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LUNAR FAR-SIDE COMMUNICATION SATELLITES

P. E. SCHMID

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ILLUSTRATIONS

ABBREVIATIONS AND DEFINITIONS USED IN THIS REPORT

CSM	Command and Service Modules (Apollo)
dB	decibel
dBm	decibels referenced to one milliwatt
f	frequency
ft	feet
GHz	10^9 Hz
Hz	cycles per second
IF	intermediate frequency
kbps	kilobits per second
kHz	10^3 Hz
km	kilometers
LM	Lunar Module (Apollo)
MHz	10^6 Hz
microwave	corresponding to 1 GHz $< f <$ 100 GHz
m	meter
omni	omnidirectional (antenna)
RF	radio frequency
S-Band	2 to 4 GHz
sec	second
TWT	traveling wave tube (amplifier)
USB	Unified S-Band (system-Apollo)
VCO	voltage controlled oscillator
VHF	very-high-frequency (30-300 MHz)

LUNAR FAR-SIDE COMMUNICATION SATELLITES

by

P. E. Schmid

ABSTRACT

This report presents an estimate of the data relay and tracking capability of a lunar communication satellite relaying signals to and from points on or 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 altitude satellite in circular polar lunar orbit.

LUNAR FAR-SIDE COMMUNICATION SATELLITES

SUMMARY

This report investigates the feasibility of communicating with and/or between Apollo type spacecraft which are located behind the moon. The relay of signals via two satellite geometries are considered, namely,

1. A libration or "Hummingbird" satellite (see reference 4) anchored 65,000 km behind the moon.

2. a 1000 km altitude lunar orbiting relay satellite.

Both VHF (300 MHz) and USB (2 GHz) Apollo frequencies are considered. The three propagation links examined in this report are:

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

2. Lunar far-side LM to CSM.

3. 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 the relay of 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. The feasibility of the various possible modes of lunar far-side radio relay investigated is summarized by the following:

<u>Feasible Without Modification of Apollo LM or CSM Electronics</u>

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 telemetry.

   Via 1000 km Satellite: VHF voice, 1.6 kilobits per sec telemetry.

2. Lunar far-side LM to CSM.

   Via 1000 km Satellite: VHF voice, 1.6 kilobits per sec telemetry.

3. Lunar far-side Surface to Surface:

Via Libration Satellite: USB voice

Via 1000 km Satellite: VHF voice

Feasible if LM or CSM Electronics Modified

1. Lunar far-side ranging data.

Via Libration Satellite: PRN ranging if longer bit-length code employed and regenerative repeater used at Libration Satellite.

2. VHF Doppler tracking data.

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

Not Feasible

Relay of wideband signals such as 51.2 kilobits per sec or real-time television.

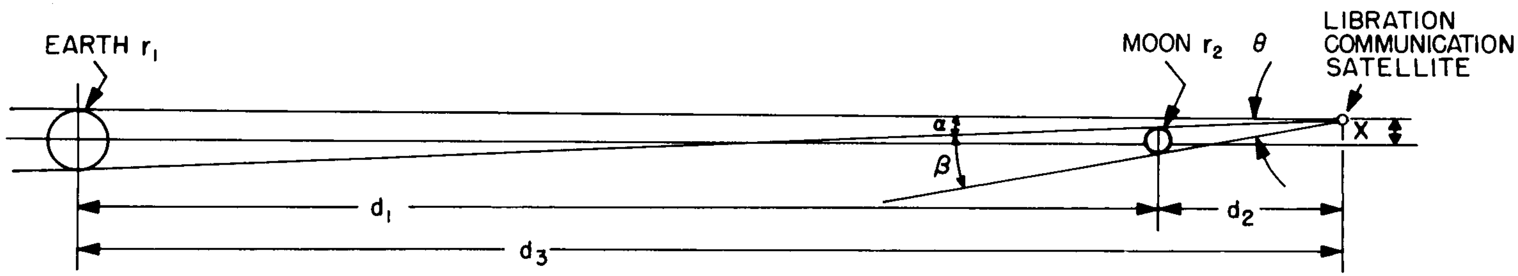
1.0 INTRODUCTION

1.1 GENERAL

This report presents an estimate of the data relay and tracking capability of a lunar communication satellite relaying signals to and from points on or up to 200 km above the lunar far-side surface. Since such a system would be of value during Apollo and post Apollo lunar landing missions (see for example reference 1) detailed calculations are presented for either the LM (lunar module) or CSM (command and service module) operating as the lunar far-side terminal. The two relay satellite locations considered are:

1. The perturbed libration point position (indicated in figure 1) providing continuous earth to moon far-side coverage.

2. A circular polar orbit (i.e., approximately normal to the earth-moon orbital plane) permitting periods of simultaneous earth to lunar far-side coverage (figure 2).



$$\alpha = \frac{2r_1}{d_3} = 1.6^\circ$$

$$\beta = \frac{2r_2}{d_2} = 3.1^\circ$$

$$\theta = \alpha + \beta = 4.7^\circ$$

Figure 1–Perturbed Libration Point Communication Satellite Geometry

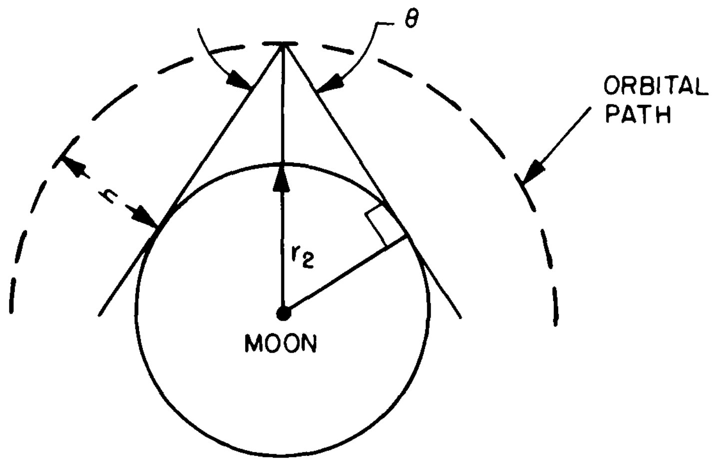


Figure 2–1000 km Altitude Lunar Satellite Geometry

1.2 GEOMETRY

The libration satellite is offset from the natural lunar far-side libration point by approximately 3000 km in order to provide maximum earth to moon far-side coverage. Reference 2 presents a detailed discussion of the 5 earth-moon libration points indicated in figure 3.

Referring to figure 1, the required offset from the lunar far-side libration point is given by:

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

where

- X = offset required for non-obstructed earth view
- d_1 = earth-moon distance = 3.84×10^5 km (ref. 3)
- d_2 = moon to far-side libration point distance = $0.168 d_1$ = 0.645×10^5 km (ref. 2)
- d_3 = earth to far-side libration distance = $d_1 + d_2$ = 4.48×10^5 km
- r_1 = earth radius = 6378 km (ref. 3)
- r_2 = lunar radius = 1738 km (ref. 3)

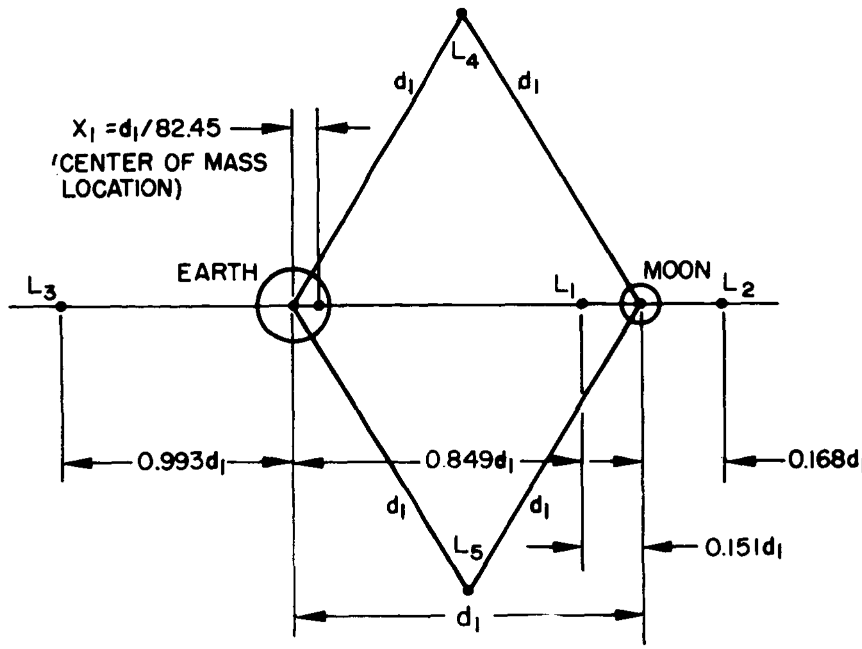


Figure 3–Libration Points of Earth-Moon System

The feasibility as well as fuel and station keeping requirements for maintaining such an offset are discussed in detail in reference.4.

With reference to figure 2, the 1000 km altitude lunar communication satellite orbit will illuminate approximately 40% of a lunar hemisphere at any given time. That is:

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

where:

θ = communication satellite antenna beamwidth required for maximum lunar coverage = 78° for 1000 km orbit.

r_2 = lunar radius = 1738 km

h = satellite altitude above lunar surface = 1000 km

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

1.3 ANTENNA POINTING

The analysis in this report is guided to a large extent by the time and effort which would be required in establishing and maintaining a satisfactory radio link via the lunar communication satellite. For example, it is not reasonable to require an astronaut upon the lunar surface to manually scan the sky with a high gain antenna (beamwidth less than 20°) in search of low altitude ($h \leq$ lunar radius) satellites which 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 widebeam (hence low gain) antennas.

Automatic rather than manual acquisition and tracking of low altitude satellites from the lunar surface would involve the same type problems encountered during earth based tracking of earth orbit satellites. Lunar far-side acquisition would be aggrevated somewhat by a lack of apriori pointing data and the fact that the radio horizon to a low altitude satellite of given altitude is less than at earth by a factor of about 2. For this reason automatic tracking of low altitude satellites from portable lunar far-side surface or near-surface terminals is not considered practical prior to the mid 1970's. By that time it is conceivable that phased arrays and modular electronics of sufficient reliability, light weight and small size, will be available to allow the complexity required for a spacecraft borne high gain antenna automatic tracking scheme. In section 2.2, it is shown that the foregoing constraints dictate the use of VHF rather than microwave propagation for the lunar far-side to 1000 km altitude communication satellite link.

In contrast however, the astronaut should be able to satisfactorily direct a high gain antenna toward a distant communication satellite (for example the libration satellite) by rather simple means such as listening to a tone modulated carrier emanating from the relay satellite. The price paid for using such a far removed relay satellite is a significant increase in path loss. As shown in section 2.1 only frequencies above 1 GHz should be considered for radio relay via the libration satellite.

In this memorandum both the 2 GHz and 300 MHz nominal Apollo frequencies are considered.

The three radio links analyzed are:

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

Means for maintaining the desired lunar communication satellite positions are not presented in this report. Such considerations are discussed at length in references 4, 5 and 6.

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

2.1 LIBRATION SATELLITE RELAY

PARAMETERS – Figure 1 indicates the relative earth-moon geometry for lunar far-side radio relay via the Libration Satellite. It is seen that a 5° beamwidth antenna at the Libration Satellite will simultaneously illuminate both the earth and 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 earth to Libration Satellite link is no more difficult to implement than current earth-moon transmission (for example, Langley Lunar Orbiter). That is, 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 attributable to range separation and is given by:

$$L = \frac{\lambda^2}{16\pi^2 d^2} \quad (3)$$

where

L = loss due to physical separation of communication terminals

d = range separation

λ = wavelength of transmission

The critical link is the lunar far-side to Libration Satellite path. This is primarily due to the 10 to 50 watt limitation on average spacecraft radiofrequency (RF) power and to physical constraints which below 3 GHz limit spacecraft antenna gain to 35 dB or less. This is in contrast to earth terminal capability with average power levels in excess of 10 kw and antenna gains up to 60 dB corresponding to a 64 m (210 ft) diameter antenna.

In order to maximize the power received at either terminal of this critical link, it is necessary to use maximum antenna gains at both the Libration Satellite and the lunar far-side terminal. At either terminal the received power is given by: (See for example ref. 7)

$$P_r = \frac{P_t G_1 G_2 \lambda^2 L}{16\pi^2 d^2} = \frac{P_t G_2 L A_e}{4\pi d^2} \quad (4)$$

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 wave-length

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 3 m (10 ft.) diameter dish. On the CM the high gain tracking antenna consists of an array of four 0.8 m (2.6 ft.) diameter antennas (ref. 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 hence physical aperture, A, independent of frequency. The effective antenna aperture for horn, lens, and parabolic dish antennas in the 300 MHz to 3000 MHz frequency range is approximately 60% of the physical aperture (ref. 10).

At the Libration Satellite it is desirable tc view both the moon and earth with a single antenna. This permits a minimum beamwidth of 5°. The gain, G_2 corresponding to this beamwidth can be approximated by: (ref. 10)

$$G_2 \doteq \frac{27000}{\theta^2} \quad (5)$$

where

θ = conical 3 dB beamwidth (degrees)

G_2 = Libration Satellite antenna gain

A 5° 3 dB conical beamwidth antenna results in 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 (6)

$$D \doteq \frac{70\lambda}{\theta}$$

where

D = antenna diameter

λ = RF wavelength

θ = 3 dB beamwidth (degrees)

For a 5° 3 dB beamwidth the required diameter is 2 meters (7 ft.) at 2 GHz and 14 meters (44 ft.) at 300 GHz. Therefore, for the Libration Satellite link only the Apollo USB frequencies are considered.

The Libration Satellite to lunar far-side terminal signal calculations 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. The Libration Satellite orientation is assumed to be maintained by locking to the sun and the star Canopus in the same manner as Mariner IV and Langley Lunar Orbiter.

The only calculation which warrants some elaboration is that of antenna effective noise temperature. As will be shown the antenna noise temperature at the LM or CSM is of no consequence even when viewing the sun directly with a 3° beamwidth antenna. This is a result of the 11 dB USB transponder receiver noise figure (ref. 11-a result of no preamplification) and the RF losses which in all cases exceed -7 dB (due to cable lengths, RF combiner losses and so on). The 11 dB Apollo USB noise figure is typical for the usual microwave superheterodyne receiver where the antenna is coupled directly to the first mixer. (Langley Lunar Orbiter receiver noise figure is 12 dB ref. 12). 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 which must be used to assure antenna locations clear of obstruction. The use of waveguide, with inherent low loss, is apparently considered not 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) while coaxial cable diameter such as 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. (p. 615 ref. 13 for RG-9 coaxial transmissions line – Apollo spacecraft RF cables are similar to RG-9). At 2 GHz the price paid for the flexibility, structural integrity, and ease of cable connection is appreciable RF loss for cable runs in excess of a few feet. At 300 GHz the corresponding cable loss is only -5.5 dB per 100 ft. Low-loss air dielectric semi-flexible coaxial line (ref. 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 referred to the receiver input terminals is seen from:

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

where

T_e = Effective noise temperature

T_a = Antenna noise temperature

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

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° whether viewed from earth, the Libration Satellite, or a point in the vicinity of the moon. The effective antenna noise temperature can thus be expressed for all three cases as: (ref. 15)

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

where

T_s = Antenna noise attributed to a direct view of the sun's disc (°k)

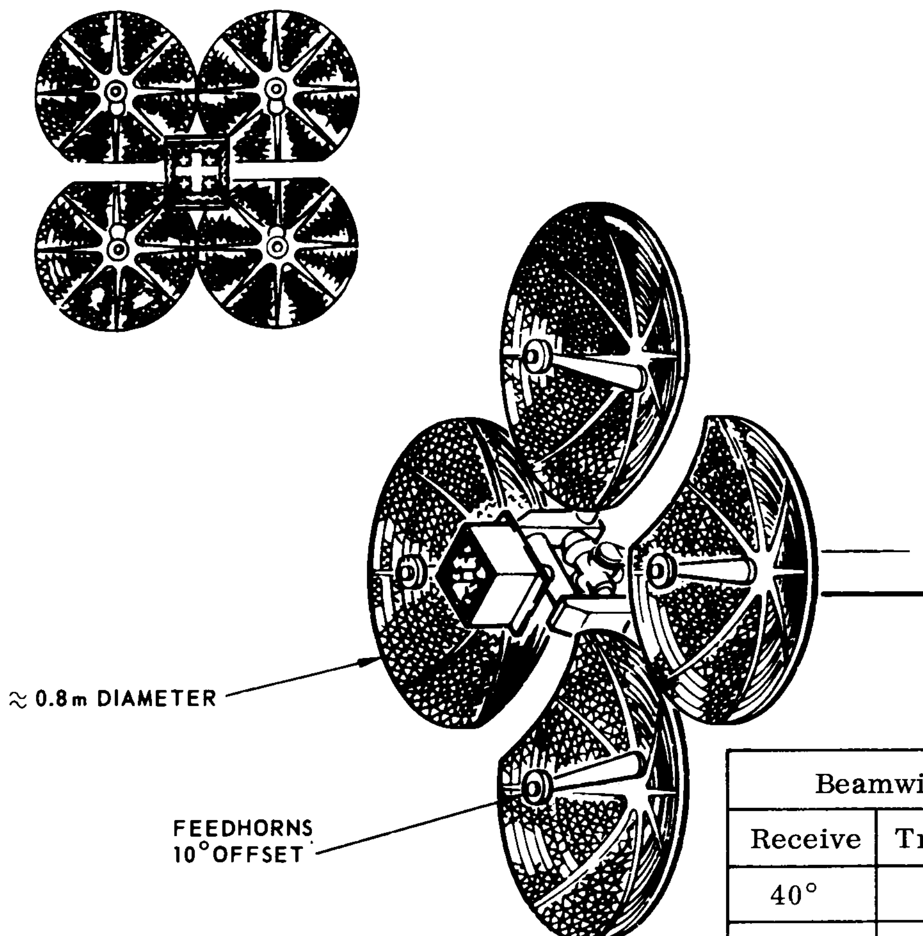
f = Radio frequency to which receiver is tuned (Hz)

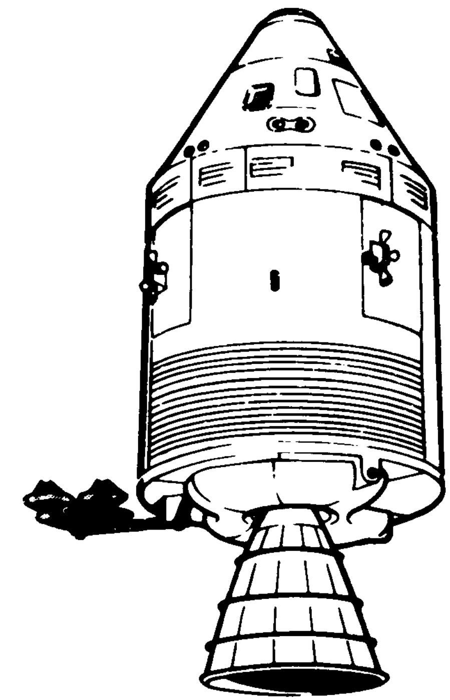
θ = 3 dB antenna beamwidth (degrees)

Example:

For f = 2 GHz and $\theta \doteq 5°$ (CSM high Gain Antenna, figure 4), T_s = 1000°K. By equation 7 it is seen that the noise spectral density at either LM or CSM receiver input is -163 dBm per Hz of RF bandwidth independent of 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 and by shortening 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 ref. 12). The total received power to noise power ratio at the receiver input will for this case be directly affected by the noise power intercepted by the antenna. If the 5° Libration Satellite beamwidth antenna views the sun directly the result by equation 9 is an antenna noise temperature of 1000°K. As shown by figure 5, the Libration Satellite would view the sun for approximately 9 hours out of each month. That is assuming a 28 day period of moon revolution about the earth (13° per day) the Libration Satellite -3 dB beamwidth of 5° will intercept the sun for only 5/13 of a day or 9.2 hours. The time of maximum solar noise pick-up (~ 1000°K neglecting earth occulation) can be considered during the pass of -1.5 dB antenna beamwidth points. The -1.5 dB beamwidth is given by: (ref. 10)

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





Beamwidth		Gain		RF Loss
Receive	Transmit	Receive	Transmit	L ± 7 dB in all cases See section 2.1 "Parameters"
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	

ref. 9 and 10

Figure 4—CSM High Gain Antenna

θ = Angular width of main lobe for decay of k_{dB} $k = 1.5$

θ_{3dB} = -3 dB beamwidth = 5°

Or direct solar illumination is on the order of 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 by:

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

where

T_1 = Earth radio noise temperature = 300°K

α = Angular antenna coverage of earth = 1.6°

θ = -3 dB antenna beamwidth = 5°

T_2 = Lunar radio noise temperature at 2 GHz = 220°K (independent of solar illumination - ref. 16).

β = Angular coverage of moon = 3.1°

For the assumed Libration Satellite noise figure of 3 dB and RF losses of 2 dB by equations (7), (8), (9) and (11) the noise spectral density referred to the receiver input is seen to be -172 dBm per Hz when not viewing the sun and -168 dBm per Hz when viewing the sun directly. It is noted that even while viewing the sun directly, the Libration Satellite receiver noise spectral density is 5 dB below that which would be present at either the Apollo LM or CSM transponder receiver input. For this reason Libration Satellite transmission to lunar far-side is considered the limiting factor in this link.

CARRIER DOPPLER TRACKING

With the parameters indicated in table 1, the total maximum received power at the LM while resting upon the lunar surface is -105 dBm, and that at the lunar orbiting CSM -111 dBm. Acquisition of the carrier by USB (LM or CSM) transponder requires a -114 dBm carrier component and subsequent carrier tracking requires at least -127 dBm of carrier component (ref. 17). Therefore, both acquisition and subsequent carrier Doppler frequency tracking appear feasible. By phase-locking the entire link (i.e., MSFN-Libration Satellite transponder-lunar terminal transponder) the Doppler as recorded at the MSFN USB sites would be sufficient to compute the orbit of a lunar orbiting vehicle such as the Apollo CSM.

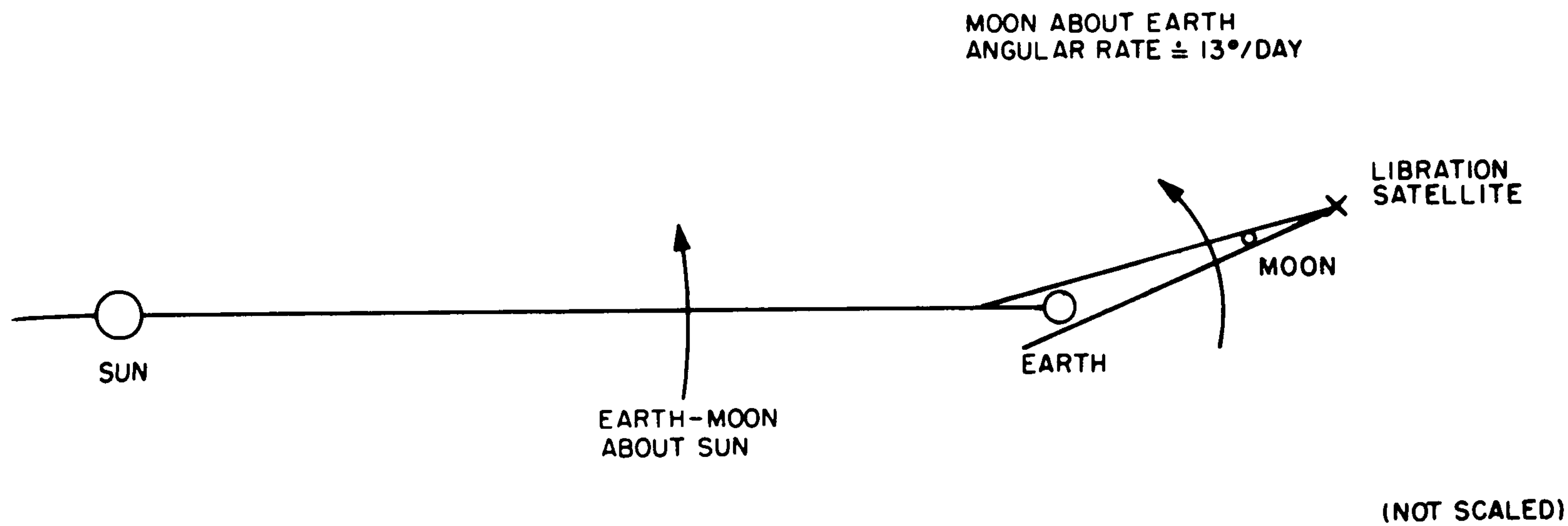


Figure 5—Illumination of Sun by Libration Satellite Antenna

Table 1

2 GHz Relay Via Libration Satellite

Libration Communication Satellite Transmit 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	2108.8 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 -3dB beamwidth	3°	5°
		Total received power	-105 dBm	-111 dBm

RANGING

The present USB Apollo transponder Pseudo Random Noise (PRN) ranging channel is required to meet certain specifications for total signal power inputs from -80 dBm to -50 dBm (ref. 17). Such levels (excess of -80 dBm) are required to assure a demodulated ranging signal of constant amplitude at the USB transponder phase modulator input (see figure 6). Also the current transponder checkout procedure includes ranging tests for input power levels of -100 dBm to -50 dBm (ref. 18). While the forementioned transponder input power levels are consistent with Manned Space Flight Network (MSFN) operation, they could not be met via the Libration Satellite.

The overall transponder ranging channel bandwidth must be maintained at 4 MHz to minimize transponder delay variations (ref. 19). There have been a number of theoretical discussions indicating that the PRN ranging scheme can be utilized even though the total ranging signal to noise power in the required 4 MHz overall bandwidth at the transponder is appreciably less than unity (e.g. ref. 20 and 21). The argument here 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 would require a 4 MHz bandwidth ranging channel if a straight feed-through relay is employed. There is the possibility of making the range measurement at the Libration Satellite (so-called "regenerative transponder") and then telemetering this data back to earth, however this scheme would not be consistent with the present USB coding technique.

The basic Apollo transponder ranging turnaround scheme is as indicated by figure 6. While schemes to turn around the ranging code at extremely low signal to noise ratios are a subject of continuing study, Apollo transponder hardware as presently configured does not appear to have this capability. For this reason a ranging measurement via the Libration Satellite is assumed not feasible for those missions constrained to use current Apollo hardware and signal coding. It should be mentioned that range-rate data (in the absence of range data) as derived from carrier Doppler is sufficient to determine orbits of spacecraft in the vicinity of the moon.

VOICE AND TELEMETRY

As an estimate of the type of data rates which 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. For this case the peak phase deviation (β) is 1.85 (ref. 11) and the available sideband power accounts for approximately

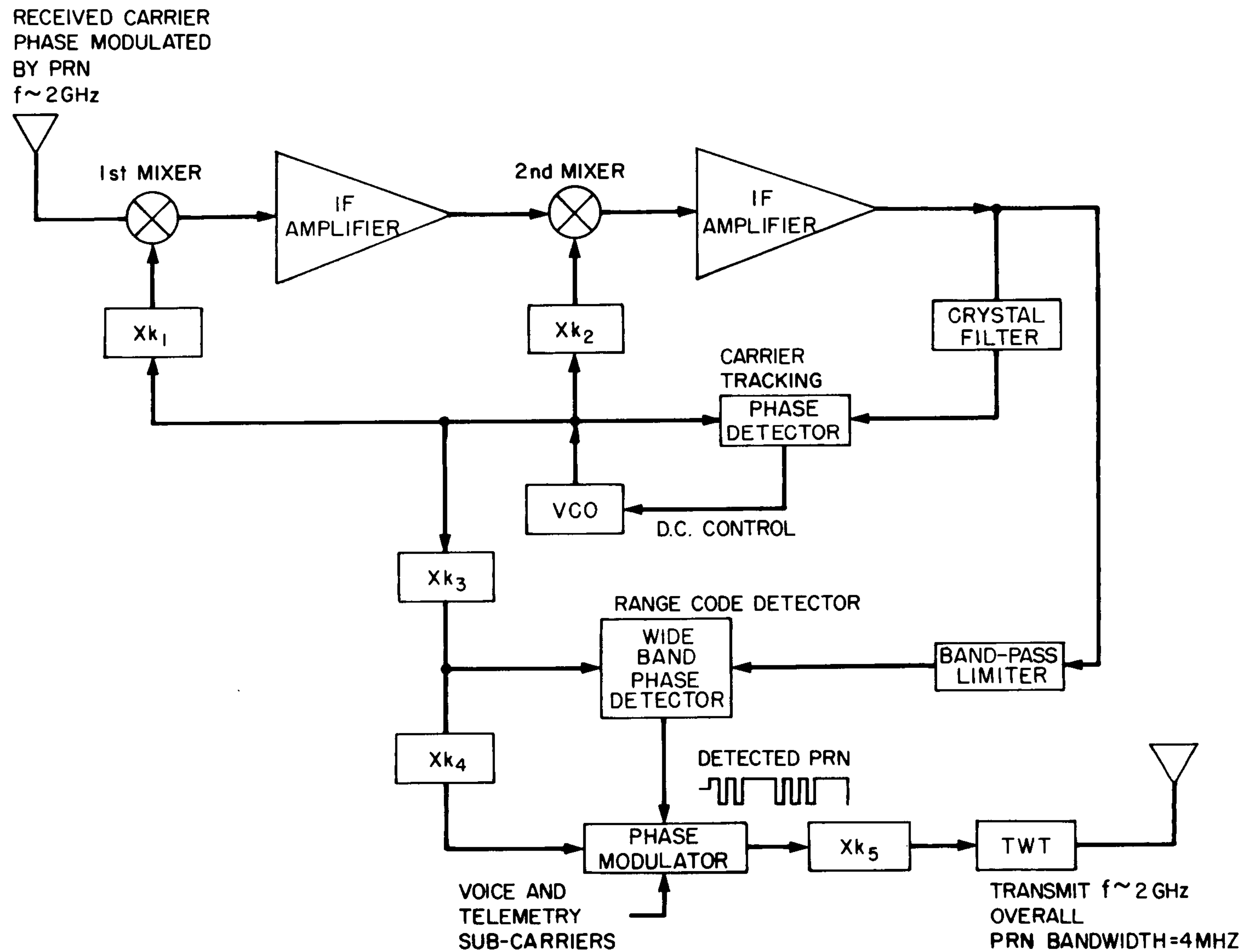


Figure 6–Simplified Block Diagram – PRN Turnaround by Apollo Transponder

85% of the total available power (ref. 22). That is, available sideband power for voice-only is on the order of 1 dB below total available power, while carrier power is on the order of 8 dB below total available power. The carrier components for this case are -114 (LM) dBm and -120 dBm (CSM) still above the -127 dBm needed for carrier tracking and 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 (ref. 17). Using the noise spectral density figure of -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 required predetection bandwidth for voice with β of 1.85 is given as: (ref. 23)

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

f_m = Highest significant modulation frequency = 3 KHz for voice

β = Modulation index = 1.85 in this example

Therefore, voice and 1.6 kilobits per second (kbps) USB data relay are considered feasible. Because of required predetection bandwidths in excess of 150 kHz, 51.2 kbps telemetry and real-time TV relay via the Libration Satellite are not considered feasible.

2.2 1000 KM SATELLITE RELAY

An estimate of the data rates which can be relayed to earth at 2 GHz via a 1000 km altitude lunar orbiting satellite can be made as follows. The maximum spacecraft to communication satellite range separation (radio horizon = 2000 km) relative to the Libration Satellite decreases the path loss by 30 dB. In order to obviate antenna tracking, the communication satellite must illuminate the maximum lunar surface where the antenna beamwidth is given by:

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

where θ = Communication satellite beamwidth

H = Satellite altitude = 1000 km

r_2 = Lunar radius = 1738 km

A conical -3 dB antenna beamwidth of 78° corresponds to a 6 dB maximum on-axis gain. The lunar surface (LM) or near surface (CSM) antenna would need to be "omni directional" 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 Satellite is considered not practical. As pointed out previously, it is not reasonable to expect the astronaut to scan the sky in search of a low altitude relay satellite, in the absence of apriori pointing data.

It is suggested therefore that this link be considered only from the standpoint of VHF for 1000 km Satellite to lunar far-side and S-Band for the 1000 km Satellite to earth link. Both the CSM and LM carry a 5 Watt 296.8 MHz transmitter coupled to an "omni-directional" antenna. Direct VHF transmission to earth from CSM or LM is not possible 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 which employed Unified S-Band (USB) frequencies on the link to earth. Several such lunar communication satellites would be required to provide continuous lunar far-side to earth coverage. As in the case of the Libration Satellite, the earth to communication satellite link is not considered critical. The VHF link (satellite to lunar far-side) parameters are listed in table 2.

The maximum lunar radio temperature at VHF is on the order of 250°K (ref. 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 noise figure at 6 dB. A 10 watt VHF transmitter at the lunar communication satellite is also readily implemented. With these parameters along with the Apollo spacecraft VHF parameters (table 2), it is noted that the up and down VHF links display essentially the same overall communication efficiency. Therefore, only the 1000 km Satellite to lunar far-side VHF transmission is discussed.

The RF cable losses at 300 MHz are 5.5 dB per 100 feet (compared to 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 be at a surface temperature anywhere from 120°K to 407°K (ref. 16). For the LM and CSM noise calculation a radio antenna temperature of 300°K (mean Galactic noise at 300 GHz ref. 24) is used. For the LM 400°K is used for the transmission line temperature. With these parameters, the

Table 2
300 GHz Relay via 1000 km Altitude Satellite

1000 km Communication Satellite Transmit Parameters		APOLLO Lunar Far-Side Receive Parameters		
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
Transmit 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

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 primarilv by receiver noise figure.

For AM voice reception, the maximum predetection bandwidth required is on the order of 4 kHz. In addition, ±2 kHz of RF bandwidth is 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 by:

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

where

r_2 = Lunar radius = 1738 km

h = Communication satellite altitude = 1000 km

λ = RF wavelength = 1 m

τ = Period of satellite orbit = 12.8×10^3 sec. for 1000 km circular lunar orbit

Δf = one-way Doppler frequency shift

The period, τ, in equation (14) for the circular orbit is given by:

$$\tau = 2\pi \left(\frac{h^{3/2}}{\mu_m^{\ 1/2}} \right) \text{ seconds} \qquad (15)$$

where

μ_m = gravitational parameter for moon = GM = $4.903 \times 10^{12} \text{m}^3/\text{sec}^2$ (ref. 3)

G = Universal gravitational constant

m = Mass of the moon

h = Altitude (m)

Between CSM (200 km parking orbit) and the 1000 km Satellite, the Doppler shift could for short periods of time be approximately 3 times that experienced by the lunar far-side LM.

If an 8 kHz predetection bandwidth is assumed and a carrier to noise ratio of 15 dB used, it is seen that -111 dBm of total received power is required. Table 2 indicates received powers of -108 dBm (LM) and -107 dBm (CSM), which, for the stated assumptions, implies that the VHF relay of voice and 1.6 kbps is realizable via the 1000 km Satellite.

3.0 LUNAR FAR-SIDE LM TO CSM

The primary voice link between the Apollo LM and CSM is at VHF (ref. 25). Assuming a nominal CSM circular lunar parking orbit of 150 km (ref. 3) the geometric horizon between lunar surface and CSM is given as:

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

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 outlined in section 2.2. Voice communication appears feasible. As indicated in section 2.1, voice relay between CSM and LM could be conducted via the Libration Satellite if 2 GHz is employed. The necessary frequency translation at the Libration Satellite could be made at the ratio required to leave unchanged the CSM and LM USB frequency assignments.

4.0 LUNAR FAR-SIDE SURFACE TO SURFACE

Point to point lunar far-side surface voice communication could be accomplished by either the Libration Satellite or the 1000 km Satellite. The 2GHz Libration relay appears attractive for this mode of operation since full hemispherical coverage is provided on a continuous basis with little or no antenna tracking. As pointed out in section 2.2, only 40% of hemispherical coverage is provided at any given time by the 1000 km satellite.

As a matter of speculation, lunar surface communication might be conducted at LF (100 kHz). One study by the National Bureau of Standards (ref. 26) estimates a power level of 16 watts at 100 kHz for propagating a distance of 100 km over 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 a 10^8 electrons/m^3 lunar ionosphere electron density 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 (see for example ref. 27). Based on 10^8 electrons/m^3, the "critical frequency" would also be in the 100 kHz range, that is, the highest frequency which would experience total reflection at normal incidence is given by:

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

where

N_e = Electrons/m^3 = 10^8

5.0 CONCLUSIONS

Libration ("Hummingbird") Lunar Communication Satellite

The "Hummingbird" libration satellite discussed in reference 4 presents a means of relaying USB data between earth and lunar far-side. Such a USB link is considered not feasible with low altitude lunar relay satellites primarily because of antenna pointing requirements. These requirements are restated in the next section.

The earth-libration satellite link, in terms of signal path loss, is only 1.4 db "weaker" than present earth-moon links such as Surveyor and Langley Lunar Orbiter. Therefore, this link presents no new problems. The librating satellite to lunar far-side (LM upon lunar surface and/or lunar orbiting CSM) transmission path is the most critical link chiefly due to the significant spatial separation between Apollo spacecraft and communication satellite (refer to Section 2.1). However, as a result of this separation, antenna pointing is not a severe problem.

As shown in section 2.1, the libration satellite relay of USB Doppler information, 1.6 Kilobit per second data, and voice can be considered feasible with no modification to present Apollo spacecraft hardware. Thus, with this scheme, lunar far-side earth based orbit determination as well as communication is possible. 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 which is fixed relative to the lunar surface. To conserve electrical power, the libration satellite 20 watt transmitter (table 1) could be turned on by means of earth originating command signals.

<u>1000 km Altitude Lunar Communication Satellite</u>

Above 1 GHz, acquisition of signals from low altitude lunar communication satellites presents problems analogous to earth acquisition of low orbit satellites. 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. It is true that the propagation loss between an omni spacecraft antenna and an antenna aperture of given physical size is independent of frequency providing the omni pattern falls within the beamwidth of the latter. For example, a 10 ft diameter antenna at 2 GHz results in a -3db beamwidth of 3.5° (by equation 6) while at 300 MHz the corresponding beamwidth is 23°. All other parameters being equal, the 10 ft diameter antenna if pointed at the spacecraft would intercept the same amount of energy independent of frequency. However, the resultant narrow beamwidth at 2 GHz necessitates some type of automatic spatial scan (either mechanical or electronic) for acquisition in a reasonable time.

For this reason, in the case of low altitude relay of lunar far-side signals where apriori pointing information is necessarily lacking, only VHF (30 to 300 MHz) affords an acceptable propagation frequency range. 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 in section 3.0, such a satellite can, assuming a 150 km altitude CSM orbit, extend the radio horizon from 740 km to 2110 km. Providing the geometry is satisfactory, S-Band voice communication could be relayed back 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 section 2.2, near future relay of Apollo USB signals by low altitude lunar satellites is considered not feasible.

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