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ANTENNA AND PROPAGATION STUDIES FOR SPACECRAFT

TASK E-53F

TECHNICAL REPORT

AN ANALYSIS OF THE RANGING SYSTEM FOR THE LUNAR SURFACE ELECTRICAL PROPERTIES EXPERIMENT

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TABLE OF CONTENTS

ILLUSTRATIONS

1.0 INTRODUCTION

This report covers an analysis of a ranging system which has been proposed by the Massachusetts Institute of Technology for use on the Surface Electrical Properties (SEP) Experiment. The proposed ranging system measures range by measuring the power level of the received signal, and it measures azimuth angle by comparing the phase of a signal received from a rotating antenna beam to that of a marker pulse received from a non-rotating beam. The phase difference between these two signals is a measure of azimuth angle. The method for generating the rotating beam is discussed in detail in Reference 1. The experiment in the deployed configuration using the above ranging system is illustrated in Figure 1.0 where the receiver is shown mounted on the Lunar Rover Vehicle (LRV). If the LRV is used in the experiment, the range will be extended out to a maximum of 10 km.

Power measurements for determing range and phase measurements for determining azimuth angle are made at the frequencies used for electromagnetic detection, so no separate antenna is required for either function. This does, however, require that crossed dipoles be used at the transmitter to generate the rotating antenna beam used in the phase measurement. The antenna is shown in Figure 2.0 in the deployed configuration.

It is concluded in this report that the method of determining range by received power measurement will not provide the required range accuracy of 1% which is specified in Reference 2. This conclusion is based upon an analysis of propagation in a free-space environment which is extended to include the approximate effects of deploying the transmitter and receiver on the lunar surface. For the azimuth angle measurement, it is concluded that it is feasible to obtain the required accuracy of $\pm$ 5 degrees which is also specified in Reference 2.

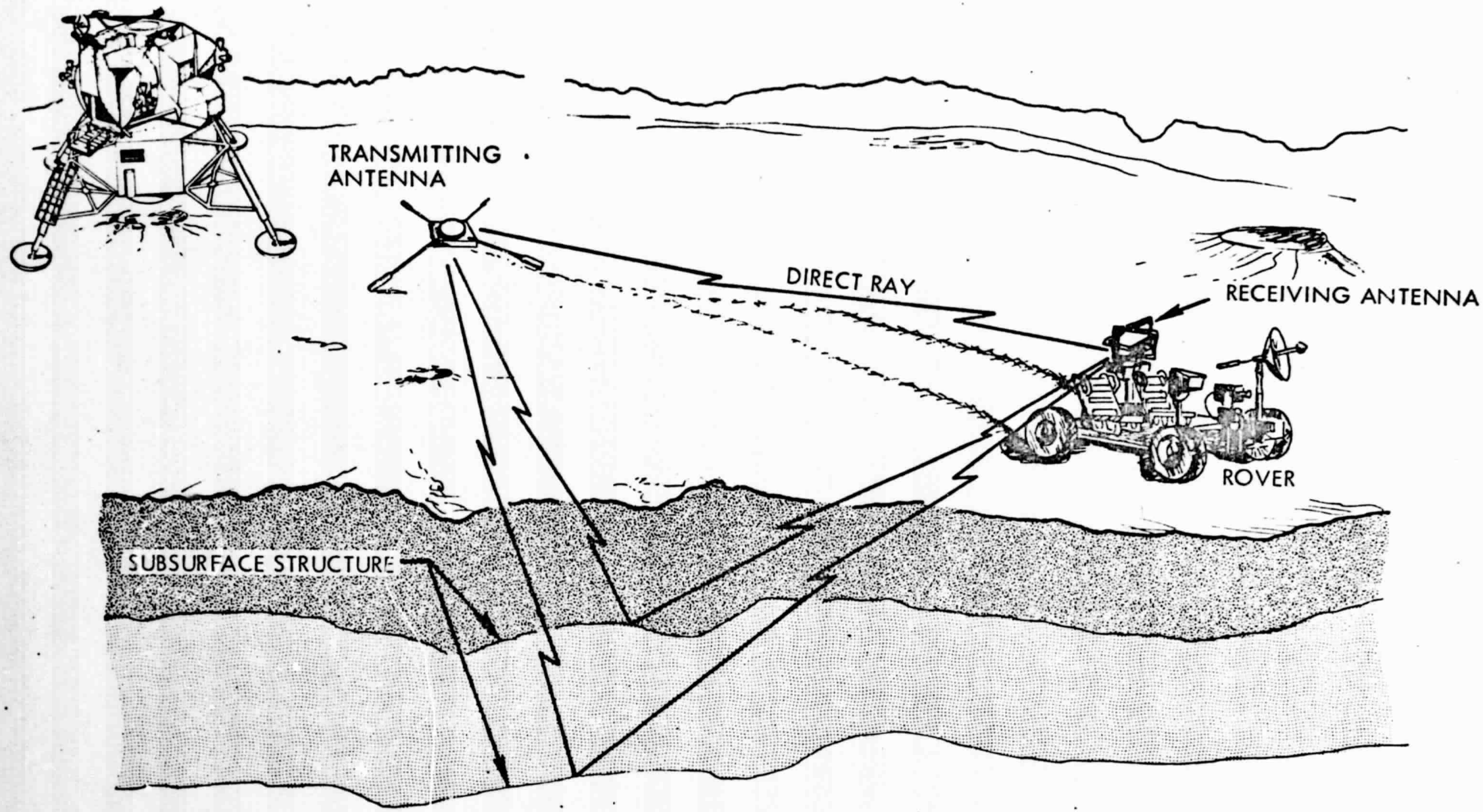

Figure 1.0 The SEP Experiment in the Deployed Configuration

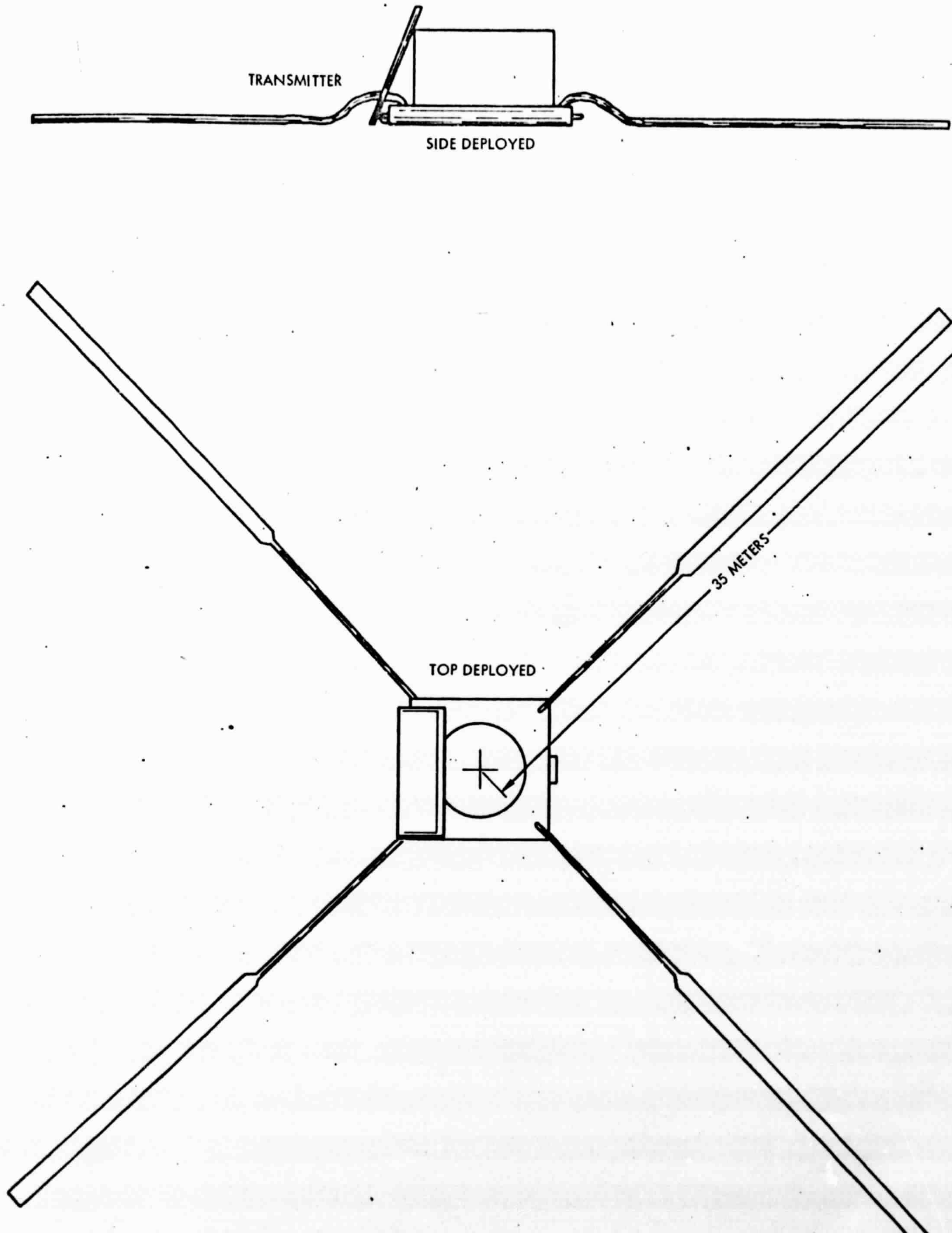

Figure 2.0 Transmitter Antenna

2.0 RANGING SYSTEM ANALYSIS

Since a model for the SEP experiment on the lunar surface has not been completed to date, the ranging system accuracy is determined for a free space environment, and measured data taken from Reference 3 are used to estimate the effects of deployment on the lunar surface. In Reference 3, experimental data was obtained by the Massachusetts Institute of Technology by recording electromagnetic interference patterns from the water table under the Gorner Glacier. These data are informative because the dielectric properties of the glacier and the lunar surface are similar.

2.1 RANGING SYSTEM ACCURACY IN FREE SPACE

This analysis is confined to free space in order to obtain first approximations to the range accuracy which can be obtained with this system. The effect of locating the transmitter and receiver on the lunar surface will be examined in later paragraphs.

In free space, the power at the receiver is given by the Friis transmission equation

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2 \qquad (2\text{-}1)$$

where

G_t = the gain of the transmitter antenna

G_r = the gain of the receiver antenna

P_t = the transmitter power

P_r = the receiver power

λ = wavelength

r = range

The parameters P_t, G_t, and G_r are constants, so the received power will vary in direct proportion to the path loss, l_p, which is

$$l_p = \left(\frac{\lambda}{4\pi r}\right)^2 \qquad (2\text{-}2)$$

In dB this becomes

$$L_p = 20 \log \left(\frac{\lambda}{4\pi r}\right) \tag{2-3}$$

The path loss for the eight operating frequencies is shown plotted in Figure 3 which illustrates the relative insenitivity of the power level to incrimental charges in range. If the range is to be measured using power level, then a high degree of precision will be required in the measurements. To illustrate, the power level changes by only 6 dB for every octave change in range, and the SEP specifications call for a range accuracy of 1% of the actual range. The power level accuracy required is determined from the following:

Using Eq 1, the received power is

$$P_r = k \left(\frac{\lambda}{4\pi r}\right)^2 \tag{2-4}$$

where $k = P_t G_t G_r$, a constant. The power level change for a change in range can be determined by expressing the derivative

$$\frac{dP_r}{dr} = -2k \left(\frac{\lambda}{4\pi}\right)^2 r^{-3} \tag{2-5}$$

in the differential form

$$\Delta P_r = -2k \left(\frac{\lambda}{4\pi}\right)^2 r^{-3} \Delta r \tag{2-6}$$

Since the range accuracy is expressed in percent of the actual, the parameter

$$a = \frac{\Delta r}{r} \tag{2-7}$$

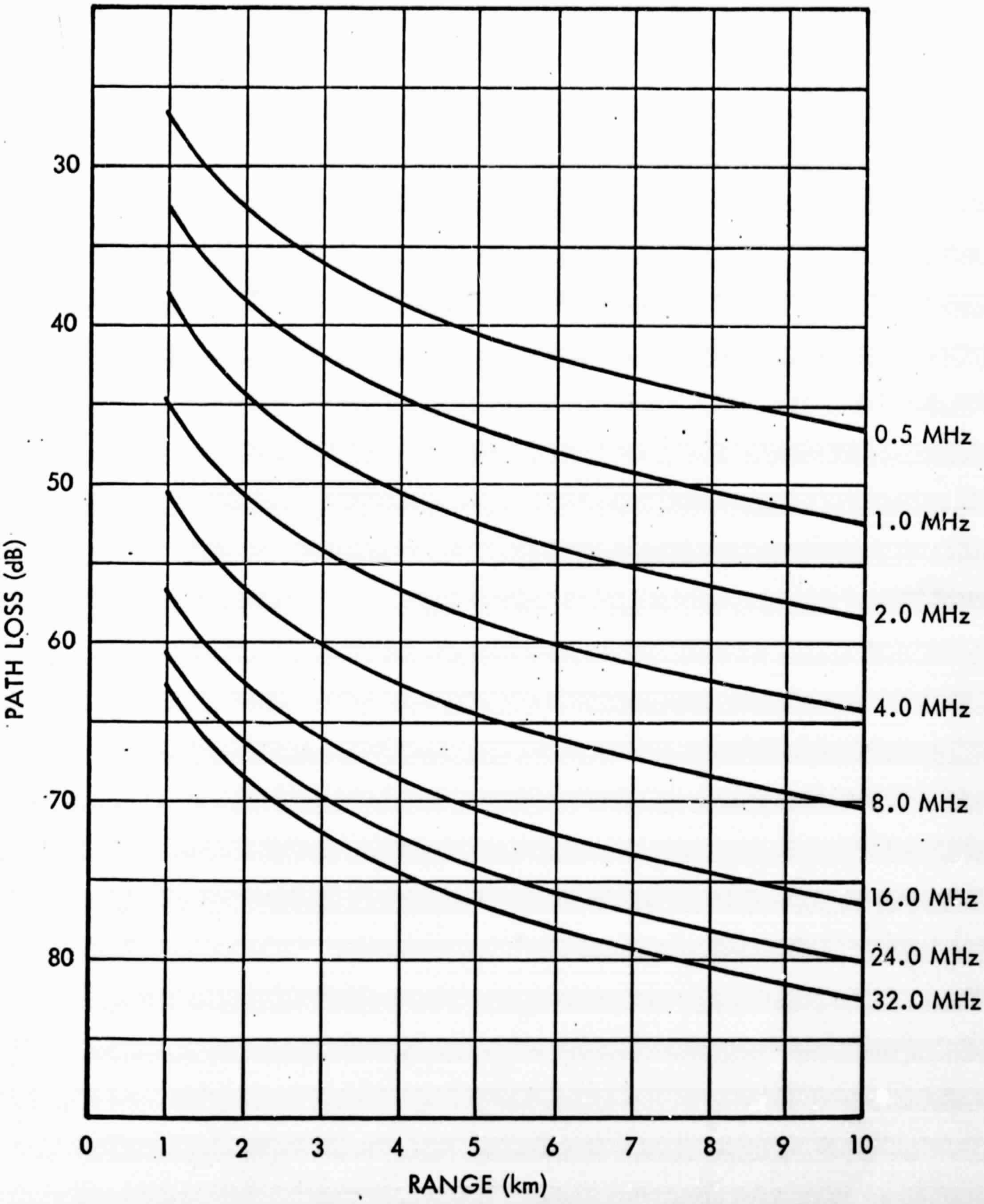

Figure 3.0 Free Space Path Loss

may be substitued in Equation (6). This gives

$$\Delta P_r = -2ka\left(\frac{\lambda}{4\pi r}\right)^2 \tag{2-8}$$

The power level accuracy, PLA, in dB is

$$PLA = 10\log\left[\frac{P_r + \Delta P_r}{P_r}\right] \tag{2-9}$$

or

$$PLA = 10\log\left[\frac{k\left(\frac{\lambda}{4\pi r}\right)^2 + 2ka\left(\frac{\lambda}{4\pi r}\right)^2}{k\left(\frac{\lambda}{4\pi r}\right)^2}\right] \tag{2-10}$$

which reduces to simply

$$PLA = 10\log(1 + 2a) \tag{2-11}$$

For the specified accuracy of 1% (a = 0.01), the required power level accuracy is

$$PLA = 10\log(1 + 0.02) = 0.09\text{ dB} \tag{2-12}$$

That is, the receiver power will have to be determined to an accuracy of $\pm$ 0.09 dB to meet the requirement for a 1% range accuracy. This is an extreme requirement for power measurement accuracy which will probably be unattainable in a practical system.

Further insight into the relationship between range accuracy and power measurement accuracy can be obtained from the ratio of the incrimental power, ΔP_r, and received power, P_r. This ratio is

$$\frac{\Delta P_r}{P_r} = \frac{2ka\left(\frac{\lambda}{4\pi r}\right)^2}{k\left(\frac{\lambda}{4\pi r}\right)^2} \qquad \text{(2-13)}$$

or

$$\frac{\Delta P_r}{P_r} = 2a \qquad \text{(2-14)}$$

Using the substitution $a = \frac{\Delta r}{r}$ this becomes

$$\frac{\Delta P_r}{P_r} = 2\,\frac{\Delta r}{r} \qquad \text{(2-15)}$$

This leads to the following conclusions:

1. The percent tolerance on the power measurement is twice the percent tolerance on the range. The specified 1% range accuracy gives a required power accuracy of 2%.
2. The % range error is equal to half the power measurement accuracy in percent.
3. In dB, the required power level accuracy is PLA = 10 log (1 + 2a) where a is the range accuracy $\frac{\Delta r}{r}$.

2.2 RANGING SYSTEM ACCURACY ON THE LUNAR SURFACE

When the SEP equipment is deployed on the lunar surface, the mode of propagation will not be the same as that of free space as suggested by the analysis in Reference 4. Data taken from field measurements on the water level below the Gorner Glacier also suggest that the mode of propagation is not that of free space. In addition, the data suggest that the mode is dependent upon frequency. Data from the glacier measurements were obtained from Reference 2 and reproduced in Figure 4. It is assumed that the ordinate represents field strength in dB, and the abscissa represents distance from the transmitter to receiver in wavelength. It should be observed from Figure 4 that the average slope of each pattern decreases with frequency. If the mode of propagation were that of free space, the slopes would be equal and the curves simply displaced as in Figure 3. This change in slope with frequency suggests that power is being transmitted in both the space and surface wave propagation modes. The proportion of total transmitter power contained in each mode is dependent upon frequency as indicated in Reference 4.

If received power level is to be used to determine range, the functional relationship between power and range must be known to within an accuracy on the order of 1%. This requirement for exact knowledge of the functional relationship between power and range for propagation on the lunar surface places further limitations on the ranging method. In addition, surface roughness will add uncertainty into the accuracy of the power measurements.

2.3 AZIMUTH ACCURACY

The proposed method for determining azimuth angle involves comparing the phase of a signal received from a rotating antenna beam to the phase of a marker pulse from beam that does not rotate. An analysis of this technique is contained in Reference 1 where it is shown that the phase angle is equal to the azimuth angle. The specified azimuth accuracy is 5 degrees which implies that the phase between the two signals must be measured to within a 5 degree tolerance. This would appear to be feasible with a moderately sophisticated method of phase measurement.

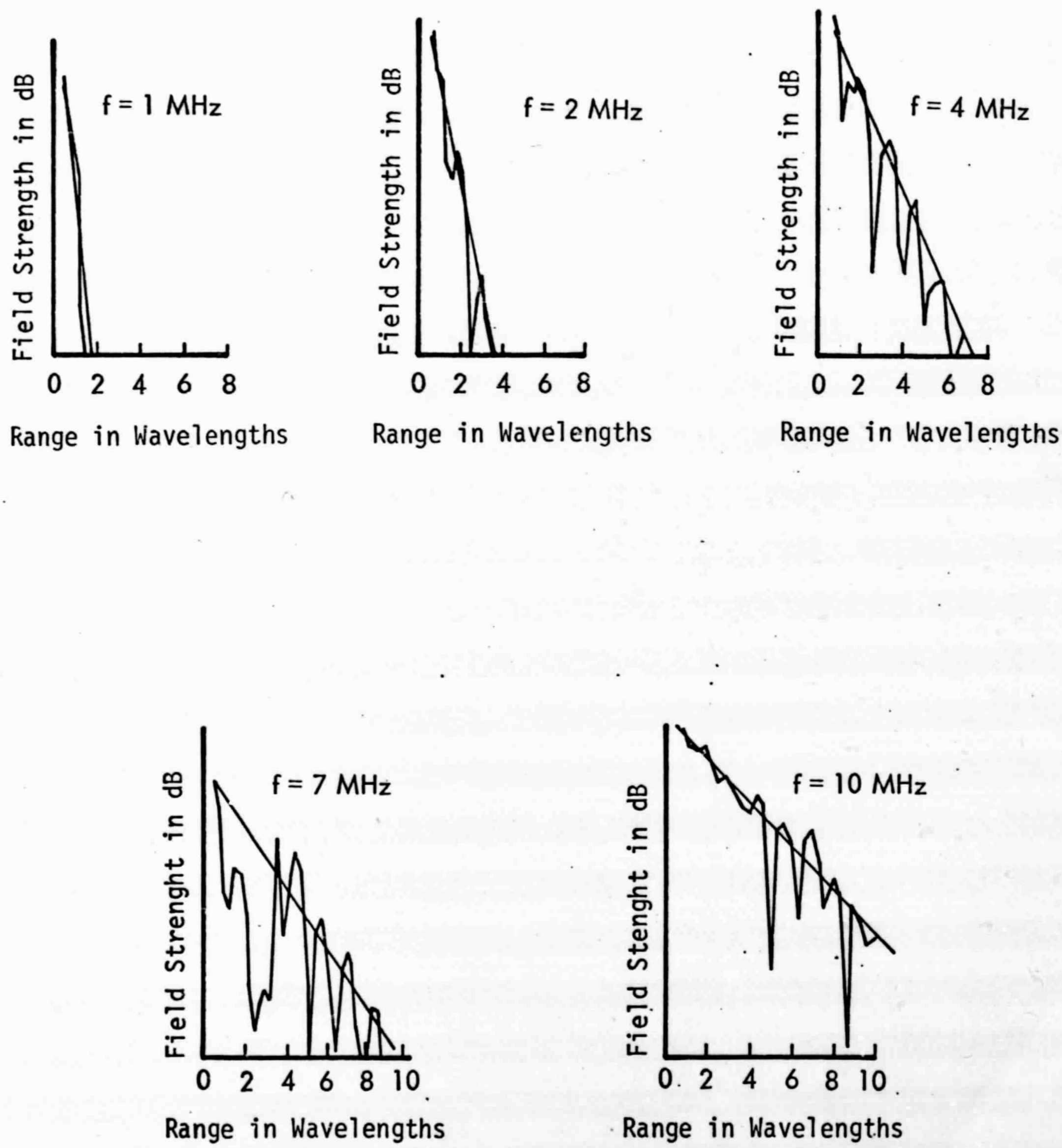

Figure 4.0 Measured Field Data From Reference 3

3.0 CONCLUSIONS

It is concluded that measuring range from received power will require precision in the power measurement and exact knowledge of the functional relationship between range and power, both of which will be difficult or impossible to obtain in a practical situation. It will be particularly difficult to obtain an exact functional relationship between power and range because there is both theoretical and empirical data which suggest that two propagation modes exist when the equipment is deployed on the lunar surface. That is, power is transmitted in both the surface and space wave modes, and the relative power contained in each mode is dependent upon frequency.

For idealized free space propagation, the power measurement accuracy is $\pm$ 0.09 dB for the specified range accuracy of $\pm$ 1%. Even in the ideal situation of free space propagation, this is an extreme requirement for power accuracy.

The required azimuth accuracy is specified as $\pm$ 5 degrees in Reference 2. There is a direct relationship between the phase angle and geometrical angle which implies that the required accuracy of the phase measurement is also $\pm$ 5 degrees. This is not an extreme requirement for the phase measurement accuracy.