Millimeter Wave Scattering from a Rough Surface

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MILLIMETER WAVE SCATTERING
FROM A ROUGH SURFACE

BY

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THESIS

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ABSTRACT

This thesis presents an introduction to rough surface scattering and describes techniques that were used during the course of this project to measure and characterize electromagnetic scattering from a rough surface. An analytical model is described that accurately predicts the statistics of the measured scattering data. The CW measurement process that was used is described and scattering measurement results are presented. Calculated and measured statistical moments are compared in order to show agreement of measurements with various statistical scattering models. Recommendations for additional work in the area of measurement and analytical modeling of rough surface scattering are given.
There are many people who have helped with various parts of this project, and I would like to thank them all. In particular, Dr. Ron Phillips supplied his vision, understanding and great energy to help make this project a success. I only wish that every graduate student could be as fortunate as I have been in having the guidance, assistance and friendship that Dr. Phillips has given to me.

I would also like to thank Bob Martin for his guidance and assistance in designing and building a high gain amplifier that allowed good data to be taken.

At the time of this writing, I am especially grateful to Nancy Thomas for the long hours and diligence that she put into preparing and editing this report. I would also like to thank Lynn Kirby for her preparation of the equations. Finally, I would like to thank Michele, my wife, and Lauren and Brion for their support and understanding during all of the nights and weekends that it took to reach this point in our lives.
# TABLE OF CONTENTS

LIST OF TABLES ........................................... v
LIST OF FIGURES ........................................ vi
INTRODUCTION ........................................ viii

Chapter

1. ANALYTICAL DEVELOPMENT OF ROUGH SURFACE SCATTERING .................. 1
   Electromagnetic Scattering from a Rough Surface ................................ 1
   Stochastic Scattering Models .................................................. 7

2. THE MILLIMETER WAVE MEASUREMENT SYSTEM ................................. 12

3. STATISTICAL ANALYSIS OF MEASURED DATA ................................... 38
   Surface Height Data .......................................................... 38
   Electromagnetic Scattering Data .......................................... 44

4. CONCLUSIONS AND RECOMMENDATIONS ........................................ 60

APPENDIX I. Amplifier Design .................................................. 62

APPENDIX II. Stochastic Model Calculator Programs ............................ 65

REFERENCES ......................................................... 71
LIST OF TABLES

1. Antenna Scattering Parameters ............... 23
2. Signal Margin Calculation Results ............ 30
3. Measured and Predicted Statistical ........... 55
   Scattering Moments
4. Measured Parameter Values for use in the ...... 56
   Integrated Gamma Distribution
5. Calculated Moments for the Generalized-N ...... 57
   Distribution
LIST OF FIGURES

1. Rough Surface Scattering Geometry .................. 2
2. Microwave Scattering Test Bed and Instrumentation . 13
3. The Measurement Derrick Shown Positioned over ... 14
   Gravel Surface
4. A Close-up of the Measurement Derrick ............ 15
5. The Measurement Derrick Shown with the ............ 16
   Receiving Antenna Adjusted to a $60^\circ$
   Bistatic Angle
6. A Close-Up View of the RF Measurement .......... 18
   Instrumentation
7. Test and Measurement Equipment .................... 21
8. Measured RF Reflection Levels for Coated Gravel .. 25
9. RF Reflection Levels for Coated Gravel Shown ...... 27
   with the Anechoic Chamber Background Levels
   Reduced
10. Measured RF Reflection Levels for Coated Gravel .. 28
    with a Metal Ground Plane
11. Square Law Response for the Crystal Detector .... 31
12. A Surface Scattering Measurement that was Made .. 34
    before Background Reduction
13. A Surface Scattering Measurement that was Made .. 35
    after Reduction of the RF Background Level
14. A Representative Set of Surface Height .......... 39
    Measurements
15. A Frequency Plot of the Measured Surface Slope .. 41
16. A Probability Plot of Surface Length as a Function of Surface Slope

17. Measured Facet Length Statistical Moments

18. Measured Facet Slope Statistical Moments

19. Measured and Calculated Moments for Measurements Made at a 0° Bistatic Angle

20. Calculated K-Distribution Moments for Measurements Made at a 0° Bistatic Angle

21. Measured and Calculated Moments for Measurements Made at a 30° Bistatic Angle

22. Calculated K-Distribution Moments for Measurements Made at a 30° Bistatic Angle

23. Measured and Calculated Moments for Measurements Made at a 60° Bistatic Angle

24. Calculated K-Distribution Moments for Measurements Made at a 60° Bistatic Angle

25. Circuit Diagram for the Two-Stage Voltage Amplifier

26. Amplifier Module
INTRODUCTION

The scattering of electromagnetic waves from rough surfaces has been investigated by numerous scientists and engineers during the past 30 years. Notable contributors to the literature include Beckman and Spizzichino [1], Jakeman [2-6], Goodman [7], Bahar [8, 9, 11], Wait [10], Barrick [11, 13] and Davies [12].

Because of the complexity of performing a deterministic analysis of rough surface scattering, a great deal of the theoretical work on this subject has been devoted to statistical treatments of the problem. Most analyses have dealt with either relatively high frequency scattering or relatively low frequency scattering. The high frequency region is composed of those frequencies at which the surface roughness size is significantly greater than the incident wavelength. The low frequency region is composed of those wavelengths at which the surface roughness size is significantly smaller than the wavelength. A commonly cited measure of surface roughness is the so-called "Rayleigh Criterion" [1] that relates the mean surface roughness height, the angle of incidence and the angle of the reflected field with respect to the rough surface. This criterion was applied by Nacouzi [17] with the result that at 35 GHz, the surface that was
used for this experiment meets the criterion for a rough surface.

This research project was concerned with millimeter wave scattering at 34.3 GHz from a conductive, randomly rough surface. The experiment consisted of a gravel surface that was coated with a conductive paint, a derrick that supported a transmitter with the antenna fixed so that the transmitted energy was incident normal to the surface and a receiver that was mounted on a movable arm that was attached to the derrick that allowed the receiving antenna to be moved from normal incidence to grazing incidence. Measurements were always made in the plane of incidence.

It is the intent of this report to describe the methods that were used to measure scattering, to present results of the scattering measurement and to show that measured results can be successfully related to an appropriate analytical model of the scattering process.
CHAPTER 1

ANALYTICAL DEVELOPMENT OF ROUGH SURFACE SCATTERING

The research that is described in this report is a report on the scattering of electromagnetic energy from rough surfaces. This subject has been studied by several authors and some of the results that have been published on this subject will be summarized in this section.

Electromagnetic Scattering from a Rough Surface

Beckman And Spizzichino [1] presented the general Kirchhoff solution for the scattering of plane waves in Cartesian space. The scattering geometry is shown in Figure 1. This surface is described by the function

\[ Z = Z(x) \]

which is one dimensional in x for simplicity. As seen in Figure 1, scattering is only considered in the plane of incidence, again for simplicity. The scattered field at an observation point \( (P) \) is given by the Helmholtz integral as

\[ E_s (P) = \frac{1}{4\pi} \int_s \left( E \frac{\partial \psi}{\partial n} - \psi \frac{\partial E}{\partial n} \right) \, dS \]

where \( S \) is the rough surface

\( E \) is the total electric field

\( n \) is the normal to the surface
Figure 1. Rough Surface Scattering Geometry

\[ S = f(x, Z(x)) \]
We will let \( P \) move into the far field so that we are dealing with plane scattered waves. It is seen from Figure 1 that

\[
\begin{align*}
\mathbf{k}_2 \cdot \mathbf{r} &= k_2 \mathbf{R}_0 - \mathbf{k}_2 \cdot \mathbf{r} \\
\psi &= e^{i k_2 R_0 - i k_2 \cdot \mathbf{r}}
\end{align*}
\]

If we assume that the surface is perfectly conducting, then it can be shown that a scattering coefficient that is given as

\[
\rho = \frac{E_s}{E_{ss}}
\]

where \( E_s \) is the field scattered from the rough surface; \( E_{ss} \) is the field reflected in the direction of specular reflection \((\theta_1 = \theta_2)\) by a smooth perfectly conducting plane with the same general conditions as the rough surface can be derived to have the form

\[
\rho = \frac{\sec \theta_1 [1 + \cos (\theta_1 + \theta_2)]}{2 L (\cos \theta_1 + \cos \theta_2)} \left\{ \exp \left[ \frac{i 2 \pi}{\lambda} [ \sin \theta_1 - \sin \theta_2] x \right] - \left[ (\cos \theta_1 + \cos \theta_2) Z(x) \right] \right\} dx
\]
where $L$ is the half length of the surface and $L \gg \lambda$.

The expression shown above gives a quantitative expression for the scattered field in one dimension. This can be extended to a surface that is rough in two dimensions by defining a two dimensional surface roughness and integrating in the other dimension. This treatment serves to illustrate the complexity of calculating the scattered field from a rough surface. It does not appear to be practical to use a deterministic model for the surface scattering because of the lack of a general function $Z(x,y)$ that describes the characteristics of a randomly rough surface. Another approach that has been taken by other researchers is to characterize the scattering from a rough surface as either one of two types: scattering from a very rough surface and scattering from a slightly rough surface. The commonly used method for differentiating between these two phenomena is to use the Rayleigh criterion. As described by Nacouzie, [17] the criterion is stated such that the surface is considered smooth if

$$\sigma < \frac{\lambda}{8 \sin \theta}$$
where $\sigma$ is the standard deviation of the surface height
\[ \lambda \]
is the radiation wavelength;
\[ \theta \]
is the specular angle of incidence and reflection.

This application of the Rayleigh criterion is supported by discussion that is given by Davies [12]. According to the results that are reported by Nacouzie [17], who worked with the same surface that was used for this research project, the gravel surface that was used for this project is classified as a rough surface by the Rayleigh criterion.

There is a class of rough surfaces that is composed of randomly sized and randomly oriented flat areas. This type of surface is referred to as a faceted surface. The gravel surface that was used for this experiment was largely a faceted surface because of the characteristics of the gravel that was used. Since the receiving antenna footprint covered a small area of the total surface, it is feasible to simulate the scattering from this surface as the sum of a discrete number of scatterers. This approach was taken by Jakeman and Pusey [2] in order to explain non-Rayleigh statistics that were observed in radar cross section measurements of sea surfaces. The scattered field is represented as
\[ E(r,t) = e^{j\omega t} \sum_{i=1}^{N} A_i(r,t) e^{j\phi_i(r,t)} \]
where $N$ is the number of scatterers;

$A_i(r,t)$ is an amplitude factor that relates the angular distribution of radiation from the $i$th scatterer.

$\phi_i(r,t)$ is a phase factor that relates phase for the individual scatterers as a function of time and position.

One method of determining the $A_i$ is to use the physical optics approximation for scattering from a square flat plate. The radar cross section from each plate or facet is then given as

$$A_i(\lambda, \theta) = \frac{4\pi b^4}{\lambda^2} \sin^2 \alpha \sin^2 \left( \frac{\pi}{2} - \theta \right)$$

where

$$\alpha = \frac{2\pi b}{\lambda} \sin \theta$$

$b$ is the width of the facet;

$\lambda$ is the wavelength of the incident radiation;

$\theta$ is the angle between the surface normal of the facet and the line of sight vector.

This approach results in a model that can be simply related to the scattering geometry. Measurements of surface statistics can give a statistical distribution for facet dimensions and facet angular orientation. Surface statistics for the gravel surface that was used for this project are presented in Chapter 3.
Stochastic Scattering Models

Jakeman and Pusey [2] note that a probability distribution cannot be evaluated analytically for arbitrary probability distribution functions of the general $A_i$ that are discussed above. They propose that a useful statistical model for this problem is the K-distribution which has a density function that is given as

$$P(a,r) = \frac{2b}{\Gamma(1+\nu)} \left( \frac{ba}{2} \right)^{\nu+1} K_\nu(ba), \nu > -1$$

with moments defined as

$$\langle a^{2n} \rangle = \left( \frac{2}{b} \right)^{2n} \frac{n!}{\Gamma(1+\nu)} \frac{\Gamma(n+\nu+1)}{\Gamma(M)}$$

where $K_\nu(ba)$ is the modified Bessel function; $b$ and $\nu$ are functions of the line of sight vector $r$. The radar cross section distribution for scattering from a faceted rough surface can be established analytically and statistical moments for this distribution are given as

$$\langle \sigma^n \rangle = \left( \frac{2}{b} \right)^{2n} \frac{\Gamma(n+M)}{\Gamma(M)}$$

where $n$ is the order of the moment; $M$ and $b$ are parameters of the distribution.

This results in a mean of

...
and a normalized variance of

\[
\frac{\langle \sigma^2 \rangle}{\langle \sigma \rangle^2} = 2 + \frac{2}{M}
\]

It is possible to calculate moments for a K-distribution model of surface scattering from a set of measured data. This was done for data that were measured during the course of this project by calculating the normalized variance for measured data. The parameters \( b \) and \( M \) were next calculated from the expressions for mean and variance that are given above. Higher order K-distribution moments were then calculated for comparison with calculated moments for the measured data. The results of these calculations are summarized in Chapter 3.

Jakeman [3] notes that gamma distributions are often used for modeling detection processes for various types of electromagnetic measurements. For the general case of an integrated intensity

\[
E(t) = \int_{t_0}^{t_1} I(t) \, dt
\]

it has been shown that a probability density function of the form
\[ P(E) = \alpha \left( \frac{\alpha E}{\langle E \rangle} \right)^{\alpha - 1} \exp \left( \frac{-\alpha E}{\langle E \rangle} \right) \frac{\Gamma(\alpha)}{\langle E \rangle} \quad \alpha, E > 0 \]

can be used to accurately model the detection of gaussian-distributed electromagnetic energy. Jakeman [3] points out that when the parameter \( \alpha \) satisfies the relationship

\[ \alpha = \frac{n}{2} \]

where \( n \) is an integer, then the integrated intensity, \( E \), can be interpreted as resulting from a random walk in \( n \) dimensions. The approach of working with integer and half-integer values of \( \alpha \) has received most of the attention that has been directed toward this area. Jakeman [3] has also derived a model that allows arbitrary values of \( \alpha \) to be used. The resulting probability distribution has a normalized variance of

\[ \frac{\langle I^2 \rangle}{\langle I \rangle} = 1 + \alpha^{-1} \]

and higher order normalized moments of

\[ \frac{\langle I^n \rangle}{\langle I \rangle^n} = \frac{\alpha^{-n} \Gamma(n+\alpha)}{\Gamma(\alpha)} \]

There is justification for using an approach of this type to model the surface scattering phenomena that were
investigated during the course of this project because of the fact that the microwave measurements are integrated intensity measurements. The beamwidth of the receiving antenna was broad enough such that the 3 dB footprint of the antenna on the surface was greater than 10 wavelengths in diameter and contained numerous scatters. The antenna effectively integrated the field that was scattered from the surface footprint area and this integrated quantity was measured by the waveguide crystal detector which is a square law device. During the course of this project, it was found that the integrated gamma distribution moments matched the measured moments with a high degree of precision. These results are presented in Chapter 3.

It was found that it was not possible to eliminate all of the background interference that occurred in the measurements. Steps were taken to reduce the background, as described in Chapter 2, that significantly reduced the background. An effort was made to model the data contamination that resulted from the background levels. It was felt that this could potentially produce even better agreement between measured and calculated moments. A generalized n-distribution has been derived by Phillips and Andrews [18] that allows background interference to be modeled as a constant additive term that is present in the measured data. The moments of the generalized n-distribution have the form
\[
\frac{<I^n>}{<I^n>} = \frac{1}{(m + mr)^n} \sum_{k=0}^{n} \binom{n}{k} \frac{\Gamma(m+n)}{\Gamma(m+k)} (mr)^k
\]

where

\[
m = \frac{1}{a-1}
\]

\[
a = \frac{(1+r)^2 x - r^2}{2r^2 + 1}
\]

\[
x = \frac{<I^2>}{<I>^2}
\]

r is the ratio of the constant background intensity level to the intensity of the energy scattered from the surface.

Calculated moments for the generalized n-distribution are presented in Chapter 3.
CHAPTER 2
THE MILLIMETER WAVE MEASUREMENT SYSTEM

In order to evaluate the feasibility of conducting this experiment, a thorough evaluation of the experimental test set and the surface was conducted. This section describes the results of this evaluation and describes the procedures that were used as well as some of the problems that were encountered.

Measurements of rough surface scattering were made with a remotely controlled, movable derrick that contained the K band transmitter and receiver. This derrick was moved over a gravel surface and was guided by aluminum channels that were positioned along either side of the 240" x 24" rough surface. Figure 2 illustrates the various parts of the measurement test set. The major components are the gravel bed, the derrick with transmitter and receiver and motorized drive, and the measurement and control instrumentation.

Figures 3 and 4 show the derrick located at one end of the rough surface with the receiving antenna positioned at a bistatic angle of 0° (monostatic position). Figure 5 shows the derrick with the receiving antenna adjusted to a 60° bistatic angle. The transmitter platform was fixed to the derrick and the receiver antenna and detector were mounted
Figure 2. Microwave Scattering Test Bed and Instrumentation
Figure 3. The Measurement Derrick Shown Positioned Over Gravel Surface
Figure 4. A Close-Up of the Measurement Derrick
Figure 5. The Measurement Derrick Shown With the Receiving Antenna Adjusted to a 60° Bistatic Angle
on a movable swing-arm that allowed measurements at bistatic angles from 0° to nearly 90°. The derrick was powered by an on-board SCR-controlled motor that allowed the measurement set to be moved horizontally from one end of the surface to the other end. The antennas were both mounted so that each antenna was always located 36" from the illuminated area of the surface.

The surface was composed of ballast stones that had been selected by using a sieve that passed rocks in the .5" to .75" size range. The stones were coated with a conductive copper paint that provided a surface resistivity of approximately one ohm per square after the paint had been applied to the rocks. The rocks were placed on the wooden surface of the test bed in a layer that was approximately 24" wide, 240" long and 2" thick. The rocks were packed with a horizontally positioned wooden board in order to maintain a constant mean surface height.

Figure 6 shows a close-up view of the transmitter and receiver instrumentation. Important features of this instrumentation package include the klystron transmitter source, transmitter precision attenuator, transmitting antenna, receiving antenna, receiver precision attenuator and receiver crystal detector. The klystron is an OKI 35V11 klystron that is rated at 400 mW output power. This corresponds to a power level of 26.0 dBm. For the purposes of this analysis, it is assumed that the transmitted power
Figure 6. A Close-Up View of the RF Measurement Instrumentation
level was 26 dBm. The isolation attenuator introduced approximately 3 dB of isolation so that the net transmitted power level was approximately 23 dBm. The klystron is controlled by an FXR Z815B klystron power supply. The klystron frequency was tuned to 34.3 GHz with a calibrated frequency meter for maximum power output. The transmitting antenna that is shown is a Microwave Associates standard gain horn which has a 25 dB gain at 34.9 GHz with an aperture dimension of 2.25" x 2.75. Both the transmitter and the receiver attenuators were variable flap attenuators that contained a slotted waveguide section with a matched resistive strip insert. The attenuators provided 0 to 20 dB attenuation. The transmitter attenuator was used for isolation between the klystron and the transmitting antenna. The receiving attenuator was used to control the received signal so that the crystal diode receiver was always operating in the linear range of the diode. The receiver antenna had an aperture dimension of 3.75" x 5" and a calculated gain of 30 dB so that it provided relatively high gain and a narrow beam width for the receiver. The relatively narrow beam width was important to this experiment because of the fact that it allowed the receiver to look at a uniformly illuminated portion of the surface and because of the fact that it was desired that the number of scatterers in the field of view of the receiver be kept to a relatively small number. This was necessary in order to maintain similarity between this
experiment and the analytical scattering model that was used to interpret the results of these measurements. The receiver was an HP R422A crystal detector. The output from the crystal detector was amplified and fed into the MINC-11 computer controlled measurement system that is shown in Figure 7. The output was then stored on floppy disc by the PDP 11 computer-controller. Data was processed on the PDP 11 and on a VAX 11/780 computer after the data was taken. Data processing procedures included raw data plotting, statistical moment calculations, autocorrelation calculations and plotting of moments and autocorrelation results.

Krause [16] gives some approximate relationships for antennas. The so called "Far Field Criterion" for two antennas is given as

\[ R = \frac{2D^2}{\lambda} \]

where \( R \) is the range;

\( D \) is the maximum aperture size;

\( \lambda \) is the wavelength in the transmitting medium between the antennas.

By using this relationship, we see that the far field criterion for a 5" aperture is 148" at 35 GHz. For a 2.75" aperture, the criterion is 45". It is noted that the far field criterion is sometimes also defined as
\[ R = \frac{D^2}{\lambda} \]

This reduces the range by a factor of two. When we consider that the propagation path length between the transmitting and receiving horns is 72", it is found that it is reasonable to assume that the antennas that were used for this experiment are positioned so that the far field criterion is observed. The half power beamwidth for a rectangular antenna is given as

\[ \theta \approx \frac{51 \lambda}{D} \]

Simple geometry shows that the area of the surface that is illuminated within the half power beamwidth (or the footprint) has a radius of

\[ r = R \tan \theta \]

where \( r \) is the radius of the illuminated surface area; \( R \) is the range from the antenna to the surface; \( \theta \) is the half power beamwidth of the antenna. By using these relationships, we are able to calculate parameters for the antennas that were used in this experiment. These parameters are given in Table 1.
TABLE 1
ANTENNA SCATTERING PARAMETERS

<table>
<thead>
<tr>
<th>Aperture Size (in)</th>
<th>Distance from Surface (in)</th>
<th>Half Power Beamwidth (deg)</th>
<th>Radius of Surface Footprint (in)</th>
<th>Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>36</td>
<td>8.2</td>
<td>5.2</td>
<td>24</td>
</tr>
<tr>
<td>2.75</td>
<td>36</td>
<td>6.3</td>
<td>4.0</td>
<td>26</td>
</tr>
<tr>
<td>5.0</td>
<td>36</td>
<td>3.5</td>
<td>2.2</td>
<td>30</td>
</tr>
</tbody>
</table>

From this analysis, we see that the illuminated area is well within the limits of the gravel bed width and that the receiving antenna footprint is well within the transmitting antenna footprint. It is therefore expected that uniform illumination is obtained over the measured portions of the surface.

The system sensitivity that is required for accurate measurements is determined by the individual components of the system, the distance of the receiving and transmitting antennas from the surface and the scattered power levels from the surface. In order to estimate the surface scattering levels, a sample of gravel was tested from 2 to 18 GHz. Even though this project was conducted at 35 GHz, it was felt that the higher frequency (12-18 GHz) results that were obtained would give an indication of the scattering levels that would be encountered at 35 GHz. The scattered power levels from the surface were estimated by testing a sample of the gravel in an RF reflection measurement facility.

This facility consists of an anechoic chamber with broadband
transmit and receive horns mounted in the ceiling and a styrofoam sample mounting platform embedded in the pyramidal absorber on the floor of the chamber. Swept frequency instrumentation measures and records the reflections from a sample (usually a flat panel) from 2 to 18 GHz. A 12" x 12" flat metal plate is normally used as the reflection reference. The gravel was placed in a shallow box with a 12" x 12" interior size that was made out of styrofoam. The styrofoam is essentially invisible at the 2 to 18 GHz frequencies that are used for measurements in this facility. The reflection levels from the gravel were then measured, referenced to a 12" x 12" flat plate and recorded. The test was conducted at several different orientations of each sample and with several different samples that were formed by rearranging the gravel in the box. The samples were measured both with and without a metal base plate in the sample box in order to determine if the energy was being transmitted through the sample. Figure 8 shows a representative set of data that was taken for a gravel sample. Two rotational positions of the gravel box on the sample platform are referred to as 0° and 90°. These data are representative of all the data that were taken, and it is observed that an average level of 20 dB was measured in the 10 to 18 GHz frequency range. On the plot, REFLECTION refers to the amount by which the sample is lower in scattered power than the 12" x 12" reference metal plate. The chamber background is
Figure 8. Measured RF Reflection Levels for Coated Gravel
plotted as indicated and it is noticed that in the 14 to 18 GHz range, the measured data "runs into the background." This increase of background at the higher frequencies is caused by increased losses in the coaxial transmission lines that were used for this experiment. This same experiment was later run over the 8 to 18 GHz frequency band as shown in Figure 9 with a TWT power amplifier that increased the output power by roughly 100 times. This resulted in a much lower background because of the fact that with more transmitted power the system sensitivity was not decreased by losses in the coaxial transmission line. The high frequency response of the sample was found to be roughly the same as the 8 to 14 GHz response shown in Figure 8. This indicates that the scattering levels are approximately uniform in the 8 to 18 GHz range. Figure 10 shows data that were measured for a sample with a metal ground plane placed in the box beneath the sample. Again, numerous data sets were taken and this plot is representative of the results that were obtained. If we compare Figure 10 to Figure 8, we see that they are very similar except at the lower frequencies. In both plots, the average scattering levels are in the 20 dB range for the higher frequencies. The higher levels that are observed at the lower frequencies in Figure 10 are due to the fact that at the lower frequencies the energy is transmitted through the rocks and reflected from the metal plate back through the rocks to the receiver. The point of
Figure 9. RF Reflection Levels for Coated Gravel Shown with the Anechoic Chamber Background Levels Reduced
Figure 10. Measured RF Reflection Levels for Coated Gravel with a Metal Ground Plane
this discussion is that at the higher frequencies it appears that all of the energy is reflected by the rocks and is not transmitted. Therefore, when we make our measurements at the higher frequencies we do not have to worry about a component of the incident field being transmitted through the surface. Because of the relatively constant average levels that are measured in the 8 to 18 GHz range, for the purposes of this analysis, it will be assumed that the surface has an average reflection coefficient of -20 dB at 35 GHz.

One more consideration is needed before we can calculate the sensitivity of the 35 GHz receiver. The propagation loss (or space loss) from the transmit antenna to the surface to the receive antenna must be calculated. The attenuation due to space loss can be expressed as

\[ \alpha_{sp} = 22 \text{ dB} + 20 \log \left( \frac{d}{\lambda} \right) \]

where \( \alpha_{sp} \) is the space loss attenuation;
\( d \) is the distance;
\( \lambda \) is the wavelength of the transmitted energy.

We now have enough information to calculate the signal margin for the equipment that we are using. The results of this calculation are given in Table 2.
TABLE 2

SIGNAL MARGIN CALCULATION RESULTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter power</td>
<td>+23 dBm</td>
</tr>
<tr>
<td>Transmit antenna gain</td>
<td>+25 dB</td>
</tr>
<tr>
<td>Transmit space loss</td>
<td>-34 dB</td>
</tr>
<tr>
<td>Surface reflection loss</td>
<td>-20 dB</td>
</tr>
<tr>
<td>Return space loss</td>
<td>-34 dB</td>
</tr>
<tr>
<td>Receive antenna gain</td>
<td>+30 dB</td>
</tr>
<tr>
<td>Signal margin</td>
<td>-10 dBm total</td>
</tr>
</tbody>
</table>

The receiver consisted of a Hewlett-Packard R422A waveguide crystal detector. The square law response for this detector is shown in Figure 11. In order to stay within this range, the maximum scattering levels were measured for each test and the receiver attenuator was adjusted so that the maximum scattering levels did not produce an output voltage from the crystal detector that exceeded 5.0 mV. If we assume that we can measure voltage down to the 5 microvolt levels shown in Figure 11, then we effectively have a signal margin of 30 dBm with a 30 dB dynamic range over which we can obtain a linear receiver response.

After this analysis was performed, it was then necessary to see if the signal levels could be accurately measured and recorded. Several problems were encountered during the process of putting together a system that would have the sensitivity that was required for this experiment. Initially, the preamp system that is part of the MINC-11 was used in an attempt to measure the crystal detector output. It was found, however, that the high impedance output of the
Figure 11. Square Law Response for the Crystal Detector
crystal detector was a poor match for the low impedance pre-amp input. There was an abundance of 60 cycle and 100 KHz noise that made it impossible to measure signals at levels below 40 mV. At low signal levels there were also grounding problems which were difficult to control. As a result of these problems, a two-stage high gain amplifier was built for this experiment. This amplifier served as a buffer between the crystal detector and the MINC-11 A/D converter, it filtered out the high frequency noise above 20 Hz and it provided a gain of approximately 840. This amplifier effectively allowed signals down to .05 mV to be accurately measured. The effective dynamic range of the measurement was therefore 100 or 20 dB since the maximum voltage that could accurately be recorded from the crystal detector was 5 mV because of the square law characteristics of the crystal receiver. The amplifier was also totally isolated from the environment by enclosing it in a metal chassis box, by using shielded coaxial cable for input and output and by using a dual 9V battery power supply with the batteries contained in the chassis box along with the amplifier. Further information regarding the amplifier is given in Appendix I.

The amplified signal was input to the MINC-11 A/D converter. The MINC-11 is controlled by a PDP 11/03 computer. The signal was sampled by the MINC-11 at the rate of 125 samples per second and the resulting data was stored on floppy discs by the PDP-11 computer. This data was later
processed on the PDP-11 and it was transferred to a VAX 11/780 for further processing.

After the measurement sensitivity was increased to a suitable level, measurements were recorded for the first time.

As is usually the case with CW measurement schemes of this type, it was found that there was a microwave "background" problem. This problem occurred because of the scattering of energy from the surface to surrounding structure that was then scattered back to the rocks and then back to the receiving antenna. The first measurements appeared to have a dc component. Figure 12 shows a representative data set. This data represents the receiver output voltage that is measured as the derrick is moved from one end of the surface to the other end. It was found that the first data set was contaminated by high background levels. Background problems are inherent in most CW measurement systems. The background levels were reduced by treating the receiver horn and the structure of the measurement test bed. Figure 6 shows the receiver horn after treatment with Emerson & Cuming AN-72 RF absorber. Figure 13 shows a measurement data set that was taken after the absorber treatments were made. The reduction in background levels is apparent when compared to Figure 12. Covering the receiving antenna with absorber reduced the background because an absorber covered horn generally has a narrower beam width and extraneous
Figure 12. A Surface Scattering Measurement that was made before background reduction (Surface position in feet is equal to .008 * Time)
Figure 13. A Surface Scattering Measurement that was made after reduction of the RF background level (Surface Position in feet is equal to .008 * Time)
energy is not as easily picked up in the antenna sidelobes. Secondly, sheets of AN 72 absorber were placed on the inside "legs" of the derrick in order to minimize scattering from the surface to the derrick and back. The placement of absorber can be seen in Figure 4. This action produced another considerable reduction of the background. The resultant background levels were relatively low and this helped to produce high integrity scattering measurements.

A typical measurement procedure can be described as follows. First the equipment was turned on, adjusted and allowed to stabilize. The derrick was then moved several times from one end of the surface to the other end so that the peak scattering levels could be observed. The receiver and/or transmitter attenuators were then adjusted so that the input signal power to the crystal detector was at a maximum that did not exceed the linear range of the diode. The derrick was then placed at one end of the surface. The MINC-11 system was brought into action by running a computer program that initialized the system and sampled the amplifier output at specified time intervals. The derrick was then moved at constant velocity to the other end of the surface while the PDP 11 sampled and stored the scattered field as measured above the rough surface. Typically, 10 or more repetitions of a particular measurement were made. Each measurement collected 2500 samples so that each set collected 25000 or more samples. After a set was complete, the
bistatic angle of the receiver antenna was changed. Measurements were taken in 10° increments from 0° to 80°. Data were stored and processed after a series of measurements that usually consisted of a full night's work.
CHAPTER 3
STATISTICAL ANALYSIS OF MEASURED DATA

Surface Height Data

Surface height for the gravel surface was measured by using a comb-like depth gauge. This device consists of an aluminum bar that contains 299 equally spaced metal pins. The pins are .040" in diameter and are spaced .060" apart. The pins move vertically, and they can be fixed at a given position by means of a tension bar that presses against the pins. A typical height measurement was made by placing the device on the surface and allowing the pins to fall into place along the contour of the surface. The pins were then constrained and the device was removed from the surface. The height of the pin from the flat bottom surface of the device was then measured with a ruler. This process was repeated 15 times at different surface locations so that 15 independent samples of the surface height were obtained. Figure 14 shows the data that were collected for one of the height measurements.

Because of problems with the first three surface data sets, only the last 12 sets were used for statistical calculations. This provided a total of nearly 3600 points that could be used to calculate surface statistics.
Figure 14. A Representative Set of Surface Height Measurements
slopes were calculated for all of the data sets. The surface slope is given as

\[ M = \frac{\Delta y}{\Delta x} \]

where \( \Delta Y \) is the change in surface height; \( \Delta X \) is the change in lateral position along the surface (constant = .060'').

The distribution of surface slopes as a function of cumulative facet length is shown in Figure 15. The facet length was calculated as the distance between successive measured surface data points. The facet length is given as

\[ L_i = \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \]

where \( x_i \) and \( y_i \) are the coordinates of the \( i \)th surface points; \( x_{i+1} \) and \( y_{i+1} \) are the coordinates of the next surface point after the \( i \)th position.

The lateral positions of the surface points were fixed by the measurement device at .060'' intervals. The above equation therefore reduces to

\[ L_i = \sqrt{.060^2 + (y_{i+1} - y_i)^2} \]

The data that are shown in Figure 15 were prepared by calculating the slope and length between each pair of measured
Figure 15. A Frequency Plot of the Measured Surface Slope
surface points and then sorting and accumulating surface lengths according to slope. Each pair of points is viewed as constituting a facet or flat area of the rough surface. The facet lengths were accumulated in slope bins of 0.2. This seemed to be an optimum accumulation size that allowed enough data to collect in each bin to give a continuous distribution while still maintaining as much resolution as possible along the slope axis. The distribution that is shown in Figure 15 shows that most of the surface length is in the small slope range with the maximum occurring at 0 slope which corresponds to a horizontal orientation. This feature is obvious in the data that are shown in Figure 14. It is seen that most of the surface slopes are in the near horizontal slope region. This is explained by the fact that the surface was packed and smoothed with a flat board in order to produce a uniform mean surface height across the entire surface. Another feature of the distribution that is shown in Figure 15 is that the shape of the distribution appears to be gaussian. This was verified by plotting the cumulative facet length that was calculated as a function of surface slope. The facet length was accumulated continuously and plotted as a percentage of the total accumulated facet length for the surface measurements on probability paper. The results of this process are shown in Figure 16. The nearly complete linearity of the data points demonstrates that the distribution of surface facet length as a function
Figure 16. A Probability Plot of Surface Length as a Function of Surface Slope
of surface slope is a gaussian distribution. Statistical moments for the facet length distribution and the facet slope distribution were calculated from the measured surface height data. These moments are plotted in Figures 17 and 18. Further information regarding the size and volume of the individual ballast stones that were used for this experiment is reported by Nacouzie [17].

Electromagnetic Scattering Data

Over 160 sets of RF measurements were made during the course of this project. These measurements were made over a range of bistatic scattering angles from 0° to 80° in 10° increments. Because of system noise, microwave background and other instrumentation problems that were encountered during the course of this experiment, it is felt that the last 40 sets of data that were taken are the only data sets that should be considered for comparisons with data that are calculated with statistical scattering models. These measurements were made with a 2.11" transmitting antenna and a 2.75" receiver antenna. This series of measurements consists of 20 data sets that were taken at a 0° (monostatic) receiving antenna orientation and 10 data sets each that were taken at 30° and 60° bistatic angles. Statistical moments were calculated by accumulating all of the data points at each angle and generating the moments with a computer program. Results of these calculations are shown in Table 3.
Figure 17. Measured Facet Length Statistical Moments
Figure 18. Measured Facet Slope Statistical Moments
and Figures 19 through 24. It can be seen that the integrated gamma distribution moments give good agreement for the third, fourth, fifth and sixth moments when compared to the measured moments. It was found that the K-distribution did not accurately predict the higher order moments for the scattering measurements that were made during this project. Because of the relatively good agreement between the third and fourth order measured statistical moments and the K-distribution moments, the researcher felt that other types of distributions that are based on the gamma function could be applied to this problem. The K-distribution moments are seen to quickly diverge toward higher values in the fifth and higher order moments. The integrated gamma moments maintain good agreement with the measured statistical moments at 0°, 30° and 60° receiving antenna angles. This is interesting because of the fact that the nature of the scattering must be different at 0° than it is at the 60° angle. This observation follows from the fact that the surface slopes are heavily weighted toward the horizontal orientation and that surfaces tend to exhibit quite different scattering characteristics for normal incidence backscattering as compared to obtuse bistatic angles. It should be noted here that the mean scattering levels generally decreased as the bistatic angle between the transmitting and receiving antennas increased. In order to maintain the maximum signal to noise ratio within the linear region of the receiver, the
Figure 19. Measured and Calculated Moments for Measurement at a 0° Bistatic Angle
Figure 20. Calculated K-Distribution Moments for Measurements Made at 0° Bistatic Angle
Figure 21. Measured and Calculated Moments Made at a 30° Bistatic Angle
Figure 22. Calculated K-Distribution Moments for Measurements Made at a 30° Bistatic Angle
Figure 23. Measured and Calculated Moments for Measurements Made at a 60° Bistatic Angle
Figure 24. Calculated K-Distribution Moments for Measurements Made at a 60° Bistatic Angle.
receiver attenuator was adjusted at each angle to give about the same output for the peak scattering levels that were measured across the surface. This is the reason that the mean scattering levels in Table 3 are roughly equivalent. Values of the $\alpha$ parameter that were calculated for the integrated gamma distribution are given in Table 4. These values indicate that $\alpha$ is not a half integer multiple. The values that are calculated are all fractional integer values that are interpreted by Jakeman [3] as representing a random walk in a fractional number of dimensions.

Statistical moments for the generalized $n$-distribution were also calculated and are given in Table 5 (a) through (c). The parameter $r$ is the ratio of background noise to scattered power from the surface. It was thought that this model would yield better results by allowing an adjustment for the RF background. Best agreement is seen to occur for values of $r$ that are either 0 or 0.01. This would seem to indicate that this distribution does not accurately model the RF background problem because of the fact that the generalized $n$-distribution gives the same result as the integrated gamma distribution when $r = 0$. 
### TABLE 3
MEASURED AND PREDICTED STATISTICAL SCATTERING MOMENTS

<table>
<thead>
<tr>
<th>Bistatic Scattering Angle</th>
<th>Order of Moment</th>
<th>Measured Moment Value*</th>
<th>Calculated Integrated Gamma Moment Values</th>
<th>Calculated K-Distribution Moment Values</th>
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<td>19.96</td>
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*All moments except for the first are normalized by the mean value (first moment)
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<th>Scattering Angle</th>
<th>Measured Normalized Variance</th>
<th>Calculated Parameter Value</th>
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### TABLE 5(a).
CALCULATED N-DISTRIBUTION MOMENTS FOR MEASURED SCATTERING DATA TAKEN AT 0° BISTATIC ANGLE

**GENERALIZED N-DISTRIBUTION MOMENTS**

MOMENT 2 = 1.84000

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<th>R = 10.000-03</th>
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**MOMENTS**

- **MOMENT 3.**
  - Generalized Moments:
    - $R = 0.000000$: MOMENT 3. = 4.8343+00
    - $R = 30.000-03$: MOMENT 3. = 5.5180+00
    - $R = 10.000-03$: MOMENT 3. = 5.0685+00
    - $R = 40.000-03$: MOMENT 3. = 5.7436+00
    - $R = 20.000-03$: MOMENT 3. = 5.2908+00
    - $R = 50.000-03$: MOMENT 3. = 5.9668+00

- **MOMENT 4.**
  - Generalized Moments:
    - $R = 0.000000$: MOMENT 4. = 17.082+00
    - $R = 30.000-03$: MOMENT 4. = 21.267+00
    - $R = 10.000-03$: MOMENT 4. = 18.472+00
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    - $R = 20.000-03$: MOMENT 4. = 19.841+00
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- **MOMENT 5.**
  - Generalized Moments:
    - $R = 0.000000$: MOMENT 5. = 74.669+00
    - $R = 30.000-03$: MOMENT 5. = 102.00+00
    - $R = 10.000-03$: MOMENT 5. = 83.472+00
    - $R = 40.000-03$: MOMENT 5. = 111.97+00
    - $R = 20.000-03$: MOMENT 5. = 92.438+00
    - $R = 50.000-03$: MOMENT 5. = 122.29+00

- **MOMENT 6.**
  - Generalized Moments:
    - $R = 0.000000$: MOMENT 6. = 389.01+00
    - $R = 30.000-03$: MOMENT 6. = 585.36+00
    - $R = 10.000-03$: MOMENT 6. = 450.20+00
    - $R = 40.000-03$: MOMENT 6. = 660.99+00
    - $R = 20.000-03$: MOMENT 6. = 514.70+00
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- **MOMENT 7.**
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    - $R = 0.000000$: MOMENT 7. = 2.3529+03
    - $R = 30.000-03$: MOMENT 7. = 3.9107+03
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- **MOMENT 8.**
  - Generalized Moments:
    - $R = 0.000000$: MOMENT 8. = 74.669+00
    - $R = 30.000-03$: MOMENT 8. = 102.00+00
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    - $R = 40.000-03$: MOMENT 8. = 111.97+00
    - $R = 20.000-03$: MOMENT 8. = 92.438+00
    - $R = 50.000-03$: MOMENT 8. = 122.29+00

- **MOMENT 9.**
  - Generalized Moments:
    - $R = 0.000000$: MOMENT 9. = 389.01+00
    - $R = 30.000-03$: MOMENT 9. = 585.36+00
    - $R = 10.000-03$: MOMENT 9. = 450.20+00
    - $R = 40.000-03$: MOMENT 9. = 660.99+00
    - $R = 20.000-03$: MOMENT 9. = 514.70+00
    - $R = 50.000-03$: MOMENT 9. = 741.31+00

- **MOMENT 10.**
  - Generalized Moments:
    - $R = 0.000000$: MOMENT 10. = 2.3529+03
    - $R = 30.000-03$: MOMENT 10. = 3.9107+03
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    - $R = 20.000-03$: MOMENT 10. = 5.2908+00
    - $R = 50.000-03$: MOMENT 10. = 5.9668+00
**TABLE 5(b).**
CALCULATED N-DISTRIBUTION MOMENTS FOR MEASURED SCATTERING DATA TAKEN AT 30° BISTATIC ANGLE

**GENERALIZED N-DISTRIBUTION MOMENTS**
MOMENT 2 = 1.8140

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TABLE 5(c).
CALCULATED N-DISTRIBUTION MOMENTS FOR MEASURED SCATTERING DATA TAKEN AT 60° BISTATIC ANGLE

GENERALIZED N-DISTRIBUTION MOMENTS
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<td>50.000 - 03</td>
<td>5.6112 + 00</td>
<td>21.850 + 00</td>
<td>105.92 + 00</td>
<td>614.33 + 00</td>
<td>4.1479 + 03</td>
</tr>
</tbody>
</table>
CHAPTER 4
CONCLUSIONS AND RECOMMENDATIONS

The results of this research project indicate that microwave scattering from a conductive rough surface can be modeled by using a gamma function based probability distribution function. The integrated gamma distribution was found to accurately predict the statistics of scattering that was measured in this experiment. This correlation between measured and predicted statistics can be partially explained in physical terms since the microwave antenna measurements were effectively integrated intensity measurements because of the beamwidth of the antenna. In order to fully understand the process that is occurring, it would be necessary to derive a mathematical model that is based on the scattering geometry and detection processes that were used here. The work that Jakeman et al have produced in the area of rough surface scattering is a good foundation for further work that can be done in this particular area of interest. Recommendations for future work in this area are as follows:

1) Make additional measurements with the surface and equipment that were used for this project with emphasis on reducing the RF background and building a larger database of reliable measurements.
2) Develop a surface scattering model that allows measured surface roughness characteristics to be incorporated into the statistical model. A possible approach that could be taken is to develop a physical optics model for scattering from a faceted surface that takes shadowing, multipath and edge diffraction into account.

3) Develop a detection process model that incorporates the physical and mathematical properties of the system that was used for this project. Even though it was found that good agreement could be obtained by using an integrated gamma distribution, there was a lack of similarity between the derivation of the integrated gamma model and the characteristics of the system that was used for this project.
APPENDIX I

Amplifier Design

The amplifier that was designed for this research project provides high gain and low noise characteristics. Figure 25 shows the circuit that was used. This circuit was enclosed in an aluminum chassis box and used a 9 volt battery power supply so that the amplification process was totally isolated from environmental noise. Figure 26 shows this amplifier module.
Figure 25. Circuit Diagram for the Two-State Voltage Amplifier
APPENDIX II

Stochastic Model Calculator Programs

This appendix contains programs for the Hewlett Packard 41CV calculator that was used to calculate moments for the stochastic models that were used for this project.
01 LBL "INGAMOM"
02 "PROGRAM INGAMOM"
03 ""
04 "THIS PROGRAM"
05 "CALCULATES"
06 "MOMENTS FOR THE"
07 "INTEGRATED"
08 "GAMMA"
09 "DISTRIBUTION"
10 ""
11 "ENTER M2"
12 PROMPT
13 1
14 -
15 1/X
16 STO 13
17 XEQ "GAMMA"
18 1/X
19 STO 16
20 LBL A
21 "ENTER M NO."
22 PROMPT
23 STO 14
24 LBL A
25 RCL 14
26 RCL 13
27 +
28 XEQ "GAMMA"
29 RCL 16
30 *
31 ENTER↑
32 ENTER↑
33 RCL 13
34 RCL 14
35 CHS
36 Y+X
37 *
38 STOP
39 GTO A
40 END

01 LBL "KMOM"
02 "PROGRAM KMOM"
03 ""
04 "THIS PROGRAM"
05 "CALCULATES"
06 "MOMENTS FOR THE"
07 "K-DISTRIBUTION"
08 "ENTER M1"
09 PROMPT
10 STO 16
11 "ENTER M2"
12 PROMPT
13 2
14 -
15 1/X
16 CHS
17 2
18 *
19 STO 13
20 4
21 *
22 RCL 16
23 /
24 SQRT
25 1/X
26 2
27 *
28 STO 16
29 LBL A
30 "ENTER M NO."
31 PROMPT
32 STO 14
33 RCL 13
34 +
35 XEQ "GAMMA"
36 STO 15
37 RCL 13
38 XEQ "GAMMA"
39 RCL 15
\begin{verbatim}
01*LBL "GMOM"
02 "PROGRAM GMOM"
03 "-
04 "THIS PROGRAM"
05 "CALCULATES"
06 "MOMENTS FOR THE"
07 "GENERALIZED-N"
08 "DISTRIBUTION"
09 "-
10 "G00"
11 1.84
12 STO 30
13 "G30"
14 1.814
15 STO 31
16 "G60"
17 1.792
18 STO 32
19 30.03221
20 STO 23
21*LBL A
22 ADV
23 ADV
24 "GENERALIZED"
25 AVIEW
26 "N-DISTRIBUTION"
27 AVIEW
28 "MOMENTS"
29 AVIEW
30 RCL IND 23
31 STO 18
32 "MOMENT 2 ="
33 AVIEW
34 RCL 18
35 FRK
36 8
37 STO 19
38 3
39 STO 15
40 .05010
41 STO 22
42*LBL b
43 RCL 22
\end{verbatim}
01 LBL "GAMMA"
02 "PROGRAM GAMMA"
03 ""
04 "THIS PROGRAM"
05 "CALCULATES"
06 "VALUES OF THE"
07 "GAMMA FUNCTION"
08 "FOR ARBITRARY"
09 "ARGUMENTS"
10 ""
11 SF 00
12 STO 11
13 STO 10
14 2.1
15 X=Y?
16 GTO a
17 RCL 11
18 1
19 X<Y?
20 CF 00
21 FS? 00
22 GTO a
23 1
24 ST+ 11
25 LBL A
26 RCL 11
27 1
28 -
29 STO 10
30 1
31 STO 11
32 RCL 10
33 -.577180166
34 *
35 ST+ 11
36 RCL 10
37 2
38 Y^X
39 .98585399
40 *
41 ST+ 11
42 RCL 10
43 3
44 Y\*X
45 -.87642182
46 *
47 ST+ 11
48 RCL 10
49 4
50 Y\*X
51 .83282120
52 *
53 ST+ 11
54 RCL 10
55 5
56 Y\*X
57 -.56847290
58 *
59 ST+ 11
60 RCL 10
61 6
62 Y\*X
63 .25482049
64 *
65 ST+ 11
66 RCL 10
67 7
68 Y\*X
69 -.0514993
70 *
71 ST+ 11
72 RCL 11
73 FS? 00
74 GTO b
75 RCL 10
76 /
77 GTO b
78*LBL a
79 RCL 11
80 ENTER†
81 ENTER†
82 .5
83 -
84 Y\*X
85 RCL 11
86 CHS
87 E\*X
88 *
89 ENTER†
REFERENCES


