shown using the gateway for the communications from these elements. A further analysis of requirements is necessary to confirm the need for a high-rate link from the individual elements.

The goal of the architecture was to limit the number of individual elements requiring direct access to the lunar relay from the surface. Considering the bandwidth required of high-data rate links, it was assumed that high-rate links would use the Ka-band frequency allocation. This would imply a requirement for directional (e.g., phased array) transmit antennas to send data from the surface element to the relay satellite. It was further assumed that the links would be asymmetric and a high-rate directional receive antenna would not be necessary. These technology trades have impact to mass, power, and cost analysis. High-rate links and directional antennas were used sparingly in the architecture concept to minimize resources.

Lunar Communication Relay and Navigation Constellations

Recent studies have provided assessments of communications relay functionality and radiometric navigation for constellations of orbiting spacecraft around the Moon [1,2]. By deploying an infrastructure of communications relay and navigation satellites around the Moon, NASA can reduce communications "user burden" of mission elements such as lunar orbiters, LSAMs, EVA assets, and rovers. A constellation of lunar communications and navigation orbiters can also provide communications capability to regions of the Moon, for which direct communications with Earth is impractical or impossible. Additionally, the microwave communications system onboard the orbiters can be developed in such a way as to offer accurate, absolute, position-fixing services to suitably equipped mission elements on or near the Moon.

The primary focus of these studies has been on determining the overall cost and performance associated with each of a number of candidate constellation designs in order to specify the lunar portion of an architectural framework for NASA space communications. Performance of the constellation design is evaluated in terms of the fold of coverage provided to the lunar globe by the constellation, user burden, navigation "system availability," as well as a number of more qualitative Figures of Merit (FOMs) such as "adaptability" or "evolvability." Cost estimation is performed assuming a normalized user burden for a mission element on the surface of the Moon. These constellation designs fall into a number of "classes" including the following:

1. Libration point constellations,
2. Highly elliptical,
3. Walker-style circular constellations, and
4. Hybrid (i.e., combinations of all of the above).

Within each of these classes, the number of satellites, number of distinct planes, orbiter inclination, and orbiter altitude can be varied. The possibilities are limited only by the imaginations of the studies' authors. A short list of constellations is developed for study and is justified in qualitative/engineering judgment terms.

The libration-point constellations include communication/navigation satellites at the Earth-moon L1 and L2 points. These constellations tend to provide very good communications coverage, relative to the number of deployed satellites. However, navigational performance can be limited if the number of deployed satellites is low (less than four.) Highly elliptical orbits can provide extremely good coverage over limited regions of the Moon such as the lunar south pole. Additionally, these orbits can be made to be quite "stable" so as to reduce the need for station keeping. Long dwell times associated with highly elliptical orbits reduce pointing and handover requirements for users. Walker-style constellations provide highly uniform coverage over the lunar globe. Proposals of hybrid constellations attempt to provide benefits of the concepts from which they were derived.

Overall life-cycle cost is a strong function of the number of satellites in the constellation, with fewer satellites being preferred to more satellites. Reductions in launch cost are frequently anticipated through the use of fewer planes in a candidate constellation. Coverage (or elevation angle at "Edge of Coverage") and dwell time is improved by increasing orbiter attitude. However, station keeping costs tend to start a dramatic increase at about 6,000 km altitude due to gravitational influences from the Earth.

Studies performed within the Space Communications Architecture Working Group (SCAWG) favored a Walker 8/2/1 constellation with an orbital radius of approximately four moon radii and polar inclination angle. The Walker 8/2/1 provides very good coverage, having a high user-elevation angle at EoC, and also provides good navigation system availability. If navigation is not a primary consideration for lunar applications, a Walker 6/2/1 constellation, as appears in Figure 4H-2, provides nominal lunar surface coverage.

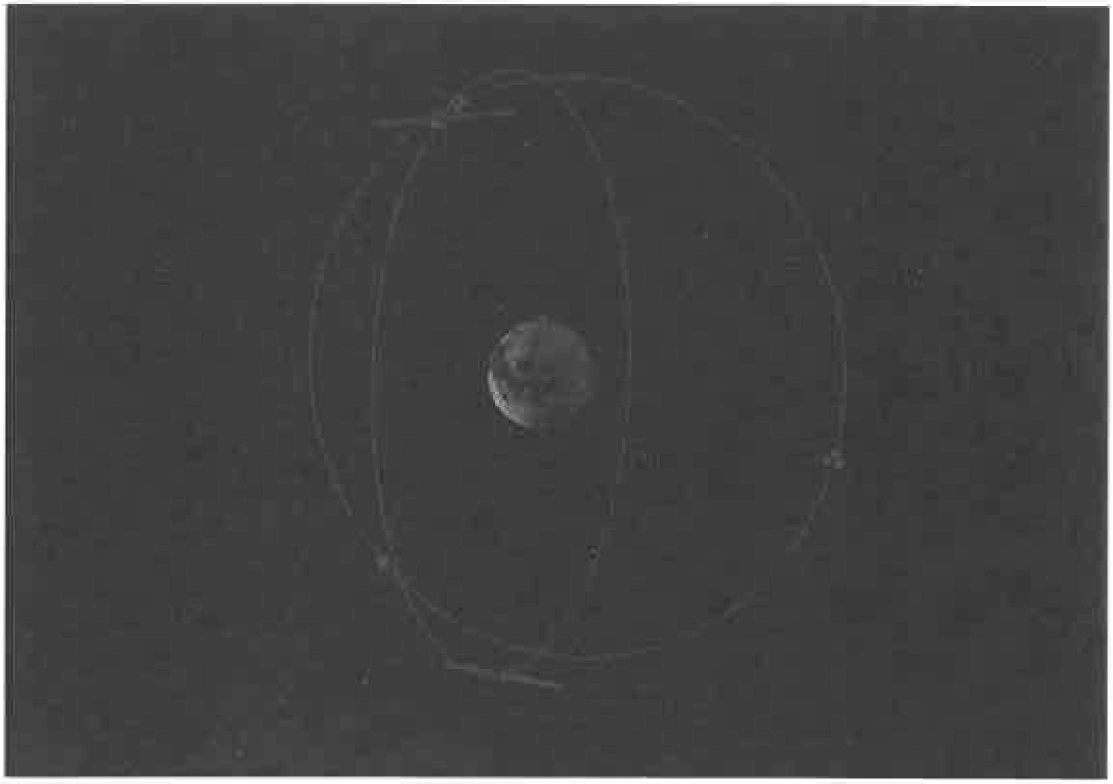


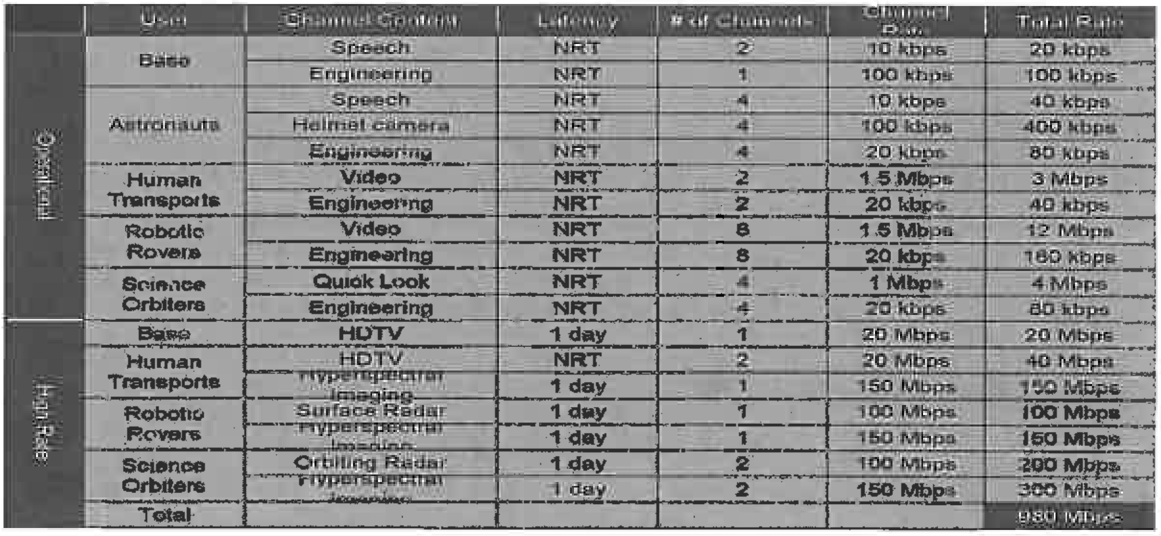
Figure 4H-2. Walker 6/2/1 Lunar Constellation.

[1] J. Schier, J. Rush, W. Williams and P. Vrotsos "*Space Communication Architecture Supporting Exploration and science: Plans and Studies for 2010-2030*" AIAA 1st Space Exploration Conference, Jan 2005, Orlando FL, Available at: https://www.spacecomm.nasa.gov/Link_Doc/architecture/AIAA_architecture.pdf.

[2] "*ARCHITECTURE STUDY 2: A Report on Communication Architecture Study*" August, 2003 Space Communications Project Document 1.

Frequency Band and Data Rate Analysis

To make a first cut analysis, communication requirements were derived from the work of the SCAWG as shown in Figure 3 and various white papers concerning lunar exploration (i.e., ESMD RFT 0016.04). Communication applications include voice, video, and data to and from each surface element. Assumptions were made for the architecture concept concerning surface elements and data rates between the respective elements. The forward and return links were then analyzed to estimate data rate requirements and subsequent frequency band and radio sizing. An example of the estimated data rates between elements are summarized in **Table 4H-1**.



	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	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

Figure 4H-3. Application Data Rate Assumptions (Ref SCAWG)

<u>Frequency Band</u>

The following options were a result of a winnowing-down process in identifying areas of the radio spectrum to support lunar surface and proximity communications.

Table 4H-1. Summary of Frequency Selections

	Frequency (GHz)	Tx Power (W)	Tx Antenna Diameter (m)	Path Length (km)	Rx Antenna Diameter (m)	Data Rate (Mbps)
DTE						
Option 1	26.5	61	1.0	385000	34.0	1000
Option 2	26.5	6.8	3.0	385000	34.0	1000
Surface-Orbiter (Relay)						
Option 1	0.44	10	Omni	10000	1.0	0.016165224
Option 2	0.44	10	Omni	10000	3.0	0.439267277
Option 3	40	2	0.5	10000	1.0	75.30914275
Inter-Orbiter (Crosslinks)						
Option 1	27.5	4.7	0.5	16000	0.5	300
Option 2	2.2	40	1.0	16000	1.0	300
Surface-Surface						
Option 1	0.44	0.013	Omni	3	Omni	13.2
Option 2	2.2	0.1	Omni	3	Omni	12.70192604
Option 3	0.44	0.01	Omni	0.2	Omni	13.2
Option 4	2.2	0.073	Omni	0.2	Omni	36
Over The Horizon						
Option 1	0.01	5	Omni	30	Omni	0.3

The preceding table lists the various spectrum options considered for the links of interest. These specific links were under consideration: Direct-To-Earth (DTE), Surface-Orbiter (Relay), Inter-Orbiter (Cross-links), and Surface-Surface.

Additionally, some alternative bands were considered for low-rate, highly reliable channels on the lunar surface. Coverage is limited by the lunar horizon and cost prohibitive in terms of lunar-based infrastructure. Therefore, signaling at frequencies with attractive propagation properties were scrutinized and may be considered for contingency links.

1.1 DTE

The 25.5-27 GHz band was identified as the most favorable option for DTE links. As indicated in Table 1, a 1 Gbps link can be achieved via a 3-m aperture antenna on a surface asset transmitting to a 34-m Deep Space Network (DSN) dish on the surface of the Earth for a transmit power of 6.8 W.

1.2 Surface-Orbiter (Relay)

The 40-40.5 GHz was identified as the most favorable option for Surface-Orbiter (Relay) links. As indicated in Table 1, a 75 Mbps link can be achieved via a 0.5-m aperture antenna on a surface asset transmitting to a 1-m dish on an orbiting relay for a transmit power of 2 W.

1.3 Inter-Orbiter (Cross-links)

The 27-27.5 GHz was identified as the most favorable option for Inter-Orbiter (Cross-links) links. As indicated in Table 1, a 300 Mbps link can be achieved between two 0.5-m antennas on the orbiters for a transmit power of 4.7 W.

1.4 Surface-Surface

Two different configurations were identified for S-band (2.2 GHz) solutions on the lunar surface due to two distinctly different requirements. These resulted in two different modes of operation.

First, an EVA astronaut must be able to communicate with the base and navigate back out to 3 km without going through an orbiting infrastructure. Therefore, an omni antenna with 100 mW transmitting power allowed a 12 Mbps link to be achieved.

In closer proximity (<= 200 m – e.g. astronaut to pressurized rover), a 73 mW transmit power allowed a 66 Mbps link to be achieved.

1.5 Alternative Over-The-Horizon (OTH) Options

Two OTH options were considered due to their attractive propagation properties. There are a number of sources from data collected in the Apollo era that bound the conductivity and dielectric constant of the lunar surface (dielectric constants of 1.4 to 4.0, and conductivities of 10-5 and 10-3 mhos/m). This indicates that the lunar surface is highly conductive.

Radio waves at and below High Frequency (HF) tend to induce currents in the ground. These currents cause a "bending" of the wavefront near the surface. Although this phenomena adds to the loss (greater than d2 loss), it does enable surface wave propagation. This results in OTH capabilities.

Therefore, two additional solutions were considered. First, at HF (e.g., 10 MHz), a 300 Kbps data rate link can be closed out to 30 Km between omni (whip) antennas at a transmit power of 5 W.

Second, a Low Frequency (LF) (100 KHz) carrier was considered for either extremely low-data rate or analog voice. In the Apollo era, the National Bureau of Standards estimated that at a transmit power of 16 W, a 100 KHz carrier would propagate 100 Km on the lunar surface. Additionally, Luna 10 (launched March 1966) measured lunar ionosphere electron density of 108 electrons/m^3 electron density at 400 km. Subsequent Luna and Apollo missions confirmed this data, indicating that some modest ionospheric skip may be possible to extend the range of a LF-HF carrier.

Communications at LF-HF frequencies would require larger power amplifiers (PAs), yet simplistic whip omni antennas. This area of communications could leverage heavily from military communication techniques.

These findings confirm the need for further investigation into lunar surface area and proximity propagation. This is especially true when considering wideband signaling on the lunar surface, with the potential for multi-path and frequency selective fades.

Reconfigurable Transceiver Assessment

It is recommended that all deployed assets with communication systems will be capable of remote re-configurability via Software-Defined Radios (SDR). This approach will enable increased flexibility, adaptability, advanced operations, interoperability, and a reduction of mission life-cycle costs. An SDR on board the lunar relay and the habitat will provide long-term capability to remotely modify the modem to support communication with systems that have characteristics that were not developed at launch. Compensation for unexpected failures, such as the inability to deploy an antenna or a reduction in the output capability of a traveling wave tube amplifier (TWTA), can occur with the remote upload of a new modulation or coding techniques. Smaller software-defined radios for the EVA and rovers will be designed to provide re-configurability with a similar architecture but less mass. The open-architecture approach for SDR will save mission costs through the use of software reuse, platform independence, and similarity of pre-launch validation and verification procedures between platforms. The SDR will also be able to easily integrate other functions such as radiometric ranging and navigation support.

Microwave Antenna Considerations

The main assumptions related to communication needs in the ESAS report were as follows: redundancy, 24/7 support, autonomous connectivity, operational reliability, and minimal technology risks. The identified communication links were (a) proximity communication (<3 km), (b) surface communication (3-15 km), (c) surface-to-orbiter communication, and (d) outpost-to-Earth communications. Low-data rate proximity communication link in uncertain terrain suggests antenna technology of highest Technology Readiness Level (TRL) (i.e., a UHF antenna with omni-directional coverage). Cell tower proximity communication is not feasible for excessive tower height requirements to maintain point-to-point communication. S-band surface communication is needed for medium-rate science data transmission and within surface assets. Ka-band links from the outpost to Earth is recommended for high-rate, high-quality video and science data transmission. The X-band link to Earth is for emergency and housekeeping purposes. For missions 2022 plus, currently lower TRL antennas technologies with potential low-cost and efficient scanning capabilities can be matured to higher TRL levels for lunar applications. Two examples are (1) a scanning space-fed lens is a lower-cost, efficient solution to a phased array antenna, and (2) active oscillator antennas on lunar surface sensors can provide information retrieval on demand by the orbiter. A possible risk mitigation strategy with high pay-off low-TRL technology would require development work to boost current 4-5 TRL levels on these antenna technologies.

Surface Radio Resource Estimates

Table 4H-2 provides a ROM estimate of the costs associated with the elements of the lunar communications architecture. This information was not included in the original report but is presented here for completeness. The estimates were developed using parametric techniques, comparing the requirements of the surface elements with known flight hardware elements, as available. Additional effort would be needed to increase the accuracy of these estimates.

(b) (5)

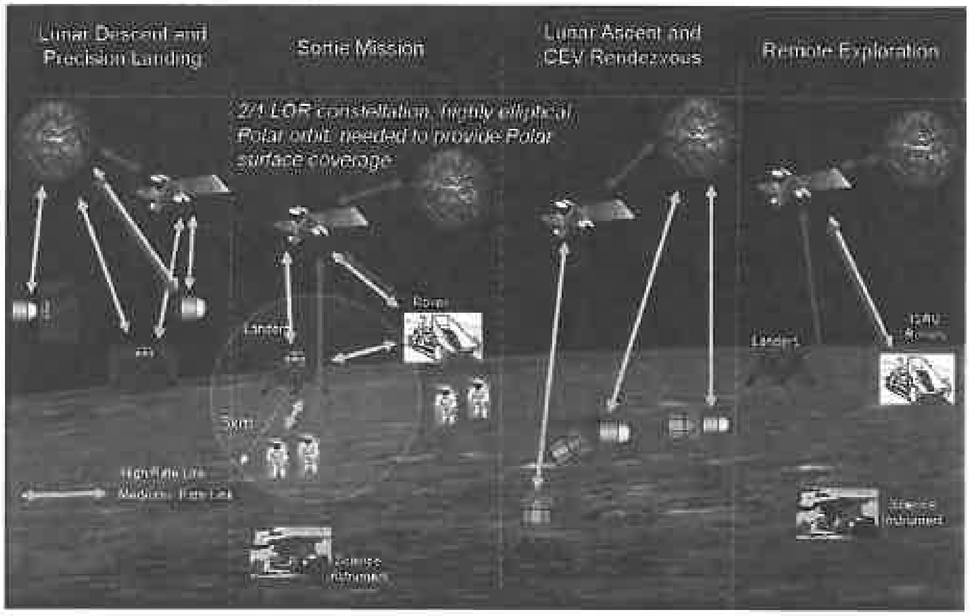


Figure 4H-4. Sortie Communications for Lunar Exploration