NASA/TM—2007-214825

Path Loss Prediction Over the Lunar Surface Utilizing a Modified Longley-Rice Irregular Terrain Model

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July 2007

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Prepared for the
Wireless for Space Workshop
sponsored by the Consultative Committee for Space Data Systems (CCSDS)
Colorado Springs, Colorado, January 22, 2007

National Aeronautics and
Space Administration

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July 2007

This report contains preliminary findings, subject to revision as analysis proceeds.

Level of Review: This material has been technically reviewed by technical management.

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Abstract

This study introduces the use of a modified Longley-Rice irregular terrain model and digital elevation data representative of an analogue lunar site for the prediction of RF path loss over the lunar surface. The results are validated by theoretical models and past Apollo studies. The model is used to approximate the path loss deviation from theoretical attenuation over a reflecting sphere. Analysis of the simulation results provides statistics on the fade depths for frequencies of interest, and correspondingly a method for determining the maximum range of communications for various coverage confidence intervals. Communication system engineers and mission planners are provided a link margin and path loss policy for communication frequencies of interest.

1. Introduction

In 2004, the Bush administration unveiled the United State's Vision for Space Exploration (VSE) (ref. 1). This included the very ambitious goal of creating and sustaining a human presence on the Moon and Mars. NASA's plan for achieving the VSE was first introduced in the Exploration Systems Architecture Study (ESAS) released in November of 2005 (ref. 2). Since this time, NASA has embarked upon a number of agency-wide, inter-center studies to further develop and refine the exploration architecture as presented in the ESAS final report.

One area gaining particular interests is that of radio signal propagation over the lunar surface. Mission concepts, as introduced in the ESAS final report, describe both lunar sortie missions and outpost deployments. Further operational concepts for these missions have made general assumptions about the range of communications for lunar surface-to-surface radio frequency (RF) links based on assumed vehicle structures, rovers, astronaut heights, and potential communications towers.

This study provides a mechanism for determining range limitations for surface-to-surface RF links. Not only are the geometrical features of possible lunar destinations considered, but also the lunar surface composition so that the effects of diffraction are better estimated. Realistic path loss analyses were sought that could be performed in a relatively short amount of time with low computational complexity.

The objectives of the study are:

(1) Develop a model or utilize an existing model for path loss that considers site-specific terrain and surface composition.
(2) Identify a path loss mechanism for use in link budget planning.
(3) Develop link (or fade) margin policies for the frequency bands and RF links of interest to NASA for lunar surface operations and exploration.

2. Methodology

The approach taken is outlined below:

(1) Identify or create a suitable model for analyses.
(2) Identify or create a model (in terms of both terrain and surface composition) of either an actual lunar site of interest or an analogue of such a site.
(3) Use the path loss model combined with the terrain information to generate path loss information and margin polices for RF bands of potential interest to NASA missions.

The trade study that considered path loss models identified the National Telecommunications and Information Administration's Institute for Telecommunication Sciences (NTIA/ITS) Irregular Terrain Model (ITM) as having the highest potential for application to the lunar surface (ref. 3). This model is an implementation of the Longley-Rice computer model presented in their classic 1968 paper (ref. 4).

The ITM implementation, however, is not appropriate to use unmodified. The ITM is based on electromagnetic (EM) theory and empirical data in consideration of terrain information for the Earth's surface. The model's EM propagation and statistical descriptions of diffraction about varying terrain are relevant to this study. However, the model has been modified to ensure that the effective radius of the spherical body is fixed to that of the mean radius of the moon (thus, removing any atmospheric bending phenomena from the evaluation).

The most notable modification to the Longley-Rice model concerns equation (1.3) listed in the original paper (ref. 4), which follows:

$$\gamma_e = \gamma_a \left(1 - 0.04655\ e^{\left(N_s / N_1\right)}\right) \quad (1)$$

*Fellow, IEEE.

This equation expresses the Earth's effective curvature, γ_e, as the actual curvature, γ_a, modified by a bending factor due to atmospheric effects. The Earth's effective curvature is the reciprocal of it's effective radius.

Radio waves propagating over the lunar surface will not experience atmospheric reflected nor refracted effects. Therefore, equation (1) was modified as follows:

$$\gamma_e = \gamma_a \tag{2}$$

For the model γ_a is set to the reciprocal of the mean Moon radius (1/(1737.4 km)).

The model has also been parameterized so that desert-like conditions are imposed, minimizing seasonal and diurnal effects of foliage.

An additional benefit was discovered in this trade analysis. An open source software package called SPLAT! utilizes the ITM in conjunction with digital elevation data to perform propagation analysis and to plot path loss on a regional basis (ref. 5). The SPLAT! software has also been modified to perform path loss analysis for digital elevation data applied to a sphere the with the size of the mean Moon radius rather than a sphere of the size of the mean Earth radius.

Two aspects of the modified ITM software have been verified. First, the modified SPLAT! software has been used to evaluate null elevation data. This has the effect of performing a path loss analysis over a smooth sphere the size of the mean lunar radius. Second, it has been ensured that the model predicted the correct line-of-sight distance for antennas of given heights.

Parsons illustrates on pages 22–23 of his text (ref. 6) with a two-ray path loss prediction technique that the power at a receiving antenna can be calculated as follows:

$$P_R = 4P_T\left(\frac{\lambda}{4\pi d}\right)^2 G_T G_R \sin^2\left(\frac{2\pi h_T h_R}{\lambda d}\right) \tag{3}$$

where

P_T, P_R	tx/rx powers
h_T, h_R	heights of tx/rx antennas
G_T, G_R	tx/rx antenna gains
d	distance between tx and rx
λ	wavelength

Assuming that that $d >> h_T, h_R$, the equation simplifies to:

$$L = \frac{P_R}{P_T} = G_T G_R\left(\frac{h_T h_R}{d^2}\right)^2 \tag{4}$$

where L is the loss (a negative value).

Note that the basic path loss in this case varies according to d^4, or "d^4 loss."

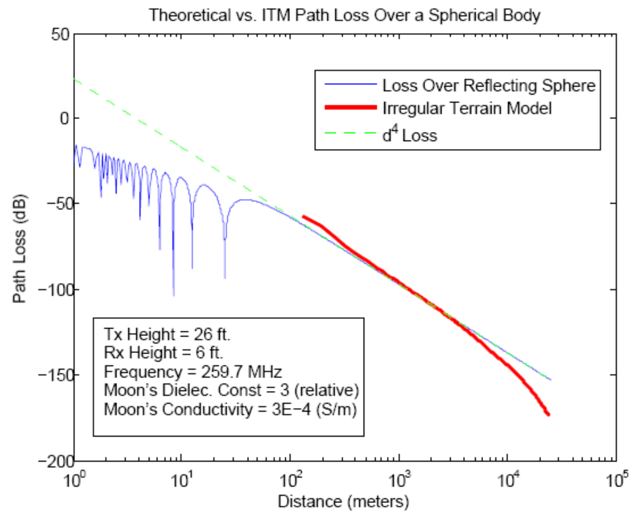

Figure 1.—Smooth Moon path loss.

This type of analysis was also developed for the prediction of path loss for the Apollo era astronauts, in which voice communications were considered at 259.7 and 279.0 MHz (ref. 7).

In parallel, Apollo era data has also been reviewed to include realistic lunar surface composition properties in the model (ref. 8). A conductivity of 0.0001 S/m and a relative dielectric constant of 3 have been chosen as base values.

Figure 1 displays a plot of the ITM results, ideal loss over a reflecting sphere (as illustrated in (ref. 7)), and a plot of d^4 loss.

The ITM model predicts a slightly better performance than d^4 loss prior to 1 km, and slightly worse past approximately 7 km. This is due to the inclusion of realistic lunar surface composition parameters. Prior to 1 km, the destructive interference of the reflected ray is reduced due to the loss in amplitude from reflecting off of a highly non-conductive body. Additionally, as the distance approaches grazing angle a greater amount of the absorbing sphere enters the first Fresnel zone. This significantly reduces the received power for larger distances.

The model predicted nearly the exact same line of sight distance as was provided in (ref. 7) for the same parameter set, approximately 7.5 km.

Additional results have been analyzed for antennas of various heights and various frequency ranges. Most trials result in an approximate d^4 loss curve versus distance for reasonable ranges, as shown in figure 1.

Next, suitable terrain information has been identified for the characterization of path loss. This trade study researched existing lunar terrain information and the possibility of creating a representative landscape for import into the modified SPLAT! software.

The software package provides the capability to import SRTM–3 digital elevation data. This data resulted from the STS–99 shuttle mission, which flew a multi-frequency radar.

The elevation data provides an approximate 20 m horizontal resolution and a 16 m vertical resolution at a 90 percent confidence interval (ref. 9). Alternatively, the lunar elevation data derived from the Clementine mission was considered.

However, with a vertical accuracy of 100 m and a spatial resolution of 2.5°, the SRTM–3 data is more appropriate (ref. 10). An analogue lunar site has been constructed using the elevation data of a location on Earth with geological features of interest.

Meteor Crater, Arizona has been chosen as the analogue lunar site because it provided many of the geological features of interests for possible lunar excursions. An image of the crater can be seen in figure 2.

The crater, itself, is approximately 1 km in diameter. The local terrain is fairly flat, with occasional rock outcrops. The altitude above mean sea level gently increases traversing from the northeast to the southwest. Additionally, there are local maxima around the crater wall and peaks off to the east and west of the crater.

The SRTM3 data for this area has been applied to a sphere the size of the mean lunar radius by modifying the SPLAT! software. The great circle distance of 1 radian on the Moon is approximately 1/3 of the distance of 1 radian on the Earth. Therefore, the Meteor Crater elevation data (relative to the mean lunar radius) has been reduced to 1/3 of it's magnitude to reduce the severity of terrain variability. Otherwise, the terrain represented an unrealistic exploration site for NASA missions. Figure 3 illustrates this rationale.

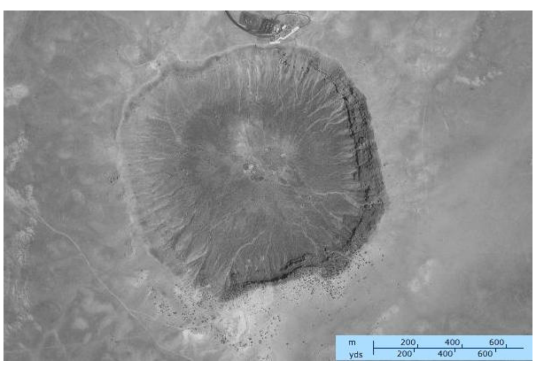

Figure 2.—Meteor Crater, Arizona.

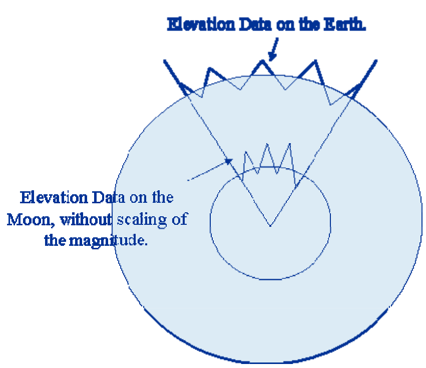

Figure 3.—Rationale for elevation data scaling.

The ITM and SPLAT! software, combined with suitable elevation data provides the necessary tools for performing a path loss characterization.

The following assumptions have been made pertaining to the investigation:

(1) The range of frequencies to be investigated is HF (30 MHz), UHF (401 MHz) and S-band (2.4 GHz).

(2) The mean radius of the lunar sphere is 1737.4 km.

(3) Transmit antenna heights are based on assumptions of an astronaut height (2 m), a rover height (3 m), a base height (5 m), and a potential lunar communication tower (15 m). The receiving antenna is always considered to be an astronaut (2 m).

(4) Conductivity and relative dielectric constant values are set to: $\sigma = 1\times10^{-4}$ S/m, $\mu_r = 3$.

(5) The transmitter location is situated approximately 1 km north of the center of the crater.

3. Results

Fade depth statistics have been calculated beyond d^4 loss for all frequencies and antenna heights assumed.

It should be noted that the results of this study are specific to the analogue lunar site. A site containing more severe terrain would induce more severe fading conditions altering the statistics of the results. This is discussed in further section 5 (Future Work).

Table I presents the results of all trial runs.

TABLE I.—SUMMARY OF RESULTS

Frequency	Average fade depth, dB	Standard deviation, dB
Astronaut (height = 2 m)		
30 MHz	N/A	N/A
401 MHz	2.76	2.97
2.4 GHz	6.27	4.65
Rover (height = 3 m)		
30 MHz	1.03	0.61
401 MHz	3.25	3.26
2.4 GHz	6.31	4.98
Base (height = 5 m)		
30 MHz	1.67	1.32
401 MHz	3.70	3.53
2.4 GHz	6.38	5.26
Tower (height = 15 m)		
30 MHz	2.66	2.47
401 MHz	3.35	3.32
2.4 GHz	4.32	5.50

The statistics above characterize the fade depths below d^4 loss for a particular frequency and set of antennas (Astronaut, Rover, Base, or Tower at the transmitter to Astronaut at the receiver). The average and standard deviation of the sample values have been calculated for each scenario individually.

4. Conclusions

The results presented in table I provide communication system engineers the necessary data for designing enough power margin into their RF links for a desired level of coverage.

Note that at HF (30 MHz), the statistics show that no fades below d^4 loss were experienced for astronaut-to-astronaut communications. The loss curve for HF propagation approximates a d^4 loss curve in slope on a log-log scale, however the magnitude of the loss is not as severe. As expected, the HF band has much better diffraction capability than higher frequencies. This is discussed in further section 5 (Future Work).

Also note from table I that, in many cases, that the mean is approximately equal to the standard deviation. This suggests that shadowing and/or fading for this particular area is exponentially distributed rather than normally distributed on a decibel scale (lognormal shadowing). It is likely that an appropriate Rician K-factor can be derived for this channel that explains this distribution.

This study recommends the use of a d^4 loss equation (equation (4) or (6)) instead of the Friis equation (spreading loss) in link budget planning (with the possible exception of HF links). Additionally, a correction for the average fade depth and a number of additional standard deviations of power should be included to achieve the desired coverage confidence interval (CI) (1 std. dev. = 68 percent CI, 2 std. dev. = 95 percent CI, 3 std. dev. = 99 percent CI, etc.).

The total loss margin can be represented in the form of the following equation:

$$M_{Total} = M_{AvgFadeDepth} + M_{CI} \tag{5}$$

where

M_{Total} total margin,

$M_{AvgFadeDepth}$ margin required for the average fade depth,

M_{CI} additional margin to achieve the desired coverage confidence interval (multiple numbers of the standard deviations found in table I).

Note that equation (5) is a function of both frequency and transmit/receive antenna heights.

Equation (4) may be represented in logarithmic form as follows:

$$L_{dB} = 10\log(G_T G_R) + 20\log(h_T h_R) - 40\log(d) \tag{6}$$

where L_{dB} is the path loss in dB. Note that this results in a negative value.

A suitable equation has been formulated for the maximum link distance derived from equations (5) and (6). Note that all values in the following equation, with the exception of the maximum distance, are given in dB:

$$d_{\max} = 10^{\left(\frac{G_{TdB} + G_{RdB} - P_{TdB} + P_{RdB} + 2(h_{TdB} + h_{RdB}) - M_{Total}}{40}\right)} \tag{7}$$

Here, d_{max} is the maximum distance. P_{RdB} in this equation represents the minimum required receive power for proper demodulation.

Note that the margin policies introduced by this study will often produce margins of 15–20 dB of additional power. This is not at all uncommon in terrestrial RF links considering lognormal shadowing and Rayleigh fading conditions (ref. 11).

5. Future Work

This study is only concerned with RF path loss over an assumed lunar site. There has been no effort put forth to characterize the delay spread that may cause inter-symbol interference. Future work should investigate how this model may be extended to do such a characterization.

Additionally, it would be helpful to further characterize the statistical nature of the fade depths presented in this study. As suggested previously, it is likely that an appropriate Rician K-factor can be determined to describe these results for this analogue lunar site.

Currently, there are efforts at NASA's Jet Propulsion Laboratory, the Goddard Space Flight Center, and the Glenn Research Center with the goal of developing higher resolution elevation data for lunar sites of interest. Once this information is available, the path loss environment for these sites will be evaluated using the methods presented here.

HF performance presented in this study (as on Earth) suggests non-line-of-sight, over the horizon potential. Although this type of link would be restricted to either very low data rate information or analog voice, it does present a very viable over-the-horizon option.

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
05-07-2007	Technical Memorandum	

4. TITLE AND SUBTITLE
Path Loss Prediction Over the Lunar Surface Utilizing a Modified Longley-Rice Irregular Terrain Model

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Foore, Larry; Ida, Nathan

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 141141.02.05.03

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-16017

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORS ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2007-214825

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 32
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 301-621-0390

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This study introduces the use of a modified Longley-Rice irregular terrain model and digital elevation data representative of an analogue lunar site for the prediction of RF path loss over the lunar surface. The results are validated by theoretical models and past Apollo studies. The model is used to approximate the path loss deviation from theoretical attenuation over a reflecting sphere. Analysis of the simulation results provides statistics on the fade depths for frequencies of interest, and correspondingly a method for determining the maximum range of communications for various coverage confidence intervals. Communication system engineers and mission planners are provided a link margin and path loss policy for communication frequencies of interest.

15. SUBJECT TERMS
Electromagnetic wave transmission; Radio transmission; Multipath transmission; Wave propagation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE		11	Larry Foore
U	U	U			19b. TELEPHONE NUMBER *(include area code)* 216-433-2346