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LUNAR FAR-SIDE COMMUNICATION SATELLITES

by P. E. Schmid

Goddard Space Flight Center
Greenbelt, Md.

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ABSTRACT

This report discusses a lunar communication satellite relaying signals to and from points up to 200 km above the lunar far-side surface. Two lunar satellite geometries are considered, namely, a libration point satellite anchored 65,000 km behind the moon and a 1000-km lunar-orbiting relay satellite.

CONTENTS

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SUMMARY

This report investigates the feasibility of communicating with Apollo spacecraft behind the moon and of communications between two such spacecraft. Two satellite geometries are considered for signal relay: a libration or "Hummingbird" satellite anchored 65,000 km behind the moon and a lunar-orbiting relay satellite at 1000-km altitude. The signal transmission frequencies of the Apollo spacecraft are VHF and unified S-band (USB) operating at 300 MHz and 2 GHz, respectively. The three propagation links examined in this report include: lunar far side, i.e., Lunar Module (LM) on lunar surface and/or lunar-orbiting command and service module (CSM), to earth; lunar far side LM to CSM; lunar far side surface to surface.

It is shown that as a result of antenna pointing constraints, only the libration or "Hummingbird" satellite is suitable for relaying USB tracking and communication data to earth. It is also shown that acquisition of a 1000-km altitude lunar satellite by an Apollo spacecraft dictates the use of VHF. Various modes—feasible and unfeasible—of lunar far-side radio relays are listed below, with their respective methods of communication.

Feasible Modes Without Modification of Apollo LM or CSM Electronics

1. Lunar far side (LM on lunar surface and/or orbiting CSM) to earth.

   Via libration satellite: USB Doppler tracking data, voice, 1.6 kilobits per sec (kbps) telemetry.

   Via 1000-km satellite: VHF voice, 1.6 kbps telemetry.

2. Lunar far side, LM to CSM.

   Via 1000-km satellite: VHF voice, 1.6 kbps telemetry.

3. Lunar far side, surface to surface.

   Via libration satellite: USB voice.

   Via 1000-km satellite: VHF voice.

Feasible Mode With LM or CSM Electronics Modified

1. Lunar far-side ranging.

   Via libration satellite: pseudo-random noise (PRN) ranging if longer bit-length code employed and regenerative repeater used at libration satellite.

2. VHF Doppler tracking.

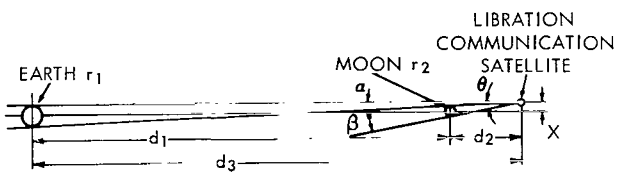
   Via 1000-km satellite: VHF carrier Doppler frequency tracking if phase-lock turnaround transponder employed at LM and/or CSM.

Unfeasible Mode

Relay of wideband signals such as 51.2 kbps or real-time television.

INTRODUCTION

This report estimates the data relay and tracking capability of a lunar communication satellite relaying signals to and from points up to 200 km above the lunar far-side surface. Because such a relay system would be valuable during Apollo and post-Apollo lunar-landing missions (Reference 1) detailed calculations are presented for cases where either the LM or the CSM operates as the lunar far-side terminal. Two relay satellite locations are considered: the perturbed libration point position (Figure 1) providing continuous earth-to-moon far-side coverage and a circular lunar polar orbit (i.e., approximately normal to the earth-moon orbital plane), permitting periods of simultaneous coverage of earth and lunar far side (Figure 2).



$\alpha = \frac{2r_1}{d_3} = 1.6°$ $\beta = \frac{2r_2}{d_2} = 3.1°$ $\theta = \alpha + \beta = 4.7°$

Figure 1—Perturbed libration point communication satellite geometry.

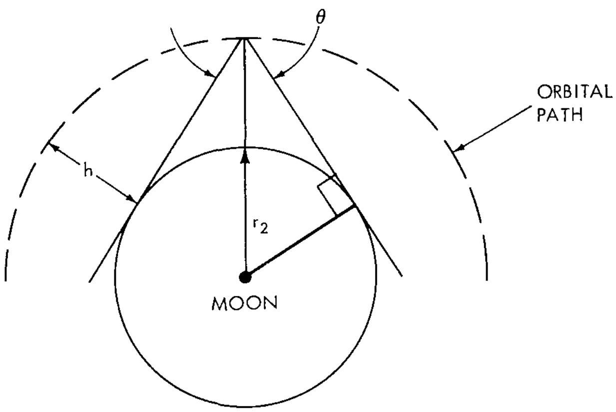


Figure 2—1000-km altitude lunar satellite geometry.

The libration satellite is offset from the natural lunar far-side libration point by approximately 3000 km in order to command more of the earth's surface, thus providing maximum coverage of earth to lunar far side. Reference 2 presents a detailed discussion of the five earth-moon libration points indicated in Figure 3. The required offset from the lunar far-side libration point (Figure 1) is given by

$$X = \frac{d_3}{d_1}\left(r_1 + r_2\right) - r_1 \doteq 3100 \text{ km}, \qquad (1)$$

where

X = offset required for non-obstructed earth view,

d_1 = earth-moon distance = 3.84×10^5 km (Reference 3),

d_2 = moon-to-far-side libration point distance = 0.168 d_1 = 0.645×10^5 km (Reference 2),

d_3 = earth-to-far-side libration point distance = $d_1 + d_2$ = 4.48×10^5 km,

r_1 = earth radius = 6378 km (Reference 3),

r_2 = lunar radius = 1738 km (Reference 3).

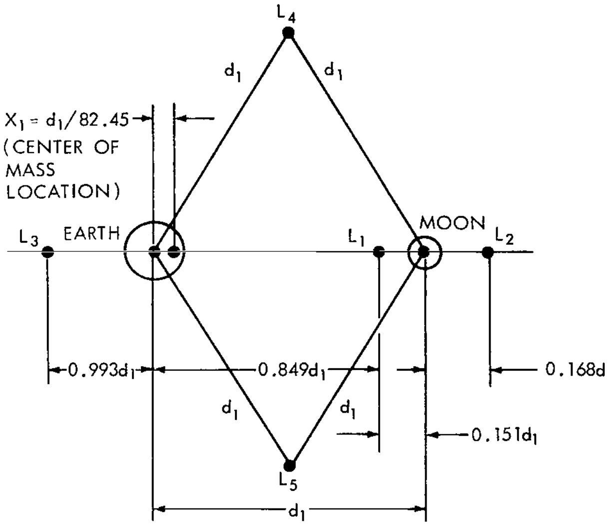


Figure 3—Libration points of earth-moon system.

The feasibility of maintaining such an offset, as well as fuel and station-keeping requirements, are discussed in detail in Reference 4.

The 1000-km altitude lunar communication satellite orbit (Figure 2), illuminates approximately 40 percent of a lunar hemisphere at any given time. This relationship is expressed by

$$\frac{\text{area illuminated}}{2\pi r_2^2} = \left(1 - \sin\frac{\theta}{2}\right) = \frac{h}{r_2 + h} = 0.37\ , \tag{2}$$

where

θ = communication satellite antenna beamwidth required for maximum lunar coverage = 78 degrees for a 1000-km orbit,

r_2 = lunar radius = 1738 km,

h = satellite altitude above lunar surface = 1000 km.

For 80-percent coverage of a lunar hemisphere, the required altitude, h, is 6950 km.

Analysis here is guided primarily by the time and effort required to establish and maintain a satisfactory radio relay link via the lunar communication satellite. For example, it is unreasonable to require an astronaut upon the lunar surface to manually scan the sky with a high-gain antenna (beamwidth less than 20 degrees) in search of low-altitude ($h \leq$ lunar radius) satellites that could never be in radio view for more than 1 hour. For this case, the relatively high angular rate and extreme angular excursion of the radio line-of-sight dictates the use of wide-beam (hence low-gain) antennas.

Automatic (rather than manual) acquisition and tracking of low-altitude satellites from the lunar surface would involve the same type of problems as those encountered during earth-based tracking of earth-orbit satellites. Lunar far-side acquisition would be aggravated by a lack of a priori pointing data and by the fact that the radio horizon to a satellite of given low altitude is about half what it would be on earth. For this reason, automatic tracking of low-altitude satellites from portable terminals on or near the surface of the far side of the moon is not expected to be practicable before the mid 1970's. Perhaps, by that time, it will be possible to make reliable, light-weight, small-size arrangements of phased arrays and modular electronics, that are sufficiently complex for a spacecraft-borne automatic tracking scheme with a high-gain antenna. Later, it is shown that the foregoing constraints require VHF rather than microwave propagation for the communications satellite link from the lunar far side to a 1000-km altitude.

The astronaut should nevertheless be able to direct a high-gain antenna toward a distant communication satellite (for example, the libration satellite) by fairly simple means, such as listening to a tone-modulated carrier emanating from the relay satellite. The cost of using so distant a relay satellite is a significant increase in path loss. The next section shows that only frequencies above 1 GHz should be considered for radio relay via the libration satellite. (This report considers both the 2-GHz and 300-MHz nominal Apollo frequencies.)

Means for maintaining the desired lunar communication satellite positions are not presented here; they are discussed at length in References 4, 5, and 6.

LUNAR FAR-SIDE (LM ON LUNAR SURFACES AND/OR ORBITING CSM) TO EARTH

Libration Satellite Relay

Figure 1 indicates the earth-moon geometry for lunar far-side radio relay via the libration satellite. A 5-degree beamwidth antenna at the libration satellite will illuminate simultaneously the earth and the lunar far side. Because of the range separation a high-gain antenna at the lunar far side, once directed toward the libration satellite, would require little or no subsequent pointing adjustment. The relay link between earth and the libration satellite is no more difficult to implement than current earth-moon transmission (for example, Langley Lunar Orbiter). Consequently, increasing the range separation from 3.84×10^5 km to 4.48×10^5 km increases the one-way path loss by only 1.4 db.

Path loss is the propagation loss due to range separation and is given by

$$L = \frac{\lambda^2}{16\pi^2 d^2}, \tag{3}$$

where

L = loss due to physical separation of communication terminals,

d = range separation,

λ = wavelength of transmission.

The critical link is from the lunar far side to the libration satellite, and is primarily a result of the 10- to 50-watt limitation on average spacecraft RF power and physical constraints which, below 3 GHz, limit spacecraft antenna gain to 35 db or less. (This contrasts with earth terminal capability, where average power is greater than 10 kw and antenna gains are up to 60 db, corresponding to a 64-m (210-ft)-diameter antenna.) To maximize the power received at either terminal of this critical link, maximum antenna gains must be obtained both at the libration satellite and at the lunar far-side terminal. At either terminal, the power received is given by (Reference 7)

$$P_r = \frac{P_t G_1 G_2 \lambda^2 L}{16\pi^2 d^2} = \frac{P_t G_2 L A_e}{4\pi d^2}, \tag{4}$$

where

P_r = total power received at one terminal,

P_t = total power transmitted from other terminal,

G_1 = antenna gain at lunar far-side terminal,

G_2 = antenna gain at libration satellite terminal,

λ = RF wavelength,

L = total RF system loss,

A_e = effective lunar terminal antenna aperture $= G_1 \lambda^2/4\pi$.

For the LM the lunar-surface transportable antenna is a dish 3 meters (10 feet) in diameter. On the Command Module (CM) the high-gain tracking antenna consists of an array of four 0.8-m (2.6-ft)-diameter antennas (References 8 and 9). In Equation 4 these physical size constraints at the LM or CSM operating as the lunar far-side terminal result in a fixed value for the effective aperture, A_e, and therefore for the physical aperture, A, irrespective of frequency. The effective antenna aperture for horn, lens, and parabolic dish antennas in the 300- to 3000-MHz frequency range is approximately 60 percent of the physical aperture (Reference 10).

At the libration satellite it is desirable to view both the moon and earth with a single antenna. This permits a minimum beamwidth of 5 degrees. The gain, G_2 corresponding to this beamwidth can be approximated (Reference 10) by

$$G_2 \doteq \frac{27000}{\theta^2}, \tag{5}$$

where

θ = conical 3-db beamwidth (degrees),

G_2 = libration satellite antenna gain.

A 5-degree 3-db conical-beam antenna has an on-axis gain of 30 db. The diameter required at various frequencies can be estimated by combining Equation 5 with the expression for circular physical cross-section, A, given as

$$A = \frac{A_e}{0.6} = \frac{G_2 \lambda^2}{0.6(4\pi)} = \frac{\pi D^2}{4} ,$$

or

$$D \doteq \frac{70\lambda}{\theta} , \tag{6}$$

where

D = antenna diameter,

λ = RF wavelength,

θ = 3-db beamwidth (degrees).

For a 5-degree 3-db beamwidth the required diameter is 2 meters (7 feet) at 2 GHz and 14 meters (44 feet) at 300 GHz. Therefore, for the libration satellite relay only the Apollo USB frequencies are considered.

Signal loss calculation of the libration satellite to the lunar far-side terminal are straightforward. For the Apollo CSM or LM (i.e., lunar far-side terminal), USB parameters are assumed. The parameters assumed at the libration satellite reflect current technology. Libration-satellite orientation is assumed to be maintained by locking on the sun and the star Canopus in the same manner as with Mariner IV and Langley Lunar Orbiter.

The only calculation warranting some elaboration is that of antenna effective-noise temperature. It will be shown that the antenna noise temperature at the LM or CSM is of no consequence, even when the sun is viewed directly with a 3-degree beamwidth antenna. This is because of the 11-db USB transponder receiver noise figure (Reference 11, a result of no preamplification) and the RF losses, which in all cases exceed -7 db (because of cable lengths and RF combiner losses). The 11-db Apollo USB noise figure is typical of the usual microwave superheterodyne receiver where the antenna is coupled directly to the first mixer. (Langley Lunar Orbiter receiver noise value is 12 db, Reference 12.) The spacecraft-qualified low-noise preamplifiers required to lower this noise figure to 2 or 3 db are just becoming available. The cable losses at the CSM and LM are a result of the RF coaxial lines that must be used to assure antenna locations clear of obstruction. The use of a waveguide, with inherent low loss, is apparently not considered practical in the Apollo program because of prohibitive physical dimensions and lack of flexibility. At 2-GHz, waveguide width is on the order of $\lambda/2$ or 7.5 cm (3 inches), whereas the coaxial cable diameter such as that currently employed at the CSM or LM is on the order of 1.2 cm (0.5 inches). At 2.2 GHz, the dielectric loss of standard coaxial RF cable is -15 db per 100 ft (Reference 13 tabulates cable losses for RG-9 coaxial transmissions line—Apollo spacecraft RF cables are similar to RG-9). At 2 GHz, the flexibility, structural integrity and ease of cable connection cause an appreciable RF loss for cable runs longer than a few feet. At 300 GHz, the corresponding cable loss is only -5.5 db per 100 feet. A low-loss air-dielectric semiflexible coaxial line (Reference 14, p. 80, 1/2-inch diameter, 50-ohm Heliax), while attractive from an electrical standpoint (-4 db loss per 100 ft of line at 2 GHz), lacks the flexibility required, at least for the lunar surface terminal.

The effect of noise figure and RF cable losses on the effective receiver noise temperature at the receiver input terminals is apparent from this equation:

$$T_e = \frac{T_a}{L} + T_L \left(1 - \frac{1}{L}\right) + (F - 1)\, T_r \,, \tag{7}$$

where

T_e = effective noise temperature,

T_a = antenna noise temperature,

L = RF transmission loss factor $(1 < L < \infty)$,

T_L = transmission-line and associated-hardware temperature,

F = receiver noise figure (as measured at temperature T_r),

T_r = receiver temperature.

The noise spectral density is then calculated as:

$$\Phi_n = T_e\, k \text{ watts/Hz} \,, \tag{8}$$

where

T_e = effective noise temperature referred to receiver input (°K),

k = Boltzmann's constant = 1.38×10^{-23} Joules/°K.

The sun subtends approximately 0.5 degree whether viewed from earth, the libration satellite, or from a point near the moon. The effective antenna noise temperature can thus be expressed for all three cases by (Reference 15)

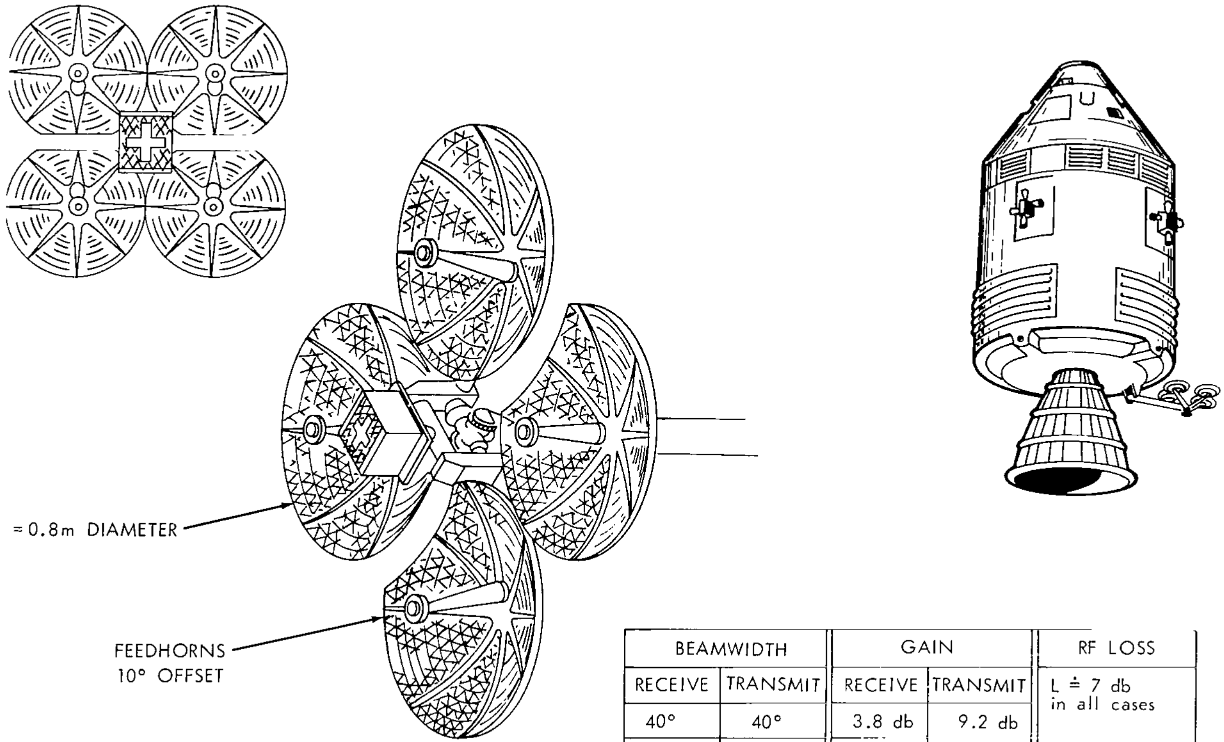
$$T_s = \left(\frac{2 \times 10^{14}}{f}\right) \left(\frac{0.5}{\theta}\right)^2 \,, \tag{9}$$

where

T_s = antenna noise attributed to a direct view of the sun's disc (°K),

f = radio frequency to which receiver is tuned (Hz),

θ = 3-db antenna beamwidth (degrees).



BEAMWIDTH		GAIN		RF LOSS
RECEIVE	TRANSMIT	RECEIVE	TRANSMIT	$L \doteq 7$ db in all cases
40°	40°	3.8 db	9.2 db	
4.5°	11.3°	22.8 db	20.7 db	
4.5°	3.9°	23.7 db	27.4 db	

Figure 4—CSM high-gain antenna (References 9 and 10).

For example, if $f = 2$ GHz and $\theta \doteq 5$ degrees (Figure 4), $T_s = 1000$°K.

From Equation 7 it can be shown that the noise spectral density at either LM or CSM receiver input is -163 dbm per Hz of RF bandwidth, whether the sun is viewed or not. At the libration satellite, however, a 20- to 30-db gain preamplifier can reduce the receiver noise figure to 3 db; by shortening of the RF coaxial cable runs, the cable loss at 2 GHz could be held to -2 db (down-link RF losses for Langley Lunar Orbiter are -2.4 db, Reference 12). The total received power-to-noise ratio at the receiver input will in this case be directly affected by the noise power intercepted by the antenna. If the 5-degree libration satellite beamwidth antenna views the sun directly, the result according to Equation 9, is an antenna noise temperature of 1000°K. As shown in Figure 5, the libration satellite would view the sun for approximately 9 hours out of each month. Assuming a 28-day period of moon revolution about the earth (13 degrees per day), the libration satellite -3 db beamwidth of 5 degrees will then intercept the sun for only 5/13 of a day or 9.2 hours. Maximum solar noise pick-up (~1000°K, neglecting earth occultation) is achieved

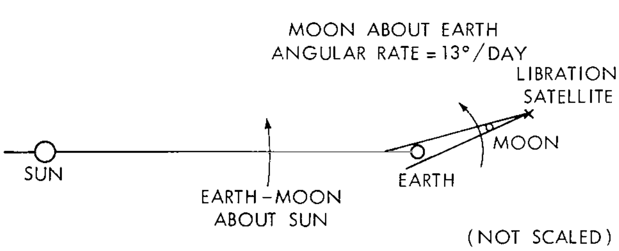


Figure 5—Illumination of sun by libration satellite antenna.

during the pass of -1.5 db antenna beamwidth points. The -1.5 db beamwidth is given by (Reference 10)

$$\theta = \left(\frac{k_{db}}{3}\right)^{1/2} \theta_{3db} = 3.5 \text{ (degrees)} \tag{10}$$

where

θ = angular width of main lobe for decay of k_{db} where $k_{db} = 1.5$,

θ_{3db} = -3 db beamwidth = 5 degrees.

Or, the antenna directly faces the sun for about 6.5 hours per month. During the remainder of the time the antenna noise temperature at the libration satellite at 2 GHz will be given, in degrees K, by

$$T_a = T_1 \left(\frac{\alpha}{\theta}\right)^2 + T_2 \left(\frac{\beta}{\theta}\right)^2 = 115 , \tag{11}$$

where

T_1 = earth radio noise temperature = 300°K,

α = angular antenna coverage of earth = 1.6 degrees,

θ = -3 db antenna beamwidth = 5 degrees,

T_2 = lunar radio noise temperature at 2 GHz = 220°K (independent of solar illumination, Reference 16),

β = angular coverage of moon = 3.1 degrees.

For the assumed libration satellite noise figure of 3 db and RF losses of 2 db (according to Equations 7, 8, 9, and 11), the noise spectral density of receiver input is -172 dbm per Hz when the sun is not being viewed. It is -168 dbm/Hz when the sun is being viewed directly (even then, the libration satellite receiver noise spectral density is 5 db below what would be present at either the Apollo LM or CSM transponder receiver input). For this reason, libration satellite transmission to the lunar far-side is considered the limiting factor in this link.

Carrier Doppler Tracking

According to Table 1, the total maximum power received at the LM while it is resting on the lunar surface is -105 dbm; and at the lunar orbiting CSM is -111 dbm. Acquisition of the carrier by a USB (LM or CSM) transponder requires a -114 dbm carrier component; subsequent carrier tracking requires at least a -127-dbm carrier component (Reference 17). Therefore, both acquisition and subsequent carrier Doppler frequency tracking appear feasible. By phase-locking the entire link (i.e., Manned Space Flight Network (MSFN)-libration satellite transponder-lunar terminal

Table 1

2-GHz Relay via Libration Satellite.

Libration Communication Satellite Transmission Parameters		Lunar Far-side Receiver Parameters	LM	CSM
Transmitter power	20 watts	Receiver noise figure	11 db	11 db
RF losses	-2 db	RF losses	-10 db	-7 db
Antenna diameter	6.5 ft	Antenna diameter	10 ft	7 ft
On-axis antenna Gain-circular polarization	30 db	On-axis antenna Gain-circular polarization	32.5 db (lunar surface antenna)	23.7 db (high gain antenna)
Transmit frequency	2101.8 MHz	Noise referred to receiver input terminals	-163 dbm/Hz maximum	-163 dbm/Hz maximum
Path loss ($d = 65 \times 10^3$ km)	-195 db			
Antenna -3 db beamwidth	5°	Antenna -3 db beamwidth	3°	5°
		Total power received	-105 dbm	-111 dbm

transponder) the Doppler as recorded at the MSFN USB sites would be sufficient to compute a lunar vehicle orbit such as that of the Apollo CSM.

Ranging

The present USB Apollo transponder PRN ranging channel is required to meet certain specifications for total signal-power inputs from -80 dbm to -50 dbm (Reference 17). Levels greater than -80 dbm are required to assure a demodulated ranging signal of constant amplitude at the USB transponder phase modulator input (Figure 6). The current transponder checkout procedure includes also ranging tests for input power levels of -100 to -50 dbm (Reference 18). While the forementioned transponder input-power levels are consistent with MSFN operation, they could not be achieved via the libration satellite.

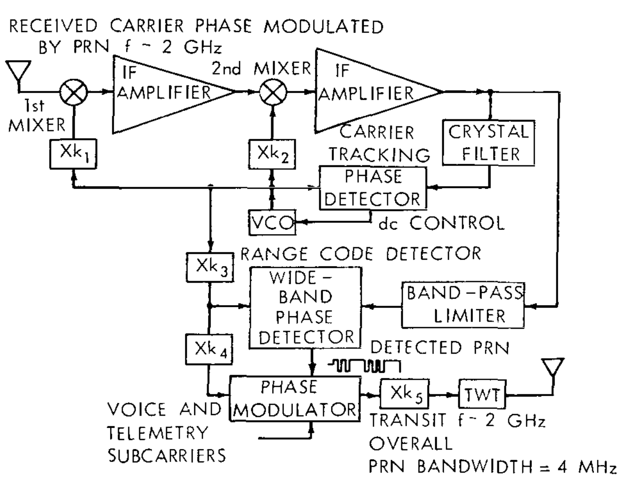


Figure 6—Simplified block diagram—PRN turnaround by Apollo transponder.

The overall transponder ranging-channel bandwidth must be maintained at 4 MHz to minimize transponder delay variations (Reference 19). A number of theoretical discussions indicate that the PRN ranging scheme can be used although the total ranging signal-to-noise ratio in the required 4-MHz overall bandwidth at the transponder is appreciably less than unity (References 20 and 21). The argument is that the ground can recover the range code, despite the turnaround degradation, by extending the range-code acquisition time. In the case of the lunar-signal relay, both the LM (or CSM) transponder and libration satellite transponder require a 4-MHz bandwidth ranging channel if a straight feed-through relay is employed. It is possible to measure the range at the libration satellite (so-called "regenerative transponder") and to telemeter it back to earth; but this would not be consistent with the present USB coding technique.

The basic Apollo transponder ranging-turnaround scheme is indicated in Figure 6. How to turn around the ranging code at extremely low signal-to-noise ratios is the subject of continued study, but current Apollo transponder hardware does not seem to be capable of this. Hence, a ranging measurement via the libration satellite is assumed unfeasible for those missions that must use current Apollo hardware and signal coding. Range-rate data (in the absence of range data) derived from carrier Doppler is sufficient to determine satellite orbits near the moon.

Voice and Telemetry

As an estimate of the type of rates at which data might be relayed, consider MSFN up-link mode 2 where only the voice subcarrier (30 kHz) is phase-modulated onto the 2101.8-MHz carrier. In this case, the maximum phase deviation (β) is 1.85 (Reference 11) and the available sideband power accounts for approximately 85 percent of the total power available (Reference 22). In other words, sideband power available for voice only is approximately 1 db below total available power, whereas carrier power is approximately 8 db below total available power. The carrier components for this case are -114 (LM) dbm and -120 dbm (CSM); i.e., they are still above the -127 dbm needed for carrier tracking; the sideband power available at the receiver input is -106 dbm (LM) and -112 dbm (CSM). A 10-db signal plus noise-to-noise ratio is adequate for either USB-data or voice communication (Reference 17). If the noise spectral density is -163 dbm/Hz (Table 1), the resulting allowable predetection bandwidths are 63 kHz for the LM upon the lunar far-side surface and 16 kHz for the lunar-orbiting CSM. The predetection bandwidth required for voice where β is 1.85 is given (Reference 23) by

$$B \doteq 2f_m (1 + \beta) \doteq 17 \text{ kHz} , \tag{12}$$

where

f_m = highest significant modulation frequency = 3 kHz for voice,

β = modulation index = 1.85 in this example.

Therefore, voice and 1.6-kbps USB data relay are considered feasible. Because of predetection bandwidth requirements, 51.2 kbps telemetry and real-time TV relay via the libration satellite are not considered feasible.

1000-km Altitude Satellite Relay

An estimate of the rates at which data can be relayed to earth at 2 GHz via a 1000-km lunar-orbiting satellite can be made as follows. The maximum range separation between spacecraft and communication satellite (radio horizon = 2000 km) compared with the libration satellite according to inverse-square law decreases the path loss by 30 db. To obviate antenna tracking, the communication satellite must illuminate the maximum lunar surface where the antenna beamwidth is given (Figure 2) by

$$\theta = 2 \text{ arc sin} \left(\frac{r_2}{r_2 + h} \right) , \tag{13}$$

where

θ = communication satellite beamwidth,

h = satellite altitude = 1000 km,

r_2 = lunar radius = 1738 km.

A conical -3-db antenna beamwidth of 78 degrees corresponds to a 6-db maximum on-axis gain. The lunar surface (LM) or near-surface (CSM) antenna would need to be omnidirectional corresponding to a typical gain of -3 db. The net loss in signal at the lunar far-side terminal relative to the libration satellite relay is -17 db for the CSM and -26 db for the LM. The maximum signal available at 2 GHz becomes -131 dbm at the LM and -128 dbm at the CSM. Since -127 dbm is required for the minimum bandwidth signal (carrier tracking), USB transmission to the 1000-km altitude satellite is considered impracticable. As pointed out previously, it is unreasonable to expect the astronaut to scan the sky looking for a low-altitude relay satellite in the absence of a priori pointing data.

Therefore, it is suggested that this link use VHF for communication from a 1000-km satellite to the lunar far side, and use the S-band for communication from the 1000-km satellite to earth. Both the CSM and LM carry a 5-watt, 296.8-MHz transmitter coupled to an omnidirectional antenna. Direct VHF transmission to earth from CSM or LM is impossible at lunar distances, because of the MSFN implementation. However, LM or CSM VHF voice and/or telemetry could be relayed via a 1000-km satellite employing USB frequencies on the link to earth. Several such lunar communication satellites would be needed in order to provide continuous coverage from the lunar far side to earth. As in the case of the libration satellite, the link between earth and communication satellite is not considered critical. The parameters of the VHF link (between satellite and lunar far side) are listed in Table 2.

The maximum lunar radio temperature at VHF is on the order of 250°K (Reference 16). It is assumed that the receiver at the 1000-km satellite incorporates a preamplifier to lower the noise figure to 4 db—a slight improvement over the Apollo VHF spacecraft receiver 6-db noise figure. A 10-watt VHF transmitter at the lunar communication satellite is also readily implemented.

Table 2

300-GHz Relay via 1000-km Altitude Satellite.

1000-km Communication Satellite Transmission Parameters		APOLLO Lunar Far Side Reception Parameters	LM	CSM
Transmitter power	10 watts	Receiver noise figure	6 db	6 db
RF losses	-1 db	RF losses	-2 db	-1 db
On-axis gain	6 db	Antenna gain	-3 db	-3 db
Transmission frequency	296.8 MHz	Noise referred to receiver terminals	-168 dbm	-168 dbm
Path loss (d = 2000 km) maximum	-148 db			
Antenna 3-db beamwidth	80°	Total received power	-108 dbm	-107 dbm
		100% clipped AM		
		Modulation loss	-3 db	-3 db

These parameters, along with the Apollo spacecraft VHF parameters (Table 2), demonstrate that the up and down VHF links display essentially the same overall communication efficiency. Therefore, only the VHF transmission from a 1000-km satellite to the lunar far side is discussed.

The RF cable losses at 300 MHz are 5.5 db per 100 feet (as compared with the 15 db per 100 feet at S-band), so a 2-db loss (~30 ft of cable) at the LM is reasonable. This cable could have a surface temperature anywhere from 120°K to 407°K (Reference 16). For the LM and CSM noise calculation a radio antenna temperature of 300°K (mean galactic noise at 300 GHz, Reference 24) is used. For the LM, 400°K is used for the transmission-line temperature. With these parameters, the noise spectral density at 300 MHz for both the LM and CSM is -168 dbm/Hz. As in the case of USB spacecraft reception, the noise spectral density is determined primarily by receiver noise.

For AM voice reception, the maximum predetection bandwidth required is approximately 4 kHz. In addition, ±2 kHz of RF bandwidth are required to accommodate the Doppler shift if no phase-lock techniques are employed. The maximum one-way Doppler frequency shift at the LM can be calculated from

$$\Delta f = \frac{2\pi \left(r_2 + h\right)}{T\lambda} \doteq 2 \text{ kHz} , \tag{14}$$

where

r_2 = lunar radius = 1738 km,

h = communication satellite altitude = 1000 km,

λ = RF wavelength = 1 m,

τ = period of satellite orbit (sec) = 12.8×10^3 sec for 1000-km circular lunar orbit,

Δf = one-way Doppler frequency shift.

The period, τ, for circular orbit in Equation 14 is given by

$$\tau = 2\pi \left[\frac{(r_2 + h)^{3/2}}{\mu_m^{1/2}}\right] , \tag{15}$$

where

μ_m = gravitational parameter for moon = GM = 4.903×10^{12} m^3/sec^2 (Reference 3),

G = universal gravitational constant = 6.67×10^{-11} $m^3/kg\text{-}sec^2$

M = mass of the moon = $7.35\ (10^{22})$ kg

h = altitude (m).

Between CSM (200-km parking orbit) and the 1000-km satellite, the Doppler shift could, for short periods, be approximately three times that experienced by the lunar far-side LM.

On the assumption of an 8-kHz predetection bandwidth and a 15-db carrier-to-noise ratio, a total received power of -111 dbm power is required. Table 2 indicates received powers of -108 dbm (LM) and -107 dbm (CSM), which, for the assumptions stated, implies that the VHF relay of voice and 1.6 kbps telemetry is realizable via the 1000-km satellite.

LUNAR FAR-SIDE LM TO CSM

The primary voice link between the Apollo LM and CSM is at VHF (Reference 25). If a nominal CSM circular lunar parking orbit of 150 km (Reference 3) is assumed, then the geometric horizon between lunar surface and CSM is given by

$$d = \sqrt{h(2r_2 + h)} = 740 \text{ km} , \tag{16}$$

where

r_2 = lunar radius = 1738 km,

h = CSM altitude = 150 km,

d = geometric horizon = radio horizon (km).

By communicating via the 1000-km satellite, the radio horizon is extended to 2110 km. The link calculations for VHF are the same as those outlined in the preceding section. Voice communication appears feasible. As indicated earlier, voice relay between CSM and LM can be conducted via the libration satellite at 2 GHz. The necessary frequency translation at the libration satellite can be made at the ratio required to maintain the standard Apollo CSM and LM USB frequency assignments.

LUNAR FAR-SIDE SURFACE TO SURFACE

Lunar far-side surface point-to-point voice communication can be accomplished by either the libration satellite or the 1000-km satellite. The 2-GHz libration relay looks promising for this mode of operation because it provides full hemispherical coverage on a continuous basis with little or no antenna tracking. As pointed out earlier, the 1000-km satellite at any given time provides only 40-percent hemispherical coverage.

As a matter of speculation, lunar-surface communication might be conducted at LF (100 kHz). A study by the National Bureau of Standards (Reference 26) estimates a power level of 16 watts at 100 kHz for propagating a distance of 100 km along the lunar surface. Confirmation of such speculations must await the outcome of lunar-surface conductivity and permittivity measurements.

The recent measurement by Luna 10 (launched 31 March 1966) of lunar ionosphere electron density 10^8 electrons/m^3 at an altitude of 400 km allows speculation regarding ionospheric or "skywave" propagation similar to earth skywave. The index of refraction at any point within the ionosphere can be related to electron density (Reference 27). For 10^8 electrons/m^3, the critical frequency would also be in the 100-kHz range, that is, the highest frequency to experience total reflection at normal incidence is expressed by

$$f_c = \sqrt{81 N_e}\ \text{Hz} \doteq 10^5\ \text{Hz} ,$$

where

N_e = electrons/m^3 = 10^8.

CONCLUSIONS

Libration ("Hummingbird") Lunar Communication Satellite

The Hummingbird libration satellite discussed in Reference 4 offers a means of relaying USB data between the earth and the lunar far side. Such a USB link is considered unfeasible with low-altitude lunar relay satellites chiefly because of antenna-pointing requirements. (These requirements are restated in the next section.)

The link between earth and libration satellite, in terms of signal path loss, is only 1.4 db weaker than present earth-moon links such as the Surveyor and Langley Lunar Orbiter. This link therefore, presents no new problems. The transmission path between libration satellite and lunar far side (LM upon lunar surface and/or lunar orbiting CSM) is the most critical link chiefly because of the significant spatial separation between Apollo spacecraft and the communication satellite. However, as a result of this separation, antenna pointing is not a severe problem.

As was previously shown, the libration satellite relay of USB Doppler information, 1.6 kbps data, and voice can be considered feasible with no modification to present Apollo spacecraft hardware. This makes it possible to determine a lunar far-side earth-based orbit, and to establish communications. The CSM high-gain sequential-lobing antenna, which will automatically track the earth during the lunar mission, is suitable for tracking the libration communication satellite. The 10-ft diameter S-band lunar surface antenna associated with the LM is suitable for continuously viewing the libration satellite that is fixed relative to the lunar surface. To conserve electrical power, the libration satellite's 20-watt transmitter (Table 1) can be turned on by earth-generated command signals.

1000-km Altitude Lunar Communication Satellite

The acquisition of signals above 1 GHz, from low-altitude lunar communication satellites is analogous to earth acquisition of low-orbit satellites and presents similar problems. Earth orbit-acquisition problems are discussed in References 28 and 29. The primary difficulty arises from the narrow antenna beamwidths associated with the higher frequencies. The propagation loss between an omnidirectional spacecraft antenna and an antenna aperture of given physical size is independent of frequency, provided that the omnidirectional pattern falls within the beamwidth of the latter. For example, a 10-ft-diameter antenna at 2 GHz results in a -3 db beamwidth of 3.5 degrees (according to Equation 6) while at 300 MHz the corresponding beamwidth is 23 degrees. All other parameters being equal, the 10-ft-diameter antenna if pointed at the spacecraft would intercept the same amount of energy irrespective of frequency. However, the narrow beamwidth resulting at 2 GHz necessitates some type of automatic spatial scan (either mechanical or electronic) for acquisition within a reasonable time.

For this reason, only VHF (30 to 300 MHz) affords an acceptable propagation frequency range for a low-altitude relay of lunar far-side signals (where a priori pointing information is necessarily lacking). Since 298.6 MHz is the primary Apollo LM-CM voice link frequency (Reference 25), a 1000-km altitude lunar satellite can be used to extend the voice communication range between a LM upon the lunar surface and a lunar orbiting CSM. As shown under "Lunar Far Side LM to CSM," such a satellite, assuming a 150-km altitude CSM orbit, can extend the radio horizon from 740 to 2110 km. Providing the geometry is satisfactory, S-band voice communication can be relayed to earth by the low-altitude lunar communication satellite. However, as a consequence of the antenna-pointing problems as well as the link calculations of the section "1000-km Altitude Satellite Relay," a relay of Apollo USB signals by low-altitude lunar satellites is not considered probable in the near future.

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National Aeronautics and Space Administration
Greenbelt, Maryland, September 26, 1967
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ABBREVIATIONS

CSM	Command and Service Modules (Apollo)
dBm	decibels referenced to one milliwatt
ft	feet
Hz	cycles per second
IF	intermediate frequency
kbps	kilobits per second
LM	Lunar Module (Apollo)
microwave	corresponding to $1 \text{ GHz} < f < 100 \text{ GHz}$
omni	omnidirectional (antenna)
S-Band	2 to 4 GHz
TWT	traveling wave tube (amplifier)
USB	Unified S-Band (system-Apollo)
VCO	voltage controlled oscillator
VHF	very-high-frequency (30-300 MHz)

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