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COMPUTER SCIENCES CORP SAN DIEGO CALIF
HF CHANNEL SIMULATOR FOR WIDEBAND SIGNALS DEVIATIVE ABSORPTION --ETC(U)
NOV 78 R LUGANNANI, H G BOOKER, L E HOFF
NOSC-TR-208-ADD-1

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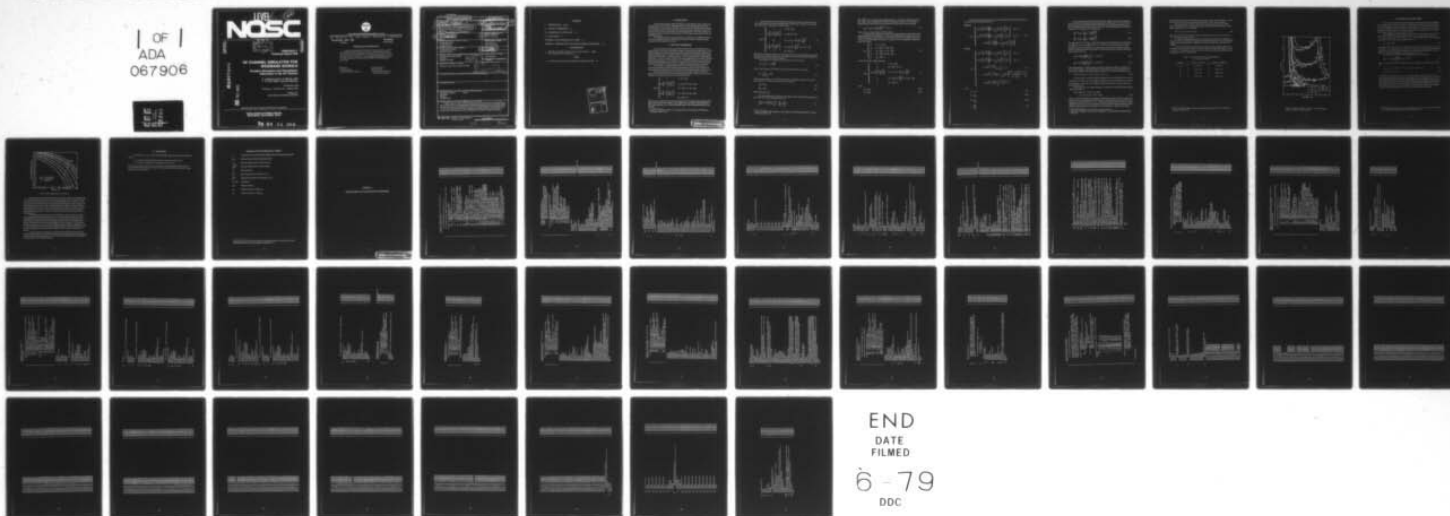
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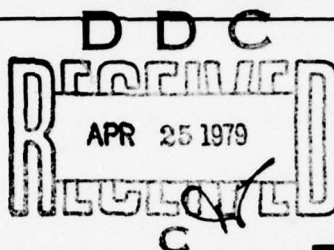
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ADDENDUM 1
NOSC TR 208



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NOSC TR 208

Addendum 1
Technical Report 208

HF CHANNEL SIMULATOR FOR WIDEBAND SIGNALS

Deviative Absorption and Groundwave
Attenuation in the HF Channel

R. Lugannani and H. G. Booker, CSC
L. E. Hoff, NOSC (Contract Monitor)

6 November 1978

Addendum 1: October 1977 - October 1978

Prepared for
Naval Electronic Systems Command

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ADMINISTRATIVE INFORMATION

This work augments NOSC TR 208 and was performed as part of the NAVELEX Skywave Communications Task, a 6.2 Block-Funded program. The work reflected in this addendum was performed under contract to Computer Science Corp., San Diego, in contract N00123-74-C-0312 for Intra-task force/SS Com Branch, Communications Systems and Technology Department, NOSC.

Released by
CA Nelson, Head
Surface Ship Systems Division

Under authority of
HD Smith, Head
Communication Systems and
Technology Department

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Addendum 1 TR-208-ADD-1	2. GOVT ACCESSION NO. 18 NOSC	3. REPORT NUMBER (9) Technical rept.
4. TITLE (and Subtitle) HF CHANNEL SIMULATOR FOR WIDEBAND SIGNALS Deviative Absorption and Groundwave Attenuation in the HF Channel • Addendum 1.		5. REPORT'S PERIOD COVERED October 1977 to October 1978
7. AUTHOR(s) R. Lugannani, HQ/Booker LE/Hoff (Contract Monitor)	8. CONTRACT OR GRANT NUMBER(s) N00123-74-C-0312	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Computer Sciences Corp. 2251 San Diego Ave. San Diego, CA 92110	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62721N; F21222; XF21222091 (B194)	
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Ocean Systems Center San Diego, CA 92152	12. REPORT DATE 6 November 1978	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Naval Electronic Systems Command Code 3105 Washington, DC 20360	13. NUMBER OF PAGES 48	15. SECURITY CLASS. (of this report) UNCLASSIFIED
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE	
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) 16 F21222 17 XF21222091		
18. SUPPLEMENTARY NOTES A 056 629 N		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) High-frequency absorption Fortran Groundwaves Simulators Broadband model		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) In NOSC TR 208, of 31 March 1978, a mathematical model of the wideband HF channel was developed and a software version of the model was presented. This addendum augments that model by including deviative absorption loss for the skywave returns and by providing for automatic calculation of the groundwave attenuation. With these additions, the model more accurately portrays the HF channel and has increased utility. A software version of the revised channel model is implemented and a listing of the program is appended. has been		

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I. INTRODUCTION

This addendum augments NOSC TR 208 (ref. 1) and should be read in conjunction with that report. In the report, a mathematical model of the wideband HF channel was developed and used for computer simulation of the channel. The purpose of this addendum is to augment the existing channel model by adding (1) a deviative absorption term for the skywave returns, and (2) an attenuation term for the groundwave. With these additions the mathematical model will more accurately portray the HF channel and its utility will be considerably enhanced.

In the following sections the two additions are described and a FORTRAN listing of the revised simulator is provided. Notations and definitions used are, wherever possible, identical to those appearing in the report.

II. DEVIATIVE ABSORPTION

The earlier channel model incorporated only three sources of attenuation for the skywave returns. These were nondeviative absorption, antenna gain and spreading ($1/r^2$) loss. Several less-important sources of attenuation, such as polarization mismatch, focusing and deviative absorption, were not included. While the losses due to these other sources are relatively small, one of them — deviative absorption — plays an important role in signal analysis applications. Both the deviative absorption loss and the signal distortion are greater for high-angle returns than they are for low-angle returns. If deviative absorption is not included in the model, the high-angle returns will have an exaggerated effect on the overall received signal, and this may lead to a more pessimistic evaluation of the channel than is warranted.

In what follows, a tractable approximation for the deviative absorption loss is described and sample calculations using this approximation are presented. We begin with some notation and assumptions; all of which have been discussed in greater detail in (ref. 1).

The electron density profile is assumed to have a parabolic shape in the E and F regions; no provision has been made for daytime splitting of the F region into distinct F_1 and F_2 regions. The nighttime electron density profile is given by

$$N(h) = \begin{cases} 0 & , \quad h < h_E - 2H_E \\ N_E \left[1 - \left(\frac{h - h_E}{2H_E} \right)^2 \right] & , \quad h_E - 2H_E \leq h \leq h_E + 2H_E \\ 0 & , \quad h_E + 2H_E < h < h_F - 2H_F \\ N_F \left[1 - \left(\frac{h - h_F}{2H_F} \right)^2 \right] & , \quad h_F - 2H_F \leq h \leq h_F + 2H_F \\ 0 & , \quad h_F + 2H_F < h \end{cases} \quad (1)$$

Here, N_E is the peak electron density (free electrons per m^3) of the E region while h_E is the height of the peak electron density in the E region in km, and $2H_E$ is the semithickness of the E region parabola in km. Similar definitions apply to the F region parameters N_F , h_F and $2H_F$.

1. NOSC TR 208, HF Channel Simulator for Wideband Signals (U), by R Lugannani and HG Booker, Unclassified, 31 March 1978.

For the daytime electron density profile, allowance is made for ionization between the E and F regions. Between these regions the electron density is assumed to be constant and equal to N_E . For the daytime profile we have,

$$N(h) = \begin{cases} 0 & , \quad h < h_E - 2H_E \\ N_E \left[1 - \left(\frac{h - h_E}{2H_E} \right)^2 \right] & , \quad h - 2H_E \leq h \leq h_E \\ N_E & , \quad h_E < h < h_F + 2H_F \left(1 - \frac{N_E}{N_F} \right)^{1/2} \\ N_F \left[1 - \left(\frac{h - h_F}{2H_F} \right)^2 \right] & , \quad h_F + 2H_F \left(1 - \frac{N_E}{N_F} \right)^{1/2} \leq h \leq h_F + 2H_F \\ 0 & , \quad h_F + 2H_F < h \end{cases} \quad (2)$$

The constants appearing in equation (2) are defined in the same manner as they were for the nighttime case, except that their values will be different because of the different heights and ionization densities in the daytime ionosphere.

In the absence of a magnetic field, the refractive index is given by,

$$\mu^2 = \mu^2(h) = 1 - K \frac{N(h)}{f^2} \quad (3)$$

where f is the frequency in Hz, $N(h)$ is given by either equation (1) or (2), and,

$$K = \frac{e^2}{4\pi^2 \epsilon_0 m} \cong 80.5. \quad (4)$$

The penetration frequency for each region is defined as the plasma frequency at the peak electron density. For the E and F regions, these are given by,

$$f_{pE}^2 = KN_E \quad (5a)$$

$$f_{pF}^2 = KN_F \quad (5b)$$

with f_{pE} and f_{pF} in Hz.

For vertical incidence in the absence of a magnetic field, the following expression will be used for the deviative absorption loss (ref. 2)

$$L_{dev}^{(vert)}(f) = \left(\frac{8.686}{c} \right) \int_0^{h_r} \nu \cdot \left[\frac{1}{\mu} - \mu \right] dh. \quad (6)$$

2. Davies, K. Ionospheric Radio Propagation, in National Bureau of Standards Monograph 80, U. S. Government Printing Office, 1965.

Here, $L_{\text{dev}}^{(\text{vert})}(f)$ is the attenuation in decibels per hop, $\nu = \nu(h)$ is the collision frequency in Hz, c is the velocity of light in km/sec and h_r is the height at which $\mu = 0$. In the case of oblique incidence the deviative loss is obtained from (6) by means of the relationship

$$L_{\text{dev}} = L_{\text{dev}}(f) = \frac{1}{\cos \theta} L_{\text{dev}}^{(\text{vert})}(f \cdot \cos \theta) \quad (7)$$

where θ is the ray angle measured from the vertical.

The integration in equation (6) is difficult to perform because of the presence of the collision frequency in the integrand. To overcome this difficulty the integrand will be simplified by taking the collision frequency to be constant in the E and F regions and allowing it to decrease exponentially between the two regions. Thus, for the nighttime collision frequency, we will use,

$$\nu(h) = \begin{cases} 0, & h < h_E - 2H_E \\ \nu_E, & h_E - 2H_E \leq h \leq h_E + 2H_E \\ 0, & h_E + 2H_E < h < h_F - 2H_F \\ \nu_F, & h_F - 2H_F \leq h \leq h_F + 2H_F \\ 0, & h_F + 2H_F < h, \end{cases} \quad (8)$$

and for the daytime collision frequency,

$$\nu(h) = \begin{cases} 0, & h < h_E - 2H_E \\ \nu_E, & h_E - 2H_E \leq h \leq h_E \\ \nu_E \exp \left[-\left(\frac{h - h_E}{2H_E} \right) \right], & h_E < h < h_F + 2H_F \left(1 - \frac{N_E}{N_F} \right)^{1/2} \\ \nu_F, & h_F + 2H_F \left(1 - \frac{N_E}{N_F} \right)^{1/2} \leq h \leq h_F + 2H_F \\ 0, & h_F + 2H_F < h \end{cases} \quad (9)$$

where

$$\nu_E = \nu(h_E) \quad (10a)$$

$$\nu_F = \nu(h_F) \quad (10b)$$

Substituting equations (8) and (9) into (6), performing the integration and using (7) we obtain for the deviative absorption loss:

Nighttime

$$L_{\text{dev}} = \begin{cases} 8.686 \left(\frac{\nu_E \cdot H_E}{2c \cdot x} \right) \left[\left(\hat{f}_{E^x} + \frac{1}{\hat{f}_{E^x}} \right) \ln \left(\frac{1 + \hat{f}_{E^x}}{1 - \hat{f}_{E^x}} \right) - 2 \right], & \hat{f}_{E^x} \leq 1 \\ 8.686 \left(\frac{\nu_E \cdot H_E}{c \cdot x} \right) \left[\left(\hat{f}_{E^x} + \frac{1}{\hat{f}_{E^x}} \right) \ln \left(\frac{\hat{f}_{E^x} + 1}{\hat{f}_{E^x} - 1} \right) - 2 \right], & \hat{f}_{E^x} > 1 \\ + 8.686 \left(\frac{\nu_F \cdot H_F}{2c \cdot x} \right) \left[\left(\hat{f}_{F^x} + \frac{1}{\hat{f}_{F^x}} \right) \ln \left(\frac{1 + \hat{f}_{F^x}}{1 - \hat{f}_{F^x}} \right) \right] \end{cases} \quad (11)$$

Daytime

$$L_{\text{dev}} = \begin{cases} 8.686 \left(\frac{\nu_E \cdot H_E}{2c \cdot x} \right) \left[\left(\hat{f}_{E^x} + \frac{1}{\hat{f}_{E^x}} \right) \ln \left(\frac{1 + \hat{f}_{E^x}}{1 - \hat{f}_{E^x}} \right) - 2 \right], & \hat{f}_{E^x} \leq 1 \\ 8.686 \left(\frac{\nu_E \cdot H_E}{2c \cdot x} \right) \left[\left(\hat{f}_{E^x} + \frac{1}{\hat{f}_{E^x}} \right) \ln \left(\frac{\hat{f}_{E^x} + 1}{\hat{f}_{E^x} - 1} \right) - 2 \right], & \hat{f}_{E^x} > 1 \\ + 8.686 \left(\frac{\nu_E \cdot H_E}{c \cdot x} \right) \frac{1}{\hat{f}_{E^x} (\hat{f}_E^2 x^2 - 1)^{1/2}} \\ + 8.686 \left(\frac{\nu_F \cdot H_F}{c \cdot x} \right) \cdot \left(\hat{f}_{F^x} + \frac{1}{\hat{f}_{F^x}} \right) \ln \left(\frac{\sqrt{1 - r^2} + \sqrt{\hat{f}_F^2 x^2 - r^2}}{\sqrt{1 - \hat{f}_F^2 x^2}} \right) \\ - 8.686 \left(\frac{\nu_F \cdot H_F}{c \cdot x} \right) \frac{\sqrt{1 - r^2}}{\hat{f}_{F^x}} \sqrt{\hat{f}_F^2 x^2 - r^2} \end{cases} \quad (12)$$

with,

$$x = \cos \theta \quad (13)$$

$$\hat{f}_E = \frac{f}{f_{pE}} \quad (14a)$$

$$\hat{f}_F = \frac{f}{f_{pF}} \quad (14b)$$

$$r^2 = \frac{f_{pE}^2}{f_{pF}^2} \quad (15)$$

In the foregoing analysis, the effect of the earth's magnetic field has been neglected, but we take this to be an adequate approximation for the ordinary wave. For the extraordinary wave, the penetration frequencies are shifted relative to those for the ordinary wave and it is essential to take this into account. As in (ref. 1) the extraordinary wave penetration frequencies are obtained using the relationships,

$$f_{pE}^{(x)} = \frac{1}{2} f_{HE} + \left[f_{HE}^2 + 4 \left(f_{pE}^{(0)} \right)^2 \right]^{1/2} \quad (16a)$$

$$f_{pF}^{(x)} = \frac{1}{2} f_{HF} + \left[f_{HF}^2 + 4 \left(f_{pF}^{(0)} \right)^2 \right]^{1/2} \quad (16b)$$

Here, the superscripts "0" and "x" denote the ordinary and extraordinary waves respectively, with $f_{pE}^{(0)}$ given by (5a) and $f_{pF}^{(0)}$ given by (5b). The frequencies f_{HE} and f_{HF} are the gyrofrequencies associated with the earth's magnetic field at the levels of maximum ionization density in the E and F regions respectively. For the gyrofrequencies we will use the approximate expressions (ref. 2),

$$f_{HE} = 0.87 \left(\frac{6370}{6370 + h_E} \right)^3 [1 + 3 \sin^2 \Phi]^{1/2} \quad (17a)$$

$$f_{HF} = 0.87 \left(\frac{6370}{6370 + h_F} \right)^3 [1 + 3 \sin^2 \Phi]^{1/2} \quad (17b)$$

where f_{HE} and f_{HF} are in MHz, and Φ is the latitude expressed in magnetic coordinates. If ϕ and λ are the respective geographic latitude and longitude, and ϕ_0 and λ_0 represent the latitude and longitude of the north magnetic pole ($\phi_0 \cong 78.3^\circ N$, $\lambda_0 \cong 69^\circ W$), then (ref. 2),

$$\sin \Phi = \sin \phi \sin \phi_0 + \cos \phi \cdot \cos \phi_0 \cdot \cos (\lambda - \lambda_0). \quad (18)$$

We assume that, to calculate deviative absorption for the extraordinary wave, we may use equations (11) and (12), but with $f_{pE}^{(x)}$ and $f_{pF}^{(x)}$ substituted for the ordinary wave penetration frequencies. Otherwise, the calculations for deviative loss take the same form as those for the ordinary wave.

To evaluate L_{dev} , the collision frequency is needed and for this the following approximation will be used,

$$\nu(h) = \exp[12.43 - 0.1773 \cdot (h - 90)] + K \cdot (3.93 \times 10^5) \cdot T^{-3/2} \cdot N(h) \quad (19)$$

Here, $T = T(h)$ is the temperature at height h in degrees Kelvin and K is given by equation (4). The first term on the right side of (19) accounts for collisions between electrons and neutral particles; it is based on table 9.4 of (ref. 3). This term is important in the E region but almost negligible in the F region. The second term in (19) accounts for collisions between electrons and ions and has been taken from equation 4.2.10 of reference 4. This term is relatively

3. Banks, PM, and Kockarts, G, *Aeronomy, Part A*, Academic Press, 1973

4. Ratcliffe, JA, *The Magneto-Ionic Theory and its Applications to the Ionosphere*, Cambridge University Press, 1959

small in the E region, but it is the dominant term in the F region. For the heights of interest here, equation (19) provides an adequate approximation to the collision frequency.

For the temperature, $T(h)$, we will use the profile appearing in the 1959 ARDC Model Atmosphere (ref. 5). Throughout the range of interest in h , this temperature profile will be approximated by the polynomial,

$$T(h) = b_0 + b_1 h + b_2 h^2 + b_3 h^3. \quad (20)$$

The coefficients have been determined using a combination of least squares and minimax fits. The results are listed in table 1.

The deviative absorption loss has been incorporated into the Fortran version of the simulator and a revised listing of the program is presented in appendix A. The changes appear mainly in the existing subroutine "ATTEN" and in the new subroutines "DEVIAT" and "TEMP."

A synthetic ionogram has been generated, using the revised computer program. The resulting curves are presented in figure 1 and they should be compared with figure 5 of this report (ref. 1). The delays are identical for the two figures, but the increased attenuation of the high-angle return is readily evident.

Table 1. Coefficients for polynomial approximation of temperature profile

Coefficient	$100 \text{ km} \leq h < 210 \text{ km}$	$210 \text{ km} \leq h \leq 600 \text{ km}$
b_0	1.414×10^3	1.424×10^3
b_1	-4.428×10^1	3.990×10^{-2}
b_2	4.217×10^{-1}	-1.040×10^{-3}
b_3	-1.004×10^{-3}	3.000×10^{-6}

5. Minzer, RA, Champion, KSW, and Pond, HL, The ARDC Model Atmosphere: Air Force Surveys in Geophysics, No. 115, 1959.

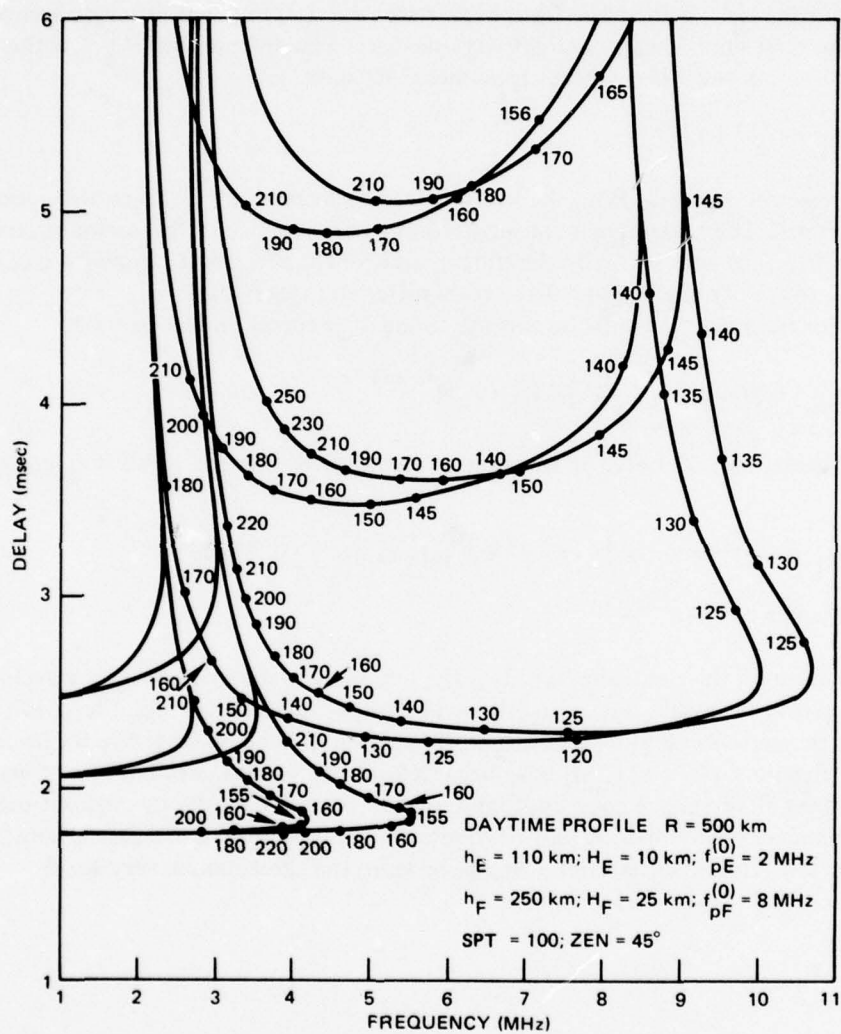


Figure 1. Computed ionosphere returns for one, two, and three hops.
 (Numbers on curve are attenuation in dB.)

III. GROUNDWAVE ATTENUATION

This section is concerned with the attenuation of a groundwave that has propagated across a rough, curved, lossy ocean surface. Our approach is based on the work of Barrick (ref. 6) and represents an attempt to reduce his expressions to a tractable form for computation. By providing for internal calculation of the groundwave attenuation, the utility of the simulator is increased; since, it is no longer necessary to enter this attenuation as a separate input whenever range, frequency, or sea state change.

Following Barrick, the groundwave loss, L_g , will be written as the sum of two terms. The first term, $L_g^{(1)}$, is the basic transmission loss due to propagation across a smooth, curved, lossy (4 mhos/meter conductivity) surface. The second term, $L_g^{(2)}$, is the additional transmission loss caused by surface roughness. We have

$$L_g = L_g^{(1)} + L_g^{(2)} \quad (21)$$

with all losses in decibels. Both the transmitter and receiver are assumed to be located at the ocean surface. The maximum error incurred as a consequence of this assumption is approximately 3% (ref. 6) and is worth tolerating in view of the attendant simplicity (viz, it is not necessary to specify the heights of the transmitter and receiver).

For the basic transmission loss the following expression will be used,

$$L_g^{(1)} = 20 \log_{10} \left(\frac{2\pi R f}{0.3} \right) + C_1(f) \cdot R^{C_2(f)} \quad (22)$$

where R is the distance between transmitter and receiver in km, f is the frequency in MHz, and

$$C_1(f) = (1.78 \times 10^{-4}) \cdot f^{2.58} \cdot \exp [-(1.40 \times 10^{-8}) \cdot f^5] \quad (23)$$

$$C_2(f) = 1.83 \cdot f^{-0.243} \quad (24)$$

The first term on the right side of (22) is the loss the signal experiences by traveling a distance R across a smooth, flat, perfectly conducting surface. The second term is a correction term for the earth's curvature and for a lossy surface; it is based on figure 8 of reference 6. The coefficients $C_1(f)$ and $C_2(f)$ have been determined using a combination of least squares and minimax fits to give a good approximation to Barrick's results throughout the ranges and frequencies of interest. A plot of equation (22) is presented in figure 2 here, together with selected values from Barrick. As can be seen, the agreement is very good.

6. Battelle Memorial Institute Report, Contract DAAH01-70-C-0312, Theory of Groundwave Propagation Across a Rough Sea at Dekameter Wavelengths, by DE Barrick, 1970.

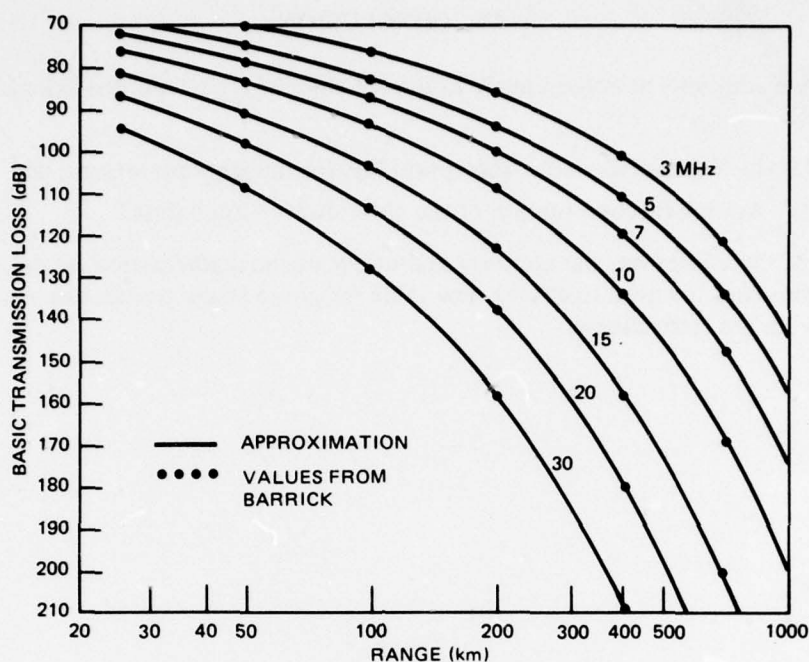


Figure 2. Basic transmission loss for groundwave.

Determination of the additional transmission loss, $L_g^{(2)}$, requires a knowledge of the ocean wave spectrum, which is characterized by specifying the sea state. Two spectra have been considered by Barrick (ref. 6): the Neumann-Pierson spectrum, modified to account for wind direction; and the Phillips spectrum, which is independent of wind direction. The Phillips spectrum was chosen because, as noted by Barrick, it appears to give better agreement with actual observations. Also, the Phillips spectrum results in losses that lie between those obtained for the upwind-downwind and crosswind directions, using the modified Neumann-Pierson spectrum, and it does not require that wind direction be specified as an additional input.

For the additional transmission loss, the dependence on range, frequency, and sea state is complicated and precludes a simple, accurate analytic approximation. However, interpolation can be used to provide good accuracy as well as ease of computation and it is this approach that will be used. The interpolation scheme is linear in both range and frequency, with reference values obtained from figures 25-31 of reference 6. The reference frequencies used are 3, 5, 7, 10, 15, 20 and 30 MHz, while the reference ranges used are 25, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900 and 1000 km. With these reference points the error attributable to the interpolation is negligible for the ranges and frequencies of interest.

A Fortran version of the calculations necessary to determine the groundwave loss has been incorporated into the simulator; a listing of this program is presented in appendix A of this addendum. The changes consist of a new subroutine "GNDATN" and a statement in the main program that calls this subroutine.

IV. CONCLUSION

Two additions have been made to the HF channel model and the associated simulator. These are:

- (1) Inclusion of deviative absorption loss for the skywave returns, and
- (2) Automatic computation of the groundwave attenuation.

The first of these improves the accuracy and utility of the mathematical model, while the second eliminates the need to enter a new value for groundwave attenuation whenever range, frequency, or sea state change.

GLOSSARY OF NEW MATHEMATICAL TERMS*

b_j	Coefficients used in the polynomial approximation of the temperature profile
$C_j(f)$	Parameters used in the approximation of $L_g^{(1)}$
L_{dev}	Deviative absorption loss, oblique incidence
$L_{dev}^{(vert)}$	Deviative absorption loss, vertical incidence
L_g	Groundwave loss
$L_g^{(1)}$	Basic transmission loss component of L_g
$L_g^{(2)}$	Additional transmission loss component of L_g
$T = T(h)$	Temperature
$\nu(h)$	Collision frequency
ν_E	Collision frequency at height h_E
ν_F	Collision frequency at height h_F

*This glossary contains only those symbols that are introduced for the first time in this addendum. Other symbols used in the text are listed in the glossary of the report (ref. 1).

APPENDIX A
PROGRAM FOR CALCULATING CHANNEL PARAMETERS


```

C      GOLLY= GROUNDWAVE DELAY (SEC.)
C      GATTE= GROUNDWAVE ATTENUATION (DB)
C      IPINT= PRINTER SELECTOR FOR T(I,J) ARRAY ('ALL' OR 'RET')
C      NPUNCH= PUNCH SELECTOR- PUNCHES DATA CARDS FOR USE IN
C              SIGNAL ANALYSIS PART OF SIMULATOR IF NPUNCHO.
C              DOES NOT PUNCH DATA CARDS IF NPUNCHO=0.
C
C      ARRAY T(I,J) CONTAINS THE FOLLOWING PARAMETERS
C      I = N1 INDEX NUMBER FOR PATH
C      J = N2 NUMBER OF MOPS
C      = 2: REGION AND MAGNETOIONIC INDICATOR (EO = E REGION -
C            ORDINARY WAVES SIMILARLY FOR EX, FU, AND FX)
C      = 3: 'HIGH' (FOR HIGH RAY) OR 'LOW' (FOR LOW RAY)
C      = 4: SOLUTION INDICATOR (0=NO SOLUTION, 1=SOLUTION)
C      = 5: INCIDENCE ANGLE MEASURED FROM VERTICAL (DEGREES)
C      = 6: PATH LENGTH (KM.)
C      = 7: DELAY AT CARRIER FREQUENCY (SEC.)
C      = 8: RECEIVED CARRIER PHASE (CYCLES)
C      = 9: SIGNAL DELAY (SEC.)
C      =10: AMPLITUDE DISTORTION (SEC/MHZ)
C      =11: PHASE DISTORTION (SEC/MHZ**2)
C      =12: ATTENUATION (DB.)
C      =13: DOPPLER SHIFT (MHZ.)
C      =14: DOPPLER SPREAD (MHZ.)
C
C      PI=3.14159265359
C      IM='INITIAL'
C      PRET='PRET'
C      READ DATA
C      READ//FC,BN
C
C      READ//XLONG,XLAT
C      READ//R
C      READ//RAG
C      READ//FSEA
C      READ//SPT
C      READ//ZLN
C      READ(C,NV09)TIME
C      READ//HLM,HLE,FPEU
C      READ//HF,MHF,FPFU
C      READ//CHUC(1),CHUC(2),CHUC(3),CHUC(4)
C      READ//ABSMILT,SPTMILT,SOLEXP
C      READ//SHIFTFL,EASMTL,SPDRF,FXSPRL,RFRHQF
C      READ//SHIFTFL,EASMTL,SPDRF,FXSPRL,RFRHQF
C      READ//ALTDI
C      READ(C,NV09)TPKINT
C      READ//NPUNCH
C
C      ENDU READ DATA
C      COMPUTE PENETRATION FREQUENCIES FOR EXTRAORDINARY WAVES
C      CALL GETINMAC(XLAT,XLONG,XLATM,XLONGM)
C      SINPI=PI/(180./XLATM)
C      XMLAT=.87*SQR(T(1..3))*SINPMI**2))
C      FME=XMLAT*((.6370/.(6370.*MEM))**.3)
C      FMF=XMLAT*((.6370/.(6370.*MFH))**.3)
C      FPCF=.5*(FMF+SQRT((FPCFO**2)+(.25*(FMF**2))))
C      FPF=.5*(FMF+SQRT((FPCFO**2)+(.25*(FMF**2))))
C      ENDU COMPUTATION OF PENETRATION FREQUENCIES FOR EXTRAORDINARY WAVES
C      COMPUTE BEARING OF RECEIVER IN MAGNETIC COORDINATES
C      CALL RMGMC(XLAT,XLONG,RNARGRAM)
C      ENDU COMPUTATION OF RECEIVER BEARING

```



```

      RMAG/XNHOP
      XNHOP=0*(XNHOP-1)
      DUTS=1.0
      I=1+XNHOP
      T(1,1)=XNHOP
      CONTINUE
      I=1+XNHOP
      ASSIGN LABELS TO EACH TRANSMISSION MODE
      T(1,2)='EU'
      T(1,3)='LOW'
      I=1
      T(1,2)='EQ'
      T(1,3)='HIGH'
      I=1
      T(1,2)='FU'
      T(1,3)='LOW'
      I=1
      T(1,2)='FO'
      T(1,3)='HIGH'
      I=1
      T(1,2)='EX'
      T(1,3)='LOW'
      I=1
      T(1,2)='EX'
      T(1,3)='HIGH'
      I=1
      T(1,2)='FX'
      T(1,3)='LOW'
      I=1
      T(1,2)='FX'
      T(1,3)='HIGH'
      END LABEL ASSIGNMENT
      NMAG = 1 FOR ORDINARY WAVES; NMAG = 2 FOR EXTRAORDINARY WAVE
      DUTS=NMAG*1.2
      IF (NMAG-1) 36,36,37
      SUBROUTINE 'PAIM' RETURNS ARRAY P(I,J) CONTAINING SIGNAL
      PAIM LENGTH, DELAY AND DELAY DERIVATIVES
      CALL PAIM(RH,PFEX,PFDO,FC,P)
      GOTO 38
      CALL PAIM(RH,PFEX,PFDO,FC,P)
      DUTS=1.4
      I=1+4*(NMAG-1)+XNHOP
      T(1,4)=P(I,1)
      T(1,5)=(180./PI)*AMCOS(P(I,3))*P(I,1)
      T(1,6)=XNHOP*P(I,4)
      T(1,7)=P(I,5)*XNHOP
      T(1,8)=FC*P(I,5)*XNHOP*(1.E+06)
      INT=T(1,8)
      T(1,8)=T(1,8)-FLUAT(INT)
      T(1,9)=C(P(I,5)+FC*P(I,6))*XNHOP
      T(1,10)=C(P(I,6)+5*FC*P(I,7))*XNHOP
      T(1,11)=C(C*P(I,7)+((FC*P(I,8))/6.))*XNHOP
      COMPUTE ATTENUATION
      XINH=P(I,11)-(1.E+08)
      IF (XINH) 21,21,20
      FM=1/(1+5)
      DIS=1/T(1,6)
      XMAC=3.-7.*FLUAT(NMAG)
      A(1)=ARSHLT
      A(2)=SPINLT

```

```

C 002101E15
C 002101E11
C 002101F010
C 002101F110
C 002101F213
C 002101F315
C 002101F410
C 002101F712
C 002101F712
C 002101FA11
C 002101FA11
C 002101FA13
C 0021020111
C 0021020411
C 0021020513
C 0021020611
C 0021020811
C 0021020813
C 0021020911
C 0021021211
C 0021021413
C 0021021611
C 0021021911
C 0021021A13
C 0021021A13
C 0021022011
C 0021022113
C 0021022411
C 0021022711
C 0021022813
C 0021022811
C 0021022L11
C 0021022L11
C 0021022L11
C 0021022810
C 0021023014
C 0021023014
C 0021023014
C 0021023014
C 0021023410
C 0021023413
C 0021023715
C 0021023910
C 0021023915
C 0021023L10
C 0021024313
C 0021024414
C 0021024A10
C 0021024712
C 0021025010
C 0021025213
C 0021025314
C 0021025L14
C 0021026012
C 0021026012
C 0021026514
C 0021026A13
C 0021026L11
C 0021026U15
C 0021026714
C 0021027015

```


22

[illegible]


```

30 CONTINUE
C      IF MIN. AE(X) .GT. R, THENL ARE NO RETURNS FROM E REGION
      IF (AMIN-R)40,40,31
11  OUTJ=1,R
      P(1,J)=0,
      P(2,J)=0,
35  CONTINUE
      OUTUBO
C      DO 50 DETERMINS X = COS(THETA) FOR E REGION LOW RAY
      XIAX=1.E-10
      OUTUL=1,R
      DIFF=1./((10.**L)
      X=XLAST+DIFF
      IF(X-XMIN)37,49,49
      CALL AE(FPE,F,X,A)
      IF(A-R)49,49,48
      XIAX=X
      OUTUBO
      XIAX=X-DIFF
50  CONTINUE
      P(1,1)=1,
      P(1,2)=R
      X=AMIN(X,1.)
      P(1,3)=X
      P(1,4)=R/SQRT(1.-X**2)
      CALL DELAYE(R,F,PL,F,X,T,D1T,D2T,D3T)
      P(1,5)=1
      P(1,6)=D1T
      P(1,7)=D2T
      P(1,8)=D3T
      IF(FNE-1.)200,200,60
C      DO 70 DETERMINS X = COS(THETA) FOR E REGION HIGH RAY
      XIAX=(1./FNE)-1.E-10
      OUTUL=1,9
      DIFF=1./((10.**L)
      X=XLAST-DIFF
      IF(X-XMIN)69,69,67
      CALL AE(FPF,F,X,A)
      IF(A-R)69,69,68
      XIAX=X
      OUTUBO
      XIAX=X+DIFF
70  CONTINUE
      P(2,1)=1,
      P(2,2)=R
      X=AMIN(X,1.)
      P(2,3)=X
      P(2,4)=R/SQRT(1.-X**2)
      CALL DELAYE(R,F,PL,F,X,T,D1T,D2T,D3T)
      P(2,5)=1
      P(2,6)=D1T
      P(2,7)=D2T
      P(2,8)=D3T
      IF(FNF-1.)90,90,100
      A0

```

```

C 0141002411
C 0141002512
C 0141002612
C 0141002712
C 0141002812
C 0141002912
C 0141002L14
C 0141002L10
C 0141003014
C 0141003112
C 0141003213
C 0141003310
C 0141003410
C 0141003510
C 0141003613
C 0141003710
C 0141003813
C 0141003910
C 0141003L13
C 0141003U15
C 0141003L15
C 0141004113
C 0141004215
C 0141004314
C 0141004411
C 0141004513
C 0141004614
C 0141004714
C 0141004815
C 0141004912
C 0141004L11
C 0141005215
C 0141005713
C 0141005912
C 0141005B11
C 0141005U10
C 0141005L15
C 0141006013
C 0141006013
C 0141006013
C 0141006013
C 0141006314
C 0141006510
C 0141006713
C 0141006815
C 0141006915
C 0141006L13
C 0141006U15
C 0141006L14
C 0141006F11
C 0141007013
C 0141007214
C 0141007411
C 0141007610
C 0141007814
C 0141007A13
C 0141007L11
C 0141008215
C 0141008414
C 0141008613
C 0141008812
C 0141008A11

```



```

C      DO 150 DETERMINES X = COS(THETA) FOR F REGION HIGH RAY
140  XIAXT=(1./FNF)-1.E-11
    DUTSOL=1,10
    DIFF=1./((10.**1))
146  X=XLAST-DIFF
    IF(X-XMIN)149,149,147
147  CALL AF(FPE,FNF,F,X,A)
    IF(A-R)149,149,148
148  XIAXT=
    GOTO 146
149  XIAXT=X+DIFF
150  CONTINUE
    P(4,1)=1.
    P(4,2)=X
    X=AMINI(X,1.)
    P(4,3)=X
    P(4,4)=X/SORT(1./X**2)
    CALL DELAY(F,FPE,FNF,F,X,T,0.1,0.2,0.3)
    P(4,5)=1
    P(4,6)=U1T
    P(4,7)=U2T
    P(4,8)=U3T
200  RETURN
    END

```

```

C 014100E010
C 014100E010
C 014100E010
C 014100E014
C 014100E010
C 014100E013
C 014100E015
C 014100E015
C 014100F210
C 014100F312
C 014100F411
C 014100F414
C 014100F610
C 014100F611
C 014100F915
C 014100F914
C 014100FL12
C 0141010011
C 0141010415
C 0141010910
C 0141010A15
C 0141010L14
C 0141010L13
C 0141011012
C 0141011015

```

START OF SEGMENT 015

```

C 0151000010
C 0151000010
C 0151000010
C 0151000010
C 0151000010
C 0151000010
C 0151000010
C 0151000010
C 0151000010
C 0151000010
C 0151000010
C 0151000010
C 0151000010
C 0151000015
C 0151000011
C 0151000014

```

```

SURROUTINE AE(FPE,F,X,A)
COMMON ME,ME*MF,MFM*TIME
C      EVALUATES A(X)=A FOR THE E REGION
C      4ME = THICKNESS OF E REGION (KM.)
C      MEH = HEIGHT OF MAX. ELECTRON DENSITY IN E REGION (KM.)
C      FPE = PENETRATION FREQUENCY OF F REGION (MHZ.)
C      X = COS(THETA) THETA=RAY ANGLE MEASURED FROM VERTICAL
C      WARNING: FPE MUST BE LESS THAN FPF
    FPE=F*FPE
    A=2.*SORT((1./X**2)-1.)*(MFM*2.*ME*ME*FFF*ALQ((1.*FFE)/(1.*FFE)))
    RETURN
END

```

```

C
C
C
C
C
C

```


[illegible]

```

SUBROUTINE DEVIAT(F,X,XNU,DDDEV)
  DIMENSION F(3),XNU(4)
  COMMON ME,HEM,HP,FM,TIME

  ***** PROGRAM WRITTEN DECEMBER 1977 *****

  SUBROUTINE COMPUTES DEVIATIVE ABSORPTION

  GLOSSARY OF MOST IMPORTANT TERMS
    AML = THICKNESS OF E REGION (KM.)
    HEM = HEIGHT OF MAX. ELECTRON DENSITY IN E REGION (KM.)
    F(2) = PENETRATION FREQUENCY OF E REGION (MHZ.)
    AMF = THICKNESS OF F REGION (KM.)
    HFM = HEIGHT OF MAX. ELECTRON DENSITY IN F REGION (KM.)
    F(3) = PENETRATION FREQUENCY OF F REGION (MHZ.)
    X =  $\cos(\theta/2)$ ,  $\theta$  = IONOSPHERIC ANGLE MEASURED FROM VERTICAL
    F(1) = CARRIER FREQUENCY (MHZ.)
    TIME = TIME OF DAY ('DAY' OR 'NITE')
    C = VELOCITY OF LIGHT (KM/SEC)
    XNU(1) = COLLISION FREQ. AT HEIGHT HEM (MHZ.)
    XNU(2) = COLLISION FREQ. AT HEIGHT HFM (MHZ.)
    DDDEV = DEVIATIVE ABSORPTION (UR.)

  C=3.E+09
  TIME='NITE'
  FFM=(F(1)+X)/F(2)
  SLM=FMX+(1./FMX)
  IF(FMX=1.)GO11,12
  EL=(1.-FMX)/F(1)-FMX
  DDDEV=XNU(1)+ML*(.5*SE+ALOG(EE)-1.)
  GUTU190
  DDDEV=2U00.
  GUTU200
  IF(FMX=1.)GO13,13
  DDDEV=2U00.
  GUTU200
  SP=FMX+(1./FMX)
  RM=(F(2)/F(3))-.2
  HM=SQRT(1.-RM)
  EE=(FMX+1.)/(FMX-1.)
  IF(TIME='D')GOTO19
  EP=(RM+SQRT(FMX+.2-RM))/SQRT(1.-FMX+.2)
  EQ=(RM+SQRT(FMX+.2-RM))/FMX
  EM1./(FMX+SQRT(FMX+.2-1.))
  DDDEV=XNU(1)+ML*(.5*SE+ALOG(EE)-1.)+HM*(2)*HF+SP*ALOG(EP)+XNU(1)+M
  1E+FM-XNU(2)+HF+EG
  GUTU190
  EF=(1.-FMX)/F(1)-FMX
  DDDEV=2.*XNU(1)+ME*(.5*SE+ALOG(EE)-1.)+XNU(2)+HF*(.5*SE+ALOG(EP)-1
  1.)
  190 DDDEV=(8.686+DDDEV)/(X+1)
  200 RETURN
  END

```



```

C      ASSIGN VALUES TO CONSTANTS USED IN XLASC
      D1=1.7AL-04
      D=2.5R
      U3=1.4AL-04
      E1=1.43
      E2=-.243
      ENU ASSIGNMENT OF VALUES TO CONSTANTS IN XLASC
      ASSIGN REFERENCE FREQUENCY VALUES TO ARRAY FF
      FF(1)=3.
      FF(2)=5.
      FF(3)=7.
      FF(4)=10.
      FF(5)=15.
      FF(6)=20.
      FF(7)=30.
      ENU ASSIGNMENT OF REFERENCE FREQUENCIES
      ASSIGN REFERENCE RANGE VALUES TO ARRAY RR
      RR(1)=25.
      RR(2)=50.
      RR(3)=100.
      RR(4)=200.
      RR(5)=300.
      RR(6)=400.
      RR(7)=500.
      RR(8)=600.
      RR(9)=700.
      RR(10)=800.
      RR(11)=900.
      RR(12)=1000.
      ENU ASSIGNMENT OF REFERENCE RANGES
      ASSIGN VALUES TO ARRAY XA
      XA(1,1)=12=-.6000E-01
      XA(1,1)=2=-.7500E-01
      XA(1,1)=3=-.1000E+00
      XA(1,1)=4=-.1500E+00
      XA(1,1)=5=-.2000E+00
      XA(1,1)=6=-.2500E+00
      XA(1,1)=7=-.3000E+00
      XA(1,1)=8=-.3400E+00
      XA(1,1)=9=-.4000E+00
      XA(1,1)=10=-.4500E+00
      XA(1,1)=11=-.4900E+00
      XA(1,1)=12=-.5500E+00
      XA(1,2)=12=0.
      XA(1,2)=2=-.6000E-01
      XA(1,2)=3=-.9000E-01
      XA(1,2)=4=-.1200E+00
      XA(1,2)=5=-.1500E+00
      XA(1,2)=6=-.1800E+00
      XA(1,2)=7=-.2000E+00
      XA(1,2)=8=-.2400E+00
      XA(1,2)=9=-.2700E+00
      XA(1,2)=10=-.3500E+00
      XA(1,2)=11=-.4000E+00
      XA(1,2)=12=-.4800E+00
      XA(1,3)=12=0.
      XA(1,3)=2=0.
      XA(1,3)=3=-.1300E+00
      XA(1,3)=4=-.1500E+00
      XA(1,3)=5=-.1700E+00

```


XA(2,6, 6)= .9000E+01
 XA(2,6, 7)= .9300E+01
 XA(2,6, 8)= .10650E+02
 XA(2,6, 9)= .12000E+02
 XA(2,6,10)= .13300E+02
 XA(2,6,11)= .14400E+02
 XA(2,6,12)= .16000E+02
 XA(2,7, 1)= .33500E+01
 XA(2,7, 2)= .42500E+01
 XA(2,7, 3)= .42500E+01
 XA(2,7, 4)= .49000E+01
 XA(2,7, 5)= .58000E+01
 XA(2,7, 6)= .66000E+01
 XA(2,7, 7)= .77000E+01
 XA(2,7, 8)= .83500E+01
 XA(2,7, 9)= .92000E+01
 XA(2,7,10)= .10100E+02
 XA(2,7,11)= .10920E+02
 XA(2,7,12)= .11900E+02
 XA(3,1, 1)= .24000E+00
 XA(3,1, 2)= .32500E+00
 XA(3,1, 3)= .42500E+00
 XA(3,1, 4)= .60000E+00
 XA(3,1, 5)= .76000E+00
 XA(3,1, 6)= .93500E+00
 XA(3,1, 7)= .11150E+01
 XA(3,1, 8)= .12780E+01
 XA(3,1, 9)= .14750E+01
 XA(3,1,10)= .16750E+01
 XA(3,1,11)= .18520E+01
 XA(3,1,12)= .20680E+01
 XA(3,2, 1)= .50000E+00
 XA(3,2, 2)= .53000E+00
 XA(3,2, 3)= .67000E+00
 XA(3,2, 4)= .78000E+00
 XA(3,2, 5)= .90000E+00
 XA(3,2, 6)= .10000E+01
 XA(3,2, 7)= .11700E+01
 XA(3,2, 8)= .13000E+01
 XA(3,2, 9)= .14700E+01
 XA(3,2,10)= .16000E+01
 XA(3,2,11)= .18000E+01
 XA(3,2,12)= .20000E+01
 XA(3,3, 1)= .30000E+00
 XA(3,3, 2)= .15000E+00
 XA(3,3, 3)= .20000E+00
 XA(3,3, 4)= .60000E+00
 XA(3,3, 5)= .12000E+01
 XA(3,3, 6)= .16500E+01
 XA(3,3, 7)= .21000E+01
 XA(3,3, 8)= .25000E+01
 XA(3,3, 9)= .30500E+01
 XA(3,3,10)= .36000E+01
 XA(3,3,11)= .41500E+01
 XA(3,3,12)= .48000E+01
 XA(3,4, 1)= .20000E+00
 XA(3,4, 2)= .70000E+00
 XA(3,4, 3)= .17000E+01
 XA(3,4, 4)= .36000E+01
 XA(3,4, 5)= .52000E+01

01C101C011
 01C101C714
 01C101CA11
 01C101CB11
 01C101CE14
 01C101D111
 01C101D411
 01C101D514
 01C101D611
 01C101D811
 01C101D411
 01C101E111
 01C101E411
 01C101E711
 01C101EA11
 01C101EU11
 01C101FU11
 01C101F311
 01C101F411
 01C101F511
 01C101FL12
 01C101FF12
 01C102012
 01C102012
 01C1020812
 01C1020812
 01C1020L12
 01C1021112
 01C1021412
 01C1021712
 01C1021A12
 01C1021U12
 01C1022U12
 01C1022J12
 01C1022612
 01C1022V12
 01C1022L12
 01C1022U14
 01C1023U12
 01C1023U12
 01C1023612
 01C1023V12
 01C1023L12
 01C1023L10
 01C1024U12
 01C1024J12
 01C1024611
 01C1024V11
 01C1024L11
 01C1024F11
 01C1025211
 01C1025411
 01C1025611
 01C1025811
 01C1025L11
 01C1026111
 01C1026411
 01C1026711
 01C1026A11
 01C1026U11

XA(5,5, 7)= .21200E+02
 XA(5,5, 8)= .24300E+02
 XA(5,5, 9)= .27300E+02
 XA(5,5,10)= .30378E+02
 XA(5,5,11)= .33429E+02
 XA(5,5,12)= .36528E+02
 XA(5,6, 1)= .49300E+01
 XA(5,6, 2)= .85000E+01
 XA(5,6, 3)= .10600E+02
 XA(5,6, 4)= .12400E+02
 XA(5,6, 5)= .14700E+02
 XA(5,6, 6)= .17000E+02
 XA(5,6, 7)= .19400E+02
 XA(5,6, 8)= .21700E+02
 XA(5,6, 9)= .24000E+02
 XA(5,6,10)= .26224E+02
 XA(5,6,11)= .28414E+02
 XA(5,6,12)= .30579E+02
 XA(5,7, 1)= .90500E+01
 XA(5,7, 2)= .91500E+01
 XA(5,7, 3)= .90000E+01
 XA(5,7, 4)= .10400E+02
 XA(5,7, 5)= .11900E+02
 XA(5,7, 6)= .13300E+02
 XA(5,7, 7)= .14800E+02
 XA(5,7, 8)= .16300E+02
 XA(5,7, 9)= .17700E+02
 XA(5,7,10)= .19200E+02
 XA(5,7,11)= .20500E+02
 XA(5,7,12)= .21900E+02
 XA(6,1, 1)= .11700E+00
 XA(6,1, 2)= .15000E+00
 XA(6,1, 3)= .10000E+00
 XA(6,1, 4)= 0.
 XA(6,1, 5)= .70000E+01
 XA(6,1, 6)= .11000E+00
 XA(6,1, 7)= .15000E+00
 XA(6,1, 8)= .20000E+00
 XA(6,1, 9)= .23000E+00
 XA(6,1,10)= .25000E+00
 XA(6,1,11)= .26000E+00
 XA(6,1,12)= .30000E+00
 XA(6,2, 1)= .20000E+00
 XA(6,2, 2)= .48000E+00
 XA(6,2, 3)= .10500E+01
 XA(6,2, 4)= .21000E+01
 XA(6,2, 5)= .30500E+01
 XA(6,2, 6)= .39500E+01
 XA(6,2, 7)= .48500E+01
 XA(6,2, 8)= .57000E+01
 XA(6,2, 9)= .65000E+01
 XA(6,2,10)= .72000E+01
 XA(6,2,11)= .79500E+01
 XA(6,2,12)= .86500E+01
 XA(6,3, 1)= .70000E+00
 XA(6,3, 2)= .13000E+01
 XA(6,3, 3)= .27000E+01
 XA(6,3, 4)= .51000E+01
 XA(6,3, 5)= .72000E+01
 XA(6,3, 6)= .92000E+01

C 01C1047011
 C 01C1047111
 C 01C1047A11
 C 01C1047B11
 C 01C1048011
 C 01C1048A11
 C 01C1048B11
 C 01C1048V11
 C 01C1048L11
 C 01C1048F11
 C 01C1049211
 C 01C1049511
 C 01C1049A11
 C 01C1049B11
 C 01C1049V11
 C 01C1049L11
 C 01C1049U11
 C 01C104A11
 C 01C104A311
 C 01C104A611
 C 01C104A911
 C 01C104AL11
 C 01C104AU13
 C 01C104BU11
 C 01C104B311
 C 01C104B611
 C 01C104B911
 C 01C104BL11
 C 01C104BU11
 C 01C104C211
 C 01C104C511
 C 01C104C811
 C 01C104CM12
 C 01C104CL12
 C 01C104CU12
 C 01C104D213
 C 01C104D511
 C 01C104D811
 C 01C104D011
 C 01C104D011
 C 01C104E111
 C 01C104E411
 C 01C104E711
 C 01C104E911
 C 01C104F011
 C 01C104F311
 C 01C104F611
 C 01C104F911
 C 01C104FC11
 C 01C104FF11
 C 01C1050211
 C 01C1050511
 C 01C1050811
 C 01C1050A11
 C 01C1050L11
 C 01C1051111
 C 01C1051411
 C 01C1051711
 C 01C1051A11
 C 01C1051U11

```

XA(6,3,7)=.11100E+02
XA(6,3,8)=.13050E+02
XA(6,3,9)=.15100E+02
XA(6,3,10)=.17200E+02
XA(6,3,11)=.19300E+02
XA(6,3,12)=.21700E+02
XA(6,4,1)=.16500E+01
XA(6,4,2)=.31000E+01
XA(6,4,3)=.59000E+01
XA(6,4,4)=.10200E+02
XA(6,4,5)=.13700E+02
XA(6,4,6)=.17000E+02
XA(6,4,7)=.20200E+02
XA(6,4,8)=.23300E+02
XA(6,4,9)=.26000E+02
XA(6,4,10)=.28907E+02
XA(6,4,11)=.31030E+02
XA(6,4,12)=.30775E+02
XA(6,5,1)=.37000E+01
XA(6,5,2)=.70000E+01
XA(6,5,3)=.10700E+02
XA(6,5,4)=.14000E+02
XA(6,5,5)=.17600E+02
XA(6,5,6)=.21000E+02
XA(6,5,7)=.24500E+02
XA(6,5,8)=.27700E+02
XA(6,5,9)=.30843E+02
XA(6,5,10)=.33947E+02
XA(6,5,11)=.37026E+02
XA(6,5,12)=.40088E+02
XA(6,6,1)=.63000E+01
XA(6,6,2)=.10000E+02
XA(6,6,3)=.12200E+02
XA(6,6,4)=.14000E+02
XA(6,6,5)=.16500E+02
XA(6,6,6)=.19100E+02
XA(6,6,7)=.21600E+02
XA(6,6,8)=.24200E+02
XA(6,6,9)=.26800E+02
XA(6,6,10)=.29315E+02
XA(6,6,11)=.31794E+02
XA(6,6,12)=.34245E+02
XA(6,7,1)=.10800E+02
XA(6,7,2)=.10800E+02
XA(6,7,3)=.10800E+02
XA(6,7,4)=.12100E+02
XA(6,7,5)=.13700E+02
XA(6,7,6)=.15400E+02
XA(6,7,7)=.17100E+02
XA(6,7,8)=.18800E+02
XA(6,7,9)=.20500E+02
XA(6,7,10)=.22200E+02
XA(6,7,11)=.23700E+02
XA(6,7,12)=.25700E+02
      END ASSUMMENT OF VALUES TO ARRAY XA
      DETERMINE IF (=LARGEST INTEGER SUCH THAT F(I,F) .LE. F)
      IF(I-3,120,21,21
      WRITE(6,101)
      WRITE(6,102)F
      GOTO199

```

C C

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