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COMPARISON OF HF GROUNDWAVE PROPAGATION MODELS

by

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The groundwave component of high frequency (HF) radio propagation is utilized in both civilian and military applications. A variety of groundwave propagation models exist to predict field strength loss over the transmission path. In this thesis, groundwave field strength predictions were compared for programs which employ such models: GRWAVE, MIXPATH, and ADVANCED PROPHET. A range of parameter values was used to generate predictions for comparison. HF groundwave field strength predictions by PROPHET were 3 to 10 dB stronger than those of the other programs. GRWAVE and MIXPATH field strength predictions were in close agreement, the difference generally being less than 1 or 2 dB. Field measurements of path loss for two AM broadcast frequencies were evaluated by comparison with estimates provided by ADVANCED PROPHET. The measured groundwave field strengths were found to be from 8 dB weaker at short distances to 18 dB stronger at large distances It is recommended that future efforts be directed toward improving and validating the accuracy of the groundwave propagation models used in these programs. It is also recommended that more extensive documentation be developed for GRWAVE.

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Comparison of HF Groundwave Propagation Models

by

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of the requirements for the degree of

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ABSTRACT

The groundwave component of high frequency (HF) radio propagation is utilized in both civilian and military applications. A variety of groundwave propagation models exist to predict field strength loss over the transmission path. In this thesis, groundwave field strength predictions were compared for programs which employ such models: GRWAVE, MIXPATH, and ADVANCED PROPHET. A range of parameter values was used to generate predictions for comparison. HF groundwave field strength predictions by PROPHET were 3 to 10 dB stronger than those of the other programs. GRWAVE and MIXPATH field strength predictions were in close agreement, the difference generally being less than 1 or 2 dB. Field measurements of path loss for two AM broadcast frequencies were evaluated by comparison with estimates provided by ADVANCED PROPHET. The measured groundwave field strengths were found to be from 8 dB weaker at short distances to 18 dB stronger at large distances. It is recommended that future efforts be directed toward improving and validating the accuracy of the groundwave propagation models used in these programs. It is also recommended that more extensive documentation be developed for GRWAVE.

CONTENTS

LIST OF FIGURES

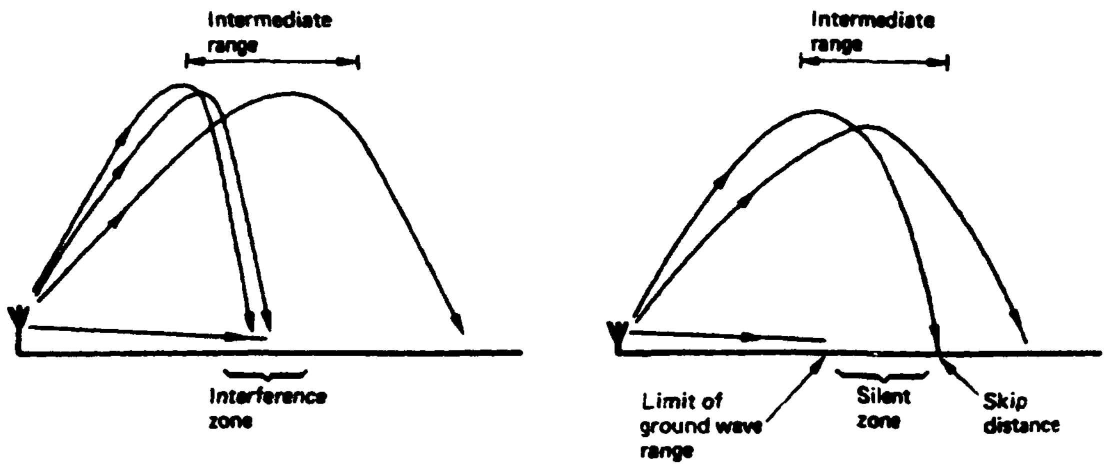
LIST OF TABLES

I. INTRODUCTION

This thesis is concerned with high-frequency (HF) communications systems, which provide an alternative to line-of-sight (LOS) satellite communications both by means of ionospheric skywave and groundwave propagation. HF military communications are in the frequency range of 2 to 32 MHz. HF wave propagation has three components: the sky, space, and ground waves. A problem inherent to HF communications, and the specific area of concern in this thesis, is to accurately predict the received signal level, commonly measured by field strength over given paths. Since the beginning of the twentieth century, scientists have worked to develop methods of predicting losses in field strength (path loss) based on known transmission parameters (distance, power, ground characteristics, etc.).

The groundwave component of the HF wave (HFGW) can provide unique capability for communications, as illustrated in Figure 1, and is important in a variety of military applications. It must be accurately modeled to predict tactical communications performance including interference from jamming sources, and to predict communications in difficult geographical environments (such as the fjord environment or mountainous terrain). Of course, the groundwave is essential for commercial broadcast beyond LOS. Because path loss increases rapidly with frequency, most groundwave propagation applications are at or below the low end of the HF band, less than a few MHz. There has been some interest at higher frequencies, since HFGW communications in the 20 to 30 MHz band have also been empirically proven to be nuclear-survivable, with non-LOS ranges as high as 115 km [Ref. 1]. In this thesis, to accommodate the entire range of interest, the groundwave propagation models were compared for the entire range of 1 MHz to 30 MHz.

Various computer modeling programs have been developed to accurately predict HF propagation modes. The principal objective of this report is to compare the field strength predictions of these programs. In Chapter II the theoretical background of groundwave propagation is introduced. In Chapter III, the three computer programs to be compared are discussed, along with the models upon which they are based. Chapter IV presents comparisons based on various transmission frequencies and ground constants. In addition, measured AM broadcast path loss is compared with loss predicted by one of the programs. In Chapter V, conclusions are presented and recommendations made.



The diagram on the left illustrates the coincidence of groundwave and skywave components, while the diagram on the right illustrates a situation in which the groundwave is the only effective method of transmission due to range.

Figure 1. Range Characteristics of HF Propagation [Ref. 2].

II. THEORETICAL BACKGROUND

A. GROUNDWAVE PROPAGATION THEORY

Since the advent of HF communications there has been a great deal of research into the propagation of waves. In 1909, Sommerfeld expressed the solution for a vertical electrical dipole on the plane interface between an insulator and a conductor, and divided the expression for the field into a "space wave," and a "surface wave," proposing a somewhat complex series of expressions to explain propagation over a flat, smooth earth [Ref. 3]. Van Der Pol and Bremmer, in 1937, made it possible to calculate field strengths at distant points, using residue series [Ref. 4]. In 1941, Norton made Sommerfeld's theory a more practical proposition for communications engineers, and introduced expressions to account for a spherical earth [Ref. 5]. Millington introduced a semi-empirical method to give fairly accurate results for a path with some variation in the earth's constants in 1949 [Ref. 6]. Hufford, in 1952, developed an integral equation for arbitrary changes of both the earth's constants and shape along the path [Ref. 7]. Since that time many individuals and organizations have conducted research into the various influences upon propagation, but a simplified model to partially explain the phenomenon is possible.

1. Groundwave Defined

"Groundwave" describes the total field (the line of sight, ground surface reflection, and surface waves) observed at a point in space due to a radiation source located a finite distance above the earth, as illustrated in Figure 2. Generally, vertical polarization is required, as horizontal polarization would generate no appreciable ground wave. Any wave component reflected from the ionosphere or upper atmospheric layer (e.g., troposcatter) is excluded, but the groundwave does include effects resulting from knife-edge and earth-spherical diffraction. The line of sight (or direct) wave and the ground reflected wave are together known as the space wave.

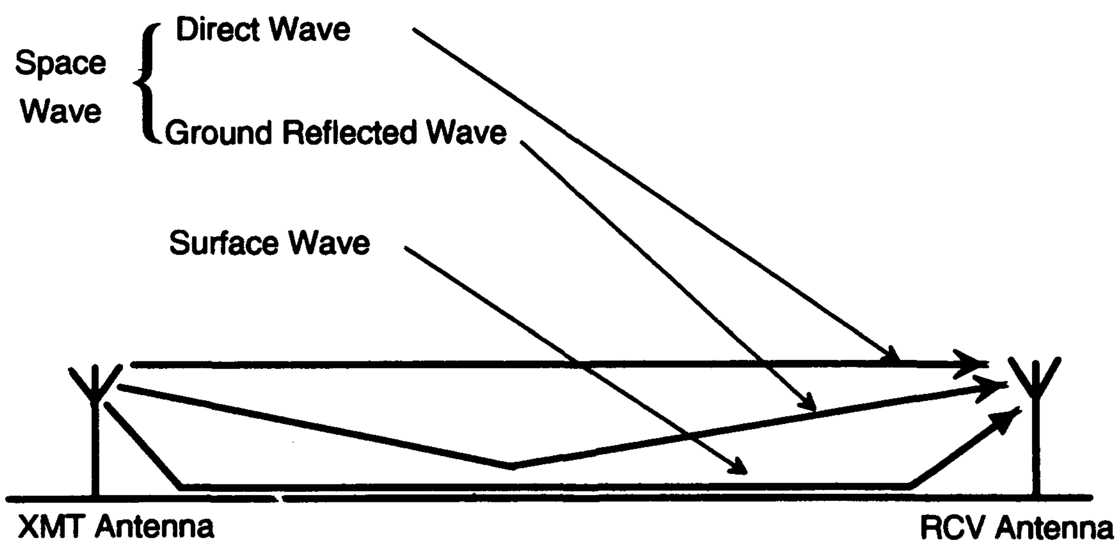


Figure 2. Components Of The Groundwave.

HF frequencies in the range 2-32 MHz are employed in groundwave communications, but at frequencies above about 4 MHz strong attenuation may occur [Ref. 2]. Above approximately 30 MHz, there is relatively little interest for communications.

2. Simple Variables in Propagation

The International Radio Consultative Committee (CCIR) has adopted the following equation to determine the root mean square (rms) field strength:

$$E_0 = 300P_k^{1/2}/d, \qquad (1)$$

where E_0 is in volts per meter, P_k is the transmitted power in kilowatts, and d is the range in meters [Ref. 2]. This assumes a very short vertical dipole near a perfectly conducting ground, and is therefore only the starting point for determining field strength at a given distance from the transmitter.

Three ground characteristics affecting groundwave propagation must also be considered in order to account for the lack of perfectly conducting ground:

- Relative Permeability -- normally regarded as unity and therefore seldom a factor in propagation problems;
- Relative Dielectric Constant -- ϵ;
- Conductivity -- σ (expressed in siemens per meter).

Note that older literature uses the unit "mhos per meter" which is identical to siemens per meter.

The influence of the latter two factors upon wave propagation is expressed by

$$\epsilon' = \epsilon - 60 i \sigma \lambda. \qquad (2)$$

This is a complex dielectric constant relative to free space, where λ is the free space wavelength in meters [Ref. 2]. The effects of ground electrical characteristics are then illustrated by

$$E/E_0 = \underbrace{1}_{\text{Direct Wave}} + \underbrace{Re^{i\Delta}}_{\text{Reflected Wave}} + \underbrace{(1-R)Ae^{i\Delta}}_{\text{Surface Wave}} + \underbrace{\cdots}_{\text{Induction Field And Secondary Effects}} \qquad (3)$$

where R, A, and Δ are all functions of ϵ', R is the complex reflection coefficient of the ground for the wave polarization of interest, A is the surface wave attenuation factor, and Δ is the phase difference caused by the path difference between the direct and ground reflected waves [Ref. 8].

3. Antennas Located on the Surface

If the transmitting and receiving antennas are both located on the surface of the earth, the radiated field can be expressed as

$$E = KFP^{1/2}/d, \qquad (4)$$

where P is the total radiated power, K is a constant which depends upon the antenna characteristics, and F is a factor which depends on frequency, ground characteristics, polarization, and distance; it decreases with increasing frequency and/or decreasing ground conductivity, and is much smaller for horizontal than vertical wave polarization. An increase in the value of F denotes a decrease in *path loss, and vice versa.*

When antennas are located on the surface, the direct wave and the ground reflected wave will cancel each other out, leaving only the surface wave, which travels along the surface through three successive zones (illustrated in Figure 3):

- The Direct Radiation Zone, where the radio waves travel a short distance as though through free space, and the attenuation factor is equal to unity;
- The Sommerfeld Zone, where the radio waves travel in a manner described by the Sommerfeld Flat Earth Theory [Ref. 3] and the factor F becomes proportional to 1/d. As shown in Figure 4, the boundary between the Direct Radiation Zone and the Sommerfeld Zone depends upon the nature of the ground.
- The Diffraction Zone, where the Earth's curvature begins to play a role and the factor F becomes independent of ground conductivity (approximately $0.62/\lambda^{2/3}$ dB/km).

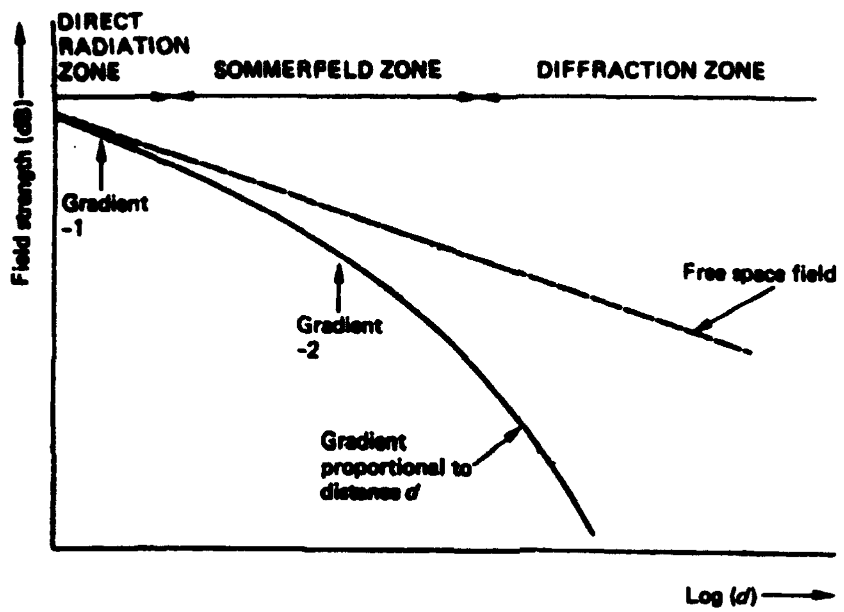


Figure 3. Surface Wave Zones [Ref. 2].

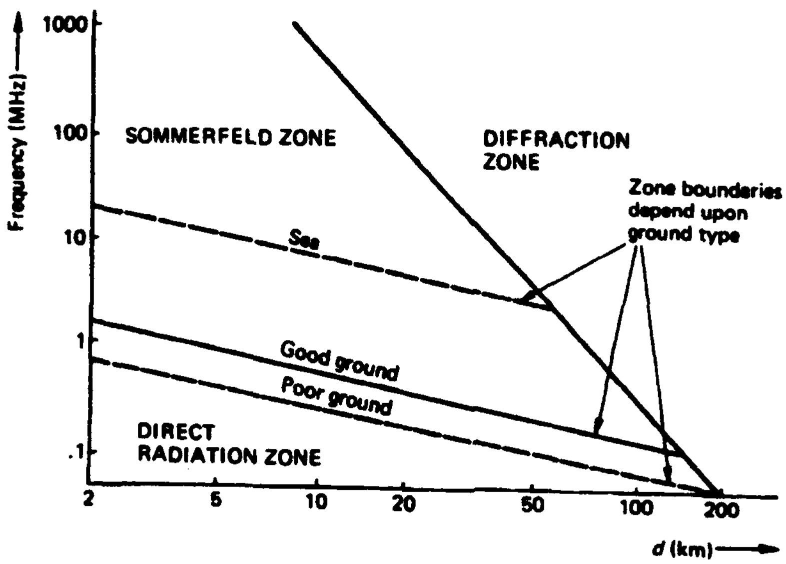


Figure 4. Effect Of Ground Type On The Sommerfeld Zone [Ref. 2].

4. Antennas above the surface

As the heights of the antennas are increased above ground level, it is necessary to modify Equation 4 to express

$$E = \frac{KFP^{1/2}H(h_1)H(h_2)}{d}, \tag{5}$$

where H(h) is the height gain factor for an antenna at height h above the surface and h_1 and h_2 are the heights of the transmitting and receiving antennas, respectively.

When antenna height above ground exceeds $35\lambda^{2/3}$, the Earth's surface plays a smaller role, and the space wave (line-of-sight and reflected waves) predominates. The space wave encounters three zones of propagation as it travels:

- The Interference Zone, where the direct wave and the ground reflected wave are summed to derive the total field;
- The Radio Horizon Zone, where the surface wave may contribute to the total field; and,
- The Diffraction Zone, where, as for the surface wave, attenuation loss has settled to a constant value.

B. PARAMETERS INFLUENCING PROPAGATION

While the above discussion presents methods of determining propagation, there are complications arising from the determination of the variables used and from other influential factors.

1. Penetration Depth

The penetration depth δ is defined as the depth at which the wave has been attenuated to 1/e (37%) of its value at the surface. Also known as "skin depth", this factor depends on the values of the effective Earth constants as shown in Table 1.

Table 1. PENETRATION DEPTH FOR DIFFERENT GROUND TYPES 10 MHz FREQUENCY [Ref. 2]

GROUND TYPE	PENETRATION DEPTH (m)
Sea Water	0.1
Wet Ground	3
Fresh Water	10
Medium Dry Ground	15

2. Ground Conductivity

Factors influencing conductivity include moisture content and temperature. In addition, it is necessary to consider the general geologic structure of the path, as well as loss due to absorption by surface objects.

3. Terrain Irregularities

Shadowing which may occur in certain locations as a result of terrain and terrain irregularities may result in attenuation and phase differences for received signals. The effect on the field strength produced by terrain irregularities varies with the frequency of transmission and the specific characteristics of the irregularity. Mountainous terrain may actually increase signal strength through knife-edge diffraction, a phenomenon known as obstacle gain. Although part of the groundwave, diffraction is not covered in this thesis, but it is modeled in such programs as the Terrain-Integrated Rough-Earth Model (TIREM), which was developed to calculate the basic propagation loss over irregular terrain at frequencies between 1 MHz and 20 GHz.

4. Vegetation

Vegetation along the propagation path also influences field strength. For instance, a densely forested area will produce different propagation results than one with no vegetation, and the effect will depend on whether the forest is in leaf, wet, or covered in snow. Below about 2 MHz, a forest environment has little effect on the groundwave.

5. Surface Clutter

Buildings, urban areas, steel framing, wiring, plumbing, lamp posts, and other surface objects affect propagation, and are collectively known as surface clutter. One model approximates the effect of clutter by means of a surface impedance, η, at the top of the clutter, height h, given as

$$\eta(h) = \eta(o) + jk \int_0^h N^2 \sin^2\beta dz, \qquad (6)$$

where $k = 2\pi/\lambda$, N is the vertical component of the refractive index, and β is the angle by which the wave is tilted downward [Ref. 8].

C. GROUNDWAVE APPLICATIONS

HFGW is useful in the tactical environment. Ships at sea can communicate even when separated by islands. Troops on the ground benefit from covert and reliable communications. Artillery and/or air support can be requested by units operating at beyond line of sight distances. Additionally, helicopter operations can rely on HFGW communications.

HF groundwave is uniquely suited to situations arising out of disaster or other emergency conditions. Champion reports that groundwave communications offer a nuclear survivable method of communication in tactical environments [Ref. 1]. Groundwave does not rely on the ionosphere for propagation of the signal, and therefore is not susceptible to ionospheric conditions resulting from EMP.

HFGW is also useful for nighttime short-range weather net data at rates of up to 2400 baud. In the range of 20 to 30 MHz, communication by HFGW has been proven effective in fjords. In areas where terrain prohibits the laying of telephone wire, HFGW can provide an ideal and low-cost communication link.

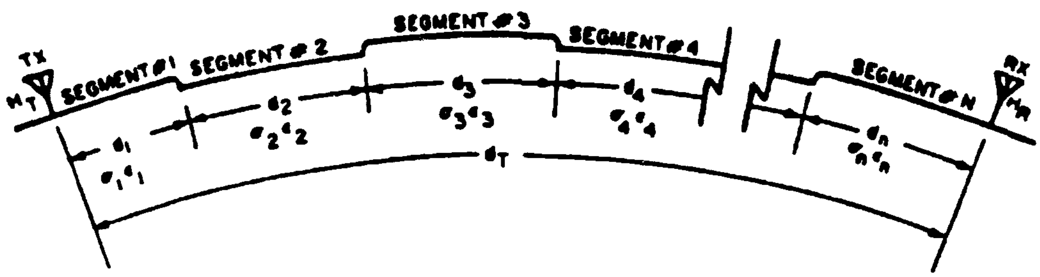
III. DESCRIPTION OF PROGRAMS

A. THE MIXPATH PROGRAM

1. Approach

The Department of Defense (DOD) Electromagnetic Compatibility Analysis Center Technology Transfer Program (ECAC-TTP) software package MIXPATH predicts groundwave propagation over a smooth earth having more than one propagation medium. This program employs Millington's method of computing surface wave transmission loss, which is highly dependent on the conductivity and dielectric constants of the Earth. MIXPATH is used in combination with the ECAC Far-Field Smooth Earth Coupling Code (EFFSECC) model, which differentiates between path distances short enough to assume planar earth and longer distances, at which the earth's curvature begins to play a significant role.

In 1949, G. Millington introduced a semi-empirical method to give fairly accurate results for quantifying the effect of propagation over mixed terrain [Ref. 6]. This procedure is known as **Millington's Model**, and assumes a semi-infinite half-space earth with a smooth surface, considering homogeneous conductivity and permittivity throughout the path. Each homogenous segment along the multiple-segment path has its own conductivity and dielectric constants, which are combined via computational averaging. The irregularities presented by the terrain are disregarded, and the antenna height-gain function is applied to the transmitter and receiver to compensate for their respective heights. Figure 5 illustrates the procedure used to compute the groundwave field strength for zero-height antennas over a path with distinct boundaries.



d_T = Total path of distance
d_1 = Length of segment #1
d_2 = Length of segment #2
d_3 = Length of segment #3
d_4 = Length of segment #4
d_n = Length of segment #*n*
$\sigma_1 \epsilon_1$ = Permittivity and conductivity of segment #1
$\sigma_2 \epsilon_2$ = Permittivity and conductivity of segment #2
$\sigma_3 \epsilon_3$ = Permittivity and conductivity of segment #3
$\sigma_4 \epsilon_4$ = Permittivity and conductivity of segment #4
$\sigma_v \epsilon_v$ = Permittivity and conductivity of segment #*n*

Figure 5. Engineering System Model

Transmission field strength is derived from

$$\xi_{TR} = \frac{\xi_1(d_1)\xi_2(d_1+d_2)}{\xi_2(d_1)} \tag{7}$$

for the transmitter, where $\xi_1(d_1)$ is the field strength at a distance d_1 over an earth having constants σ_1 and ϵ_1, $\xi_2(d_1+d_2)$ is the field strength at a distance d_1+d_2 over an earth having constants σ_2 and ϵ_2, and $\xi_2(d_1)$ is the field strength at a distance d_1 over an earth having constants σ_2 and ϵ_2; and

$$\xi_{RT} = \frac{\xi_2(d_2)\xi_1(d_2+d_1)}{\xi_1(d_2)} \tag{8}$$

for the receiver. The two equations yield the geometric mean of the values by

$$\xi_d = \sqrt{\xi_{TR}\xi_{RT}}\,. \tag{9}$$

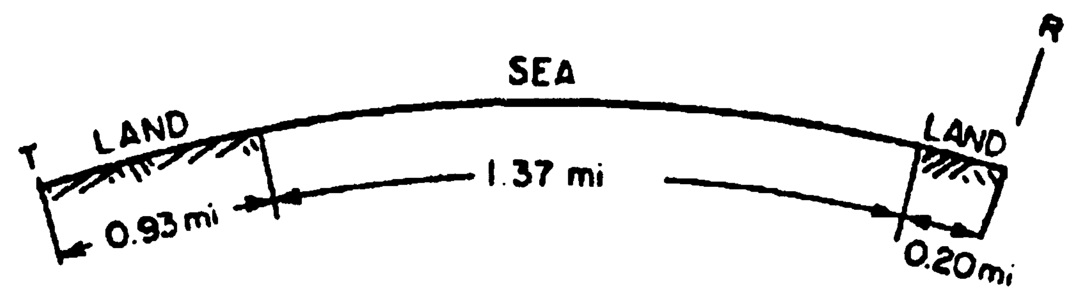
For n boundaries, the field strength in dB expressed at d_n is given by the following equations:

$$\begin{aligned} E_{TR}(dB) = {} & E_1(d_1) + E_2(d_1+d_2) + E_3(d_1+d_2+d_3) \ldots + E_n(d_T) \\ & - E_2(d_1) - E_3(d_1+d_2) \ldots E_n(d_1+d_2+\ldots+d_{n-1}) \end{aligned} \tag{10}$$

$$\begin{aligned} E_{RT}(dB) = {} & E_n(d_n) + E_{n-1}(d+d_{n-1}) + \ldots + E_1(d_T) \\ & - E_{n-1}(d_n) - \ldots - E_1(d_n+d_{n-1}+\ldots+d_2) \end{aligned} \tag{11}$$

$$E_d = \frac{E_{TR}+E_{RT}}{2}. \tag{12}$$

Figure 6 illustrates a transmission path which is composed of an initial 0.93 miles of land, a 1.37 mile segment of sea water, and a final 0.20 mile segment of land.



$d_n = d_3 = 0.20$ miles $\quad E_n = E_3 = E_{land}$
$d_{n-1} = d_2 = 1.37$ miles $\quad E_{n-1} = E_2 = E_{sea}$
$d_1 = 0.93$ miles $\quad E_n = E_3 = E_{land}$

Figure 6. Transmission Path With Three Different segments.

The effects of this mixed path upon the field strength are illustrated in Figure 7. Three ground segments are modeled; the first is the circular region centered on the transmitter with radius of 0.93 sm (statute mile). The second is the ring between 0.93 and 2.3 sm radius, and the third is the region beyond 2.3 sm radius. The field strength curve for the first segment matches that of a land path, but experiences a sharp deviation from the land path curve when it encounters the second segment, which is composed of sea water. Note that the field strength curve does not correspond to the sea water path curve while in the sea water segment, but merely moves toward the sea water path curve. This phenomenon is known as "recovery effect," and illustrates the effect of the sea water segment on the field strength curve that has already passed through a land segment. The field strength curve moves back into correspondence with the land path curve as the path encounters the final land segment of the transmission path, but previous passage through a sea water path prohibits the field strength curve from actually rejoining the land path curve as it completes the passage through the transmission path.

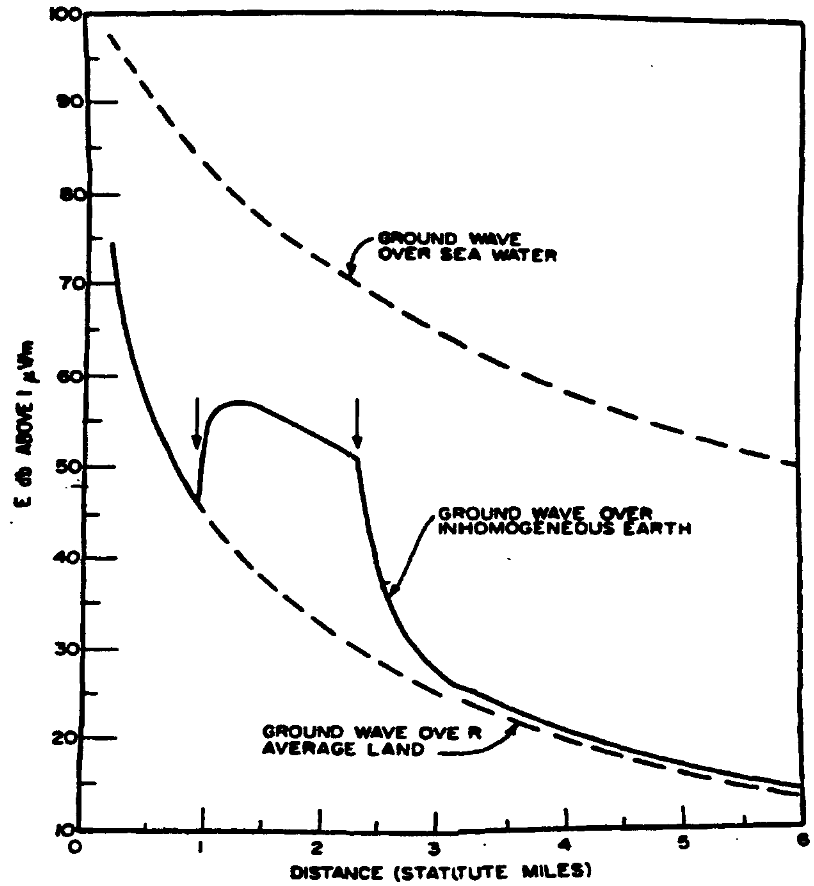


Figure 7. Effects Of A Mixed Propagation Path On The Field Strength Curve.

2. The Computer Model

The ECAC model differentiates between distances that are short enough to assume a planar earth and those long enough that the earth's curvature begins to play a role. The separation distance, d_c, between the planar and curved earth models was found empirically.

When antenna separations exceed d_c, the earth's curvature begins to play a role. The ECAC model fits this added loss as increasing linearly with distance, and the major part of this calculation is to determine the slope of this increase.

3. Input and Output Parameters

MIXPATH predicts propagation based on the input parameters for antenna and feed height and polarization, distance, number of differing path segments, and permittivity, conductivity, refractivity, and surface type for each path segment. An example of output from the MIXPATH Program is shown in Figure 8.

```
UNCLASSIFIED                                                                                                    UNCLASSIF

                                               *** MIXED PATH ***
                                               PATH ID : SAMPLE
                                          COMMENTS : SAMPLE PROBLEM
                     TX ANTENNA: HORIZONTAL DIPOLE                          RX ANTENNA: HORIZONTAL DIPOLE
        NUMBER        PATH          HERTZN        TX HEIGHT        RX HEIGHT        TX ANTENNA        RX ANTENNA
          OF        DISTANCE        POLARI-     ABOVE SMOOTH     ABOVE SMOOTH      FEED HEIGHT       FEED HEIGHT
       SEGMENTS     (ST MI)         ZATION       EARTH  (M)       EARTH  (M)          (WL)              (WL)
       ********    **********       *******     ************     ************     ***********       ***********
          3           44.3             H            50.0             50.0              .5                .5
                SEGMENT    DISTANCE    PERMITTIVITY    CONDUCTIVITY    REFRACTIVITY    SURFACE TYPE
                           (ST MI)                       (MHO/M)
                *******    ********    ************    ************    ************    ************
                   1          1.8          14.0           .00105           301.             D
                   2          8.7          69.2          5.01107           301.             A
                   3         33.8          14.0           .00105           301.             D
                                      *** NOISE CALCULATIONS ***

                                         M/M NOISE TYPE = BUSINESS

              TX
          P O W E R               D A T E        RSN                TX                       RX                         RX
   (W)      (KW)     (DBW)     MONTH   YEAR     DB*HZ     LATITUDE    LONGITUDE     LATITUDE    LONGITUDE        SITE        NAME
  *****    *****     *****     *****   ****     *****     **.**.**,   ***.**.**,    **.**.**,   ***.**.**,    ************************
  400.0     .40      26.0        11    1988      48.                                30-09-00N   075-32-00W    RX HOR DIPOLE
                                                                  *** OUTPUT ***
                                                                                     TX      RX        DAILY          RELIABLE
                                                                                    POWR    POWR       NOISE          DISTANCE
                                                                                    GAIN    GAIN     (DBW/HZ)         (ST MI)
  FREQ(MHZ)            S - Y - S - T - E - M        L - O - S - S                   (DBI)   (DBI)    MIN    MAX       MIN    MAX
  *********            *********************        *************                   *****   *****   *****  *****     *****  *****
$    2.00 - 120.8   *****  *****  *****  *****  *****  *****  *****  *****  *****    2.4     2.4    -136.  -135.     28.7   29.4
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$   24.00 - 127.6   *****  *****  *****  *****  *****  *****  *****  *****  *****    2.3     2.3    -165.  -165.     ###    ###
$   26.00 - 127.8   *****  *****  *****  *****  *****  *****  *****  *****  *****    2.3     2.3    -166.  -166.     ###    ###
$   28.00 - 128.0   *****  *****  *****  *****  *****  *****  *****  *****  *****    2.3     2.3    -167.  -167.     ###    ###
$   30.00 - 128.3   *****  *****  *****  *****  *****  *****  *****  *****  *****    2.3     2.3    -168.  -168.     ###    ###
  *********                                                *****  *****  *****    2.3     2.3
  DIST(ST MI)  44.3                                                                                               ### - RELIAB
                                                                                                                  DISTANCE EXC
                                                                                                                  INPUT PATH
                                                                                                                  DISTANCE

NOTE: $ INDICATES THAT THE MIXED PATH LOSS DOES NOT LIE BETWEEN THE MINIMUM AND MAXIMUM LOSSES CALCULATED FOR THIS PROBLEM.
```

Figure 8. Output Format For MIXPATH.

B. THE ADVANCED PROPHET PROGRAM

1. Approach

ADVANCED PROPHET (AP) is a collection of computer simulation models developed to support tactical use of the HF band (2-32 MHz). For simplicity, the program title "PROPHET" designates ADVANCED PROPHET throughout this report. PROPHET can be used to determine:

- Existence of an HF skywave channel between two sites anywhere in the world,
- The potential for a hostile force to intercept the transmission, to radiolocate the transmitter, or to jam the reception site,
- Groundwave for short range circuits (for instance, it can analyze communications between closely operating units).

To predict groundwave propagation, the program calculates the surface loss from the designated transmitter to the designated receiver. There are three output options; one lists the data in tabular form and the other two produce plots of maximum range versus frequency for the given transmitter power or maximum range versus power for the specified frequency.

2. The Computer Model

PROPHET can access four different models for determining groundwave propagation: ECAC, Booker-Lugannani, Levine, and EPM-73 [Ref. 9]. ECAC was discussed in the previous section.

Booker and Lugananni model the work of Barrick [Ref. 10, 11, 12], deriving an empirical model that considers the surface wave losses for antennas at sea surface, using signals which are vertically polarized [Ref. 13].

The **Levine** model is employed for low-antenna height, smooth-ocean-surface propagation [Ref. 14]. Loss is written in two terms, with a free space loss related term, and an approximation accounting for the additional losses due to curvature and finite earth conductivity:

EPM-73 (the Lustgarten/Madison empirical propagation model) includes calculations for direct ray, reflected ray, and the surface wave, and also considers troposcatter effects at greater distances [Ref. 15].

The model has two sections, determined by the ratio of the antenna height (h) to the wavelength (λ). The high-h/λ section has three regions of interest: the *reflection region*, the *diffraction region*, and the *troposcatter region*.

3. Input and Output Parameters

PROPHET accepts as input parameters the frequency and range of transmission, transmitter power, transmitter gain, antenna heights and polarization, required bandwidth, signal to noise ratio, terrain type, wind velocity, surface conductivity and dielectric constant, and man-made and atmospheric noise models. The program outputs the calculated groundwave transmission path loss and the required power for transmission. Output format for PROPHET is shown in Figure 9. Although not explained in the PROPHET user's manual, in order to perform goundwave calculations based on user-defined constants, it is necessary to enter the terrain type as US.

```
*** UNCLASSIFIED ***          DATE: 2/ 1  AT  12:48 UT
GROUNDWAVE FROM KGST            ON:           1.600 MHZ
  RANGE TO RCVR TEMP RANGE      IS:            17.6 KM
       TRANSMIT GROUNDWAVE GAIN:                 .0 dBi
                   POLARIZATION:                 V
        TRANSMIT ANTENNA HEIGHT:                 .0 METERS
         RECEIVE ANTENNA HEIGHT:                 .0 METERS
              TRANSMITTER POWER:             5000.0 WATTS
             REQUIRED BANDWIDTH:                2.8 KHZ
       REQUIRED SIGNAL TO NOISE:               12.0 dB
                        TERRAIN:                 US
                  SURFACE COVER:                 CL
          SURFACE CONDUCTIVITY:            .10E-02 MHO/M
                     DIELECTRIC:              15.00
            MANMADE NOISE MODEL:                 QR
             ATMOSPHERIC NOISE:                  NO
     CALCULATED GROUNDWAVE LOSS:              79.00 dB
                REQUIRED POWER:                .084 WATTS
               AVAILABLE POWER:            5000.000 WATTS
  MAX RANGE FOR POWER OF       5000.000 WATTS:        192.4 KM
 NOTE:  RECEIVE ANTENNA GROUNDWAVE GAIN ASSUMED = 0.0 dBi
```

Range to RCVR Temp Range is a parameter which allows the user to override computed distance (based on latitude and longitude). The terrain parameter "US" denotes values calculated from the user input values for permittivity and conductivity. The surface cover parameter value "CL" indicates a clear surface, and the noise model parameter "QR" indicates levels of manmade noise found in a quiet rural environment.

Figure 9. PROPHET Output Format.

C. THE GRWAVE PROGRAM

1. Approach

GRWAVE was developed by Leslie Berry at the Institute for Telecommunications Sciences in Boulder, Colorado. The program was modified for execution on a PC by Dr. John Cavanagh of the Naval Surface Warfare Center in July of 1988. Later, CCIR adopted the program to compute groundwave transmission loss. The program can be used to determine transmission loss and field strength transmission loss from the designated transmitter to the designated receiver.

2. The Computer Model

The GRWAVE model considers a smooth, homogeneous earth bounded by a troposphere with exponential height variation. GRWAVE uses three different methods to calculate field strength. At longer distances, the residue series is used, at shorter distances, the model employs the extended form of the Sommerfeld flat-earth theory, and geometric optics are used to calculate field strengths at distances not covered by either residue series or the Sommerfeld theory [Ref. 16]. An examination of the code shows that the program uses five subroutines: geometric optics (GWGO); a flat earth attenuation function using King's Equation (Eq. # 21, 1969) with curvature correction from Hill and Wait (GWFEC); Hill and Wait's (1980) series for small Q (GWSQ); a residue series module (GWRSS); and numerical integration (GWINT).

Unfortunately, the documentation for this program was never completed, therefore all of the information presented here was derived from a limited interpretation of the actual program code. A more thorough understanding of the program's operation is dependent upon further analysis.

3. Input Parameters

GRWAVE requires frequency, polarization, power, ground dielectric constant, lower and higher antenna heights, and distance. The output is illustrated in Figure 10.

```
               GW84 CALCULATION
   FREQUENCY =   1.180 MHZ,   VERTICAL  POLARIZATION.    ERP =  10.00 KW
GROUND CONSTANTS: (4.0000,81.0). (EFFECTIVE RADIUS)/(TRUE RADIUS) = 1.000
      LOWER ANTENNA AT        .0 M, HIGHER ANTENNA AT       .0 M

          DIS,KM      E, DBU      TX LOSS, DB     FS TX LOSS
           20.76      93.0           54.4            60.23
           24.70      91.5           55.9            61.74
```

E, DBU is the field strength expressed in dB.

TX LOSS, DB is the transmission loss expressed in dB.

FS TX LOSS is the free space transmission loss expressed in dB.

Figure 10. GRWAVE Output Format.

IV. COMPARISON OF PROGRAMS

In this chapter, three of the programs described in Chapter III (PROPHET, MIXPATH, and GRWAVE) are compared with respect to the predicteo field strength loss. In Sections A and B, the losses are compared for various ground types for distances from 1 to 180 km. Section C contains a comparison of measured field strengths and predictions by PROPHET. Although most groundwave applications occur at frequencies below 4 or 5 MHz, the comparisons were extended to 30 MHz, since there is one proposed application relating to nuclear survivable communications at this frequency [Ref. 1]

A. COMPARISONS FOR VARIOUS GROUND TYPES AT 1 MHz

In this section, path loss predictions at 1 MHz are compared as a function of ground type and distance over a range of 1 to 180 km. Values for permittivity and conductivity were chosen to reflect the characteristics of sea water, rich agricultural land, flat desert, and free space. These values, and those for other types of transmission paths, are listed in Appendix A. Other parameters common to each program are:

- Power: 10kW
- Antenna: Omni-directional.

- Antenna Height: 0 m.
- Modulation: SSB.
- Bandwidth: 2.8 kHz.
- Polarization: Vertical.
- Surface Cover: Clear.
- Effective Radius/True Radius = 1.

1. Sea Water at 1 MHz

Table 2 and Figure 11 present a comparison of path loss predictions obtained for ground constants representing sea water. As indicated, MIXPATH and GRWAVE agree within 1 dB over the entire range of distances from 1 to 180 km. PROPHET provides 2 to 3 dB lower estimates of path loss throughout the transmission range.

Table 2. COMPARISONS FOR SEA WATER AT 1 MHz

$\epsilon=81 \ \sigma=4$

Distance (km)	PROPHET Path Loss (dB)	MIXPATH Path Loss (dB)	GRWAVE Path Loss (dB)
1	23.94	26.4	26.4
5	37.92	40.4	40.4
10	43.94	46.4	46.4
20	49.96	52.5	52.6
30	53.48	56	56.2
40	55.98	58.5	58.8
50	57.92	60.4	60.9
60	59.5	62	62.6
90	63.03	65.6	66.6
120	65.52	68.1	69.8
180	70.6	73.9	74.8

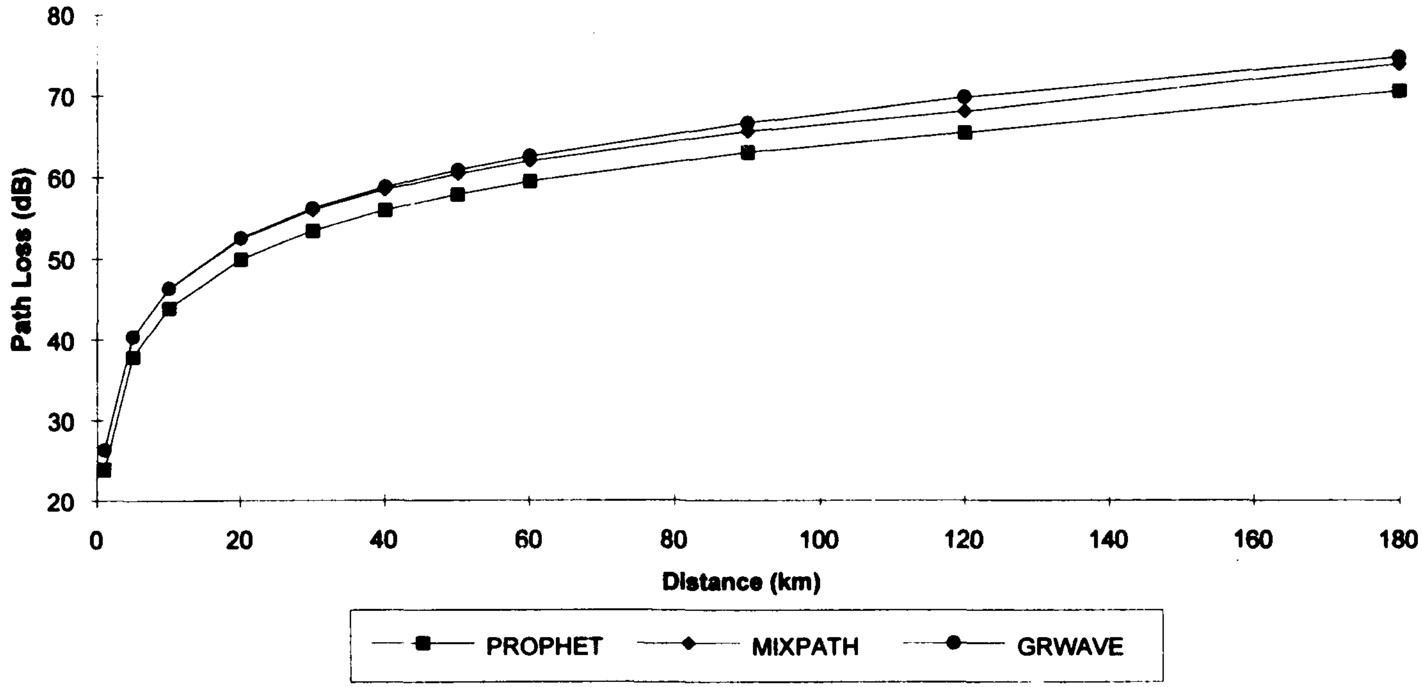

Figure 11. Comparison of Programs for Sea Water at 1 MHz

2. Rich Agricultural Land at 1 MHz

Predicted path loss is listed in Table 3 and displayed in Figure 12. GRWAVE and MIXPATH agree within 2 dB over all distances. PROPHET's path loss estimates in this environment are as much as 7 dB smaller than those of MIXPATH and GRWAVE, which is a significant difference.

Table 3. COMPARISONS FOR RICH AGRICULTURAL LAND AT 1 MHz

$\epsilon=20$ $\sigma=0.04$

Distance (km)	PROPHET Path Loss (dB)	MIXPATH Path Loss (dB)	GRWAVE Path Loss (dB)
1	20.42	26.5	26.5
5	34.4	40.7	40.7
10	40.42	47.1	47.1
20	46.44	53.6	53.8
30	49.96	57.7	57.9
40	53.76	60.8	61.1
50	57.63	63.3	63.6
60	60.8	65.4	65.9
90	67.84	70.5	71.3
120	72.84	74.5	75.8
180	83.37	81.3	83.2

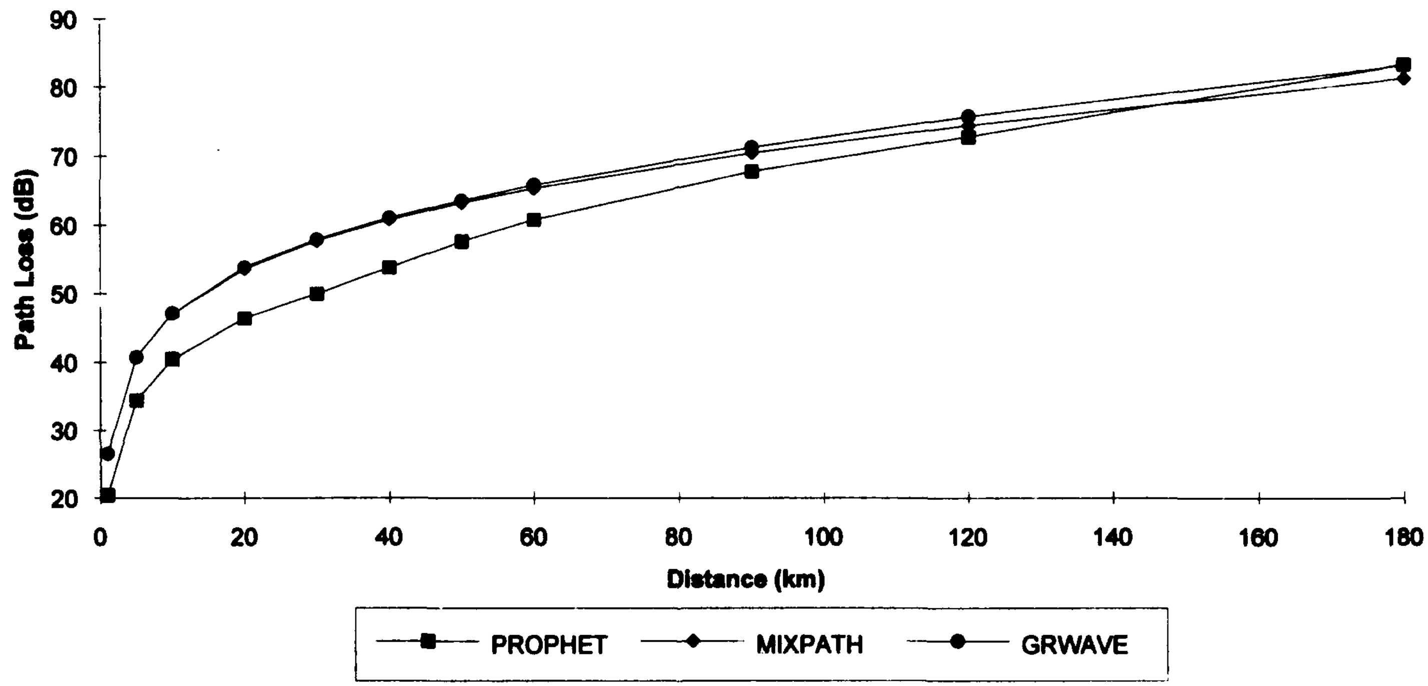

Figure 12. Comparison of Programs for Rich Agricultural Land at 1 MHz

3. Flat Desert at 1 MHz

Path loss predictions for a flat desert environment are listed in Table 4 and displayed in Figure 13. MIXPATH and GRWAVE path loss values agree within 2 dB for all distances. PROPHET's loss estimates are up to 7.6 dB smaller than those of MIXPATH and GRWAVE.

Table 4. COMPARISONS FOR FLAT DESERT AT 1 MHz

$\epsilon=4$ $\sigma=0.011$

Distance (km)	PROPHET Path Loss (dB)	MIXPATH Path Loss (dB)	GRWAVE Path Loss (dB)
1	20.42	26.7	26.7
5	34.4	41.5	41.5
10	40.89	48.5	48.5
20	52.93	56.5	56.6
30	59.97	61.9	62
40	64.97	66.2	66.4
50	68.85	69.9	70.2
60	72.01	73.1	73.5
90	79.06	81	81.8
120	84.06	87	88.3
180	95.15	97.7	98.5

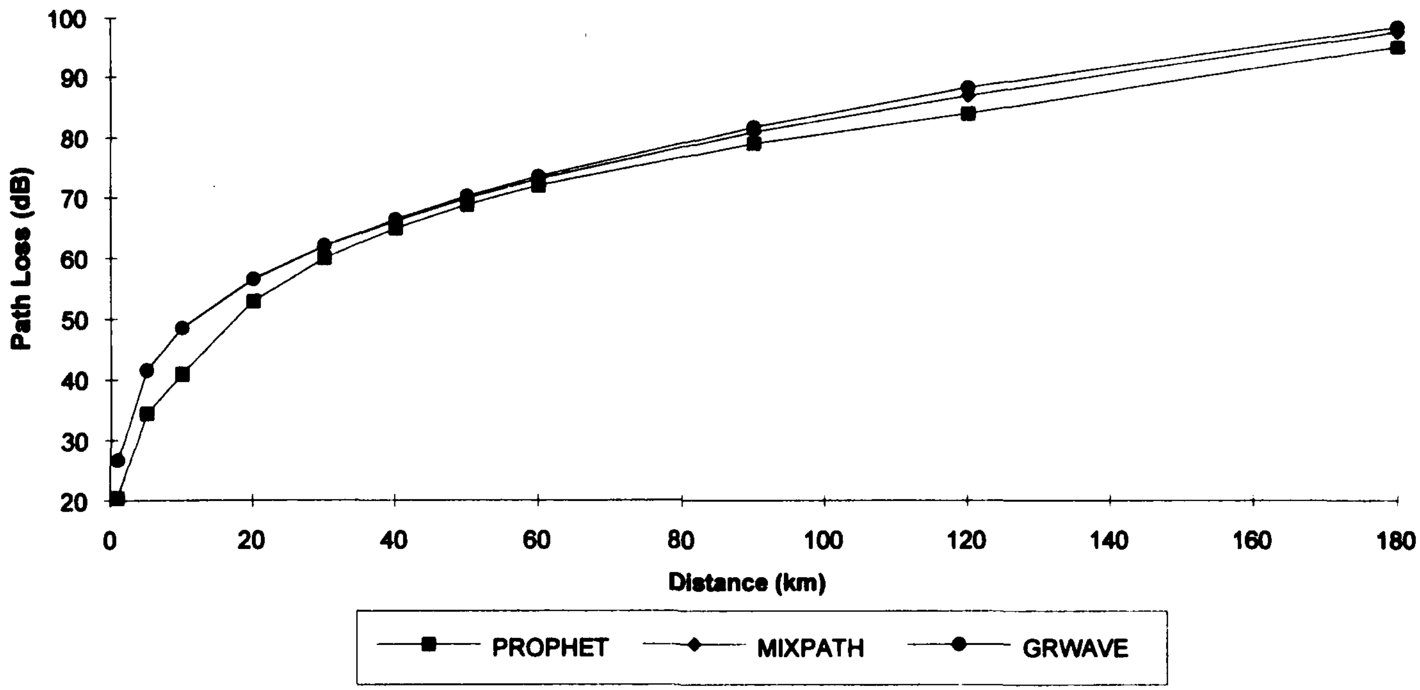

Figure 13. Comparison of Programs for Desert at 1 MHz

4. Free Space at 1 MHz

As a validity test of the programs, the predictions for the simplest of environments, free space, were compared with the exact solutions provided by the laws of physics. Only the LOS path exists with no interfering matter between transmitter and receiver. In the far field, the field strength varies inversely with distance, d, so the loss, in dB, should vary as 20logd. The far field extends from $2D^2/\lambda$ to infinity where D is the antenna dimension and λ the wavelength. For 1 MHz, the wavelength is 300m, so the far field condition is satisfied beyond d=150m in the case of a typical vertical (omnidirectional) dipole antenna. For free space, $\epsilon=1$ and $\sigma=0$. Since the programs do not accept $\sigma=0$, $\sigma=1\times10^{-6}$ mho/m was used. MIXPATH would not accept values below 0.001 mho/m so it was omitted from the comparison. It can be seen that the complex dielectric constant becomes $\epsilon'=1-0.018i$ which is reasonably close to the free space value of $\epsilon'=1.0$. Table 6 lists the program predicted path loss when permittivity and conductivity are adjusted to reflect a free space environment. For each program, predicted path loss is compared to the exact loss calculation, where the latter was adjusted to agree at d=1 km. The large departure of the program predictions from the theoretically exact losses could not be explained since the source codes and/or documentation were not available. Another test is to consider a half-space of infinite conductivity. This is approximated by sea water. In this case, the 20logd behavior of the predicted losses is clearly present in the tabulated results (see

Table 2). The 20logd behavior is expected for all three programs since the far field of an antenna above an infinitely conducting half-space is equivalent to the superposition of the fields of the antenna and its image source, both located in free space.

Table 5. COMPARISONS FOR FREE SPACE AT 1 MHz

Distance	Relative Path Loss in dB			
(km)	PROPHET	20logd	GRWAVE	20logd
1	20.42	20.42	32.5	32.5
5	39.89	34.4	52.4	46.5
10	51.93	40.4	62.2	52.5
20	63.97	46.4	72.7	58.5
30	71.01	50	79.2	62.1
40	76.01	52.5	84	64.6
50	79.89	54.4	87.9	66.5
60	83.05	56	91.1	68.1
90	90.1	59.5	98.7	71.6
120	95.09	62	104.6	74.1
180	106.37	65.5	114.2	77.6

B. COMPARISONS FOR VARIOUS GROUND TYPES AT 5, 10, AND 30 MHz

In Tables 6 and 7, path loss predictions of the programs were compared for transmission paths over sea water and desert at a frequency of 5 MHz. In Tables 8 and 9, the comparisons were based on a frequency of 10 MHz. The programs were also compared for transmission paths over sea water (Table 10) and desert

(Table 11) for a 30 MHz frequency. At 30 MHz, PROPHET appears to have a coding error since the path loss predictions were identical for sea water and desert.

1. Sea Water at 5 MHz

Table 6. COMPARISONS FOR SEA WATER AT 5 MHz

$\epsilon=81$ $\sigma=4$

Distance (km)	PROPHET Path Loss (dB)	MIXPATH Path Loss (dB)	GRWAVE Path Loss (dB)
1	37.92	40.4	40.4
5	51.9	54.5	54.5
10	57.92	60.6	60.6
20	63.94	66.7	67
30	67.46	70.4	70.8
40	69.96	73	73.7
50	71.9	75.1	76.1
60	73.48	76.8	78.1
90	77.81	82.4	83
120	82.12	86.1	87.1
180	89.25	92.4	94.1

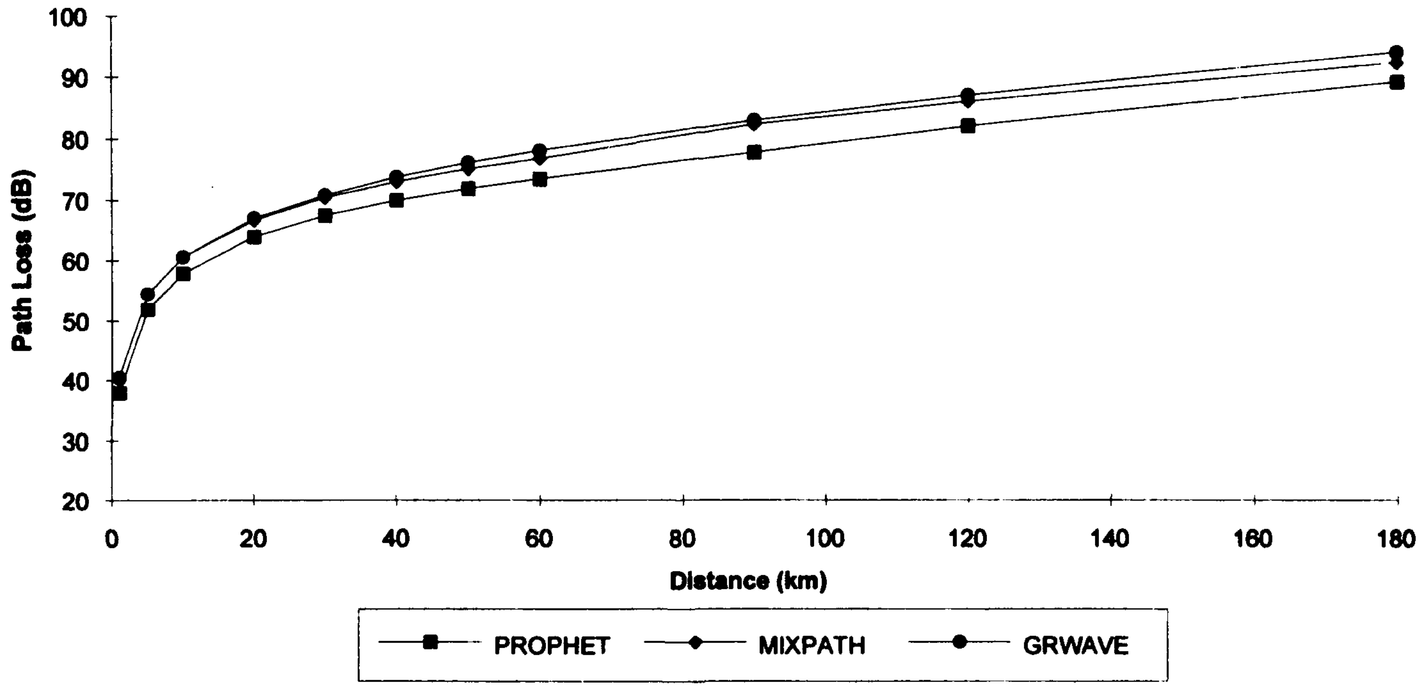

Figure 14. Comparison of Programs for Sea Water at 5 MHz

2. Desert at 5 MHz

Table 7. COMPARISONS FOR DESERT AT 5 MHz

ϵ=4 σ=0.011

Distance (km)	PROPHET Path Loss (dB)	MIXPATH Path Loss (dB)	GRWAVE Path Loss (dB)
1	42.77	46	46
5	70.72	74.1	74
10	82.77	87.6	87.6
20	94.81	100.3	100.7
30	101.85	107.5	108.3
40	106.85	112.6	113.9
50	110.72	116.6	118.5
60	113.89	119.8	122.2
90	125.2	130.2	131.5
120	131.97	137.2	139.2
180	144.03	148.9	152.5

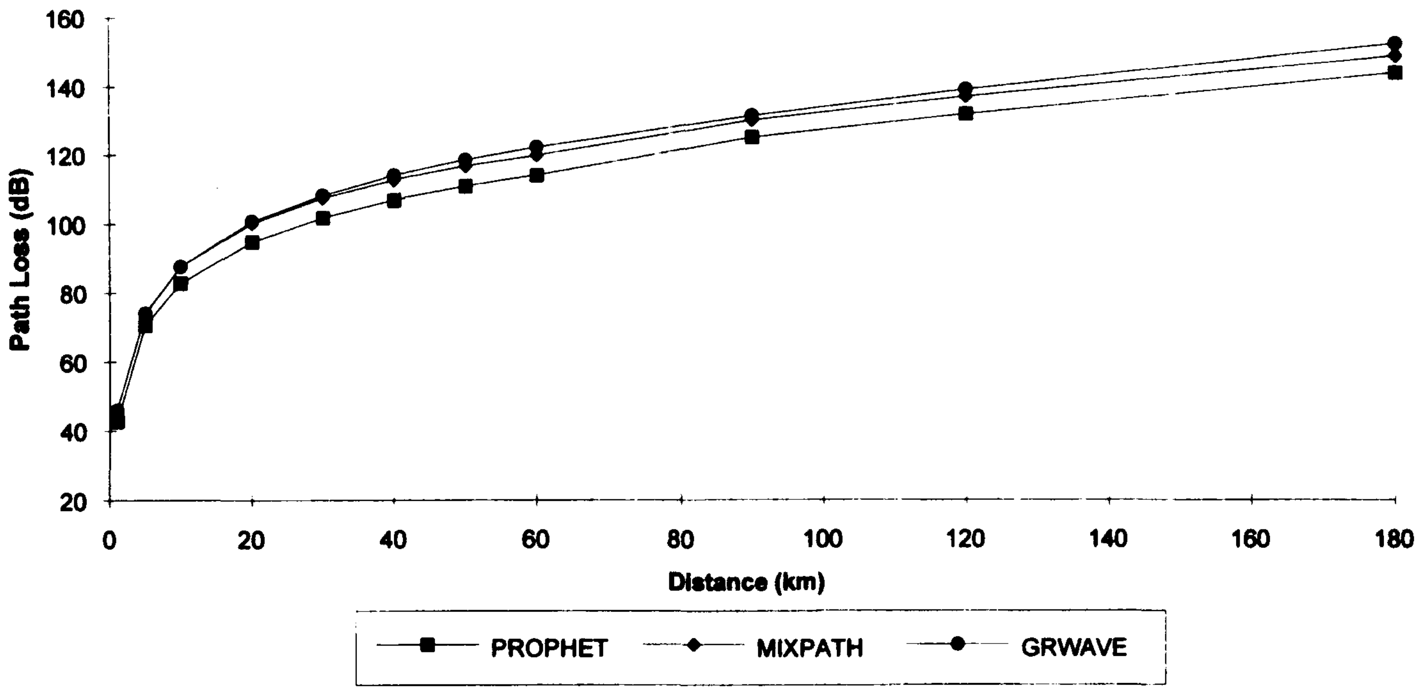

Figure 15. Comparison of Programs for Desert at 5 MHz

3. Sea Water at 10 MHz

Table 8. COMPARISONS FOR SEA WATER AT 10 MHz

$\epsilon=81$ $\sigma=4$

Distance (km)	PROPHET Path Loss (dB)	MIXPATH Path Loss (dB)	GRWAVE Path Loss (dB)
1	43.94	45.5	46.5
5	57.92	60.7	60.7
10	63.94	67	67.1
20	69.96	73.6	73.9
30	73.63	77.6	78.2
40	77.18	80.7	81.6
50	80.16	83.9	84.4
60	82.79	86.5	86.8
90	89.45	92.8	93.1
120	95.09	98	98.5
180	104.89	107.1	108.2

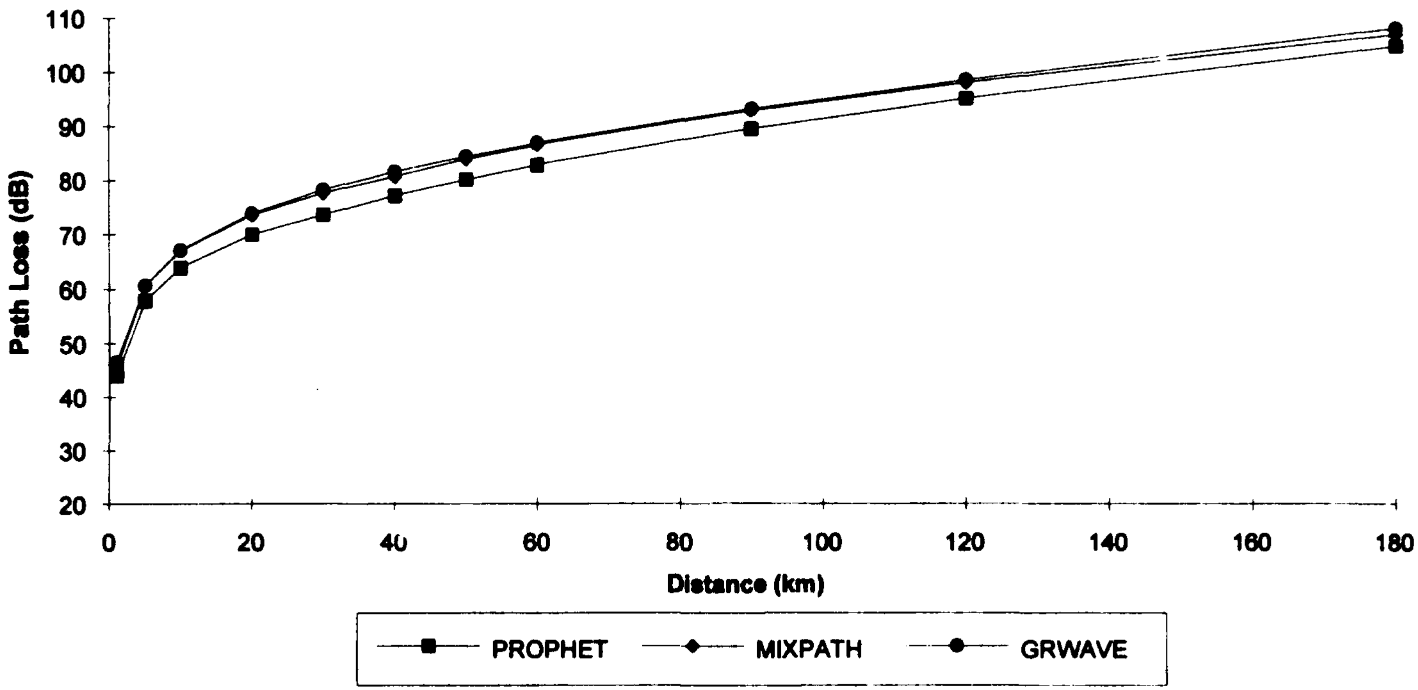

Figure 16. Comparison of Programs for Sea Water at 10 MHz

4. Desert at 10 MHz

Table 9. COMPARISONS FOR DESERT AT 10 MHz

$\epsilon=4$ $\sigma=0.011$

Distance (km)	PROPHET Path Loss (dB)	MIXPATH Path Loss (dB)	GRWAVE Path Loss (dB)
1	60.64	63.7	63.7
5	88.6	94.1	94.1
10	100.64	106.4	106.6
20	112.68	118.6	119.3
30	119.73	125.7	127
40	124.72	130.7	132.8
50	132.12	136.6	137.4
60	135.55	140.4	141.5
90	144.6	149.9	151.8
120	152.63	157.8	160.7
180	167.22	171.5	176.8

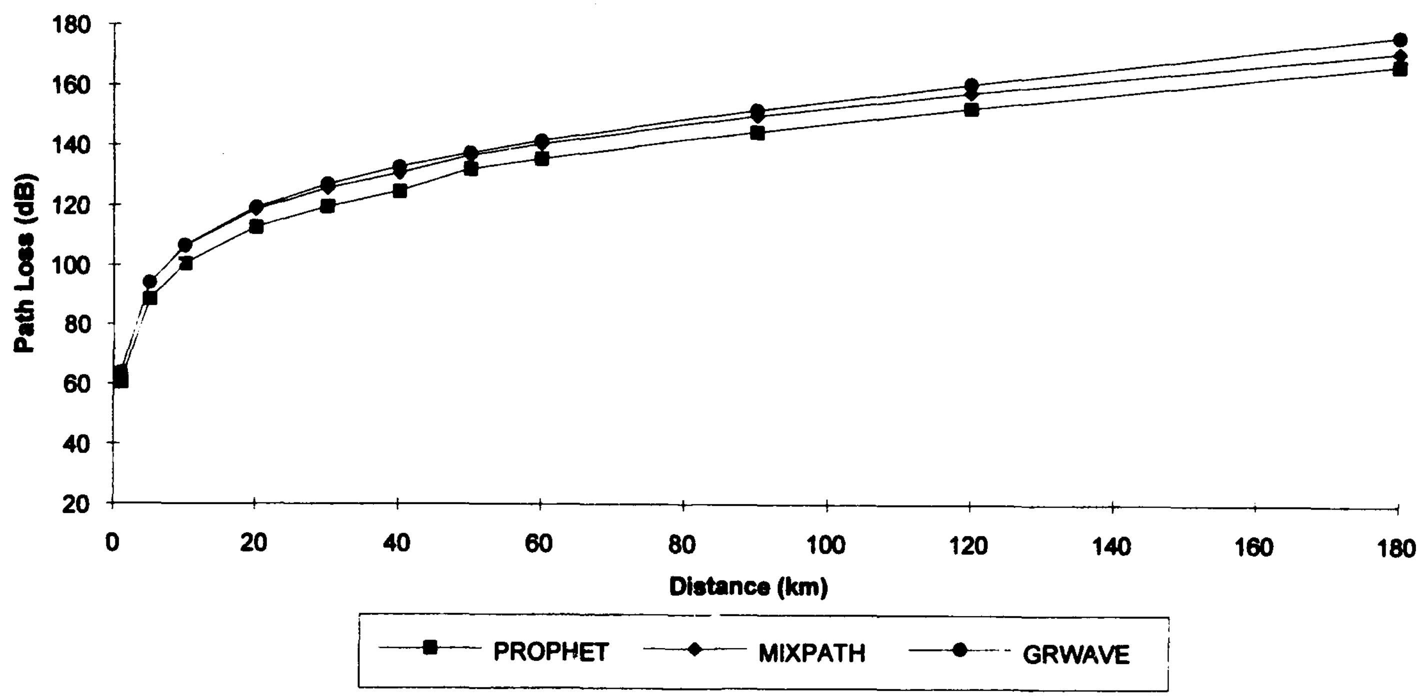

Figure 17. Comparison of Programs for Desert at 10 MHz

5. Sea Water at 30 MHz

Table 10. COMPARISONS FOR SEA WATER AT 30 MHz

ϵ=81 σ=4

Distance (km)	MIXPATH Path Loss (dB)	GRWAVE Path Loss (dB)
1	56.6	56.6
5	72.6	72.6
10	81	81.1
20	91.4	91.9
30	98.8	99.6
40	105.4	106
50	110.8	111.3
60	115.3	116
90	126.1	127.9
120	135.2	138.1
180	151.6	157.4

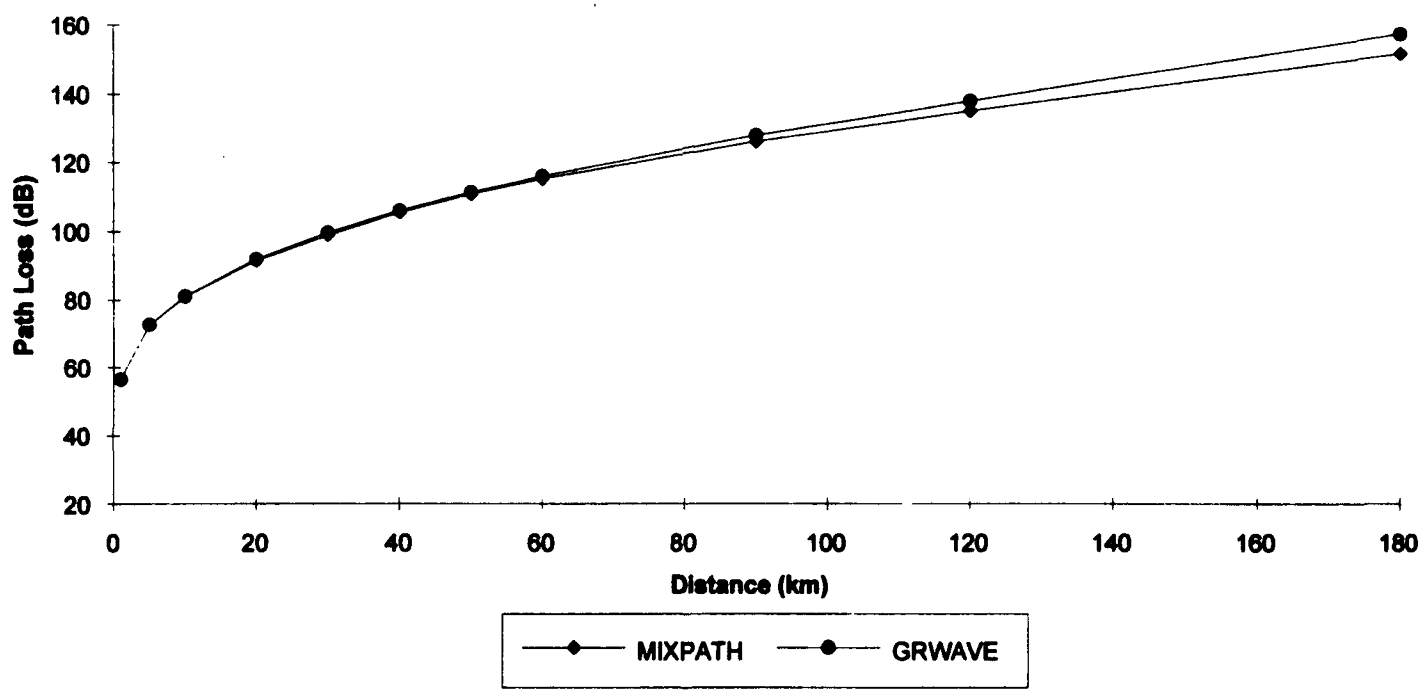

Figure 18. Comparison of Programs for Sea Water at 30 MHz

6. Desert at 30 MHz

Table 11. COMPARISONS FOR DESERT AT 30 MHz

$\epsilon=4$ $\sigma=0.011$

Distance (km)	MIXPATH Path Loss (dB)	GRWAVE Path Loss (dB)
1	93.4	93.4
5	121.6	121.6
10	133.7	134.1
20	145.7	147
30	154.4	155.1
40	160.4	161.4
50	165.4	166.8
60	169.8	171.6
90	181	184.4
120	191	196
180	209.5	218.4

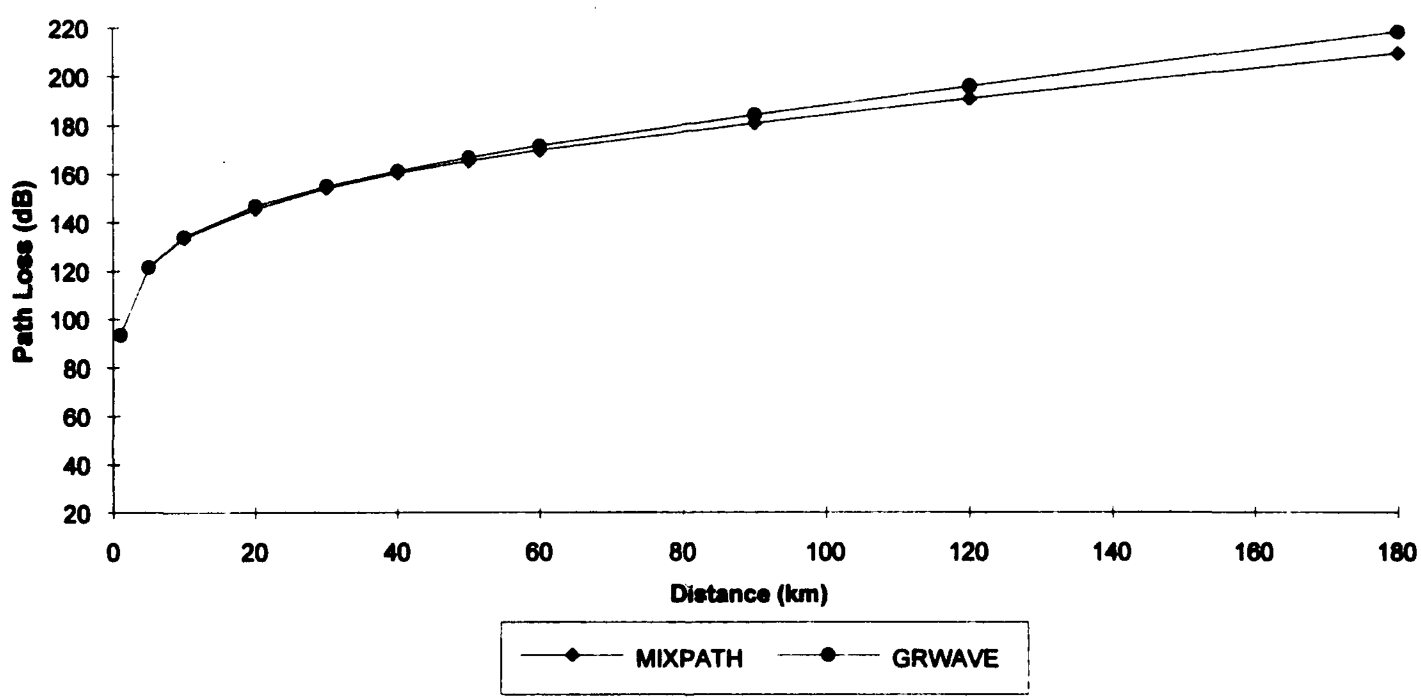

Figure 19. Comparison of Programs for Desert at 30 MHz

C. MEASURED DATA

Field data was obtained from the work of R. Lago [Ref. 21]. The parameters in existence when the field data was collected are used as input parameters for the programs. The field data reflects measurements taken along a transmission path in the case of two AM standard broadcast radio stations (KERI and KGST); the parameters are listed in Table 12.

Table 12. FIELD DATA TRANSMISSION PARAMETERS

	KERI	KGST
Latitude:	35° 34' 19.4"	36° 42' 36"
Longitude:	119° 19' 31.2"	119° 50' 06"
Power (kW):	10	5
Frequency (MHz):	1.18	1.6
Antenna:	Omni-Directional	Omni-Directional
Polarization:	Vertical	Vertical
Date Measured:	01FEB81	01JUN88

In the previous section, the PROPHET groundwave field strength (or path loss) predictions were compared with those of MIXPATH and GRWAVE. In this section PROPHET predictions are compared with measured data for two AM broadcast transmitters at 1.18 and 1.6 MHz. The large discrepancies (up to 18 dB) between the predicted and measured data illustrate the difficulty in using the latter as a yardstick for determining the fidelity of the groundwave models. In addition to unknown modeling error, the discrepancy can largely be attributed to the lack of detailed knowledge of the field environment, including ground constant variation with position and weather, as well as factors such as nearby powerlines and manmade structures.

7. Station KERI

Table 13. COMPARISON OF MEASURED PATH LOSS WITH PROPHET PREDICTIONS, STATION KERI AT 1.18 MHz

Distance (km)	Field Data Path Loss (dB)	PROPHET Path Loss (dB)	Difference (dB)
0.48	N/A	N/A	N/A
0.97	6.8	N/A	N/A
1.45	10.9	6.45	4.45
1.93	13.4	11.42	1.98
2.41	15.6	15.28	0.32
3.06	17.6	19.43	-1.83
3.54	19.4	21.96	-2.56
4.3	20.5	25.34	-4.84
5.07	22.9	28.2	-5.3
6.28	25.3	31.92	-6.62
7.24	26	34.39	-8.39
8.05	26.8	36.23	-9.43
9.5	27.4	39.11	-11.71
11.15	29.5	41.89	-12.39
15.93	33	48.09	-15.09
20.76	37.9	52.69	-14.79
24.7	37.6	55.71	-18.11

8. Station KGST

Table 14. COMPARISON OF MEASURED PATH LOSS WITH PROPHET PREDICTIONS STATION KGST AT 1.6 MHz

Distance (km)	Field Data Path Loss (dB)	PROPHET Path Loss (dB)	Difference (dB)
0.4	N/A	N/A	N/A
0.64	4.3	N/A	N/A
1.61	12.5	N/A	N/A
3.22	19.4	12.04	7.36
4.8	27.4	18.97	8.43
6.44	28.7	24.08	4.62
8.04	32.2	27.94	4.26
9.82	34.1	31.41	2.69
12.56	38.3	35.68	2.62
16.17	40.6	40.07	0.53
21.57	45.3	45.08	0.22
29.13	48.2	50.3	-2.1

V. CONCLUSIONS AND RECOMMENDATIONS

As demonstrated in Chapter 4 GRWAVE and MIXPATH show excellent agreement up to 60 kilometers, less than 1 dB difference at 1 MHz. GRWAVE predicts slightly higher path loss than MIXPATH at ranges beyond 60 kilometers, the maximum difference being 3 dB at ranges from 70 to 180 km. At 1 MHz, the ADVANCED PROPHET loss averages about 5 dB below those of the other programs, with the largest difference being 12 dB for free space (zero conductivity and unity dielectric constant).

At 30 MHz, the maximum difference between the MIXPATH and GRWAVE predictions increases to 9 dB. At 30 MHz and higher frequency, PROPHET appears to have a coding error, since the predicted loss was indentical for sea water and desert.

The comparisons of program results with measured field data show that PROPHET's predictions differ measured path loss by up to 18.1 dB. Large deviations of predictions from measured path loss unusual and can, in part, be attributed to lack of knowledge of the field environments, including ground constants, which can approach 20 dB. Table 15 is a summary of the maximum differences between PROPHET and MIXPATH/GRWAVE path loss predictions which indicate significant errors.

In the limit of an infinite conductivity half-space (approximated by sea water), the field strength predictions of the three programs exhibit the expected theoretical d^{-1} distance behavior. In the limit of free space with zero conductivity (approximated by σ = 0.000001 mho/m), the predicted field strength exhibits a $d^{-1.5}$ to d^{-2} behavior rather than the theoretical d^{-1} law. Since real earth conductivity rarely is less than 0.01 mho/m it is unknown whether the modeling error for the limiting case carries over to parameters of interest.

PROPHET's documentation is limited to a user manual, and the source code is not available. There currently exists no manual for GRWAVE although the source code is available. MIXPATH is well-documented but the source code is not available. MIXPATH and GRWAVE are specifically designed to make groundwave predictions, whereas PROPHET's groundwave routine is a small part of the total package.

It is recommended that future efforts be directed toward reducing the groundwave path loss prediction errors of the programs. Due to its widespread military use, the effort should be directed toward PROPHET. This agrees with the recommendation found in the PROJECT PENEX Quarterly Report of 15 May, 1992 [Reference 22] which advocates the development of an entirely new groundwave model for ADVANCED PROPHET.

Table 15. PROPHET PATH LOSS MINUS MIXPATH OR GRWAVE PATH LOSS IN DB, MAXIMUM DIFFERENCE OVER 180 KM RANGE

	Desert	Sea Water
1 MHz	-7.6	-3.3
5 MHz	-8.5	-5
10 MHz	-9.6	-4.6

APPENDIX

VALUES OF PERMITTIVITY AND CONDUCTIVITY FOR STANDARD TERRAIN TYPES

Terrain Type	ϵ	σ
Sea	81	4
Marsh	30	0.11
Rich Agricultural Land	20	0.04
Medium Hills	15	0.028
Forest	16	0.03
Mountains	6	0.015
Rock	5	0.014
Steep Hills	6.5	0.016
Flat Desert	4	0.011
Cities	5	0.022
Winter Permafrost	7	0.017
Summer Permafrost	2.5	0.095

LIST OF REFERENCES

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