4. FEATURES OF THE PROGRAM "ZEEMAN"

The computer program ZEEMAN has been devised to perform the many calculations we have suggested and to present the results in both tabular and graphical formats. Calculations include (1) the environmental parameters of pressure, temperature, and geomagnetic field components; (2) the refractivities N_o, N_+, N_-; (3) the eigenvalues and eigenvectors of the refractivity tensor; (4) the combination of characteristic waves that produces a given initial polarization and how this combination changes with distance; and (5) the changes in all these quantities as a wave propagates over large distances in Earth's atmosphere. The program has been written for personal microcomputers and uses Microsoft FORTRAN and the HALO graphics package.

The program's design assumes that the problems to be treated are real world problems, and this approach extends even to the environmental parameters. Part of the required input consists of the coordinates of a location--its latitude, longitude, and altitude. Using the U. S. Standard Atmosphere (COESA, 1976) the program picks out a pressure and temperature for that altitude, and using the International Geomagnetic Reference Field (IGRF) for 1985 (Baraclough, 1985) it computes a geomagnetic field vector. The U. S. Standard Atmosphere was illustrated in Table 2 and the IGRF is displayed in Figure 6. The ellipticity of Earth must also be considered, and in this respect it is assumed that the given latitude and longitude are geodetic coordinates and that the altitude is above the local sea level. These are changed to geocentric coordinates for most of the calculations--but note that the Standard Atmosphere is always determined from the local altitude.

The program is menu driven with a question and answer segment that is meant to be self-explanatory. The first task facing a user is to define a "case" for study. This will describe the overall problem that is to be treated and will require such input parameters as altitude, latitude, and longitude; the spectral line of interest and the deviation from its central frequency; the direction of propagation (azimuth and elevation angle); and the initial polarization of the signal. If desired, after a case has been defined it may be stored in a separate disk file and retrieved at a later time.

Figure 7 shows how the program introduces itself and how the first few screens appear. Answering "P" to the last question here will cause the

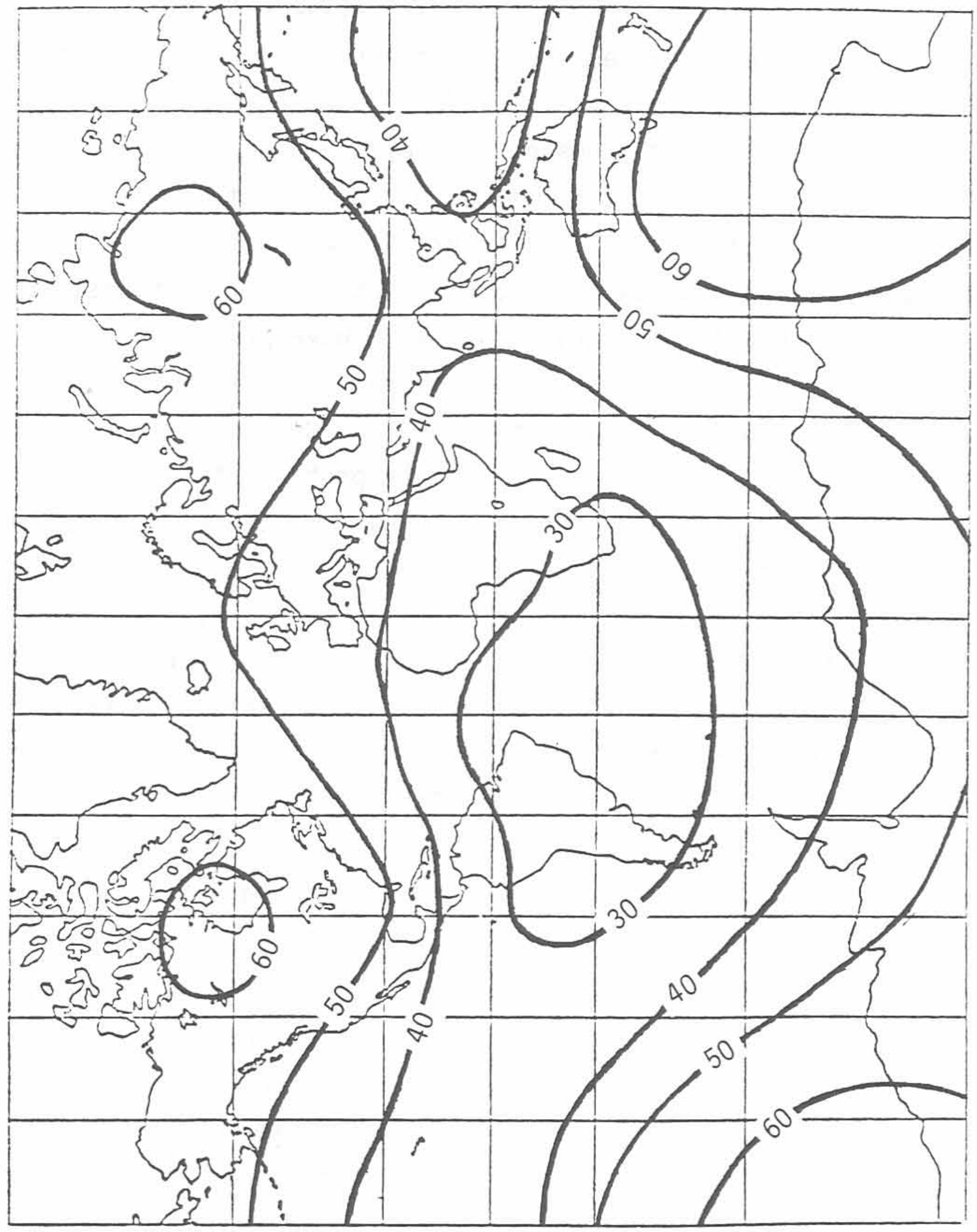


Figure 6. Magnitude of the magnetic flux density as given by the International Geomagnetic Reference Field of 1985.

```
**---------------------------------------------------------------------------**
:                                                                           :
:                                                                           :
:                                                                           :
:                                                                           :
:              Zeeman Mesosphere Wave Propagation Model V3.5                :
:                                                                           :
:                                                                           :
:                                                                           :
**---------------------------------------------------------------------------**

Would you like to enter a case file? (y/n) (N)

  1) K    =     5+          FQO = 59.590980 GHz
  2) h    =    80. km     3) LAT =     .0 deg          4) LON=      .0 deg
  5) DFQ  =    1.0 MHz    6) RES =  .003 MHz
  7) AZI  =     .0 deg    8) ELV =     .0 deg
  9) STEP=  1000         10) INCR=    1.0 km/step
 11) POL  =     .0 deg   12) HZE =    .00              13) VTE =    .00
 14) A    =    8.0 dB max path loss                    15) Screen (X/Y)=1.00

Enter new parameters or edit individual values? (p/e) (E)
Which value to edit? ( )
  1) K    =     5+          FQO = 59.590980 GHz
  2) h    =    80. km     3) LAT =     .0 deg          4) LON=      .0 deg
  5) DFQ  =    1.0 MHz    6) RES =  .003 MHz
  7) AZI  =     .0 deg    8) ELV =     .0 deg
  9) STEP=  1000         10) INCR=    1.0 km/step
 11) POL  =     .0 deg   12) HZE =    .00              13) VTE =    .00
 14) A    =    8.0 dB max path loss                    15) Screen (X/Y)=1.00

Are you satisfied with these values?  (y/n) (Y)
**---------------------------------------------------------------------------**

What output would you prefer?
   T : tables
   G : graphs to screen (default)
   S : save parameters
(T)
Would you like output to a printer?
    0 : screen only (default)
    1 : HP LaserJet
    2 : Epson dot matrix
    3 : HP Plotter file
(2)
What would you prefer to see?
   P : Parameters of propagation case
   N : N components
   E : Eigenvalues (v1,v2)
   C : Characteristic waves
   S : Radio wave propagation (Stokes' parameters, polarization, attn.)
```

Figure 7. The first few screens displayed by program ZEEMAN.

program to display a neatly written summary of the parameters of the case under current consideration. In Figure 8 we have printed out this summary for the Default Case that is coded into the program.

4.1. N Components

Answering "N" to the last question of Figure 7 will produce displays of first the real parts and second the imaginary parts of the three components N_o, N_+, N_-. They are shown as functions of the frequency deviation Δf and are computed from the formulas of Section 2.2. Normally the computations involve one single $K^{\pm}$ line, but for the four doublets flagged in Table 1, requests for one of the lines will always bring in the other as well.

In Figure 9 the graphical output is shown for the Default Case of Figure 8. In Figure 10 the corresponding tabular results are shown, where, however, we have changed RES, the frequency resolution, to 0.05 MHz so as to allow the results to appear on a single page.

4.2. Eigenvalues

If "E" is the answer to the last question in Figure 7, the program will compute and display the two eigenvalues of the matrix $\mathbf{N}^e$. These will be treated as functions of either the angle ϕ or the frequency deviation Δf. For the Default Case we show in Figure 11 the real and imaginary parts of the eigenvalues versus the angle ϕ and in Figure 12 versus the frequency deviation. In Figure 13 we again show the eigenvalues plotted against ϕ but now with $\Delta f = 0$; and the warnings of Section 3.5 become more concrete. When ϕ is near 0° or 180°, the two imaginary parts are equal and with ϕ near 90°, the real parts are equal. At about 66.1° and 113.9° both parts are equal and the refractivity matrix becomes degenerate.

4.3. Characteristic Waves

If "C" is the answer to the last question in Figure 7, the resultant responses concern the characteristic waves. These are represented by the normalized Stokes parameters, g_1, g_2, g_3, and are plotted as functions of the angle ϕ in two different ways.

```
                                  SUMMARY
     Mesospheric Propagation near an Oxygen Microwave Line (Zeeman Effect)
**-----------------------------------------------------------------------------**
        INPUT:           :
                         :      1. GEODETIC COORDINATES
                         :
 h   =      80 km        : (30-100 km, U.S. Std. Atmosphere 1976)
 LAT =      .0 deg       : (0 = equator, 90 = north pole, -90 = south pole)
 LON =      .0 deg       : (0 = Greenwich, +180 East, -180 West)
                         :
                         :      2. GEOMAGNETIC FIELD
                         :
                         :  East = -4.3006 uT   (microTesla)
                         :  North= 26.5012 uT
                         :  Up   = 13.0993 uT
                         :  :B:  = 29.8731 uT     Dip Angle= -26.0 deg
                         :
                         :      3. OXYGEN SPECTRAL LINE
                         :
 K   =       5+          : (42 lines)    FQ0= 59590.980 MHz
                         :
                         :      4. RADIOWAVE CHARACTERIZATION
                         :
                         :a) Frequency:
 DFQ =    1.00 MHz       : (MAX. +/- 250 MHz)
                         :
                         : FQ = FQ0 + DFQ  =    59591.980 MHz
                         :
 RES =    .003 MHz       : (MAX. 2000 points = 2*DEV/RES + 1)
                         :
                         :b) Direction:
 AZI =      .0 deg       : (0 = N, 90 = E, 180 = S, 270 = W)
 ELV =      .0 deg       : (0 = Horizontal, 90 = Vertical)
                         :
                         : Phi =   27.5 deg  ( 0 = parallel to :B:,
                         :                    90 = perpend. to :B:)
                         :
                         :c) Initial Polarization:
 HZE =      .0           : HZE = 0 or VTE = 0 —> linear polariz. (e.g. HL,VL)
 VTE =      .0           : HZE = VTE, POL = 90 —> RightCircular (-90 = LeftC)
 POL =      .0 deg       : Phase angle or linear polariz. orient. angle (0 = HL)
                         :
                         :d) Path Length:
 STEP=    1000           : (10 intervals are marked)
 INCR=     1.0 km/step   :
                         :
                         :e) Max. Attenuation Tolerated by Path:
 A   =       8 dB        :
**-----------------------------------------------------------------------------**
```

Figure 8. The "Summary of Parameters" for the "Default Case" for program ZEEMAN.

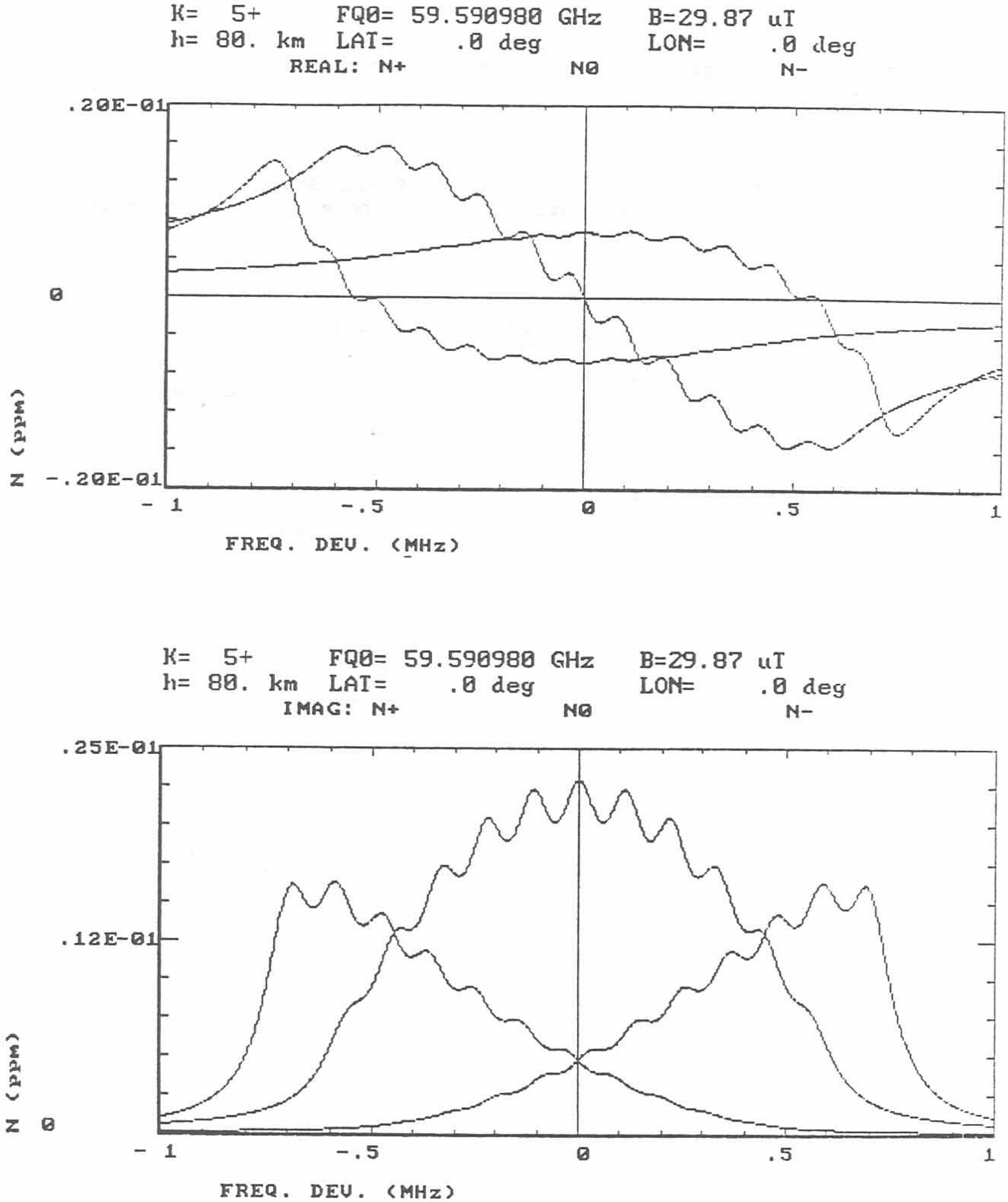


Figure 9. Real and imaginary parts of the N components for the Default Case.

K= 5+ FQO= 59.590980 GHz B=29.87 uT
h= 80. km LAT= .0 deg LON= .0 deg

FREQ. DEV	CNO (ppm)		CN+ (ppm)		CN- (ppm)	
(MHz)	Re	Im	Re	Im	Re	Im
-1.000	.758E-02	.609E-03	.690E-02	.106E-02	.253E-02	.127E-03
-.950	.808E-02	.704E-03	.777E-02	.140E-02	.263E-02	.138E-03
-.900	.865E-02	.828E-03	.891E-02	.195E-02	.274E-02	.151E-03
-.850	.933E-02	.994E-03	.104E-01	.294E-02	.286E-02	.166E-03
-.800	.101E-01	.123E-02	.124E-01	.498E-02	.299E-02	.184E-03
-.750	.111E-01	.158E-02	.141E-01	.961E-02	.314E-02	.206E-03
-.700	.124E-01	.216E-02	.100E-01	.159E-01	.331E-02	.233E-03
-.650	.140E-01	.327E-02	.530E-02	.147E-01	.350E-02	.268E-03
-.600	.155E-01	.557E-02	.366E-02	.161E-01	.372E-02	.313E-03
-.550	.150E-01	.818E-02	-.312E-03	.144E-01	.397E-02	.379E-03
-.500	.155E-01	.957E-02	-.410E-03	.139E-01	.427E-02	.485E-03
-.450	.146E-01	.130E-01	-.342E-02	.132E-01	.458E-02	.672E-03
-.400	.134E-01	.133E-01	-.325E-02	.115E-01	.486E-02	.878E-03
-.350	.131E-01	.166E-01	-.503E-02	.114E-01	.523E-02	.115E-02
-.300	.101E-01	.168E-01	-.522E-02	.937E-02	.545E-02	.154E-02
-.250	.106E-01	.188E-01	-.582E-02	.945E-02	.582E-02	.183E-02
-.200	.653E-02	.199E-01	-.641E-02	.761E-02	.603E-02	.246E-02
-.150	.690E-02	.199E-01	-.620E-02	.740E-02	.623E-02	.273E-02
-.100	.312E-02	.221E-01	-.693E-02	.612E-02	.656E-02	.357E-02
-.050	.240E-02	.203E-01	-.640E-02	.551E-02	.642E-02	.395E-02
.000	-.183E-07	.230E-01	-.692E-02	.479E-02	.692E-02	.479E-02
.050	-.240E-02	.203E-01	-.642E-02	.395E-02	.640E-02	.551E-02
.100	-.312E-02	.221E-01	-.656E-02	.357E-02	.693E-02	.612E-02
.150	-.690E-02	.199E-01	-.623E-02	.273E-02	.620E-02	.740E-02
.200	-.653E-02	.199E-01	-.603E-02	.246E-02	.641E-02	.761E-02
.250	-.106E-01	.188E-01	-.582E-02	.183E-02	.582E-02	.945E-02
.300	-.101E-01	.168E-01	-.545E-02	.154E-02	.522E-02	.937E-02
.350	-.131E-01	.166E-01	-.523E-02	.115E-02	.503E-02	.114E-01
.400	-.134E-01	.133E-01	-.486E-02	.878E-03	.325E-02	.115E-01
.450	-.146E-01	.130E-01	-.458E-02	.672E-03	.342E-02	.132E-01
.500	-.155E-01	.957E-02	-.427E-02	.485E-03	.410E-03	.139E-01
.550	-.150E-01	.818E-02	-.397E-02	.379E-03	.312E-03	.144E-01
.600	-.155E-01	.557E-02	-.372E-02	.313E-03	-.366E-02	.161E-01
.650	-.140E-01	.327E-02	-.350E-02	.268E-03	-.530E-02	.147E-01
.700	-.124E-01	.216E-02	-.331E-02	.233E-03	-.100E-01	.159E-01
.750	-.111E-01	.158E-02	-.314E-02	.206E-03	-.141E-01	.961E-02
.800	-.101E-01	.123E-02	-.299E-02	.184E-03	-.124E-01	.498E-02
.850	-.933E-02	.994E-03	-.286E-02	.166E-03	-.104E-01	.294E-02
.900	-.865E-02	.828E-03	-.274E-02	.151E-03	-.891E-02	.195E-02
.950	-.808E-02	.704E-03	-.263E-02	.138E-03	-.777E-02	.140E-02
1.000	-.758E-02	.609E-03	-.253E-02	.127E-03	-.690E-02	.106E-02

Figure 10. The tabular display of the N components for the Default Case.

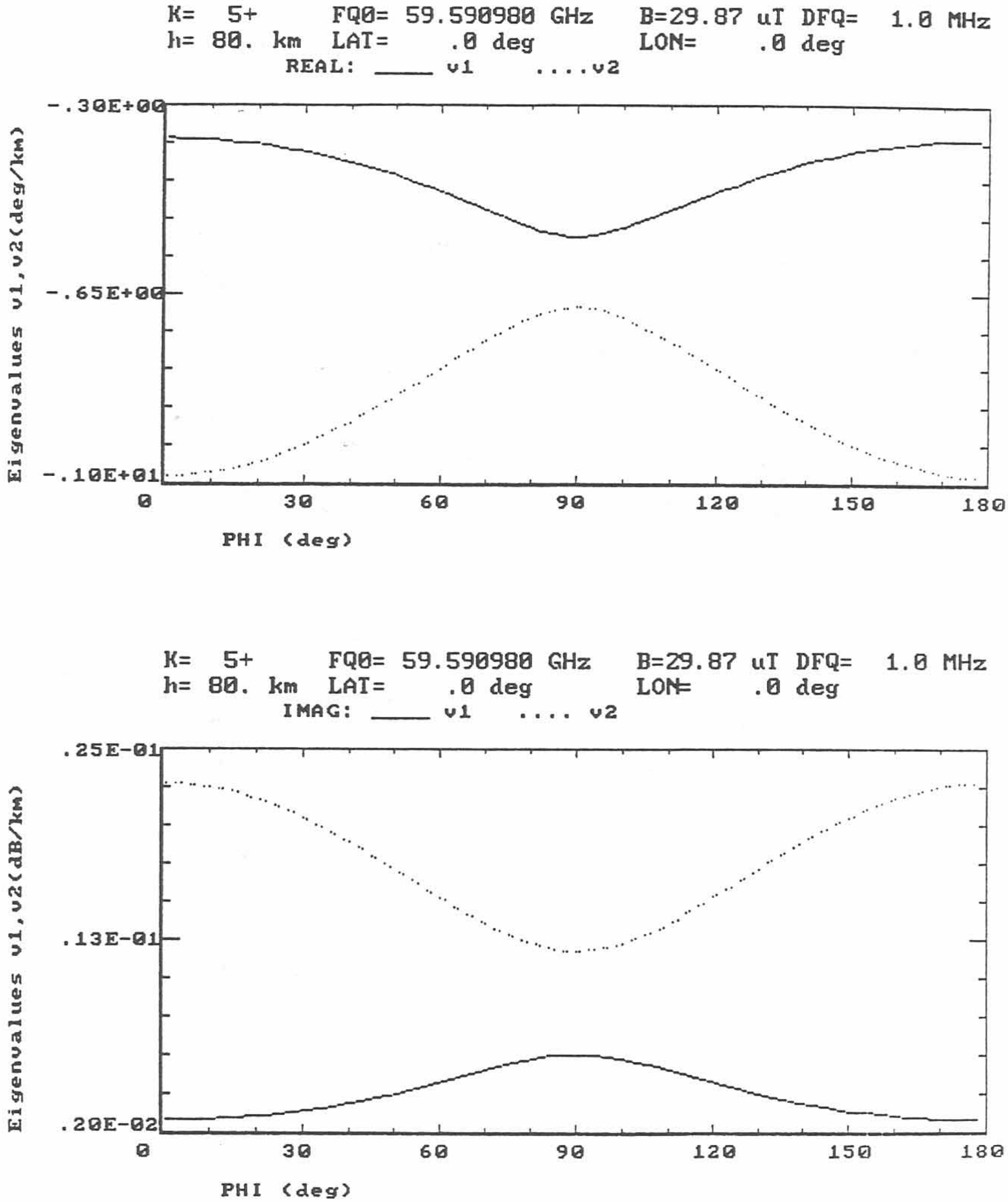
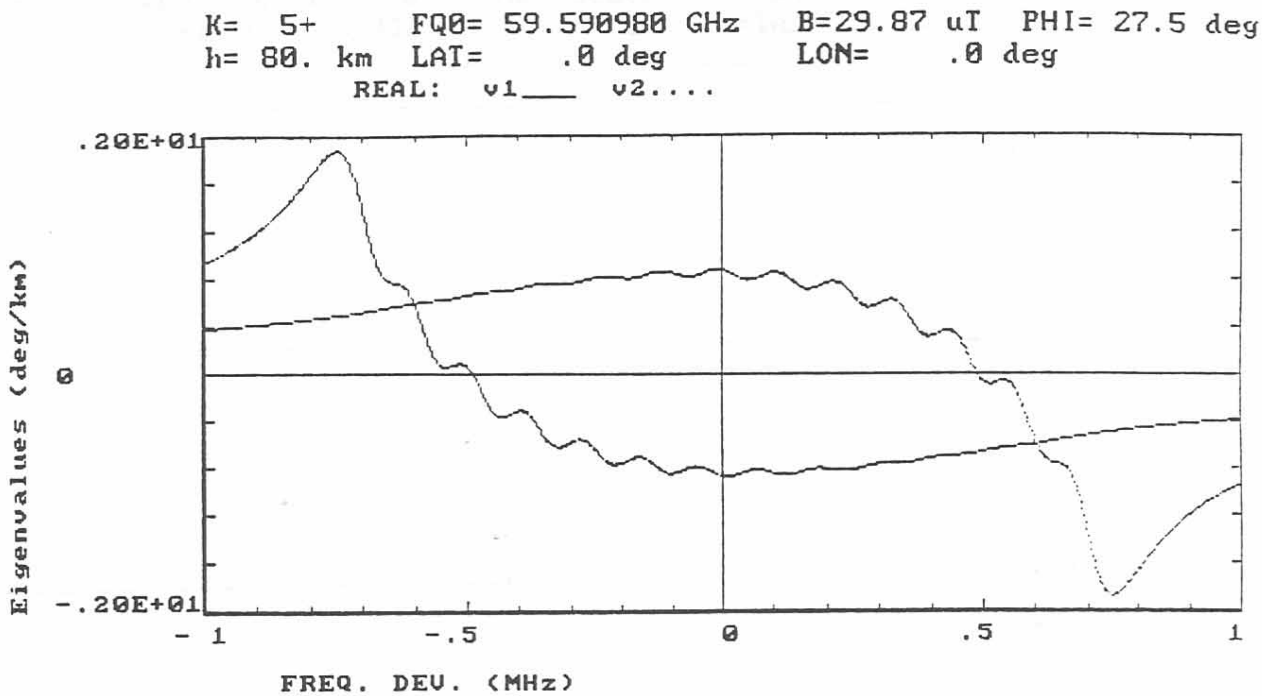


Figure 11. The eigenvalues for the Default Case. Real parts and imaginary parts plotted against the angle ϕ.



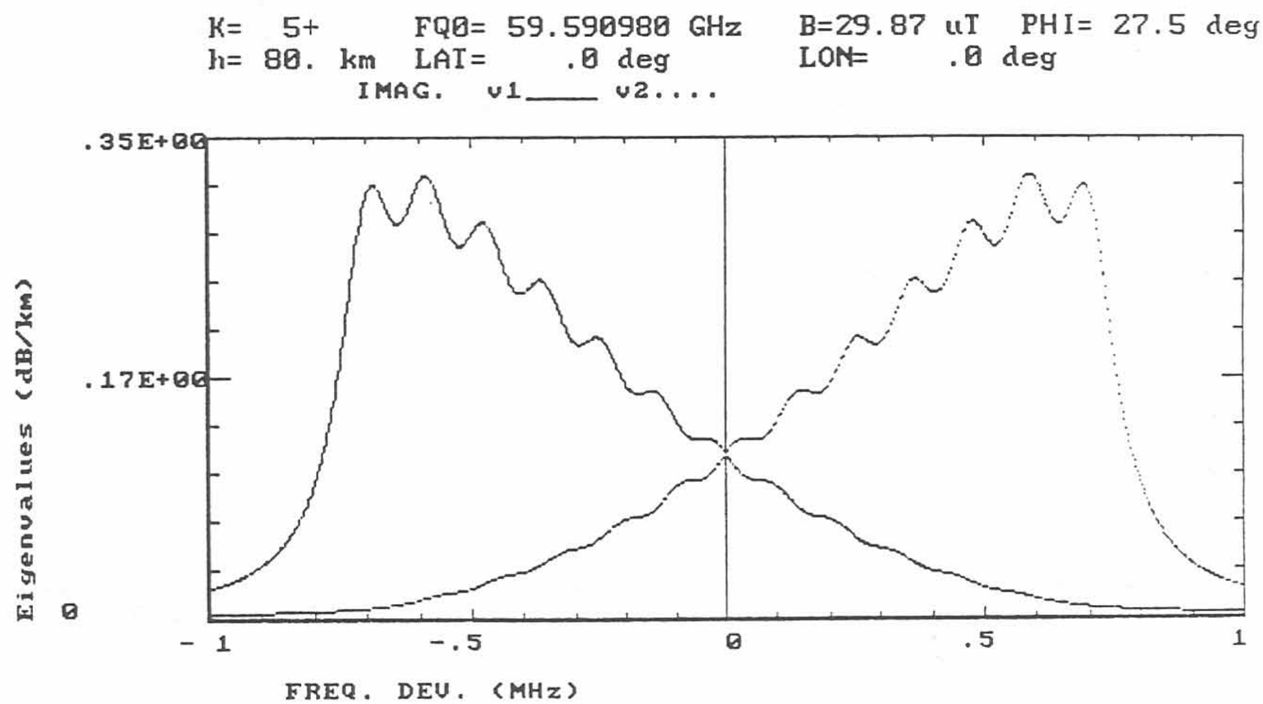


Figure 12. The eigenvalues for the Default Case. Real parts and imaginary parts plotted against the frequency deviation Δf

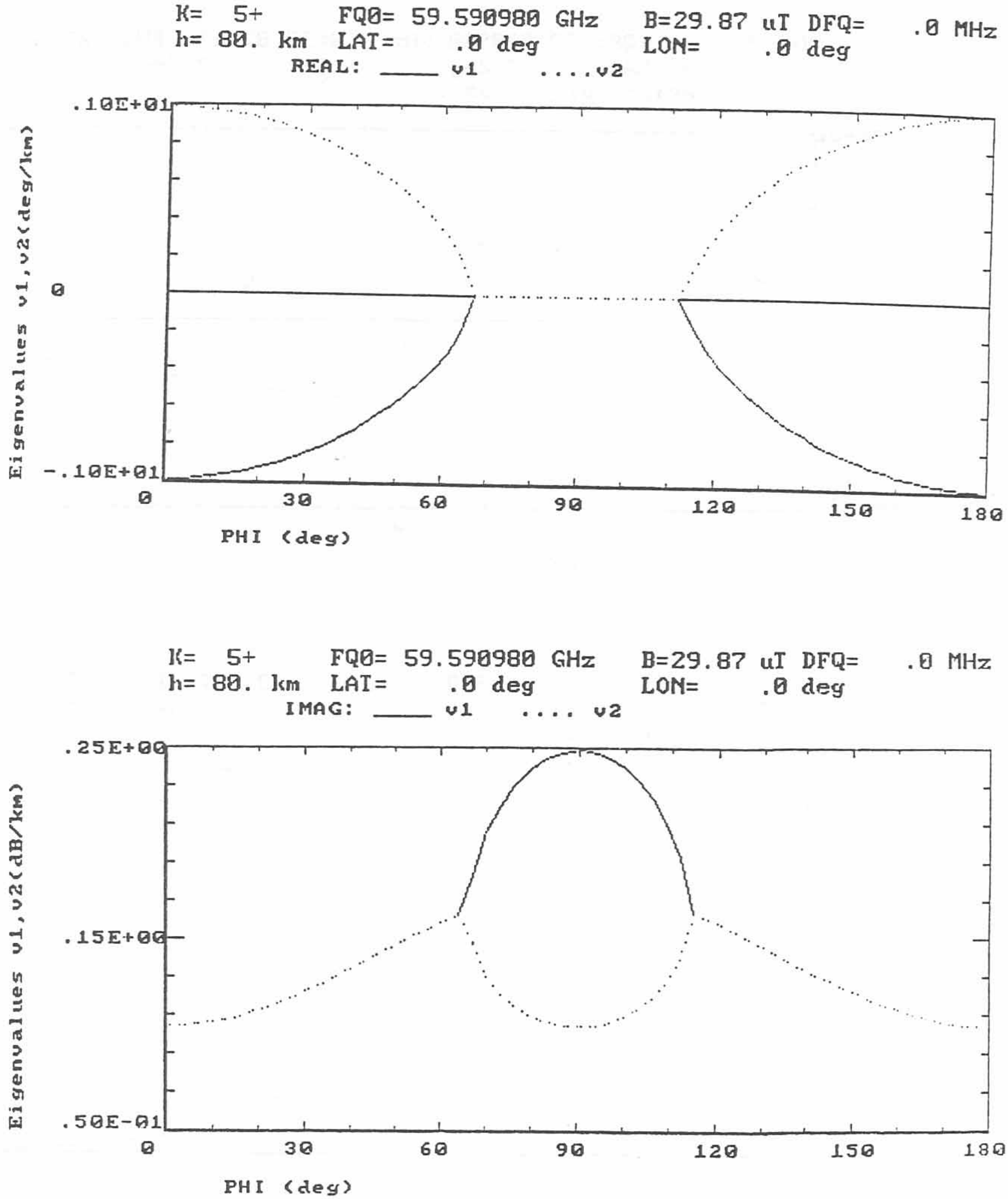


Figure 13. The eigenvalues for the Default Case where, however, $\Delta f = 0$. Real parts and imaginary parts plotted against the angle ϕ.

The first of these ways is illustrated in Figure 14. It is a simple plot of the three functions that correspond to one of the eigenvectors. As we have seen, the Stokes parameters for the other eigenvector are the same except that g_1 and g_3 have opposite signs.

In the second plot the Poincaré sphere is pictured and the eigenvectors are represented by their trajectories on the sphere using ϕ as the parameter. To better read these graphs one should remember that the eigenvectors are circularly polarized (at the North and South Poles) when ϕ is 0° or 180° and linearly polarized (on the Equator) when ϕ is 90°. The results for the Default Case are shown in Figure 15. Note that the display shows two orthographic projections. On the left is an oblique projection with the g_3 axis vertical. On the right is a polar projection in which the vantage point is directly above the sphere.

4.4. Radio Wave Propagation

The actual properties of a propagating wave with an initial arbitrary polarization are provided when "S" is given in answer to the question in Figure 7. There are four graphical options. The first three of these are concerned with propagation through a homogeneous medium having the properties of the atmosphere at the selected location. This notion is not very realistic if the path is more than a few hundred kilometers long.

In the first option there is plotted the trajectory of the electric field on the normalized Poincaré sphere. These are portrayed using an oblique orthographic projection as illustrated in Figure 16. Note how in that figure the trajectory, which starts with horizontal linear polarization at the Equator, spirals around the sphere and seems to tend toward some point nearly at the North Pole. Indeed, as one sees from Figure 14, the eigenvectors are nearly circularly polarized, and Figure 16 shows us that the left-hand polarized part of the original wave is the more severely attenuated so that the wave here tends asymptotically to its right-hand polarized part. Information on how the wave progresses along this trajectory is provided by some 10 "tick" marks that are inserted at equal distances. In the present case, these ticks are 100 km apart.

The second option to display radio wave propagation is illustrated in Figure 17. This is a simple plot of attenuation versus distance. Note how there appear to be two different rates of attenuation. This occurs because at

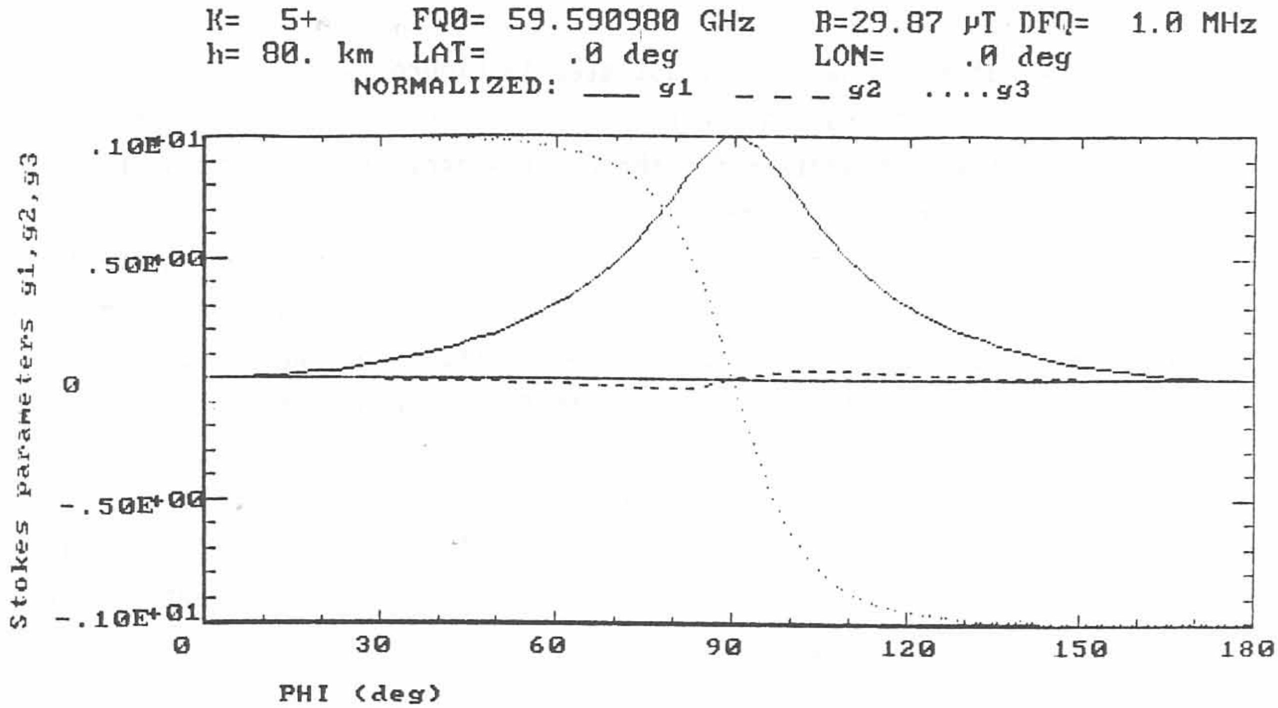


Figure 14. Normalized Stokes parameters of the eigenvectors for the Default Case plotted against the angle ϕ.

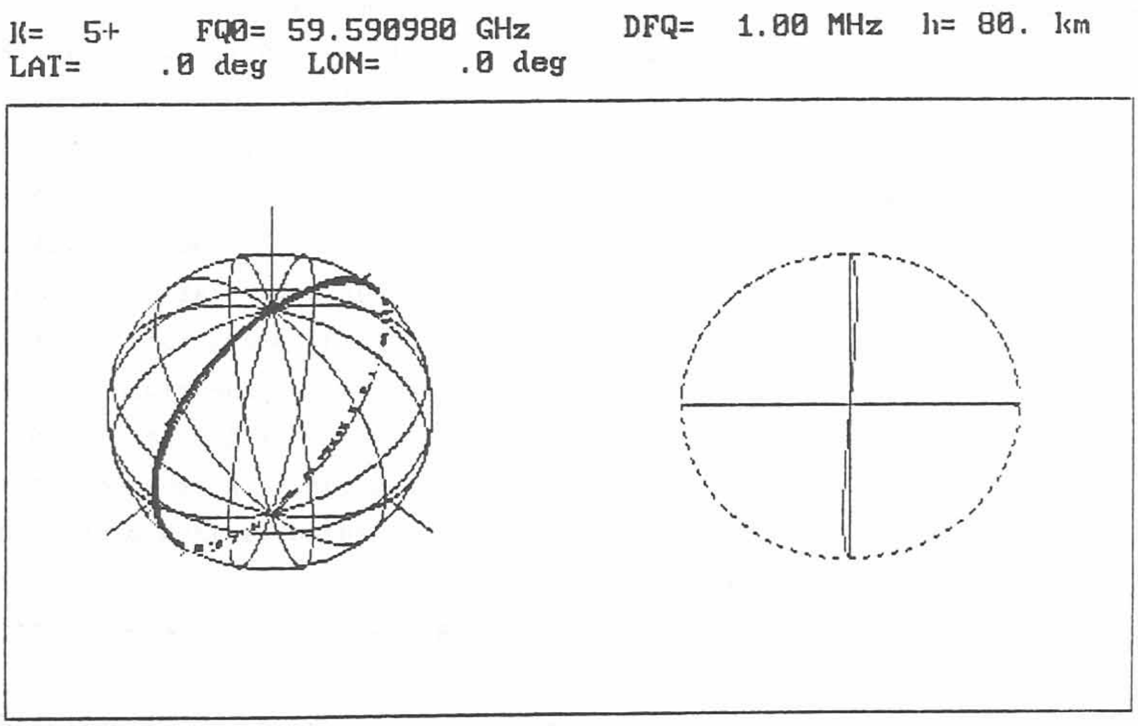


Figure 15. Trajectories of the eigenvectors for the Default Case as plotted on the Poincaré sphere.

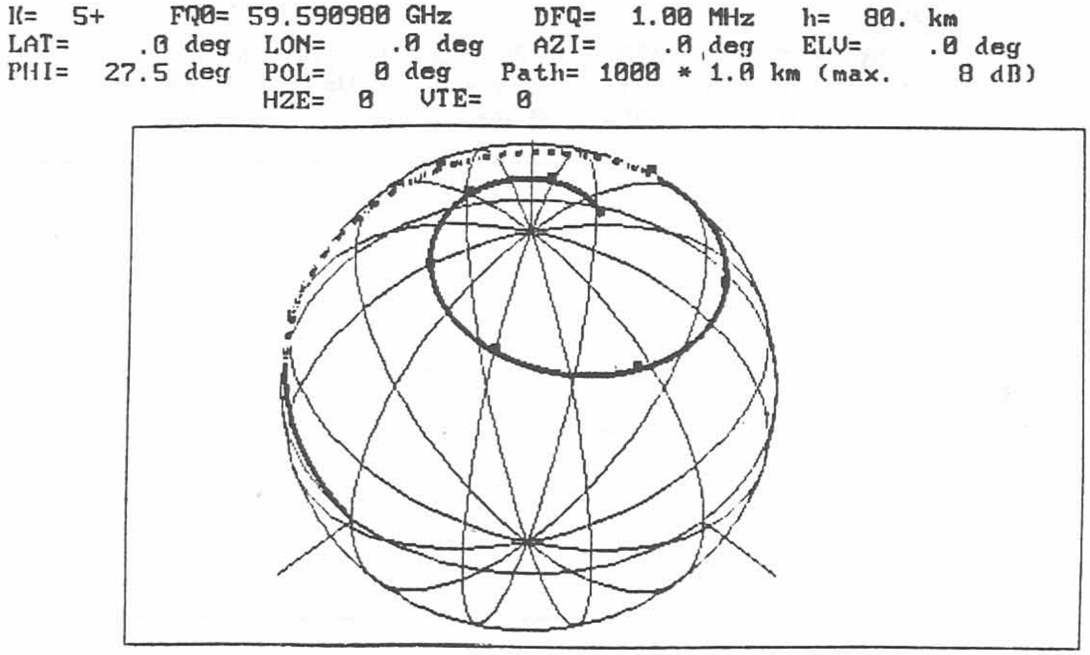


Figure 16. The trajectory on the Poincaré sphere of a wave propagating through mesospheric-like medium. Parameters are those of the Default Case.

the beginning there is a left-hand polarized part that is attenuated at a relatively high rate. When it has nearly disappeared, there is left only the right-hand polarized wave with its more sedate attenuation rate.

The third option available here provides a more pictorial representation of what happens to the polarization. At 10 equally spaced points along the path, the program stops and plots an ellipse of the proper ellipticity and orientation to imitate the trajectory in space of the electric field vector. The example in Figure 18 shows these ellipses every 100 km at just the marked points in Figure 16. Note how they steadily become more nearly circular and how they appear to rotate. The letter "-R-" that appears above each ellipse indicates that they are all traversed in the right-hand direction.

The final option here is of a somewhat different nature. The given location and the azimuth and elevation angles are all used as initial values for a wave that passes through the real-world mesosphere and emerges either at the lower boundary of 30 km or the upper at 100 km. In the course of this passage, the pressure, temperature, geomagnetic field, and the angle to the direction of propagation all change along the indicated path. The computations must find these changes and then must include them in an integration of the two-dimensional differential equation

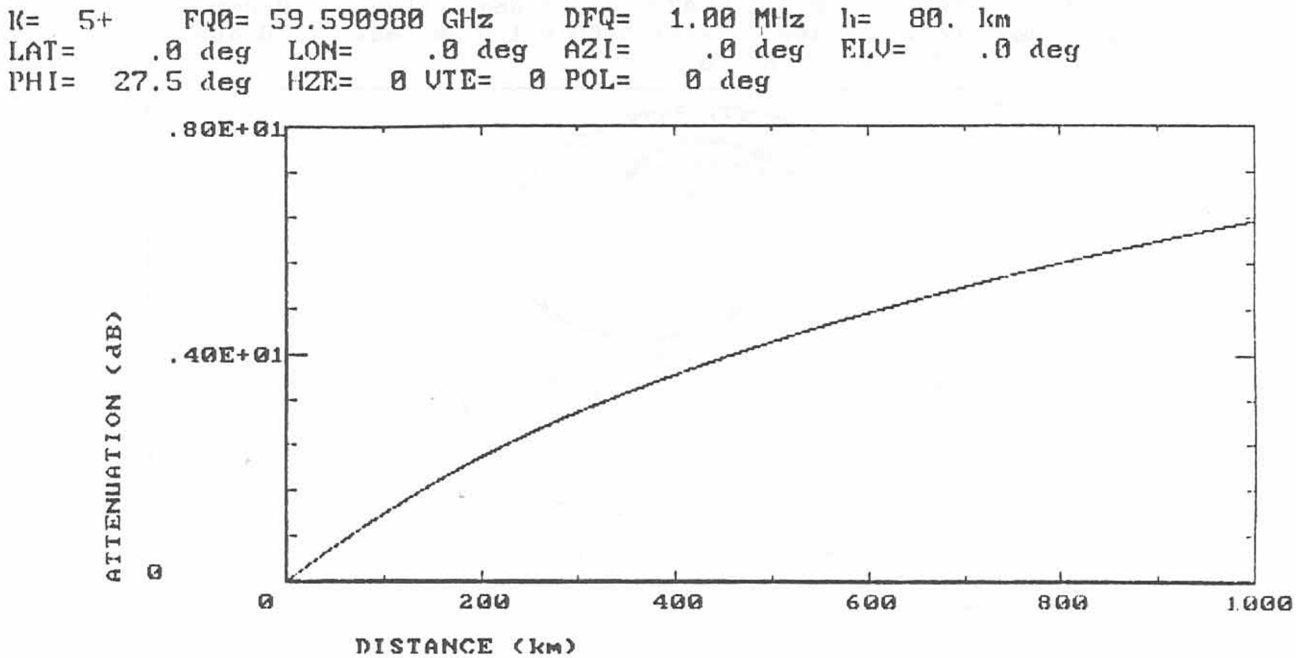


Figure 17. Attenuation versus distance for the wave in Figure 16.

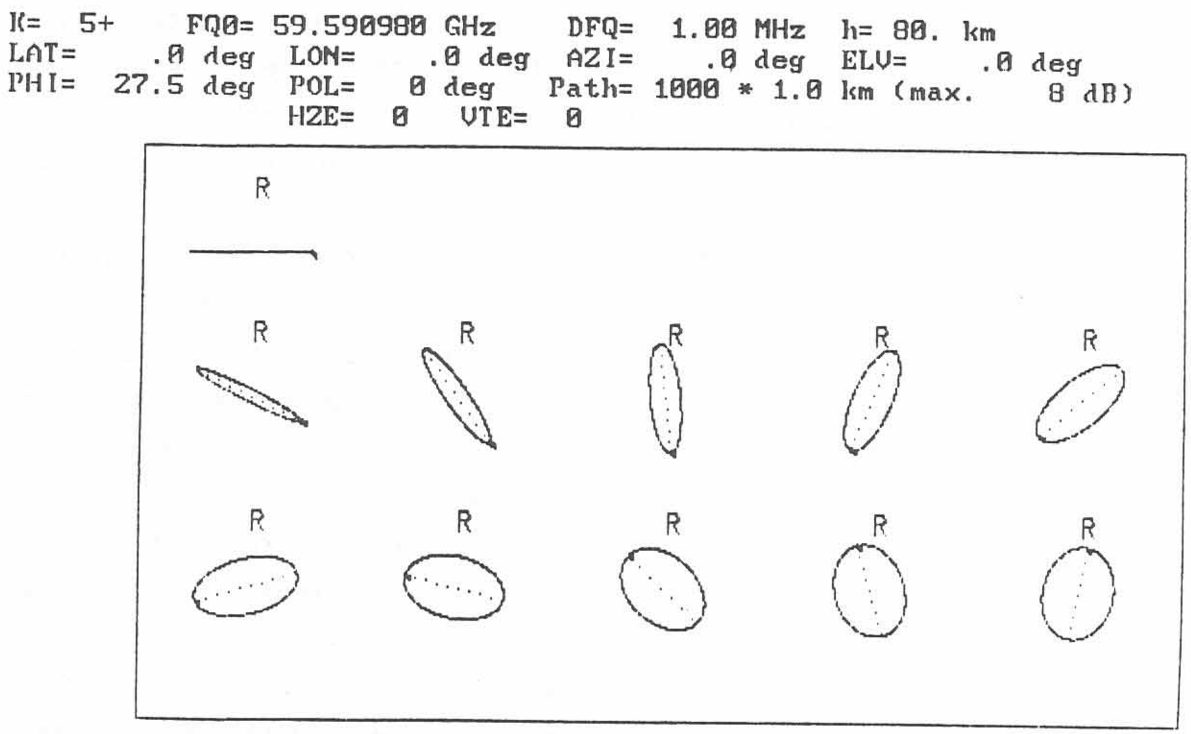


Figure 18. Elliptical trajectories of the electric field at selected distances for the wave depicted in Figure 16.

$$dE/dz = ik(I + \mathbf{N}^e)E,$$

where now the matrix $\mathbf{N}^e$ is a (known) function of z. This equation is an approximation--for example, a changing refractivity implies a bending ray--but again, because $\mathbf{N}^e$ is small, the approximation is a very good one.

In actual operation the program now performs this integration three separate times using three different initial polarizations: left circular, horizontal linear, and right circular. The graphical output for the Default Case is reproduced in Figure 19. Note how the total attenuations are given in the header and how the elliptical trajectories for each of the three polarizations are depicted below.

4.5. Propagation through the Mesosphere

There are two further program segments or overlays that help make up the ZEEMAN whole. Both segments are used, as was the last option above, to explore how a radio wave travels through a real-world mesosphere. The path begins at the selected location and ends when it has emerged from the mesosphere at either 30 km or 100 km altitude. Input to either program segment is by means of a "case file" that has been constructed in the main program segment and saved as a separate file.

The first of these additional segments is called MPI--the "mesospheric integrator." It has no graphical output, but as illustrated in Figure 20, it produces a table showing how the wave progresses as it passes through each kilometer-thick layer. The columns give in succession the latitude, longitude, and altitude along the path, the azimuthal heading, the elevation angle, the magnitude of the magnetic flux density, the angle ϕ, the attenuation the wave has suffered, the polarization, and the total distance that has been traveled. The polarization is defined by giving the magnitude of the horizontal component, the magnitude of the vertical component, and the phase angle by which the vertical component lags the horizontal component. This is all normalized by requiring the horizontal component to have unit size; this description is therefore almost identical with Beckmann's notation as given in Section 3.4.

The second alternative segment is called MPF--the "mesospheric frequency integrator." It provides tables or graphs of total attenuation versus the frequency deviation. As shown in Figure 21, there are four initial polariza-

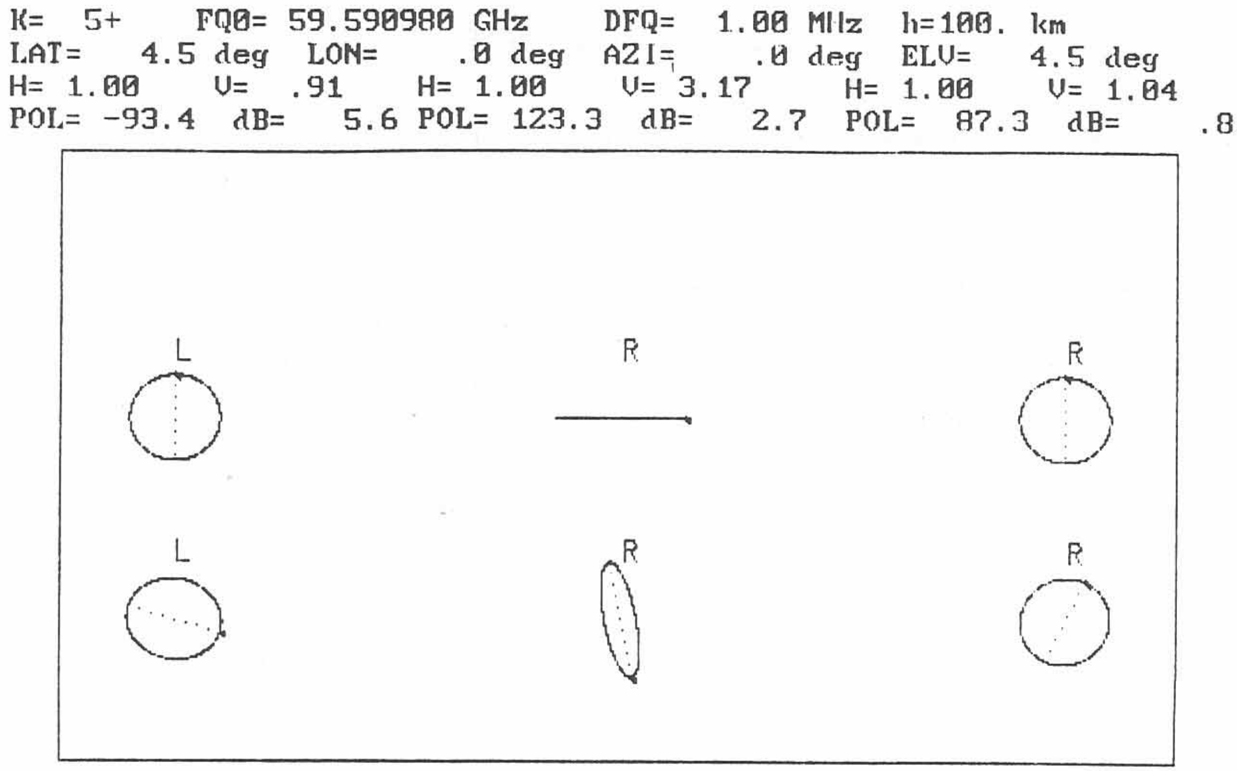
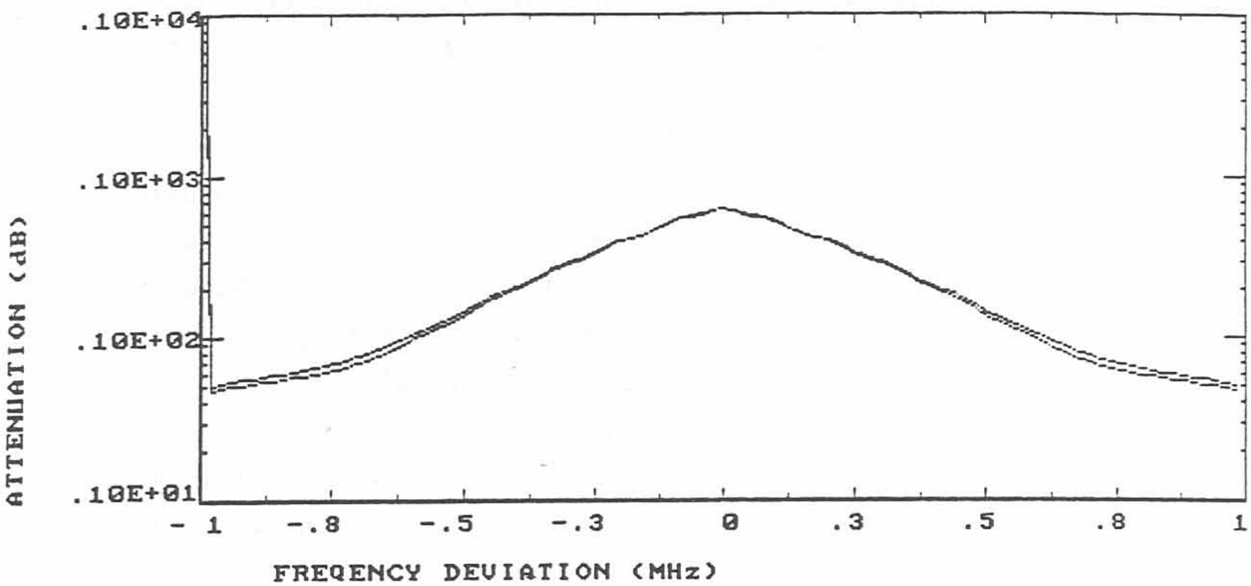


Figure 19. Total attenuation and elliptical trajectories of the electric field after a wave has emerged from the top of the mesosphere. Initial parameters are those of the Default Case and initial polarizations are left.

LAT	LON	H	AZ	EL	¦B¦	PHI	dB	POLARIZATION	S tot
.0	.0	75	.0	.0	.00	.0	.00	1.0/ .00/ 0 deg	.0
1.0	.0	76	.0	1.0	29.99	25.9	2.87	1.0/ 1.79/ 143 deg	113.6
1.4	.0	77	.0	1.4	30.03	23.7	3.55	1.0/ 2.81/ 97 deg	160.7
1.8	.0	78	.0	1.7	30.05	22.5	3.92	1.0/ 2.17/ 66 deg	196.8
2.0	.0	79	.0	2.0	30.06	21.6	4.16	1.0/ 1.61/ 55 deg	227.2
2.3	.0	80	.0	2.3	30.07	20.7	4.32	1.0/ 1.30/ 53 deg	254.1
2.5	.0	81	.0	2.5	30.07	20.0	4.44	1.0/ 1.11/ 53 deg	278.3
2.7	.0	82	:0	2.7	30.07	19.4	4.53	1.0/ .98/ 54 deg	300.7
2.9	.0	83	.0	2.9	30.08	18.8	4.60	1.0/ .90/ 55 deg	321.4
3.0	.0	84	.0	3.0	30.08	18.2	4.66	1.0/ .84/ 57 deg	340.9
3.2	.0	85	.0	3.2	30.08	17.6	4.70	1.0/ .79/ 59 deg	359.4
3.4	.0	86	.0	3.3	30.08	17.1	4.73	1.0/ .76/ 61 deg	376.9
3.5	.0	87	.0	3.5	30.08	16.7	4.76	1.0/ .74/ 62 deg	393.7
3.7	.0	88	.0	3.6	30.07	16.2	4.78	1.0/ .72/ 64 deg	409.8
3.8	.0	89	.0	3.8	30.07	15.8	4.79	1.0/ .71/ 65 deg	425.3
3.9	.0	90	.0	3.9	30.07	15.3	4.81	1.0/ .70/ 66 deg	440.2
4.1	.0	91	.0	4.0	30.07	14.9	4.82	1.0/ .69/ 67 deg	454.7
4.2	.0	92	.0	4.2	30.07	14.5	4.83	1.0/ .68/ 67 deg	468.7
4.3	.0	93	.0	4.3	30.06	14.2	4.83	1.0/ .68/ 68 deg	482.3
4.4	.0	94	.0	4.4	30.06	13.8	4.84	1.0/ .67/ 68 deg	495.6
4.5	.0	95	.0	4.5	30.06	13.5	4.84	1.0/ .67/ 69 deg	508.5
4.6	.0	96	.0	4.6	30.06	13.1	4.85	1.0/ .67/ 69 deg	521.0
4.8	.0	97	.0	4.7	30.05	12.8	4.85	1.0/ .67/ 69 deg	533.3
4.9	.0	98	.0	4.8	30.05	12.5	4.85	1.0/ .66/ 69 deg	545.3
5.0	.0	99	.0	4.9	30.05	12.2	4.85	1.0/ .66/ 70 deg	557.1
5.1	.0	100	.0	5.0	30.04	11.9	4.86	1.0/ .66/ 70 deg	568.6

Figure 20. Tabular display showing how a radio wave progresses through the mesosphere. Input parameters are those of the Default Case.



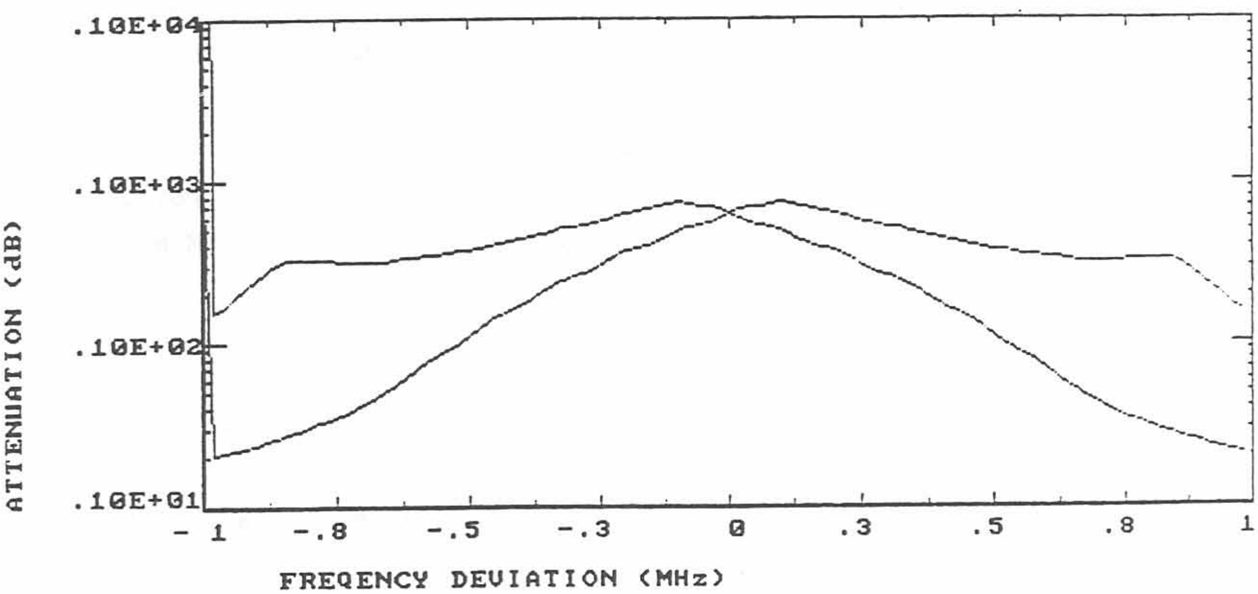


Figure 21. Total attenuation versus frequency deviation for waves emerging from the top of the mesosphere. Initial conditions are those of the Default Case. Top: vertical polarization beginning above and crossing beneath horizontal polarization. Bottom: right circular polarization beginning above and crossing beneath left circular polarization.

tions: vertical and horizontal, left and right circular. The horizontal polarization may be replaced by any elliptical polarization of interest.

5. CONCLUSIONS

At the pressures that exist in the mesosphere, the oxygen absorption lines near 60 GHz are still important but are so sharp that the geomagnetic field can effect a Zeeman splitting. Because of its nature this phenomenon converts the atmosphere into an anisotropic medium, thus making electromagnetic propagation more complicated than is usual.

We have seen how the medium can be modeled and how this model can be used to predict radio wave behavior. It turns out that a wave is likely to tend asymptotically to a wave with a particular polarization and while doing so, to exhibit a kind of Faraday rotation.

We have also described a computer program that will calculate many of the new entities that this anisotropy has made important. The program can be used to explore some of the novel features that have arisen and perhaps to help in the engineering design of radio systems that will use this medium.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

At heights between 30 and 100 km above the Earth, the oxygen absorption lines near 60 GHz together with the geomagnetic field cause the atmosphere to become an anisotropic medium. This report discusses why this is so and how to compute the consequent effects. It describes the computer program ZEEMAN, which allows the user to display in either graphical or tabular form many aspects of how radio waves propagate through this medium.

16. Key Words *(Alphabetical order, separated by semicolons)*

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