BELLCOMM, INC.
1100 SEVENTEENTH STREET, N.W. WASHINGTON, D.C. 20036

COVER SHEET FOR TECHNICAL MEMORANDUM

TITLE- Propagation Characteristics of the Apollo Dual-EVA Communication Links

TM- 68-2034-13

DATE- August 12, 1968

FILING CASE NO(S)- 320

AUTHOR(S)- K. H. Schmid

FILING SUBJECT(S)- (ASSIGNED BY AUTHOR(S)- Propagation Analysis - Lunar Communications

ABSTRACT

Propagation characteristics of the dual-EVA communication links over the lunar surface are examined. Four distinct regions of interest have been found. At short distances, the direct ray is the dominant mode of propagation. At medium distances, specular reflection occurs causing interference between the direct and reflected rays which reach the receive antenna. Beyond this region, an intermediate region exists in which energy is contributed by the direct, reflected and surface waves. A fourth region occurs at large distances in which the surface wave alone is the dominant mode of propagation.

Total path loss versus distance, as well as other parameters of interest, have been calculated. Graphs showing the results of these calculations are attached to present the results in a lucid manner. It is hoped that ready access to the results contained herein will prove helpful when evaluating future dual-EVA mission plans.

(NASA-CR-97637) PROPAGATION CHARACTERISTICS OF THE APOLLO DUAL-EVA COMMUNICATION LINKS (Bellcomm, Inc.) 30 p

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1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Propagation Characteristics of the Apollo Dual-EVA Communication Links - Case 320

DATE: August 12, 1968

FROM: K. H. Schmid

TM - 68-2034-13

TECHNICAL MEMORANDUM

I. INTRODUCTION

During future Apollo missions, both astronauts will exit onto the lunar surface from the landed Lunar Module (LM). A tandem, VHF radio communication system is being provided for establishing voice and telemetry circuits during this dual extra-vehicular astronaut (dual-EVA) activity. Using this tandem system, the more distant astronaut (from the LM), EVA-2, may establish a line-of-sight link to EVA-1; in turn, EVA-1 may establish a line-of-sight link to the LM. This mode of operation is useful when the EVA-2 is out of range of the LM.

It is the purpose of this memorandum to investigate the propagation characteristics of the EVA-2 to EVA-1 link and the EVA-1 to LM link as a function of the path length.* A maximum path length of 2 kilometers is assumed for each link.

II. LUNAR SURFACE MODEL

In order to study the propagation characteristics of these paths, a model of the lunar surface is required. For each link the surface is assumed to be relatively flat. Further, the surface is assumed to be rough due to small boulders and shallow craters which occur in a random fashion. A Gaussian model having zero mean and a standard deviation, Δh, equal to 0.25 meter is chosen to represent statistically the rough surface.

Curvature of the lunar surface is also taken into account when necessary. For example, slight changes in the reflection coefficient due to curvature can have a large effect on the resultant field strength and thus curvature is taken into account when calculating reflection coefficients. Curvature is ignored when computing grazing angles and positions of the maximums or minimums of the resultant signal, since this would overly complicate the calculations and is not of significant importance at distances out to 2 kilometers.

III. DUAL-EVA LINK PARAMETERS

Important parameters associated with these two line-of-sight links are itemized in Table I.

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*A similar analysis, pertaining to dual-EVA circuit losses at medium to large distances, and using a method outlined by Vogler[3], has been published recently by I. I. Rosenblum of Bellcomm[5].

Table I - Dual-EVA Link Parameters

Parameter	EVA-2 to EVA-1	EVA-1 to LM
f	279.0 MHz	259.7 MHz
λ	1.075 m	1.155 m
d	2 km (max)	2 km (max)
h_2	1.5 m	-
h_1	1.5 m	1.5 m
h_{LM}	-	7 m
Δh	0.25 m	0.25 m
Polarization	Vertical	Vertical

where:

f = frequency

λ = wavelength

d = path length

h_2 = EVA-2 antenna height

h_1 = EVA-1 antenna height

h_{LM} = LM antenna height

Δh = standard deviation of the surface irregularities

Other parameters related to the geometry of a line-of-sight path (with specular reflection) are shown in Figure 1. Note that in the region of specular reflection, the incident grazing angle is equal to the reflected grazing angle.

IV. PROPAGATION ANALYSIS

A. General

The propagation characteristics of each link vary widely as the path length increases from a few meters to two kilometers. The direct ray is the dominant mode of propagation at short distances. In this mode, energy that strikes the ground is diffusely scattered and little of it reaches the receiver. The surface wave is very weak compared to the direct ray and contributes little to communications capability.

When the path length is sufficiently large, as determined by the Rayleigh criterion, the rough lunar surface begins to appear more like a mirror surface due to the small incident grazing angle; at this point the surface begins to support a coherent reflected ray which reaches the receiver. The reflected ray interferes with the direct ray in a constructive or destructive manner depending on the phase difference of the two rays. This mode of propagation is valid as the path length increases until the incident grazing angle decreases to $\tan^{-1}\left(\lambda/2\pi r_o\right)^{1/3}$, where r_o is the lunar radius. At this path length the two-ray theory generally becomes invalid[1] and an intermediate form of propagation occurs until the surface wave becomes dominant at greater distances.

In this analysis the propagation characteristics are determined for the specular reflection region and the surface wave region. The propagation characteristics of the intermediate region between the termination of the specular reflection region and the beginning of the surface wave region is determined by connecting the two curves. In conclusion the total path loss vs. distance is presented for each link for distances varying from a few meters to two kilometers.

B. Direct Ray Clearance

In order to verify that some clearance for the direct ray is provided for all cases, a worst case path configuration is chosen for investigation. Thus the EVA-2 to EVA-1 link having antenna heights of 1.5 meters and a path length of 2000 meters is used. A 3σ height irregularity is assumed at mid-path, i.e., an elevation obstacle of 3Δh is assumed to exist midway between EVA-2 and EVA-1. In addition the curvature of the lunar surface is taken into account in this calculation. See Figure 2 for a diagram of the configuration. Thus,

$$\left(r_o + 3\Delta h + C\right)^2 + \left(\frac{d_{max}}{2}\right)^2 = \left(r_o + h_1\right)^2$$

where: C = clearance over the obstacle (m)

$r_o = 1.738 \cdot 10^6$ m

$$d_{max} = 2000 \text{ m}$$

$$\Delta h = 0.25 \text{ m}$$

$$h_1 = 1.5 \text{ m}$$

Solving for C yields,

$$C = 0.75 - \frac{d^2_{max}}{8\, r_o} \simeq 0.5 \text{ m}$$

and thus some clearance does exist even in this worst case situation. Therefore the two-ray model used to analyze the region of specular reflection is valid for either link with path lengths up to two kilometers.

C. Region of Specular Reflection

1. Maximum Grazing Angle

Specular reflection occurs from all points within the First Fresnal ellipse provided that the standard deviation of the irregularities within the ellipse satisfies the following relation[2].

$$\Delta h \leq \frac{1}{8} \frac{\lambda}{\sin \gamma}$$

Since Δh has been postulated to be 0.25 meters in the entire landing area, the maximum grazing angle for specular reflection to occur is given by:

$$\gamma_{max} = \sin^{-1} \frac{\lambda}{2}$$

Referring to Table 1 for values of λ, maximum grazing angles of 0.567 radians and 0.617 radians are obtained for the EVA-2 to EVA-1 and EVA-1 to LM links, respectively.

2. Minimum Grazing Angle

As mentioned previously the minimum grazing angle for specular reflection is given by:

$$\gamma_{min} = \tan^{-1} \left(\frac{\lambda}{2\pi r_o} \right)^{1/3}$$

Using this relation, minimum grazing angles of 4.61 milliradians and 4.74 milliradians are obtained for the EVA-2 to EVA-1 and EVA-1 to LM links, respectively.

3. Minimum Path Lengths

The minimum path length for specular reflection is related to γ_{max} as follows.

For the EVA-2 to EVA-1 link,

$$\frac{h_1}{d_{1\ min}} = \frac{h_2}{d_{2\ min}} = \tan \gamma_{max} \ ; \ d_{min} = d_{1\ min} + d_{2\ min}$$

Therefore the minimum path length, $d_{min} \simeq 5$ meters.

For the EVA-1 to LM link,

$$\frac{h_1}{d_{1\ min}} = \frac{h_{LM}}{d_{LM\ min}} = \tan \gamma_{max} \ ; \ d_{min} = d_{1\ min} + d_{LM\ min}$$

Therefore the minimum path length, $d_{min} \simeq 12$ meters.

4. Maximum Path Lengths

The maximum path length for specular reflection is related to γ_{min} as follows.

For the EVA-2 to EVA-1 link,

$$\frac{h_1}{d_{1\ max}} = \frac{h_2}{d_{2\ max}} = \tan \gamma_{min} \ ; \ d_{max} = d_{1\ max} + d_{2\ max}$$

Therefore $d_{max} \simeq 650$ meters.

For the EVA-1 to LM link,

$$\frac{h_1}{d_{1\ max}} = \frac{h_{LM}}{d_{LM\ max}} = \tan \gamma_{min} \ ; \ d_{max} = d_{1\ max} + d_{LM\ max}$$

Therefore $d_{max} \simeq 1800$ meters.

5. Summary of Specular Reflection Parameters

The maximum and minimum values of grazing angles and path lengths for specular reflection to occur are summarized below.

Table II - Limiting Path Parameters for Region of Specular Reflection.

Parameter	EVA-2 to EVA-1	EVA-1 to LM
γ_{max}	0.567 radians	0.617 radians
γ_{min}	4.61 milliradians	4.74 milliradians
d_{min}	5 meters	12 meters
d_{max}	650 meters	1800 meters

D. Determination of the Reflection Coefficient

1. General

When the path lengths are within the limits defined in Table II, specular reflection will occur. The amount of the signal reflected is related to the incident signal by the reflection coefficient i.e. $\bar{E}_r = R\bar{E}_i$. The reflection coefficient (RMS) is given by[2]:

$$R = \rho_{RMS} D R_o$$

where: R_o = reflection coefficient of smooth and planar lunar soil

D = divergence coefficient caused by curvature of the lunar surface

ρ_{RMS} = correction factor to account for the presence of rough surface rather than smooth surface.

Equations for each of these parameters are set forth below. In determining the grazing angle, γ, a smooth planar surface is assumed; the parameters ρ_{RMS} and D correct for the presence of rough and curved surface as explained above.

2. Reflection Coefficient of Smooth Lunar Soil

For vertical polarization[2],

$$R_o = \frac{\frac{\varepsilon_r}{\mu_r}\sin\gamma - \sqrt{\frac{\varepsilon_r}{\mu_r} - \cos^2\gamma}}{\frac{\varepsilon_r}{\mu_r}\sin\gamma + \sqrt{\frac{\varepsilon_r}{\mu_r} - \cos^2\gamma}}$$

and,

$$\varepsilon_r = \varepsilon/\varepsilon_o - j(60)\lambda\sigma$$

$$\mu_r = \mu/\mu_o$$

where:

ε_r = complex dielectric constant of surface material

ε = dielectric constant of surface material

ε_o = dielectric constant of free space

σ = surface conductivity (mhos/meter)

μ_r = relative magnetic permeability of surface material

μ = magnetic permeability of surface material

μ_o = magnetic permeability of free space

For the lunar surface[3] $\mu_r \simeq 1$, $\varepsilon/\varepsilon_o \simeq 2$ and $\sigma \simeq 10^{-3}$.

Thus, for values of γ greater than the Brewster angle,

$$R_o \simeq \frac{2\sin\gamma - \sqrt{2 - \cos^2\gamma}}{2\sin\gamma + \sqrt{2 - \cos^2\gamma}}$$

3. Divergence Coefficient

The divergence coefficient is strictly a function of the path geometry and is given by[2]:

$$D = \frac{1}{\sqrt{1 + \frac{2\, d_1 d_2}{r_o (d_1 + d_2) \sin\gamma}}}$$

where r_o is the lunar radius and the other parameters are shown in Figure 1.

4. Rough Surface Correction Factor

The correction factor, ρ_{RMS}, is given in terms of its mean square value by the following relation[2]:

$$\rho^2_{RMS} = \overline{|\rho|^2} = e^{-(\Delta\Phi)^2}$$

where:

$$\Delta\Phi = \frac{4\pi\Delta h \sin\gamma}{\lambda}$$

5. The Reflection Coefficient

Since all the above parameters have been defined, the values of the reflection coefficient, R, vs. distance, d, can be derived within the limits of d set forth in Table II. The results for each link are presented in Figures 3 through 6.

E. <u>RECEIVED SIGNAL IN THE REGION OF SPECULAR REFLECTION</u>

As the distance between terminals varies within the region of specular reflection, interference between the direct ray and the reflected ray occurs. Maximum receive signal strength occurs when the direct ray and the reflected ray are in phase at the receiver while minimum receive signal strength occurs when the rays are out-of-phase.

Relative phase differences between the two rays are caused by differences in path length and a phase reversal of the reflected ray at the ground plane, i.e., $\phi = \theta_L + \theta_R$.

The path length difference (see Figure 1) is given by:

$$\delta = \sqrt{h_1^2 + d_1^2} + \sqrt{h_2^2 + d_2^2} - \sqrt{(h_1 - h_2)^2 + d^2}$$

and since,

$$d = d_1 + d_2 \text{ and } \frac{h_1}{d_1} = \frac{h_2}{d_2}$$

then,

$$\delta = (h_2 + h_1)\sqrt{1 + \frac{d^2}{(h_2 + h_1)^2}} - d\sqrt{1 + \frac{(h_1 - h_2)^2}{d^2}}$$

If $d^2 >> (h_1 - h_2)^2$ then,

$$\delta = d\left[1 + \frac{(h_2 + h_1)^2}{2d^2}\right] - d = \frac{h_2^2 + 2\,h_1 h_2 + h_1^2}{2d}$$

Thus,

$$\theta_L = \frac{\delta}{\lambda} 2\pi = \frac{\pi}{\lambda d}(h_2^2 + 2h_1 h_2 + h_1^2)$$

If $h_2 \simeq h_1$, this equation can be simplified to,

$$\theta_L \simeq \frac{4\pi}{\lambda d} h_1 h_2$$

Provided $\theta_R = \pi$, the relative phase difference between the direct ray and the reflected ray is given by:

$$\phi = \pi\left(\frac{h_2^2 + 2h_1 h_2 + h_1^2}{\lambda d} + 1\right)$$

The resultant field is obtained by vector addition of the reflected ray to the direct ray. It is assumed that the direct and reflected ray signal strengths are modified by the antenna patterns. The effect of the antenna patterns becomes more noticeable at short distances.

Let the direct and reflected signals at the input to the receiver be given by,

$$\bar{E}_D = \bar{E}_o g_{TD} g_{RD} \quad ; \quad \bar{E}_R = |R| \bar{E}_o \, g_{TR} g_{RR} e^{j\phi}$$

where:

E_o = signal strength of direct ray at receiver input (provided the antenna heights are equal, and neglecting curvature)

g_{TD} = transmit antenna gain for the direct ray

g_{TR} = transmit antenna gain for the reflected ray

g_{RD} = receive antenna gain for the direct ray

g_{RR} = receive antenna gain for the reflected ray.

The resultant field, $\bar{E}$, is given by:

$$\bar{E} = \bar{E}_D + \bar{E}_R$$

where $\bar{E}_R$ is displaced in angle from $\bar{E}_D$ by ϕ (see Figure 7).

It is interesting to determine the ratio of the magnitude of the resultant field to the magnitude of the direct field alone in order to establish the effects of interference by the reflected ray. Thus,

$$E^2 = (E_R \sin\phi)^2 + (E_D + E_R \cos\phi)^2$$

which yields,

$$\frac{E}{E_o} = \left\{ \left[g_{TD} g_{RD} + |R| g_{TR} g_{RR} \right]^2 - 4|R| \; g_{TD} g_{RD} g_{TR} g_{RR} \sin^2 \frac{\phi}{2} \right\}^{1/2}$$

The normalized gain functions of the vertical dipoles approximate a cosθ pattern in the vertical plane. Thus for large distances and nearly equal antenna heights the gain functions are near unity while for short distances the gains are less than unity. The above applies only to the region of specular reflection as defined in Table II.

For the EVA-2 to EVA-1 link, $h_1 = h_2$ and thus $g_{TD} = g_{RD} = 1$ and,

$$\phi = \pi\left(\frac{4h_1h_2}{\lambda d} + 1\right) = \pi\left(\frac{8.37}{d} + 1\right)$$

For the EVA-1 to LM link,

$$\phi = \pi\left(\frac{h_1{}^2 + 2h_1h_{LM} + h^2{}_{LM}}{\lambda d} + 1\right) = \pi\left(\frac{62.6}{d} + 1\right)$$

The E/E_o vs. d curve is plotted in Figures 8 and 9 for the region of specular reflection for these two links.

F. Region of Surface Wave Dominance

1. General

Immediately beyond the region of specular reflection an intermediate region exists in which the received energy is contributed by direct, reflected and surface waves. This region is difficult to analyze since the relative amplitude and phase of each component is difficult to predict[1].

At still greater distances, however, the surface wave becomes the dominant source of receive energy. This region can be determined using a method presented by Norton[4]. Provided the antenna heights are less than $2000/f^{2/3}{}_{mHz}$(feet) the region in which the surface wave is dominant is defined by requiring that the following three inequalities be satisfied.

$$p>20,\ p>10\ q_1q_2,\ p>100(q_1 + q_2)$$

where:

p = the numerical distance

q = the numerical antenna height

These parameters are defined by Norton as follows:

$$p = \frac{\pi(r_1 + r_2)}{\lambda} \; \frac{\cos^2 b''}{x \cos b'}$$

$$q_{1,2} = \frac{2\pi\, h_{1,2}}{\lambda} \left(\frac{\cos^2 b''}{x \cos b'}\right)^{1/2}$$

where:

$$x = 18000\, \sigma/f_{mHz}$$

$$b' = \tan^{-1}\left[(\varepsilon - \cos^2\gamma)/x\right]$$

$$b'' = \tan^{-1}(\varepsilon/x)$$

and all other symbols have been defined previously.

Using this method the distance at which the surface wave becomes dominant can be calculated for both the EVA-2 to EVA-1 and the EVA-1 to LM links as shown below.

2. EVA-2 to EVA-1 Link

Since $h_1 = h_2 = 1.5$ meters and f = 279.0 mHz the relation $h < 2000/f^{2/3}_{mHz}$ (feet) is satisfied. Thus, the other parameters are calculated as follows:

$$\cos\gamma \simeq 1,\; x = 0.0645$$

$$\therefore \cos b' = 0.06424;\; \cos b'' = 0.03228$$

Now from the previous equations

$$q_1 = q_2 = 4.4$$

and using the relation that $r_1 + r_2 \approx d$ yields,

$$p = 0.75\ d$$

Since $10\ q_1 q_2 = 194$ and $100\ (q_1 + q_2) = 880$

then

$$p \doteq 0.75d > 880$$

satisfies all three requirements stated previously and therefore

$$d > 1200 \text{ meters}$$

defines the region of surface wave dominance for this link.

3. EVA-1 to LM Link

Since $h_1 = 1.5$ meters, $h_{LM} = 7$ meters and $f = 259.7$ mHz, the relation $h < 2000/f^{2/3}_{mHz}$ (feet) is satisfied for either antenna. Thus, the other parameters are calculated as follows:

$$\cos\gamma \simeq 1, \quad x = 0.0694$$

$$\therefore \cos b' = 0.06918\ ; \quad \cos b'' = 0.03461$$

Now from the previous equations,

$$q_1 = 4.08\ ; \quad q_{LM} = 19.0$$

and

$$p = 0.68\ d$$

Since $10\ q_1 q_2 = 776$ and $100(q_1 + q_2) = 2308$

then

$$p = 0.68\ d > 2308$$

and therefore,

$$d > 3400 \text{ meters}$$

defines the region of surface wave dominance for this link.

G. Receive Signal in the Region of Surface Wave Dominance

By using Norton's method it can be shown that in the region of surface wave dominance,

$$E/E_o = (1/p)\ f(q_1)\ f(q_2)$$

where:

$f(q_1)$, $f(q_2)$ = the antenna height gain functions of the two antennas.

Now

$$f(q) = \left[1 + q^2 - 2q \cos\left(\frac{\pi}{4} + \frac{b}{2}\right)\right]^{1/2}$$

where:

$$b = 2b'' - b' \simeq \pi/2$$

Using the values derived for p and q in the previous sections yields the following results.

$$\text{EVA-2 to EVA-1 link: } \frac{E}{E_o} = \frac{27.5}{d}, \quad d > 1200 \text{ m.}$$

$$\text{EVA-1 to LM link : } \frac{E}{E_o} = \frac{117.5}{d}, \quad d > 3400 \text{ m.}$$

These equations have been combined with the results of Figures 9 and 10 to obtain E/E_o vs. d graphs over the entire range of interest. For intermediate ranges defined by the end of the region of specular reflection to the beginning of the region of surface wave dominance, the E/E_o vs. d curve is simply a connection of the two derived curves. The results for each link, plotted in db, are shown in Figures 10 and 11. Note that only those results that extend out to 2000 meters range are of interest and thus the region of surface wave dominance for the EVA-1 to LM link which begins at 3400 meters serves only to locate the curve in the intermediate region for this plot.

Total path loss is obtained by adding the path loss in excess of free space, as shown in Figures 10 and 11, to the free space loss. The free space loss for these two links is given by:

EVA-2 to EVA-1 Link: $L_{FS} = 21.35 + 20 \log d$

EVA-1 to LM link : $L_{FS} = 20.75 + 20 \log d$

where d is measured in meters. Total path loss is shown in Figures 12 and 13.

V. CONCLUSIONS

Propagation characteristics of the dual-EVA line-of-sight communication links over the lunar surface have been examined. Four distinct regions of propagation have been identified and analyzed as discussed below.

At distances up to a few meters, the direct ray is the dominant mode of propagation. Since diffuse scattering occurs at the ground for short path lengths, little or no fading occurs at the receiver.

For medium distances, i.e., 5 to 650 meters for the EVA-2 to EVA-1 link and 12 to 1800 meters for the EVA-1 to LM link, specular reflection occurs at the ground. Thus, constructive or destructive interference occurs at the receive antenna depending on the relative phase of the direct and reflected rays.

Beyond the region of specular reflection, an intermediate region exists in which energy is contributed by direct, reflected and surface waves.

The fourth region of interest is that where the surface wave is dominant. This region begins at large distances, i.e., 1200 meters and 3400 meters for the EVA-2 to EVA-1 link and EVA-1 to LM link, respectively.

Total path loss for all of these regions have been derived according to the methods outlined in this memorandum. Results for the two links are shown in Figures 12 and 13. It is hoped that ready access to these results will prove helpful when evaluating future dual-EVA mission plans.

K. H. Schmid

2034-KHS-bw

K. H. Schmid

Attachment
(Figures 1 through 13)

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5. "Path Loss Factors in Lunar Surface Communications", I. I. Rosenblum, Case 320, Bellcomm Memorandum For File, June 28, 1968.

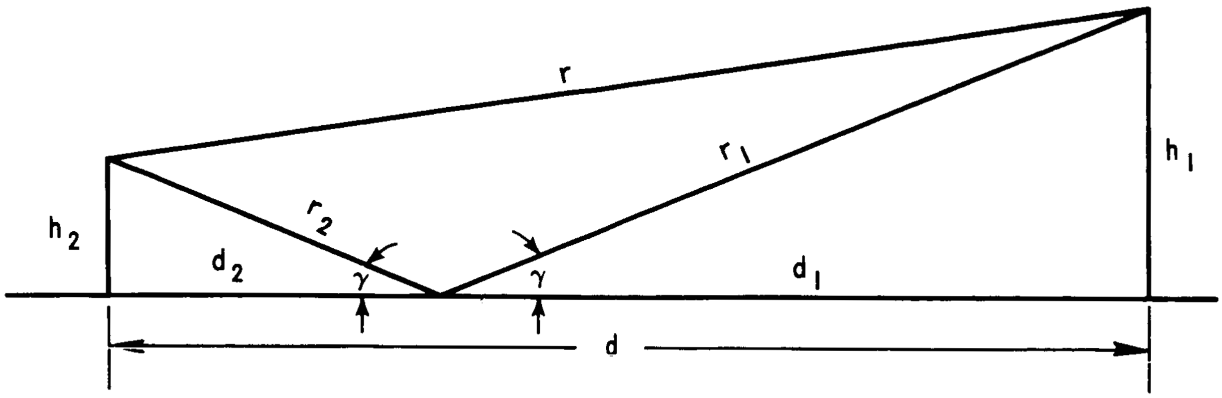

FIGURE I - TYPICAL LINE-OF-SIGHT LINK (WITH SPECULAR REFLECTION)

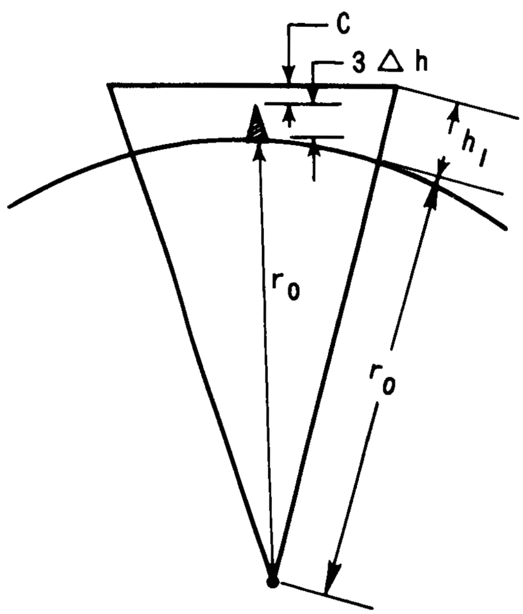

FIGURE 2 - GEOMETRY (EXAGGERATED) FOR CALCULATING WORST CASE PATH CLEARANCE

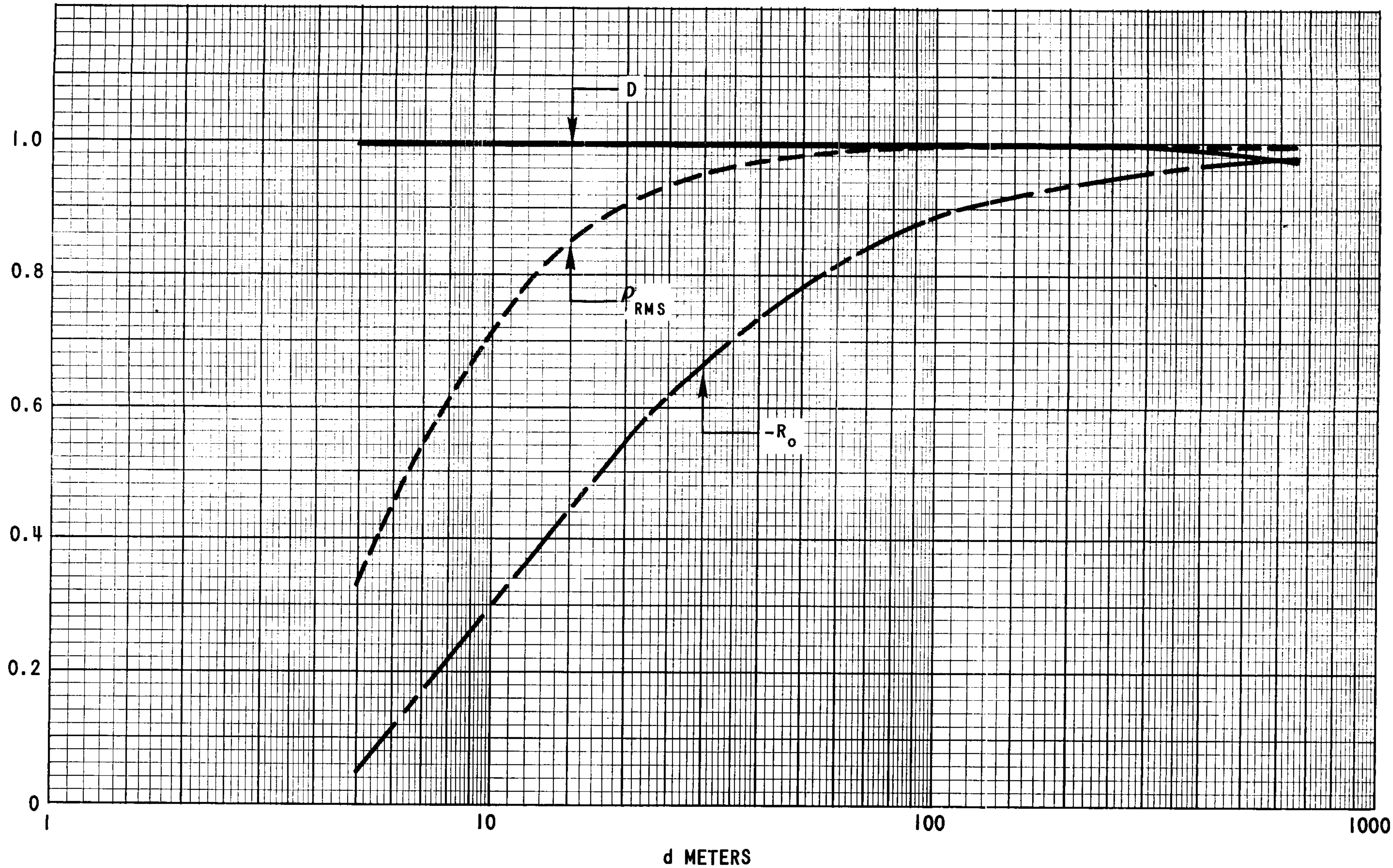

FIGURE 3 - REFLECTION COEFFICIENT PARAMETERS vs. DISTANCE; EVA-2 TO EVA-1 LINK

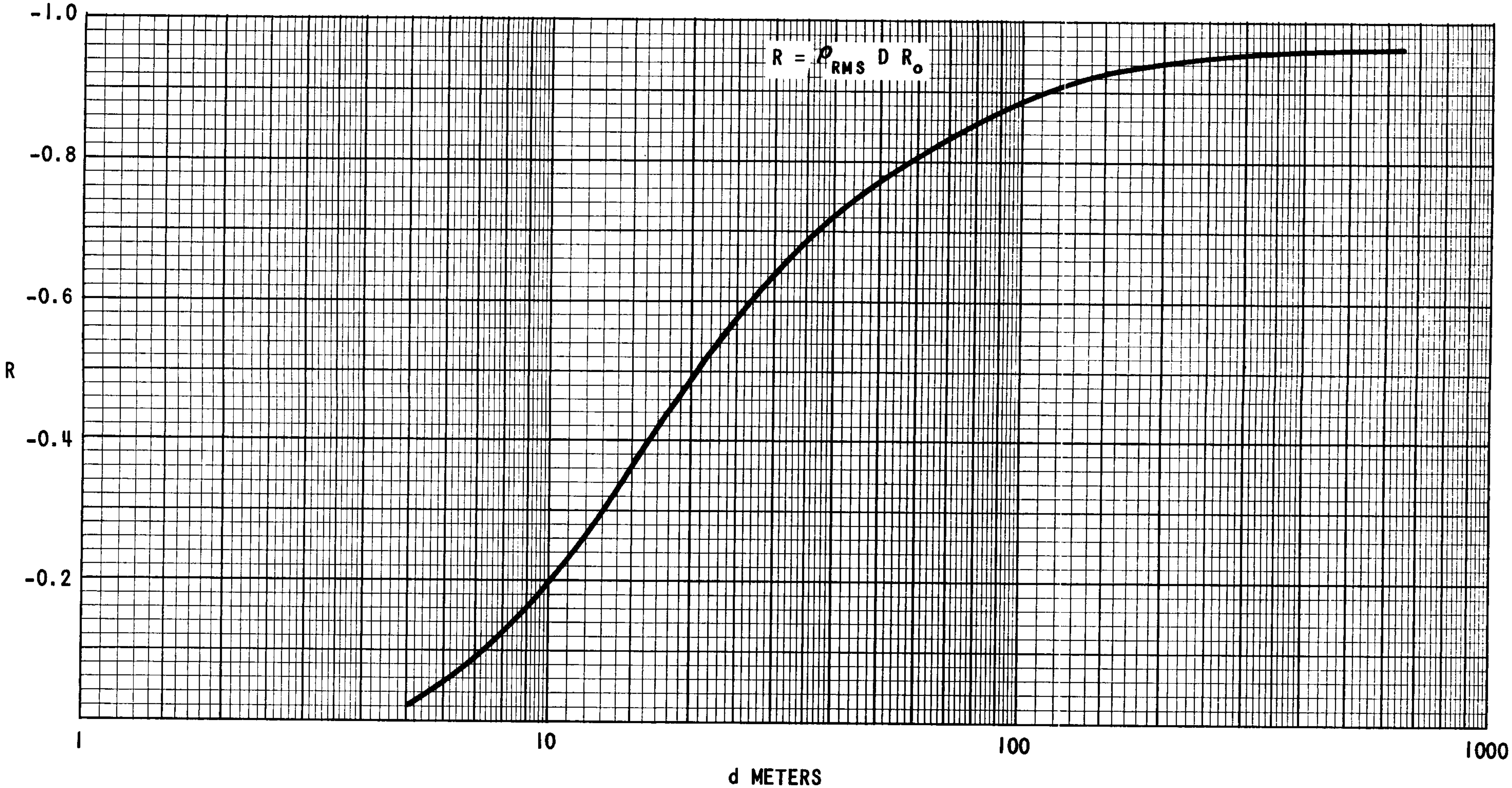

FIGURE 4 - REFLECTION COEFFICIENT vs. DISTANCE; EVA-2 TO EVA-1 LINK

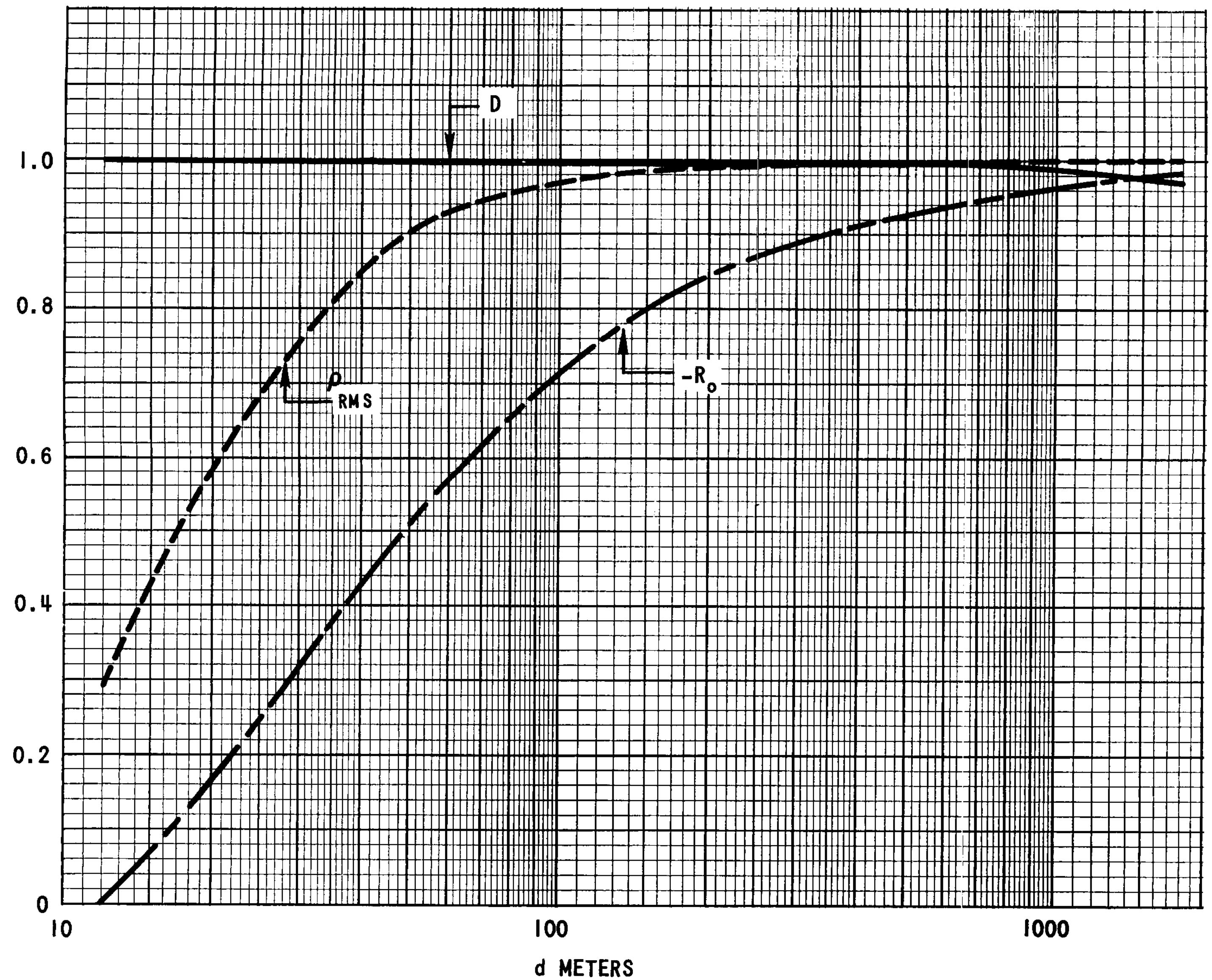

FIGURE 5 - REFLECTION COEFFICIENT PARAMETERS vs. DISTANCE; EVA-I TO LM LINK

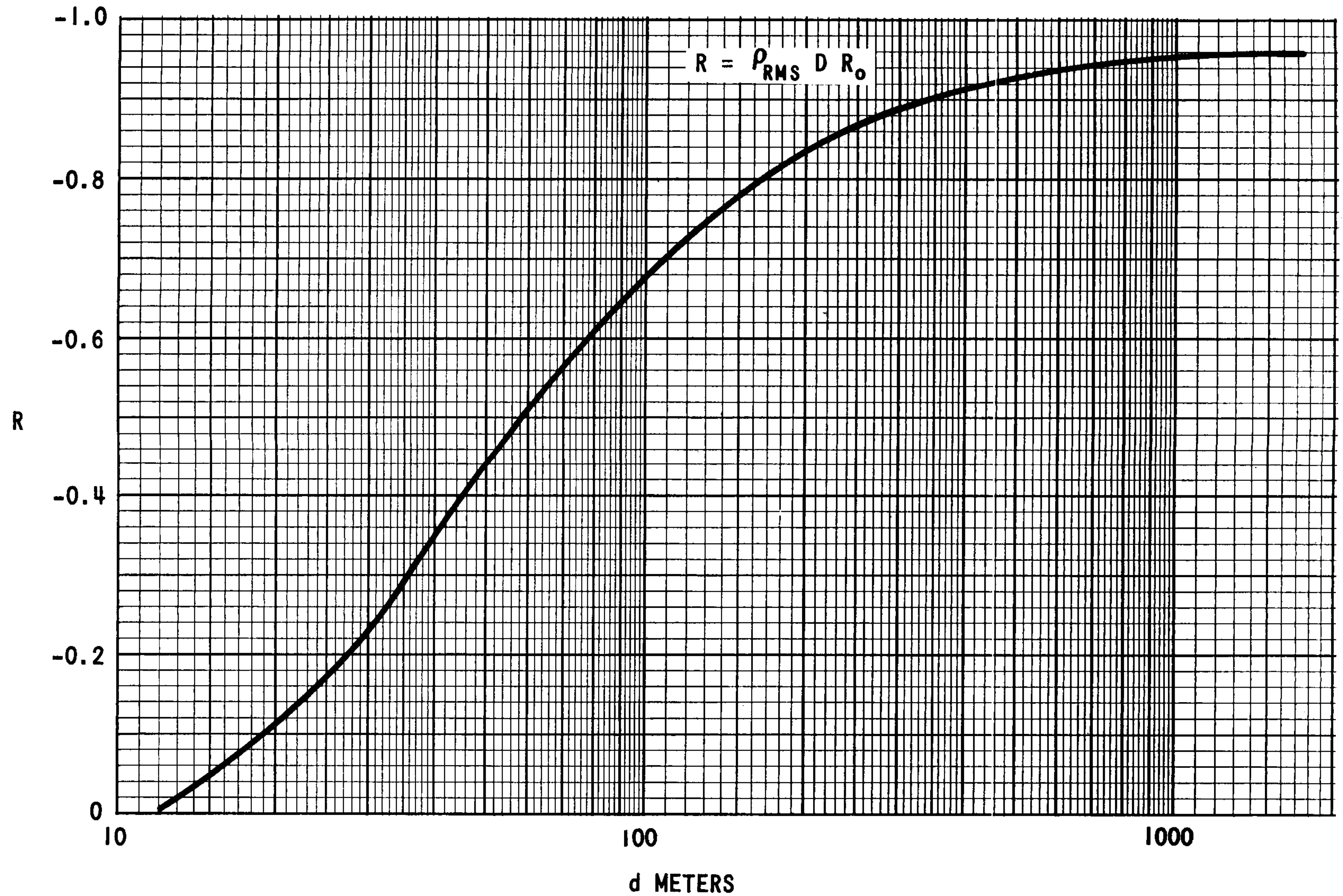

FIGURE 6 - REFLECTION COEFFICIENT vs. DISTANCE; EVA-I TO LM LINK

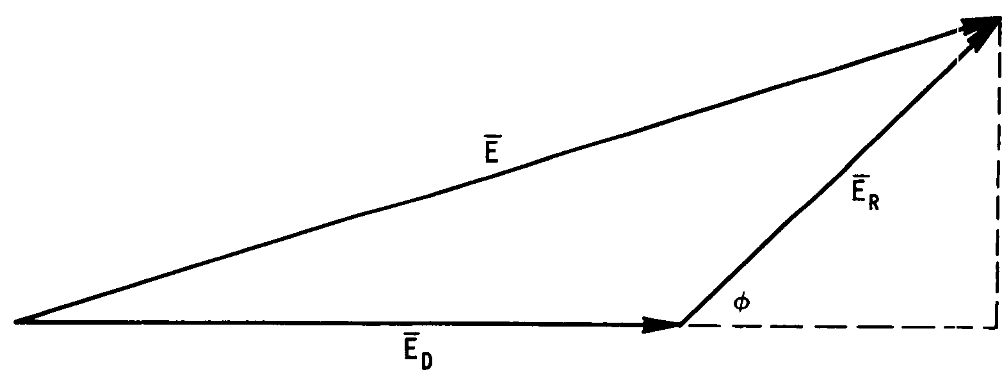

FIGURE 7 - VECTOR DIAGRAM OF RECEIVE SIGNALS IN REGION OF SPECULAR REFLECTION

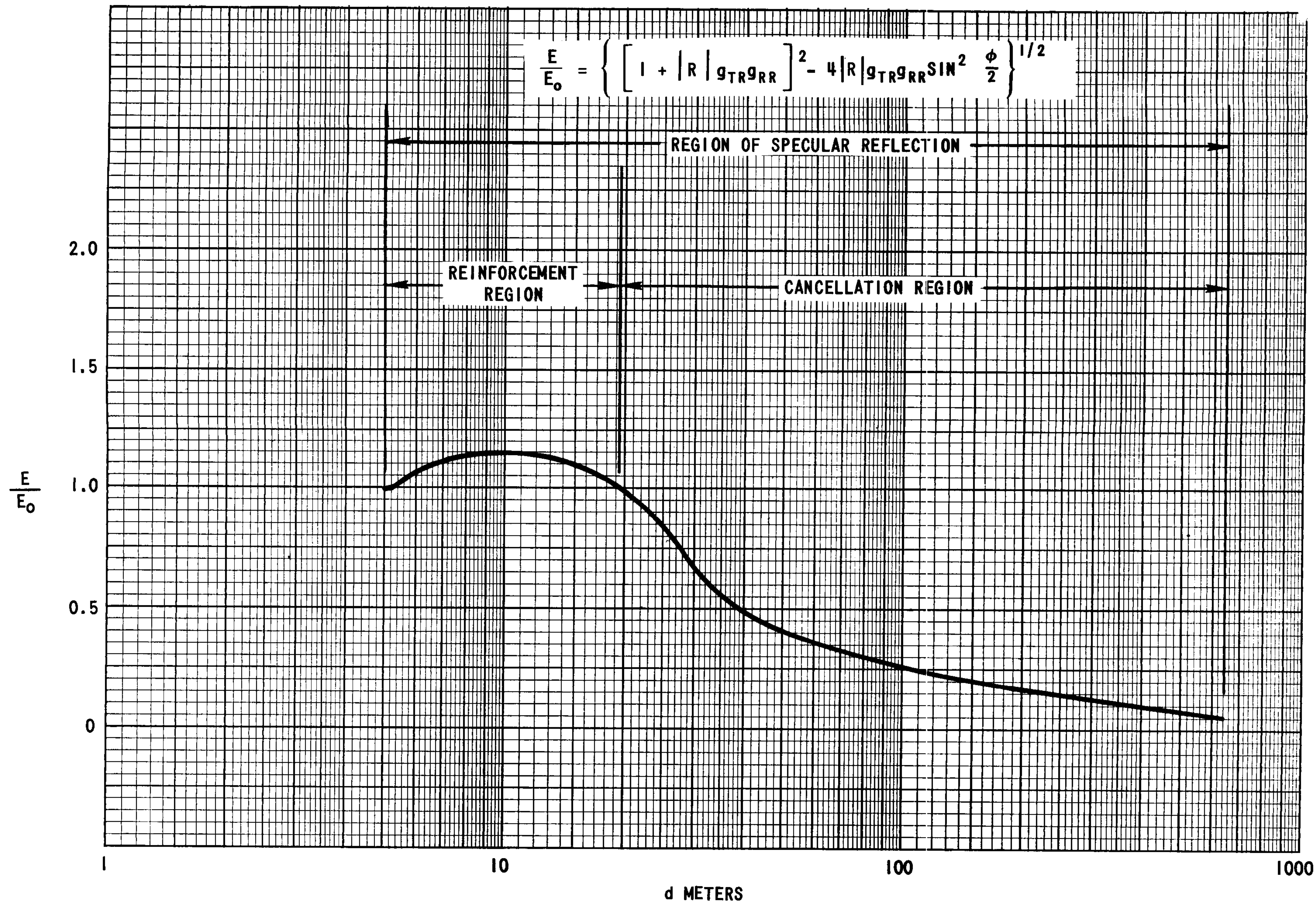

FIGURE 8 - RECEIVE SIGNAL STRENGTH RATIO vs. DISTANCE; EVA-2 TO EVA-1 LINK

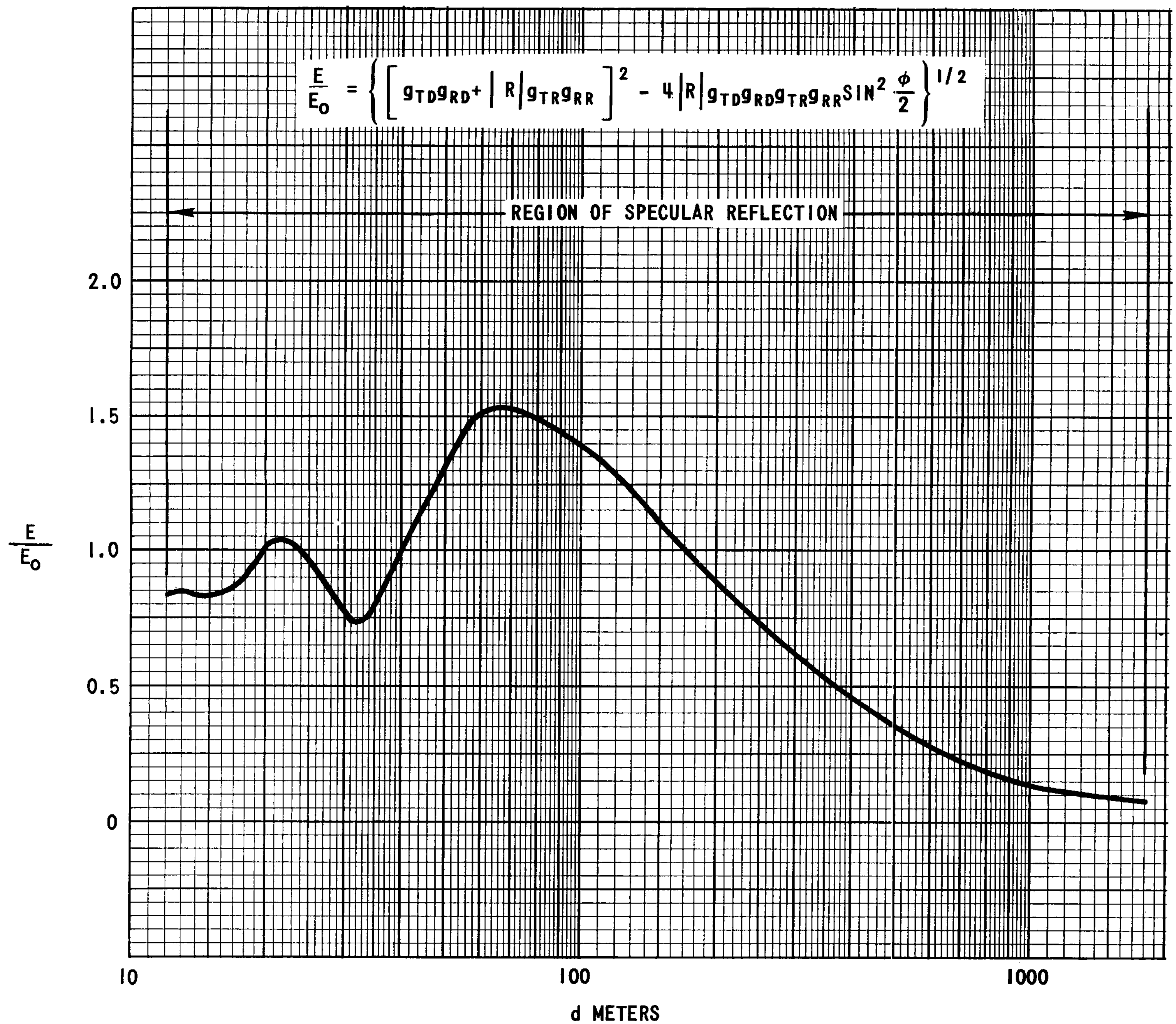

FIGURE 9 - RECEIVE SIGNAL STRENGTH RATIO vs. DISTANCE; EVA-I TO LM LINK

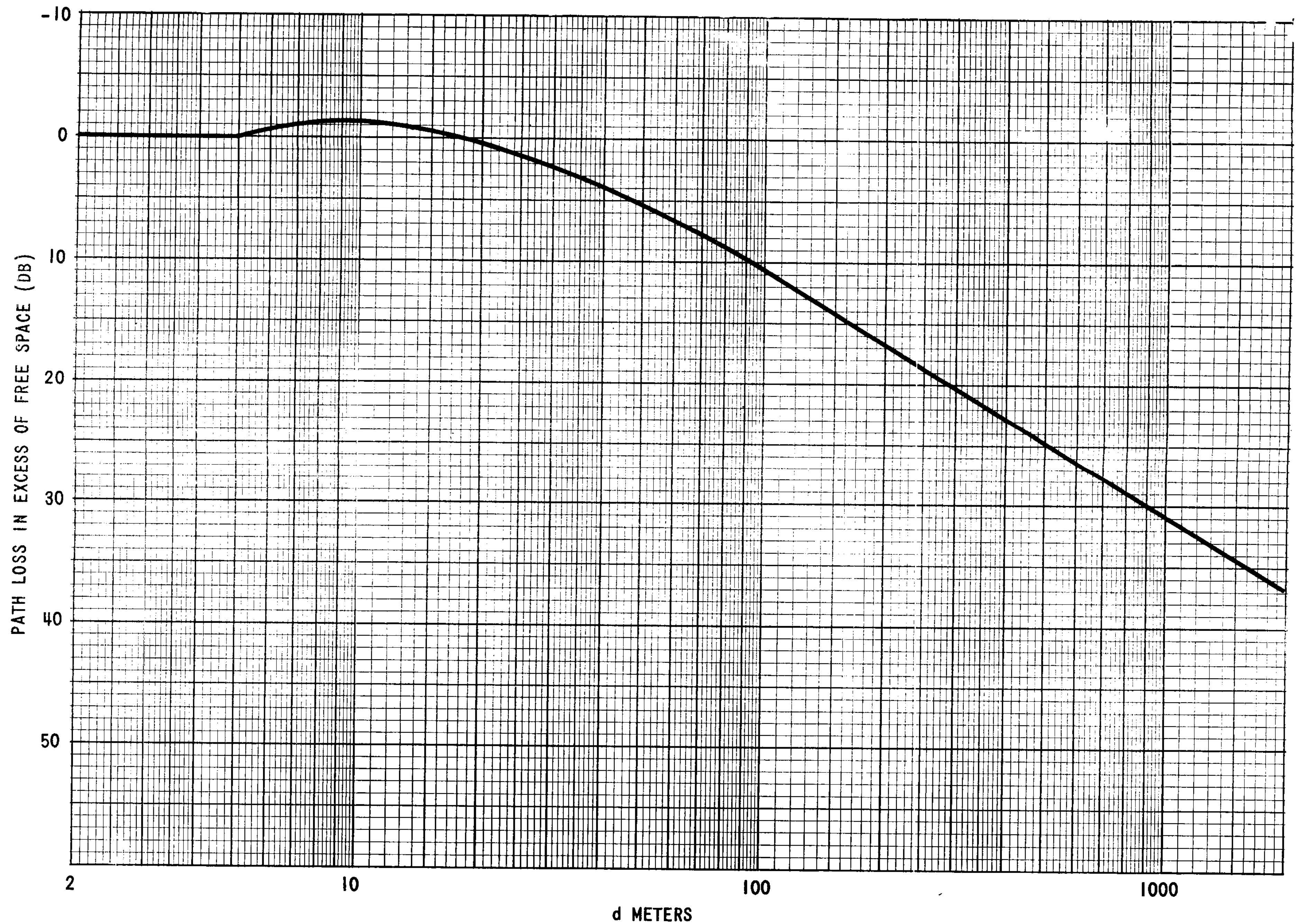

FIGURE 10 - PATH LOSS IN EXCESS OF FREE SPACE vs. DISTANCE; EVA-2 TO EVA-1 LINK

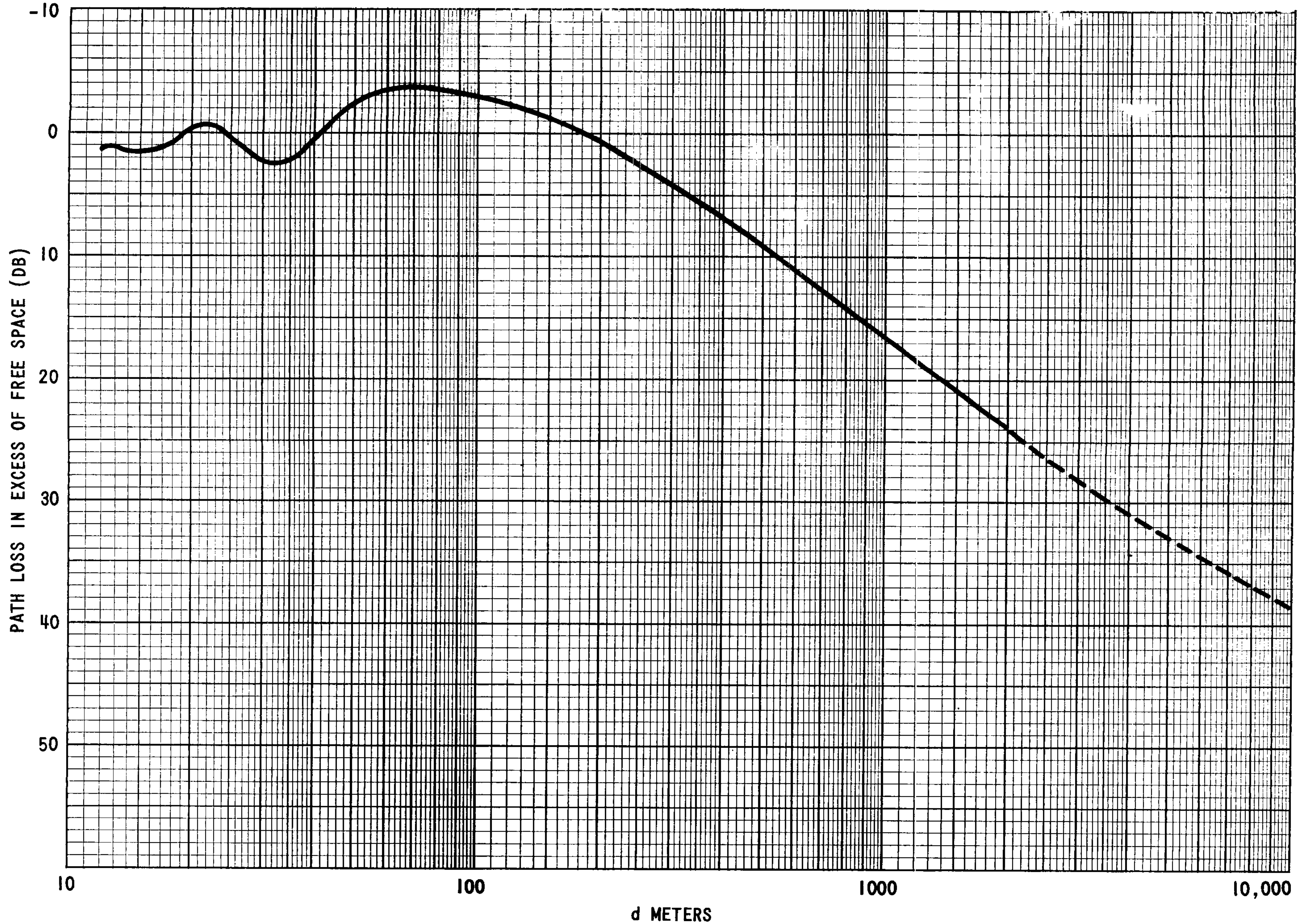

FIGURE 11 - PATH LOSS IN EXCESS OF FREE SPACE vs. DISTANCE; EVA-1 TO LM LINK

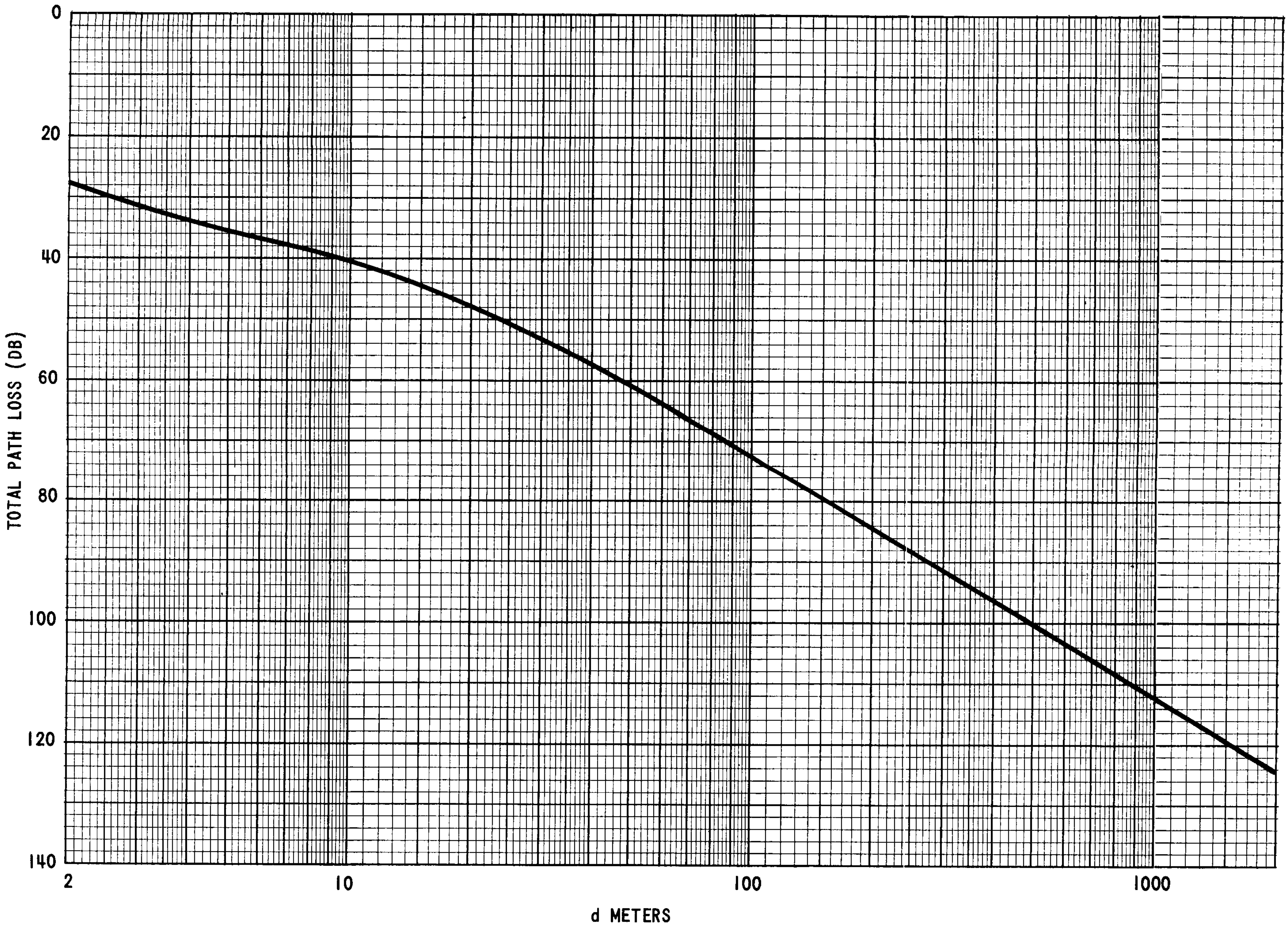

FIGURE 12 - TOTAL PATH LOSS vs. DISTANCE; EVA-2 TO EVA-1 LINK

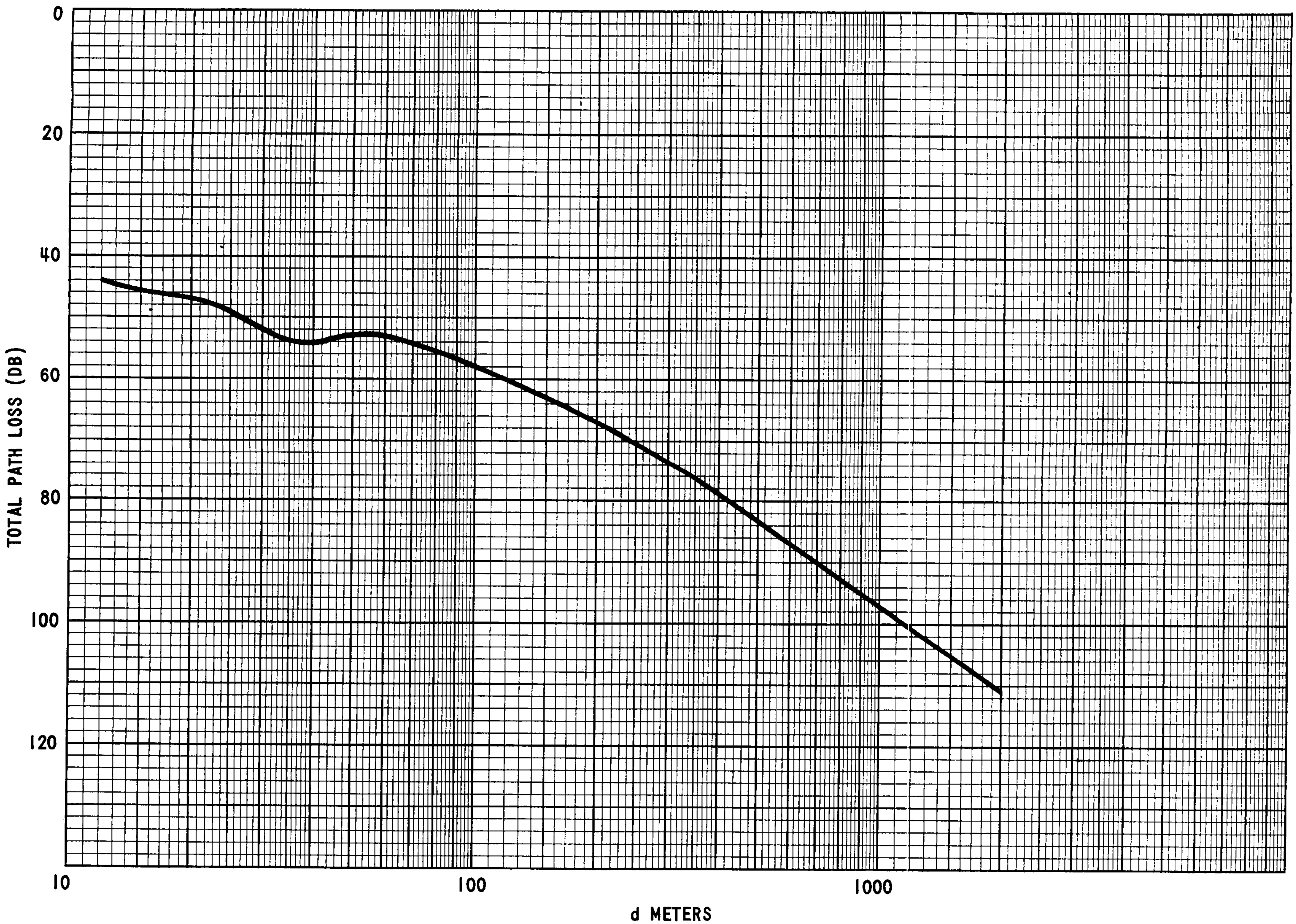

FIGURE 13 - TOTAL PATH LOSS vs. DISTANCE; EVA-1 TO LM LINK