PL-TR-97-2117
Environmental Research Papers, No. 1211

APEXRAD DOCUMENTATION

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15 September 1997

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
15 September 97

3. REPORT TYPE AND DATES COVERED
Scientific, Interim

4. TITLE AND SUBTITLE
APEXRAD Documentation

5. FUNDING NUMBERS
PE 62601F
Proj: 7601
Task: 22
Work Unit: 03

6. AUTHOR(S)
J.T. Bell, Capt, USAF, M.S. Gussenhoven

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Phillips Laboratory/GPSH
29 Randolph Road
Hanscom AFB, MA 01731-3010

8. PERFORMING ORGANIZATION REPORT NUMBER
PL-TR-97-2117
ERP. No. 1211

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release.
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This technical report documents the APEXRAD software package developed by the Phillips Laboratory, Geophysics Directorate. APEXRAD is a utility that predicts satellite dose accumulation behind four different thicknesses of aluminum (either slab or hemisphere) for specified orbits. Dose accumulation is predicted using empirical dose rate models created using data measured on the APEX (Advanced Photovoltaic and Electronics Experiments) satellite which flew in a 362 by 2544 km elliptical orbit inclined at 70°. These dose models have a higher position resolution at low altitudes than the previously released CRRESRAD models. The APEXRAD models give dose rates averaged over the entire APEX mission and for four different levels of magnetospheric disturbance, based on a 15 day (offset by 1 day) running average of linear magnetic activity index, Ap. APEXRAD is best applied to orbits with apogees less than 2500 km, perigees greater than 350 km and inclinations less than 60°, for times during solar cycle minimum. It can be useful for orbits with higher inclinations or lower perigees, but the user must account for any dose that may be received outside the region covered by the model. For higher altitude orbits the use of CRRESRAD is recommended.

14. SUBJECT TERMS
APEX, Radiation, Electron, Proton, Energetic dose, Radiation belts

15. NUMBER OF PAGES
41

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

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ACKNOWLEDGMENTS

Many people were involved with the creation of APEXRAD. E.G. Mullen supervised the APEXRAD team. CRRESRAD, CRRESPRO, CRRESELE and now APEXRAD have all benefited from his guidance. David Hardy, Don Guidice, Paul Severance, and Dave Olson of Phillips Lab handled the logistics of flying the dosimeter on APEX. Fred Hanser of Panametrics fabricated the dosimeter. Kevin Ray, also of Phillips Lab, supported the flight operations. The creation of the dose models was supported by E. Holeman and D. Madden of Boston College, Chestnut Hill, MA. CRRESRAD, written by Kevin Kerns, served as the starting point and inspiration for this program. LOKANGL.EXE and MAGMODEL.EXE were modified from the CRRESRAD versions by E. Holeman. The remaining CRRESRAD executables were modified to produce APEXRAD and improve the user interface.

APEXRAD DOCUMENTATION

1. OVERVIEW

APEXRAD uses empirical models based on data from the APEX/PASP+ dosimeter to predict the amount of radiation received in a user specified orbit behind four different aluminum shielding thicknesses. The Advanced Photovoltaic and Electronics Experiments (APEX) Satellite was operational from 3 Aug 94 to 2 Jun 96, just prior to solar minimum. APEX was in an elliptical orbit with a 70° inclination, a perigee of 362 km and an apogee of 2544 km. The instrument used to measure accumulated dose was the APEX Space Radiation Dosimeter which measures both dose rate and accumulated dose in four silicon detectors, each of which is behind an aluminum shield of a different thickness (Gussenhoven et al., 1995, Gussenhoven et al, 1997, Mullen et al., 1997). One shield was a 4.28 mil thick slab of Al. The other three were hemispheres of Al with thicknesses of 80.1, 225.8 and 444.4 mils (see Table 1).

Table 1 APEX Dosimeter Characteristics

	Aluminum Shielding		Detector	
Dome No.	(mils Al)	(g/cm^2)	Area (cm^2)	Thickness (microns)
D1	4.29	0.0294	0.0514	393
D2	82.5	0.57	0.0514	382
D3	232.5	1.59	0.0514	400
D4	457.5	3.14	1.000	396

Table 2 lists the particles that deposit dose in the silicon detectors behind the shields. The minimum energies required for particles to penetrate the shields and accumulate dose in the silicon detectors underneath are 0.15, 1, 2.5, and 5 MeV for electrons and 5, 20, 35 and 50 MeV for protons (Hanser and Morel, 1996). Dose from particles depositing 0.05-1 MeV and 1-10 MeV is accumulated in two different channels called LOLET and HILET respectively. Contributions to HILET dose are primarily from protons with energies of 5-125 MeV (as shown in Table 2), but electrons with energies >5 MeV may contribute during large electron enhancement periods. Contributions to LOLET dose are from electrons, bremsstrahlung, and protons with energies >80 MeV. Dosimeter data is available for approximately 14 of the 22 months that APEX was operational.

Table 2 APEX Dosimeter Particle Energy Detection Ranges

	LOLET Particles		HILET
Dome No.	Electrons (MeV)	Protons (MeV)	Protons (MeV)
D1	> 0.15	>80	5-80
D2	> 1.0	> 115	20-115
D3	> 2.5	> 120	32-120
D4	> 5.0	>125	52-125

The APEX spacecraft was a three axis stabilized hexagonal cylinder, with one end pointing toward the sun. It was approximately 37 inches wide and 72 inches high. The dosimeter was located on the avionics shelf approximately 24 inches from the top (sun facing) end of the cylinder. The dosimeter look direction was out the side of the spacecraft, orthogonal to the spacecraft-sun line. Thus the particles contributing to the measured dose came from the hemisphere to the side of the spacecraft.

APEXRAD has been produced to supplement the CRRESRAD dose models (Kerns and Gussenhoven, 1992) for low altitude. The CRRESRAD models are based on data from the Combined Release and Radiation Effects Spacecraft (CRRES), which was in a geosynchronous transfer orbit. Because of its orbit the CRRES spacecraft spent relatively little time at low altitudes.

Therefore the spatial resolution of CRRESRAD models for the inner edge of the inner radiation belt are limited. The CRRESRAD models are also limited in latitude and do not include the dose deposited by electrons from the outer belts that follow field lines down to low altitudes at high latitude (these electrons are often referred to as the "horns" of the outer belt). Both the location of the inner edge of the inner belt and the outer belt electrons at high latitudes may have significant impact on the dose received by the Space Shuttle, Space Station or satellites in a low Earth orbit.

The APEXRAD models contain approximately 20 bins (in L and B/B_0 space) for each low altitude bin in the CRRESRAD models, giving improved spatial resolution at low altitudes. The APEXRAD models were built using data collected just prior to solar minimum, when the dose rate due to inner belt protons is expected to be highest. Thus APEXRAD provides a worst case when compared with the CRRESRAD models, which were built using data from a period just after solar maximum.

The APEXRAD LOLET models clearly show the horns of the outer belt coming down to low altitudes at high latitudes. The flux of electrons in the outer belt is known to correlate roughly with magnetic activity (Brautigam, et al, 1992). For CRRESELE (Brautigam and Bell, 1995) the data were organized based on magnetic activity using a 15 day running average of A_P offset by one day. A similar technique was applied for APEXRAD producing separate models for each of the following activity levels : $5.0 \leq A_{P15} < 7.5$, $7.5 \leq A_{P15} < 10.0$, $10.0 \leq A_{P15} < 15.0$, $15.0 \leq A_{P15} < 20.0$ and $20.0 \leq A_{P15} < 25.0$.

APEXRAD is a DOS program. It requires an 80386 or better PC with a math coprocessor, a color VGA card, and 4.5 Mbytes of hard drive space. A printer is not needed, but it is useful. The active directory must be the one containing APEXRAD.EXE and its support files. APEXRAD is run by typing "APEXRAD" on the command line. If the orbit name is not given as the second item on the command line, APEXRAD will query the user for an orbit name (when needed). This name will be used for all of the data files subsequently created for this orbit. The data files will be written to the APEXRAD directory. No extension can be given in the filename. A sample session for determining the dose rate for a DMSP type polar orbit is shown in Appendix A.

An ASCII file, README.TXT is included with the APEXRAD software. To view the file type "EDIT README.TXT" at the DOS prompt or use the Windows Notepad. This file documents recent updates to the software, contains instructions for installing APEXRAD and has a directory list of the files included with APEXRAD. As a precaution against viral contamination, make sure that the ".EXE" files are the same size and date as given in the README file.

2. DOSE MODEL

The motion of high energy ions and electrons in the radiation belts that cause dose deposition in satellites in the Earth's magnetosphere is determined almost entirely by the Earth's magnetic field. These particles are trapped by the magnetic field, and are constrained to bounce back and forth between the northern and southern hemispheres along magnetic field lines as they circulate around the Earth. The paths the particles take form "shells." Because the particles are constrained to move on the shells, the dose resulting from these particles is best ordered by specifying the shell and relative position in the shell, that is by using magnetic field parameters instead of spatial coordinates. The magnetic field parameters used for the dose model are the McIlwain L-parameter (McIlwain, 1961) which is referred to hereafter as L, and B/B_0 (see below). In a dipole magnetic field the L-value of a given point in space is the equatorial radial distance, in Earth radii (R_E), to the field line that passes through the given point. The solid lines in Figure 1 show L shells 2, 3, 4, 5, and 6 of a dipole magnetic field centered in the Earth. The Earth's magnetic field has some non-dipole components (the major ones due to the fact that the

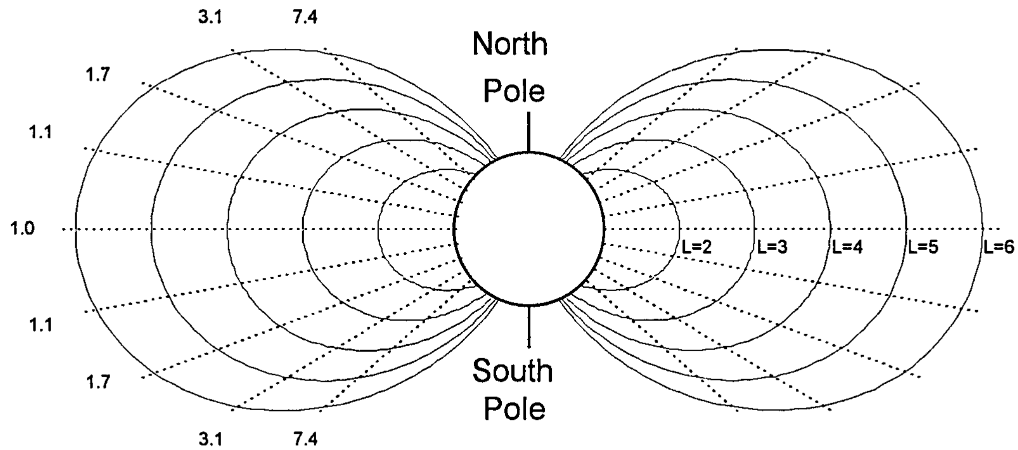

Figure 1 L Shells 2, 3, 4, 5, and 6 (solid lines) and lines of constant B/B_0 = 1.0, 1.1, 1.7, 3.1, and 7.4 (dashed lines) in a dipole field centered in the Earth.

dipole origin is not at the center of the Earth). L is calculated by determining which dipole field line the actual field line would correspond to if the Earth's magnetic field were relaxed to a dipole field. B/B_0 is the ratio of the magnetic field magnitude at a point in space divided by the minimum magnitude of the magnetic field on the same field line. The field is strongest near the poles and weakest near the equator, so $B/B_0 = 1.0$ is near the equator and increases as one moves down the field line toward the Earth. For a dipole field B/B_0 is a function only of magnetic latitude. The dotted lines in Figure 1 show constant B/B_0, spaced every 10° in a dipole field from ±40° latitude. Chapters 4 and 5 of the *Handbook of Geophysics and the Space Environment* (Knecht and Shuman, 1985 and Spjeldvik and Rothwell, 1985) contain a more complete description of the Earth's magnetosphere and the radiation belts.

The IGRF95 internal magnetic field model was used to calculate the L and B/B_0 values when binning the APEX dose rate data. New IGRF models are put out every five years by the IAGA Division I, Working Group 1. These models account for the slow time variations in the dipole magnetic moment, its tilt and position, and other non-dipole contributions to the internal field.

The dose models used by APEXRAD are based on *in situ* dose rate measurements made on board the APEX satellite. The instrument used to measure dose is the APEX Space Radiation Dosimeter described in Section 1. The delta dose measured by the dosimeter over 24-second intervals was used to build the APEXRAD models. A background subtraction is performed to remove the dose due to constant sources, which include both the on-board alpha source used for calibration, and cosmic rays (Gussenhoven, et al 1997). The measured dose rates for each dome were binned by L and B/B_0 to make average dose rate models in rads (Si) per second. The width of each bin in L is 1/100 R_E, and the width of each bin in B/B_0 is one degree of $\arcsin(B/B_0)^{-1/2}$ (approximately 0.75° latitude in a dipole field). The bins form a two-dimensional array of 500 (L) by 90 (B/B_0) and cover L values of 1 to 6 R_E and magnetic latitudes of 0° to ~60°. Many of these bins do not contain data because APEX was in a low altitude orbit and only reached high L values at high B/B_0's. To save storage space most of the empty data bins are not stored as part of the models.

Six sets of APEXRAD models were produced. The first set of models is the entire mission average. The other five sets of models are based on the Earth's magnetic activity as recorded by A_{P15}, a fifteen day running average of A_P. The location and intensity of the outer belt horns is dependent on the magnetic activity. Higher activity levels coincide with a significant increase in the LOLET dose rate where the horns of the outer belt come down to low altitudes (up to a factor of 10). The position of the horns also change with magnetic activity. The HILET dose rate in portions of the inner belt, is found to decrease slightly as the magnetic activity increases, however this decrease is small (less than 20 percent from one activity level to the next) and restricted to the inner edge of the belt. Thus varying magnetic activity has negligible effect on the HILET dose predictions for most orbits. The cumulative effect of varying magnetic activity on total dose received will depend on the orbit. For orbits that pass through the heart of the inner belt, dose from inner belt protons will dominate the total dose, and magnetic activity will have little impact. For a certain class of low altitude, high inclination orbits, increases in magnetic activity can lead to a significant increase in the total dose rate. (Gussenhoven, et al, 1997, Mullen et al. 1997)

3. APEXRAD MAIN MENU

Figure 2 shows the various execution paths that can be followed from the main menu of APEXRAD. The solid arrows indicate the direction of logical flow, and the dashed arrows indicate the input and output files required or produced at each step. When APEXRAD is started the user is presented with a menu containing nine options.

3.1. Set Filename

The first option is "Set Filename", this allows the user to specify or change the filename of the orbit to be used ({FILENAME}). This name will be used for all the files APEXRAD generates for this orbit. If the user gives a orbit name for which files already exist, the existing files will be used. (Certain commands may result in the replacement of existing files, but the user is always asked for approval before old files are replaced.) No extension can be given with the name. Files will be written to the current directory. The orbit name may also be specified on the command line when APEXRAD is started by typing "APEXRAD filename".

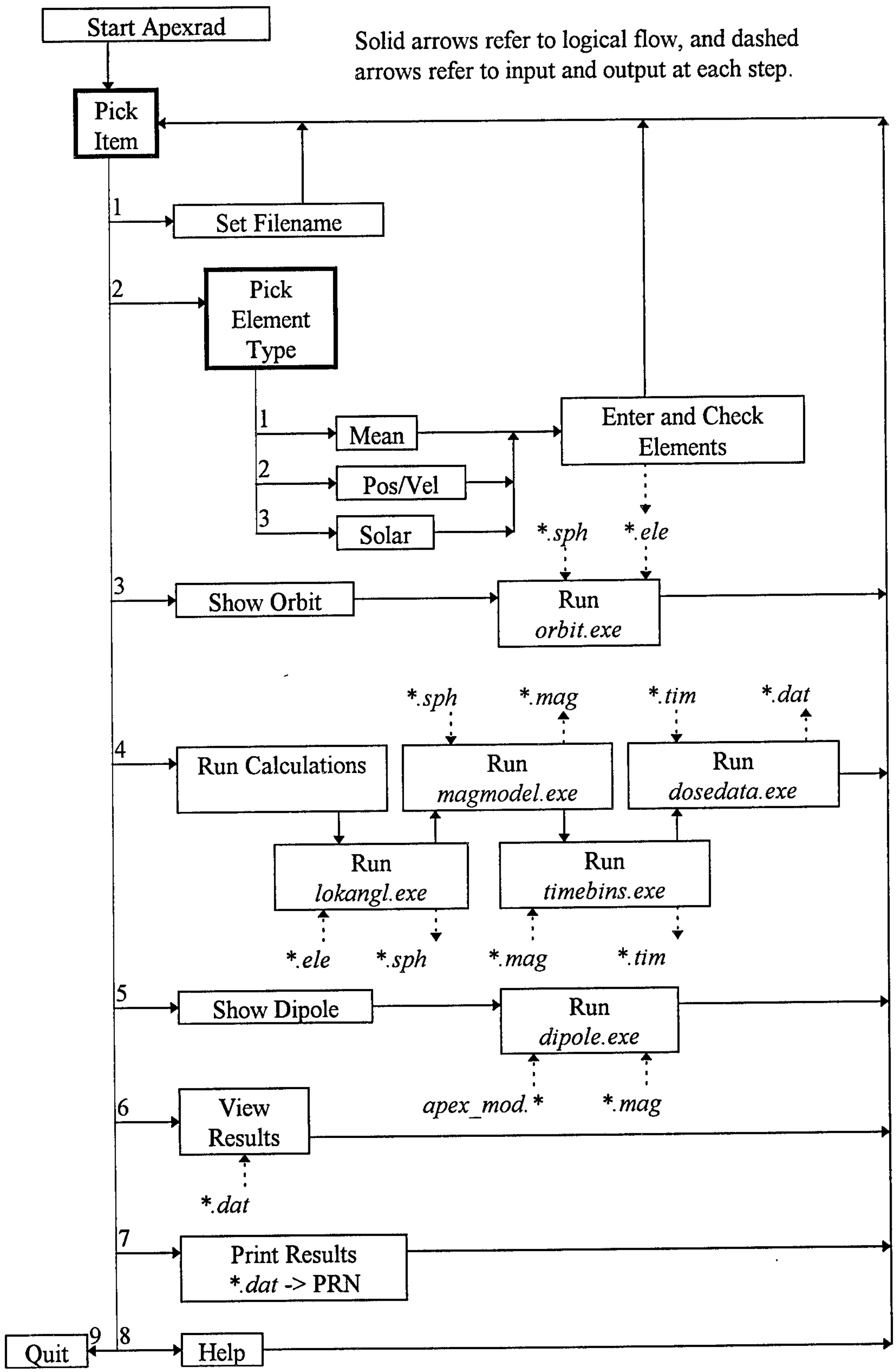

Figure 2 Simplified flow diagram of APEXRAD.

3.2. Enter Orbit

The second menu option is "Enter Orbit". This option allows the user to input the orbital elements. These elements describe the orbit to be used. There are three options for specifying orbital elements. For all three options time is given in year, day of year, hours, minutes and seconds and must be later than the start of day 1, 1985. The options for specifying orbital elements are :

Mean Orbital Elements: These are the standard orbital elements typically used by NORAD and other satellite tracking centers. Inclination, right ascension of the ascending node, argument of perigee, and mean anomaly are specified in degrees, mean motion is specified in revolutions per day, and eccentricity is specified.

Position and Velocity: The elements for position, r_x, r_y, r_z, and velocity, v_x, v_y, v_z, are specified in km and km/sec using the Earth Centered Inertial (ECI) coordinate system.

Solar Elements: Inclination is specified in degrees, while altitudes of apogee and perigee are specified in km assuming $R_E = 6378$ km, and local times of apogee and maximum inclination are specified in hours. These elements are useful to scientists and engineers concerned with where an orbit is with respect to the sun and to those who are not familiar with the standard orbital elements. A local time of apogee of 12.0 indicates that the satellite is at apogee directly between the sun and the Earth. Local time of maximum inclination indicates the local time where the geographic latitude of the satellite is at a maximum positive value. Default values of 12.0 and 18.0 are used respectively for the two local times, but these values may be changed. A 6-hour difference between the local time of apogee and the local time of maximum inclination causes apogee to be at 0° geographic latitude. In many cases this difference results in the greatest amount of radiation because the highest dose rates occur near the magnetic equator which is close to the geographic equator. There are also cases (high inclination, low altitude) where the 6-hour difference may not result in the greatest dose accumulation. The solar elements as described are not a full set of orbital elements. Six elements are needed to completely specify a satellite orbit, only five are entered for the solar elements. The sixth element is derived by assuming that the orbit is at apogee for the time at which the elements are specified. The solar elements cannot be used by LOKANGL.EXE (Appendix D) directly, so APEXRAD converts these elements into mean orbital elements using the formulas in Appendix B.

If an orbit name has not been specified prior to selecting the type of orbital elements to use, the user will be asked to specify an orbit name before the orbital elements entry screen appears. When the orbital elements entry screen appears, it will contain the last set of orbital elements entered for this orbit. If a new orbit is being used the last set of elements entered during the current session will be displayed. When the first set of elements for the current session is being entered, default settings for the orbital elements will be given. (Note: that APEXRAD deals with any needed conversions between mean and solar elements.) The user can use the <DELETE> key to clear the value for the selected element or backspace key to remove the last character. The <TAB> key selects the next element and <Shift-TAB> selects the previous one. Pressing <ENTER> accepts the current elements.

The last six items in this window define the start time and length of the study. When the user has finished entering the elements (including the start time and length of study), they are checked to make sure that the orbit is not hyperbolic and that perigee is not below the surface of the Earth (see Appendix B). The time step used in the study is chosen so that the orbit will sweep $\sim 0.5°$ arc at perigee in a single time step (see Appendix B). If the orbit is acceptable the orbital elements are saved to the file, {FILENAME}.ELE, and the user is returned to the options menu.

When performing the calculations, APEXRAD will attempt to propagate the specified orbital elements to the desired time of study. However, the propagation loses its accuracy when run for long time spans. Therefore it is recommended that the time of study be as close as practical to the time of the entered orbital elements.

3.3. Show Orbit

The third option is "Show Orbit". When this option is selected, APEXRAD will check for {FILENAME}.SPH. If the *.SPH file has not been created for the current orbit, APEXRAD will run the calculations described in the next section, to create it. When the calculations are complete, APEXRAD will call ORBIT.EXE to display the orbit. ORBIT.EXE displays the orbit from three different viewpoints. The lower left view is looking down on Earth's dusk side with the sun at the top and North to the right. The view in the lower right corner looks down on the North Pole with the sun to the top and dusk to the left. The view in the upper right corner is looking down at noon, North is down and dusk is to the left. The upper left corner contains a listing of the orbit elements, as contained in {FILENAME}.ELE. Press "Q" to quit ORBIT.EXE and return to the menu. (Appendix D contains a description of and screen capture from ORBIT.EXE.)

3.4. Run Calculations

The fourth option on the menu is "Run Calculations". When this option is selected APEXRAD verifies that orbital elements have been entered for this orbit and requests them if they have not. Then a series of other executables are called to find the dose for the orbit. If the output file from an executable already exists, the user is asked if they wish to replace it before the executable is run. The actual time required to perform the calculations will vary with the speed of the computer and the type of orbit. In general, lower altitudes take longer than higher altitudes, elliptical orbits take longer than circular, and high inclination orbits take longer than low inclination.

First APEXRAD calls LOKANGL.EXE (See Appendix D) which reads the orbital elements file and generates an ephemeris file, {FILENAME}.SPH. The ephemeris file contains a binary listing of spacecraft positions throughout the orbit. A position is calculated at each time increment for the specified period of study. Appendix C contains a description of the {FILENAME}.SPH file.

When LOKANGL.EXE is complete, APEXRAD calls MAGMODEL.EXE (See Appendix D). MAGMODEL.EXE converts the geographic coordinates in {FILENAME}.SPH into magnetospheric coordinates that are put into the binary file {FILENAME}.MAG. The routines used by MAGMODEL.EXE to calculate L and B/B_0 were developed by Karl Pfitzer at McDonnell Douglas Space Systems Corp. for the Air Force (Pfitzer, 1991). The internal magnetic field models used by MAGMODEL.EXE are only valid for times after the start of day 1, 1985. MAGMODEL.EXE has been modified, from the CRRESRAD version, to use the IGRF95 magnetic field model, which interpolates between the magnetic fields for 1985 (DGRF85), 1990 (DGRF90) and 1995 (IGRF95) or extrapolates from the 1995 field model to reach the date specified for the orbit.

APEXRAD then calls TIMEBINS.EXE. TIMEBINS.EXE reads the magnetospheric ephemeris data, {FILENAME}.MAG, and uses a cubic spline interpolation for successive points along the orbit to calculate the amount of time spent in each bin of the dose model for the given orbit. The time in each bin is placed in a data record that is written to the binary file {FILENAME}.TIM.

Then DOSEDATA.EXE is called. DOSEDATA.EXE reads in the timing record from {FILENAME}.TIM. The dose rate for each bin is read in from an APEX_DSE.## file. The average yearly dose rate for the orbit is calculated by multiplying the dose rate for each bin by the time spent in that bin, to give a dose per bin. The dose per bin values are then summed to get the dose for this study. The dose for the study is divided by the length of the study in seconds to get the average dose rate per second, which is multiplied by the number of seconds in a year to get the average dose per year for the specified orbit. This process is repeated for each APEX_DSE.## file and the results output to a formatted ASCII file called {FILENAME}.DAT. DOSEDATA.EXE also reads in the {FILENAME}.ELE file and lists the orbital elements in {FILENAME}.DAT. (Appendix E contains a sample output file.)

The first section of {FILENAME}.DAT contains the name of the orbit, the orbital elements, and the start time and duration of this study. The next section is a table listing average dose per year (rads Si/year) as predicted by the APEXRAD models. The percentage of the study time that the orbit was outside the model is listed below the predicted dose. The time out of range is listed for each model because the limits of the activity dependent models vary slightly. If the time out of range is large the user should use "View Dipole" to determine where the orbit is passing outside the models. APEXRAD handles all locations outside the models as if they had zero dose. This can result in significant errors in the predictions for orbits that pass above the models. The final section of {FILENAME}.DAT is a data table that lists the specifications of the

APEX/PASP+ dosimeter. The same information is listed in Tables 1 and 2 of this document.

3.5. View Dipole

The fifth option calls DIPOLE.EXE (see Appendix D), which displays the dose rate data contained in the APEX_DSE.## files. DIPOLE.EXE displays the data from the model as it would look if the Earth's magnetic field were a dipole field. It then plots the orbit over the model, using the same assumption. The southern hemisphere portions of the orbit are folded over onto the northern hemisphere because B/B_0 contains no information about +/- latitude. This also allows an unobstructed view of the model to be seen. This display is useful when attempting to understand the predicted dose levels for an orbit or to determine where an orbit passes outside of the models.

3.6. View Results

The sixth option opens the predicted dose file {FILENAME}.DAT and displays it on the screen. The viewer includes capabilities to scroll through the file. When finished looking at the file press "Q" to exit the viewer and return to the main menu.

3.7. Print Results

The seventh option is equivalent to executing the DOS command "COPY {FILENAME}.DAT PRN," which will print the ASCII file {FILENAME}.DAT on the printer attached to the computer.

3.8. Help

After selecting "Help" the user is presented with a menu of items to receive help on. The user selects an item and the file viewer (same as in section

3.6 above), is used to open the appropriate help file. To return to the main menu press "Q". Note: the help files are text files with "hlp" as their file extension. They can be viewed with any text viewer, if desired.

3.9. Quit

Quits APEXRAD and returns the user to DOS (or Windows).

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APPENDIX A

SAMPLE SESSION

Note : All the commands and filenames listed in this appendix are insensitive to the case of the letters.

From the DOS prompt enter the APEXRAD sub-directory by typing:

"cd \APEXRAD <Enter>"

Then type:

"APEXRAD <Enter>"

When the menu appears press "1" to select "Set Filename". Here we use "Sample" as the file name. Type:

"SAMPLE <Enter>"

Press "2" to select "Enter Orbit" from the menu. Press "3" to select "Solar Elements". On the next screen we specify an orbit that is very similar to the orbits used by the Defense Meteorological Satellite Program satellites. Enter the solar elements, the time for which those elements apply and the desired study start time and length of study.

Orbital Elements	
year	1993
day	179
hour	12
minute	0
second	0
Inclination	98
Perigee	840
Apogee	840
LT of Apogee	12
LT of Max Incl	18

Start of Study	
year	1993
day	179
hour	6
minute	0
second	0
length of study	0.5

(Note : The time of the study can differ from the time entered for the element information.) The <DELETE> key will clear the currently active item. To edit values use the backspace and arrow keys. The <TAB> key selects the next item and <SHIFT-TAB> selects the previous one. When all the elements have been set press <ENTER>.

Press "4" to select "Run Dose Calcs". A message will appear on the screen indicating that LOKANGL.EXE is executing. Once LOKANGL.EXE is done executing, APEXRAD will execute MAGMODEL.EXE. (MAGMODEL.EXE takes the most time of the utilities used.) Then TIMEBINS.EXE will be executed, and finally DOSEDATA.EXE will be run.

When DOSEDATA.EXE is finished the "Calculations are Complete" message will appear. Press any key to return to the main menu.

Once the calculations are complete there are several options for viewing the data. SAMPLE.DAT contains the APEXRAD dose predictions for a year based on the orbit and study time. "Print Results" (7) will send a copy of SAMPLE.DAT to the local printer. Appendix E is a copy of the printout of the file SAMPLE.DAT. "View Results" (6) will display SAMPLE.DAT on the screen (press "Q" to return from the viewer to the menu). "View Orbit" (3) calls ORBIT.EXE to display a plot of the orbit in geographic coordinates. "View Dipole" (5) executes DIPOLE.EXE to display the dose models with the orbit track plotted over them. The orbit track is plotted entirely in the upper quadrant. Although this may at first seem unnecessarily confusing, it does allow one to use the lower quadrant to view the radiation belt intensities without orbit track obstruction. Notice that for "Sample" the orbit is below the most intense part of the radiation belts, but the orbit passes through the "horns" of the outer radiation belt at high latitudes. This orbit is within the APEXRAD dose models, except for a small portion at very high latitudes. Note that in DIPOLE.EXE the high latitude portion of the orbit appears to "peel" away from and toward the Earth; this is an artifact of the conversion from geographic coordinates to the L and B/B_0 coordinates based on an ideal dipole field. For this orbit the dose estimate is good for all four domes and shield thicknesses. (See Appendix D for more information on ORBIT.EXE and DIPOLE.EXE.)

APPENDIX B

CALCULATIONS USED TO CREATE ELEMENT FILE

We give here the equations used (1) to convert solar elements to mean orbital elements; (2) to calculate the time step used in LOKANGL.EXE; and (3) to eliminate invalid orbits, namely those that are not closed or that pass close to or beneath the surface of the Earth. Two constants specific to Earth that are used throughout are μ, the universal gravitational constant times the mass of the Earth, and R_E the radius of the Earth assuming the Earth is spherical. These values are:

$$\mu = 398601.2 \text{ km}^3/\text{sec}^2 \qquad \text{(B.1)}$$

$$R_E = 6378.145 \text{ km} \qquad \text{(B.2)}$$

(1) To Convert Solar Elements to Mean Elements:

Use the convention that

$$\text{day} = 1 \text{ on 1 January 1992} \qquad \text{(B.3)}$$

Define the following quantities:

$$r_a = A_a + R_E \qquad \text{(B.4)}$$

$$r_p = A_p + R_E \qquad \text{(B.5)}$$

$$H_e = 6.594703 + 0.06570982463 * \text{day} + 1.00273791 * \text{hour} \qquad \text{(B.6)}$$

[U.S. Naval Observatory, 1992]

$$\Theta_a = (H_a + 12) * \pi /12 \qquad \text{(B.7)}$$

and

$$\Theta_i = (H_i - 6) * \pi /12 \qquad \text{(B.8)}$$

where A_a and A_p are altitudes from the surface of the Earth at apogee and perigee, in km, H_a is local time of apogee in hours and H_i is local time of maximum inclination in hours.

Then the six mean orbital elements are:

inclination (i) is already specified as one of the solar elements,

eccentricity

$$e = (r_a - r_p) / (r_a + r_p) \tag{B.9}$$

mean anomaly (satellite is at apogee when elements are defined)

$$M_A = 180° \tag{B.10}$$

squared mean motion

$$M_m^2 = \frac{\mu}{[½ (r_a + r_p)]^3} (12 * 3600 / \pi)^2 \tag{B.11}$$

right angle of ascending node

$$\Omega = 15(H_i - 6 + H_e) \tag{B.12}$$

argument of perigee (ω)

$$\cos(\omega) = \cos(\Theta_a) \cos(\Theta_i) + \sin(\Theta_a) \sin(\Theta_i) \tag{B.13}$$

(2) Time Step Calculation:

If Position/Velocity Elements are used, define

$$r = \sqrt{r_x^2 + r_y^2 + r_z^2} \tag{B.14}$$

$$v = \sqrt{v_x^2 + v_y^2 + v_z^2} \tag{B.15}$$

$$a^{-1} = (2 / r) - (v^2 / \mu) \tag{B.16}$$

$$h = |\vec{r} \times \vec{v}| \tag{B.17}$$

$$e^2 = 1 - h^2/\mu a \tag{B.18}$$

Where a is the semimajor axis in km, h is the angular momentum in km^2/sec, and e is the eccentricity.

If Mean Orbital Elements are used, the eccentricity e and the mean motion M_m in revolutions per day are given as elements. The semimajor axis and the magnitude of the angular momentum h are given by:

$$a^3 = \mu [(12*3600) / (\pi M_m)]^2 \quad \text{(B.19)}$$

$$h^2 = \mu a(1-e^2) \quad \text{(B.20)}$$

In terms of a, h, and e, the time step T_s, which is approximately equal to the time to traverse 0.5° arc at perigee is:

$$T_s = a^2 (1-e)^2 h^{-1} \pi/360 \quad \text{(B.21)}$$

(3) Check Elements for valid orbit:

The orbit is valid if:

a) the orbit is closed: $0 \le e < 1$;

and

b) perigee is not below the surface of the Earth: $a(1-e) \ge 6400$ km.

APPENDIX C

FORMAT OF EPHEMERIS FILES

The geographic ephemeris files end with the extension "SPH." These are binary files that are output from LOKANGL.EXE. Each record of the file specifies the position of the satellite, and the time step (T_s) between all records is constant. The equation for T_s is listed in Appendix B.

Each record of the {FILENAME}.SPH file contains, in the following order:

year	: 2 byte integer
day	: 2 byte integer
second	: 4 byte real
latitude	: 4 byte real (deg)
longitude	: 4 byte real (deg)
radius	: 4 byte real (km)

The {FILENAME}.SPH files are read by MAGMODEL.EXE which produces the magnetospheric ephemerides. The magnetospheric ephemeris files are binary files that end with the extension "MAG." Each record of the file specifies the position of a satellite in the Earth's magnetic field, and the time interval between all records is constant (T_s).

Each record of a magnetospheric ephemeris file contains, in the following order:

L value	: 4 byte real (R_E)
B/B_0	: 4 byte real

Open field lines are indicated by an L of -1 or L > 15 R_E.

The last record of each file contains, in the following order:

-100	:	4 byte real
TimeStep	:	4 byte real (time interval between steps)

The requirement for a constant time step is set by TIMEBINS.EXE, which reads in the {FILENAME}.MAG files and uses them to produce files indicating the amount of time the orbit spends in each of the magnetospheric location bins defined for the dose models.

LOKANGL.EXE can be bypassed by creating a {FILENAME}.SPH file of the proper format. A different magnetospheric model can also be used by creating a {FILENAME}.MAG file of the proper format. In both cases APEXRAD will still ask for orbital elements and produce any files associated with the orbit that don't already exist. However, before replacing any (user supplied) files it will query the user. If the user chooses to not to replace a file, the original file will be used for all remaining calculations.

APPENDIX D

APEXRAD SUPPORT PROGRAMS

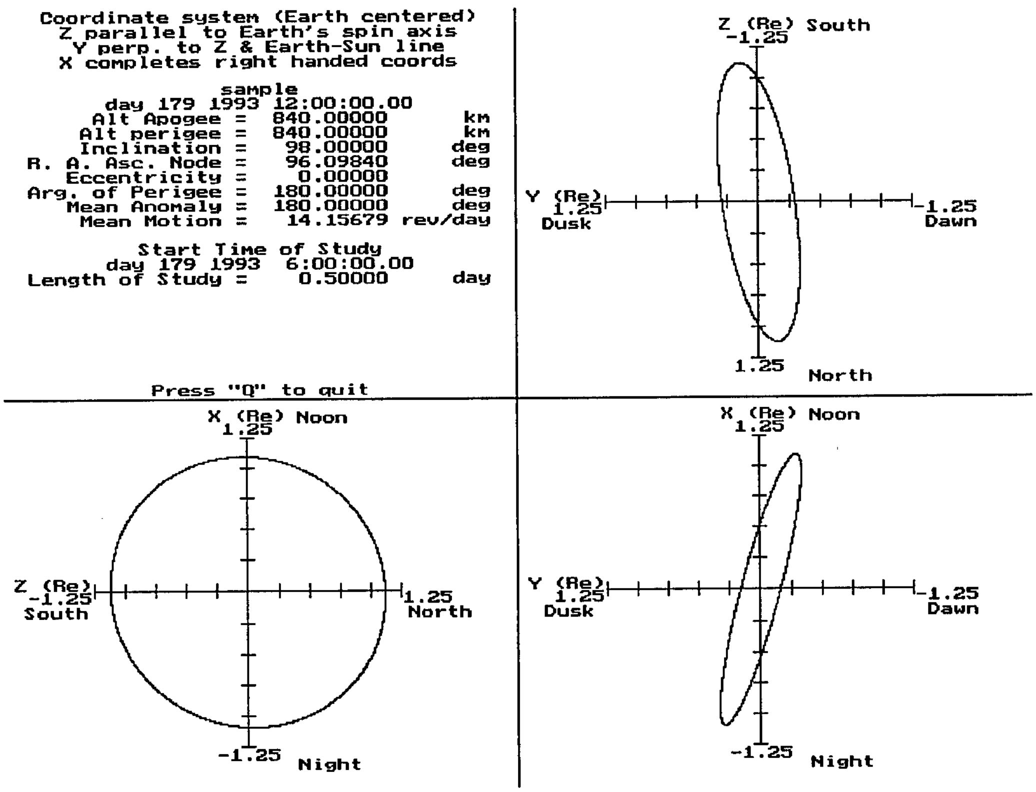

Figure D-1 ORBIT.EXE Screen

ORBIT.EXE - is a display utility program that works on a color EGA/VGA monitor. It is called by APEXRAD, but may also be called from the command line. This program reads the {FILENAME}.SPH files and plots the orbit in geographic coordinates. It also reads the associated {FILENAME}.ELE file to get the orbital elements that specify the orbit. When calling ORBIT.EXE from the command line, the name of the orbit/run must be included on the command line. The name may not include an extension. Figure D-1 shows a screen capture of ORBIT.EXE using the files created in the sample session of Appendix A. In the coordinate system used (see Figure D-2), Z points along

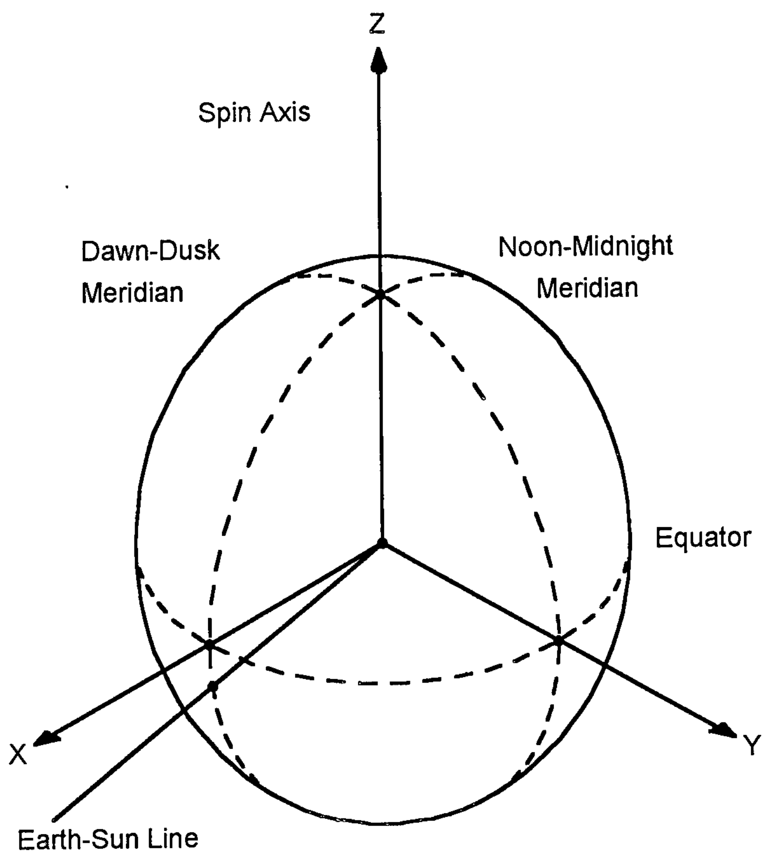

Figure D-2 Coordinate System Used for ORBIT.EXE

the Earth's spin axis and is positive toward the north pole, while Y is perpendicular to Z and the Earth-Sun line and is positive towards dusk. X completes the right handed coordinate system and goes through the noon meridian. The lower right corner of Figure D-1 shows the orbit projected into the XY plane. The other two corners show the orbit projected into the XZ, and YZ planes. The orbital elements are displayed in the upper left corner of the screen. Pressing "Q" exits the program.

LOKANGL.EXE - is used at the Geophysics Directorate to predict positions of Earth satellites using orbital elements as an input. LOKANGL.EXE expects a {FILENAME}.ELE file as an input and produces a binary file containing a series of geographic positions along the orbit, at equal time steps over the time interval specified in {FILENAME}.ELE. LOKANGL.EXE calculates the position of an Earth satellite using a perturbation expansion with the second and third zonal harmonics of the Earth's gravitational field. It is not considered accurate for times more than 100 days from a specified orbital element. Contact this office (PL/GPSH) if information on the format of the {FILENAME}.ELE file or a more detailed description of LOKANGL.EXE is needed. The output file format is described in Appendix C ({FILENAME}.SPH). To run LOKANGL.EXE from the DOS prompt the name of the input file, including extension must be specified on the command line. The output file name is specified in the {FILENAME}.ELE file.

MAGMODEL.EXE - converts geographic ephemeris data to magnetospheric ephemeris data, using the IGRF internal field models (DGRF85, DGRF90 or IGRF95 as appropriate) and Olson-Pfitzer Static Magnetic Field Model IBM PC Fortran routines developed by Karl Pfitzer (1991). It is called by APEXRAD and can be run from the command line. When executed from the command line this executable requires parameters. The first parameter is the source file (including name and extension), and the second is the destination file (including name and extension). The source file is a geographic ephemeris file, and the destination file is a magnetospheric ephemeris file. The formats of both these files are described in Appendix C.

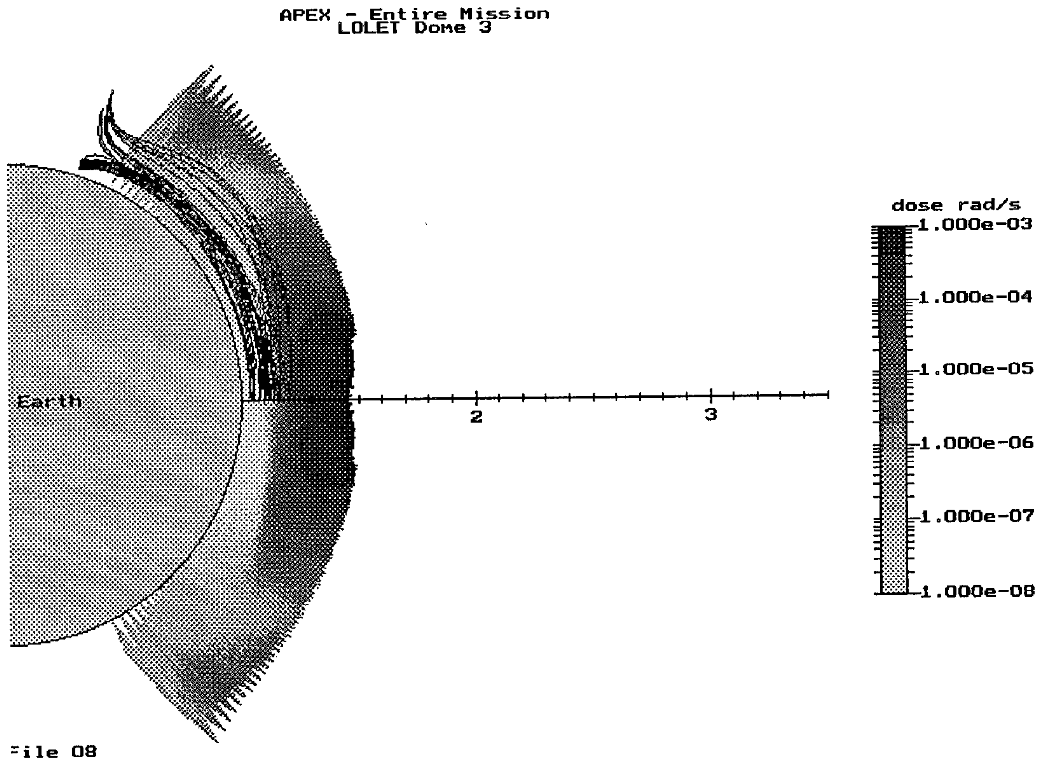

Figure D-3 DIPOLE.EXE screen displaying SAMPLE.MAG orbit.

DIPOLE.EXE - This program displays the dose rate data in the APEX_DSE.## files. The data are placed spatially on the screen as they would look if the Earth's magnetic field were a dipole (the image will not be proportioned correctly if an EGA card is used). Figure D-3 shows a copy of the screen when DIPOLE.EXE is displaying the orbit generated in Appendix A. The figure is shown in gray scale, but the program displays are in color. [Comments referring to the color display will be in brackets, while those referring to the gray scale figure, will not.] The [cyan] half circle on the left side of the screen represents the Earth with the magnetic axis pointing straight up. Gray scales [color codes] represent dose rate intensity. Higher dose rates tend towards the darker shading [reds], and lower dose rates tend towards the lighter shading [blues]. Where the dose rate is above the color scale, it will be shown as black [white], and where the dose rate is below the color scale it will be shown as very light gray [dark gray] and where there is no data available it will be shown as white [black]. Pressing the space bar displays an options menu. The color scale limits can be adjusted and the color scale can be toggled between a logarithmic and a linear scale. One can select the dose model displayed by using the plus (minus) keys to move to the next (previous) model or pressing "F" and entering the model number. (Note: model numbers range from 2 to 143, but there is not a model for every number in this range.) Pressing "Q" quits the program. The orbit in L shell versus B/B_0 is plotted as a black line on the upper quadrant of the dose rate data. The orbit is plotted in only one quadrant because B/B_0 contains no information about +/- latitude. In Figure D-3 the orbit is below 1.2 R_E and shows up as a series of dark bands at the lower edge of the inner belt in the upper quadrant. Note that when the orbit reaches high latitudes it appears to "peel" away from and toward the Earth; this is an artifact of the conversion from the real geographic coordinates to the coordinate system of an ideal dipole magnetic field. Similar features may appear in other high inclination orbits. The model displayed in Figure D-3 is LOLET dose for Dome 3 averaged over the entire mission. The inner proton belt causes the high concentration of dose near the equator. Electrons from the outer belt, following the field lines down to low altitudes, are responsible for the high dose rates at the high latitudes.

The orbit plot superimposed on the dose rate data can be used to analyze the effectiveness of APEXRAD for the given orbit. Portions of low orbits may actually be drawn below the surface of the Earth on the plots. This results from the fact that the Earth is not actually spherical, the magnetic field is not actually dipolar, and the center of the magnetic field is not at the center of the Earth. The valid range of the APEX data can be seen clearly from looking at the dose rate plots. If the orbit passes through altitudes above the model, it is recommended that CRRESRAD be used instead of APEXRAD. The upper edge of the APEXRAD models is still in the heart of the inner proton belt, where there are very significant dose rates.

DIPOLE.EXE can be run from the command line by typing "DIPOLE." Dipole will ask for the file (model) number to be displayed, and will then graph the data. The file number can also be specified on the command line. To view APEX_DSE.07 one would type "DIPOLE 7." A second command line parameter can be included to show an orbit superimposed on the dose rate map. The second parameter must be the path (including name and extension) of a magnetospheric ephemeris file, of the format given in Appendix C.

APPENDIX E

CONTENTS OF SAMPLE.DAT

```
                  APEXRAD prediction utility -    sample,          page  1

 Element Time : day 179 1993 12:00:00.00
    Alt perigee    840.000         km        Alt Apogee    840.000         km
    Inclination  98.000000        deg  Arg. of Perigee 180.000000        deg
R. A. Asc. Node  96.098400        deg     Mean Anomaly 180.000000        deg
   Eccentricity 0.00000000 (0.0-1.0)       Mean Motion  14.156789    rev/day

Start Time of Study : day 179 1993 06:00:00.00
    Length of Study =    0.500000 days

    Calculated dose for APEX LOLET (rads silicon/year)
over percent of orbit out of range.

    Activity          1B          2B           3           4
Whole Mission   5.39e+04    2.48e+02    1.47e+02    1.15e+02
                  30.27%      30.27%      30.27%      30.27%
5.0<=Ap15<7.5   6.16e+04    2.19e+02    1.48e+02    1.18e+02
                  31.12%      31.12%      31.12%      31.12%
7.5<=Ap15< 10   4.19e+04    2.02e+02    1.50e+02    1.17e+02
                  30.40%      30.40%      30.40%      30.40%
 10<=Ap15< 15   5.23e+04    2.41e+02    1.52e+02    1.20e+02
                  30.45%      30.45%      30.45%      30.45%
 15<=Ap15< 20   6.77e+04    3.98e+02    1.38e+02    1.06e+02
                  30.76%      30.76%      30.76%      30.76%
 20<=Ap15< 25   8.51e+04    5.82e+02    1.34e+02    1.02e+02
                  31.14%      31.14%      31.14%      31.14%

    Calculated dose for APEX HILET (rads silicon/year)
over percent of orbit out of range.

    Activity          1B          2B           3           4
Whole Mission   7.93e+02    4.26e+02    3.14e+02    2.35e+02
                  30.27%      30.27%      30.27%      30.27%
5.0<=Ap15<7.5   7.70e+02    4.36e+02    3.16e+02    2.39e+02
                  31.12%      31.12%      31.12%      31.12%
7.5<=Ap15< 10   7.54e+02    4.35e+02    3.22e+02    2.41e+02
                  30.40%      30.40%      30.40%      30.40%
 10<=Ap15< 15   8.36e+02    4.30e+02    3.13e+02    2.34e+02
                  30.45%      30.45%      30.45%      30.45%
 15<=Ap15< 20   8.30e+02    4.14e+02    3.12e+02    2.30e+02
                  30.76%      30.76%      30.76%      30.76%
 20<=Ap15< 25   7.84e+02    3.97e+02    3.01e+02    2.25e+02
                  31.14%      31.14%      31.14%      31.14%
```

Calculated dose for APEX total (rads silicon/year) over percent of orbit out of range.

Activity	1B	2B	3	4
Whole Mission	5.47e+04	6.74e+02	4.61e+02	3.50e+02
	30.27%	30.27%	30.27%	30.27%
5.0<=Ap15<7.5	6.24e+04	6.55e+02	4.64e+02	3.57e+02
	31.12%	31.12%	31.12%	31.12%
7.5<=Ap15< 10	4.27e+04	6.37e+02	4.71e+02	3.58e+02
	30.40%	30.40%	30.40%	30.40%
10<=Ap15< 15	5.32e+04	6.71e+02	4.65e+02	3.54e+02
	30.45%	30.45%	30.45%	30.45%
15<=Ap15< 20	6.85e+04	8.12e+02	4.50e+02	3.37e+02
	30.76%	30.76%	30.76%	30.76%
20<=Ap15< 25	8.59e+04	9.79e+02	4.35e+02	3.27e+02
	31.14%	31.14%	31.14%	31.14%

Dome Number	Aluminum Shielding (mils Al)	(g/cm^2)	Detector Area (cm^2)	Thickness (microns)
1B	4.29	0.0294	0.0514	393
2B	82.5	0.57	0.0514	382
3	232.5	1.59	0.0514	400
4	457.5	3.14	1.000	396

Dome Number	LOLET Particles Electrons (MeV)	Protons (MeV)	HILET Protons (MeV)
1 A/B	>0.15	>80	5-80
2 A/B	>1.0	>115	20-115
3	>2.5	>120	32-120
4	>5.0	>125	52-125