GEOLOGICAL SURVEY OF CANADA
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Statistical analysis of space environment on highly elliptical orbits. HEO1 and HEO3 missions data

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Publications in this series have not been edited; they are released as submitted by the author.

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Preface

This research was undertaken to provide a radiation hazard assessment for satellites in highly elliptical orbit (HEO). This study aimed to support the Polar Communications and Weather mission (PCW) planned to launch by the Canadian Space Agency to provide continuous communication and meteorological observations in northern areas of Canada. This research gives qualitative and quantitative description of the radiation environment on HEO orbits and its variability depending on the satellite location and space weather activity. The data sets selected for the study are from the HEO1 and HEO3 missions, flown by the Aerospace Corporation in cooperation with the American Air Force. The data are provided free by the ViRBO (Virtual Radiation Belt Observatory) site (http://virbo.org/HEO).

These analyses cover 11 years, 1998 - 2008. This open file comprises the description of data processing and results of the statistical analyses including annual distributions of the radiation dose and energetic particles fluxes on HEO orbits.

1 Introduction

1.1 Motivation

The Canadian Space Agency, in partnership with Environment Canada and the Department of National Defence and participation of other Canadian Government Departments is planning to launch a potential communication, weather and climate satellite system called the Polar Communications and Weather (PCW) mission. This mission will provide high capacity, continuous communication services throughout the Canadian Arctic as well as meteorological Earth observations including weather forecasting, environment monitoring and space weather monitoring.

Currently, there are a large number of artificial satellites in orbits such as geosynchronous Earth orbit (GEO) and low-Earth orbit (LEO). Both kinds of orbit have limitations. A geostationary satellite is not a practical choice for communications at high latitudes as a large amount of power is required to transmit a signal from the equator to regions near the poles. Low-Earth orbit is below the outer radiation belt and data from LEO do not cover this important area.

For this reason, the Molniya orbit was chosen as one of possible orbits for PCW mission. This type of orbit was used for its very specific physical properties which make it most suitable for use in communications at high latitudes. A Molniya orbit is a highly elliptical orbit, its inclination of approximately 63.4° is near the critical inclination. On Molniya orbit the spacecraft spends the majority of its time near its very distant apogee, and so from the perspective of an observer on the ground, appears nearly stationary. This allows operational behaviour similar to that of a geostationary satellite, but the Molniya orbit provides a communication and monitoring services of those latitude bands that are beyond reach of the geostationary observatories.

For this reason, an investigation of the energetic particle environment encountered by satellites in Molniya orbits is necessary to be undertaken to describe the hazards and harmful effect of space weather on satellites in Molniya orbit and anticipate the possible issues of the mission. Knowing the distribution of the energetic particles of different severity along the orbit would provide the necessary information for a better design of the satellites. The goal was to provide the information about the energetic particle environment along the Molniya orbit.

1.2 The HEO data sets

The data sets selected for the study are from the HEO missions, flown in Molnya orbit by the Aerospace Corporation in cooperation with the American Air Force. The data are available from the ViRBO (Virtual Radiation Belt Observatory) site (http://virbo.org/HEO), which is one of the domain-specific virtual observatories that provide access to data related to Earth's radiation belts [1]. The HEO acronym indicates satellites in a Highly Elliptical Orbit, also known as Molniya orbits. These orbits have period of roughly 12 hours, with a perigee of no more than a few hundred kilometers, apogee of roughly 7 Earth radius (Re), and an inclination of about 63 degrees. The three HEO spacecrafts are referred to as HEO-1, HEO-2, and HEO-3 or F1, F2, and F3, meaning flights 1-3.

These data consist of energetic particle measurements, given as proton counts, electron counts, and dose/dose rate. The spacecraft are equipped with a combination of dome and telescope dosimeters. Data from these instruments are available in 15-second averages and binned by magnetic L-shell in Roederer and Olson-Pfitzer (Quiet) field models [2]. Data from HEO-2 have not been processed to the level required for release.

The data available for the HEO-1 mission covers a period from mid 1994 to late 2007 and the HEO-3 mission corresponds to late 1997 up to 2008.

This report provides an analysis of the HEO data set relevant to high energetic particle influence on satellites in Molniya orbit. Almost all analyses were made for HEO-3 mission.

1.3 The Earth's radiation belts

The radiation belts of the Earth's magnetosphere are made up of electrons, protons and heavier atomic ions. These particles get trapped in the magnetic field of the Earth forming the radiation belts [3]. The belts of trapped radiation near the Earth were discovered by James Van Allen in 1958. Therefore these belts are also known as Van Allen Belts.

The radiation environment includes

- large fluxes of Solar Energetic Particles (SEPs) produced by energetic solar eruptions (Solar particle events) ;

- Galactic cosmic rays which are a continuous flux of Galactic Cosmic Ray (GCR) ions. Although the flux is low (a few particles per /cm^2 s), GCRs include energetic heavy ions.

- Secondary radiation is generated by the interaction of the above environment components with materials of the spacecraft.

The radiation environment can pose significant hazards to space missions. Energetic particles from the radiation belts and from solar particle events can cause radiation damage to electronic devices. They can easily penetrate typical spacecraft walls and deposit doses of kilorads during missions in certain orbits.

The radiation environment was studied using data from HEO1 and HEO3 mission flown in a Molniya orbit. To determine the location of a spacecraft we used the Julian date of observations, distance from the centre of the Earth, and the geomagnetic coordinates such as local magnetic time, L-shell, and geomagnetic field B.

1.4 Radiation data for a high inclination orbit

Data from HEO missions is available in archives HEO1 and HEO3 [1]. These data consist of energetic particle measurements, given as proton counts, electron counts, dose of radiation and rate of the dose of radiation. Data from these instruments is available in 15-second averages and binned by the magnetic coordinate L-shell given in IGRF [3] and Olson-Pfitzer (Quiet) field models [3].

The data were produced in files with file names f1_yearday_time_v04.exp . For example the file f1_2000182_1326_v04.exp contains data for
F1 = Flight 1 (HEO1)
2000 = year
182 = day of year (1 = January 1)
1326 = UT of start of file as HHMM (hour, minute)
v04 = version 4 of the file
exp = export file

Data is the result of 1-second measurements and averaged by 15 seconds intervals. Information is produced by 4-channels dosimeters. For HEO1 mission the description of the channels is in Table 1-Table 3.

Table 1. Dosimeter channel

Dosimeters	Mils Be	(Al equivalent)
D1/Dose 1	111	(76)
D2/Dose 2	390	(267)
D3/Dose 3	682	(467)
D4/Dose 4	950	(651)

Table 2. HEO1 electron channels

Electron Channels	energy (MeV)	Multiplicator G, 1/(cm2 sr)	Notes
E1/Elec1	>0.13	5.4E-3	Telescope
E2/Elec2	>0.23	5.4E-3	Telescope
E3/Elec3	>1.5	0.47	D1
E4/Elec4	>4.0	0.47	D2
E5/Elec5	>6.5	0.49	D3
E6/Elec6	>8.5	0.49	D4

Table 3. HEO1 proton channels

Proton Channels	energy (MeV)	Multiplicator G, 1/(cm2 sr)	Notes
P1/Prot1	>0.080	5.4E-3	Telescope
P2/Prot2	>0.160	5.4E-3	Telescope
P3/Prot3	>0.320	5.4E-3	Telescope
P4/Prot4	20 - ??	0.47	D1
P5/Prot5	40 - ??	0.47	D2
P6/Prot6	55 - ??	0.49	D3
P7/Prot7	66 - ??	0.49	D4

For HEO3 mission the description of channels is in Table 4-

Table 6.

Table 4. HEO3 dosimeter channels

Dosimeters	Al
D1/Dose 1	5
D2/Dose 2	12
D3/Dose 3	49.5
D4/Dose 4	125.5

Table 5. HEO3 electron channels

Electron Channels	energy (MeV)	Multiplicator G, 1/(cm2 sr)	Notes
E1/Elec1	>0.13	5.4E-3	Telescope
E2/Elec2	>0.23	5.4E-3	Telescope
E3/Elec3	>0.45	0.4615	D1 (Telescope)
E4/Elec4	>0.63	0.45	D2

E5/Elec5	>1.5	0.45	D3
E6/Elec6	>3	0.45	D4

Table 6. HEO3 proton channels

Proton Channels	energy (MeV)	Multiplicator G, 1/(cm2 sr)	Notes
P1/Prot1	>0.080	5.4E-3	Telescope
P2/Prot2	>0.160	5.4E-3	Telescope
P3/Prot3	>0.320	5.4E-3	Telescope
P4/Prot4	>5	0.4615	D1
P5/Prot5	8.5 - 35	0.45	D2
P6/Prot6	16 - 40	0.45	D3
P7/Prot7	27 - 45	0.45	D4

These files provide information about one orbit of the satellite. Usually there are two files corresponding to one day because the period of the orbit is almost 12 hours. The file contains the time when the data was detected, the distance of the spacecraft from the centre of the Earth, the radiation data, magnetic coordinates and some other parameters which can be important for users.

The following parameters are provided in the export text files:

Parameter	Units
Year	Years
Month	Months
Day	Days
DecDay	Days
nSeconds	Seconds
Elec1	counts/sec
Elec2	counts/sec
Elec3	counts/sec
Elec4	counts/sec
Elec5	counts/sec
Elec6	counts/sec
Prot1	counts/sec
Prot2	counts/sec
Prot3	counts/sec
Prot4	counts/sec
Prot5	counts/sec
Prot6	counts/sec
Prot7	counts/sec

Dose1	Rads
Dose2	Rads
Dose3	rads
Dose4	rads
Dose1_rate	rads/sec
Dose2_rate	rads/sec
Dose3_rate	rads/sec
Dose4_rate	rads/sec
SC_Temp	deg C
JulDate	Days
TiltAngle	deg
RadDist	Re (Earth's radii)
nDose_seconds	Seconds
dose_Toffset	Seconds

IGRF B-field model value (IGRF-epoch appropriate)
Fields computed from EPHEMLIB
Orbit_Status_IGRF flag, Identifies orbit segment

Fields computed from ONERA-DESP-LIB [1]

L*_IGRF(ONERA)	Re
Lm_IGRF(ONERA)	Re
Btot_IGRF(ONERA)	nT
Bequ_IGRF(ONERA)	nT
I_IGRF(ONERA)	Re
MLT_IGRF(ONERA)	hrs

Fields computed from ONERA-DESP-LIB [1]

L*_OP(ONERA)	Re
Lm_OP(ONERA)	Re
Btot_OP(ONERA)	nT
Bequ_OP(ONERA)	nT
I_OP(ONERA)	Re

The data are divided into separate orbit segments corresponding to the 'orbit_status' parameter (see Table 7).

Table 7. Orbit status parameters

Orbit status	Type	direction	altitude	dL/dt
0	Even	outbound	high	> 0
1	Odd	outbound	high	> 0
2	Even	inbound	high	< 0
3	Odd	inbound	high	< 0
4	Even	outbound	low	< 0
5	Odd	outbound	low	< 0
6	Even	inbound	low	> 0

7	Odd	inbound	low	> 0

For numbering purposes, orbits begin at perigee. Types 'odd' and 'even' refer to the pair of subsequent orbits per day. 'Outbound' and 'inbound' portions are perigee-to-apogee and apogee-to-perigee, respectively. During an 'inbound' 1/2 orbit, the value of L (either IGRF or Olson-Pfitzer) decreases from a local maximum near apogee to a local minimum and then increases up to a local maximum near perigee. The reverse of this description holds while following the orbit from perigee to apogee. The time of the minimum L between apogee (high altitude) and perigee (low altitude) is used as the cut-off between high- and low-altitude orbit segments. The orbit segments and their expected dL/dt are listed in the table above.

We use the data to define the radiation environment on a HEO orbit. For this purpose we selected data containing date and time, distance from the Earth's centre, radiation data (Dose1, Dose 2, Dose 3 and Dose 4 corresponding to different shielding levels), electron and proton fluxes. The idl codes clean_data.pro (see Appendix 5. Codes) were used to read HEO data files of different types. The output data for several years for HEO3 mission are placed now in files 'records_1998.dat', 'records_1999.dat' etc., up to 'records_2005.dat'. To specify data for analysis and plotting, idl codes were written. The idl codes written for this study are in Appendix 5. Codes

2 Orbit description

2.1 Orbital Elements

This section will present the relevant background on the description of orbits. Any orbit can be uniquely defined by a minimum of six parameters given a coordinate frame and starting point in time (epoch). These parameters are either a six element state vector, giving the position and velocity of the orbiting body in 3 dimensional space, or a set of scalar orbital elements describing the characteristics of the orbit trajectory [4]. Either specification completely sets up a two-body initial value problem.

For the sake of simplicity in this investigation, the most commonly used classical (Keplerian) orbital elements were considered when attempting to reconstruct the satellite orbits. Kepler's First Law of Planetary Motion states that every orbit is an ellipse with the body being orbited at one of the foci. The classical elements are six scalar quantities describing the shape and orientation of the ellipse.

The six quantities are:

- *a*, the semi-major axis. This is half the distance between the periapsis (point on the orbit closest to body being orbited) and apoapsis (point furthest from the body being orbited). If r_a is the radius of apoapsis and r_p the radius of periapsis, then

  $$a = \tfrac{1}{2}(r_a + r_p).$$

  Roughly speaking, this defines the size of the orbit. When considering satellites orbiting the Earth this quantity is usually specified in Earth's radius (R_E) or kilometers (km).

- *e*, the eccentricity. This is a dimensionless quantity specifying the shape of the ellipse. Eccentricity ranges from 0 to 1, with the former value describing the case of a circular orbit. As *e* tends to 1, *a* tends to infinity and the orbit opens and becomes a parabola. Given the radial distances as above, the eccentricity is given by the formula:

  $$e = \frac{r_a - r_p}{r_a + r_p}.$$

  Together the semi-major axis and eccentricity define the size and shape of the orbit.

- *i*, the inclination. This is the angle between the ecliptic and the orbital plane and ranges from 0 to 180°. Geocentric orbits with an inclination between 0 and 90 are said to be prograde orbits as the satellite moves in the same direction as the rotation of the Earth. Conversely, if i is between 90 and 180 then the orbit opposes the rotation of the Earth and is said to be retrograde.

- Ω, the longitude of the ascending node. The ascending node is the point where the orbiting body, travelling from north to south, crosses the line of nodes, the intersection of the orbital plane and the reference plane. Ω is the longitude of this point with respect to the reference direction of the coordinate system.

  In the case of the Earth, the reference direction is usually taken to be the First Point of Aries, and the reference plane the equatorial plane of the Earth (*i.e.* the GEI coordinate system is used). In this case Ω is referred to as the right ascension of the ascending node (RAAN) and is measured eastward from the x-axis.

- ω, the argument of periapsis. This is the angle from the ascending node to the point on the orbit closest to the body being orbited (periapsis). This gives the rotation of the orbital plane about the focus, that is, specifies the location of periapsis. For geocentric orbits this is referred to as the argument of perigee.

  Together i, Ω and ω define the orientation of the orbital plane in space.

- υ, the true anomaly. This is the angle between periapsis and the orbiting body, and gives the position of the body on the orbit for a time elapsed from epoch. Often the mean anomaly, M_o, which does not correspond to the true position will be used instead. It is mathematically convenient as it varies linearly with time.

The six orbital elements are depicted in Figure 2-1.

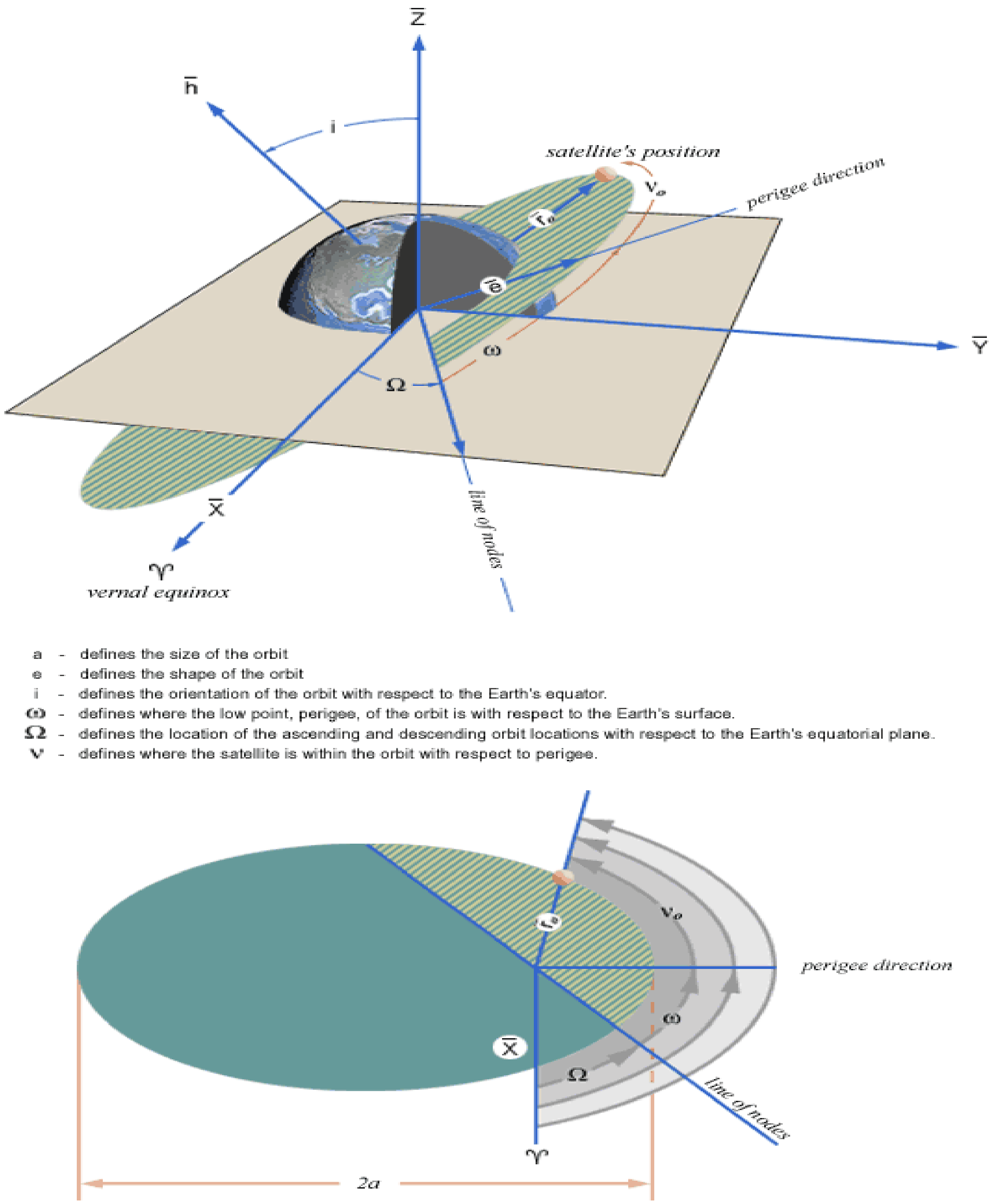


Figure 2-1. **Classical Orbital Elements. Credit: http://spaceflight.nasa.gov/realdata/elements/graphs.html**

2.2 Molniya Orbit

Now that the relevant background on orbital elements has been discussed, this section will describe the Molniya orbit and its properties.

Molniya orbit is named after a series of Russian communications satellites which were first flown in early 1960s. The name, from the word Молния ("lightning"), referred to the extreme speed of the spacecraft when close to their very low perigee [5].

Molniya orbits have an inclination of 63.4°, a period of half a sidereal day, and are highly elliptical, typically having eccentricities near 0.7. This type of orbit was used for its very specific physical properties which make it most suitable for use in communications at high latitudes.

The Molniya orbit is a highly eccentric orbit with a stable high-latitude apogee. Due to the second Kepler law of planetary motion, the satellite spends about two thirds of the time near the apogee where it will provide an extension of coverage all the way to the Pole (see Figure 2-2).

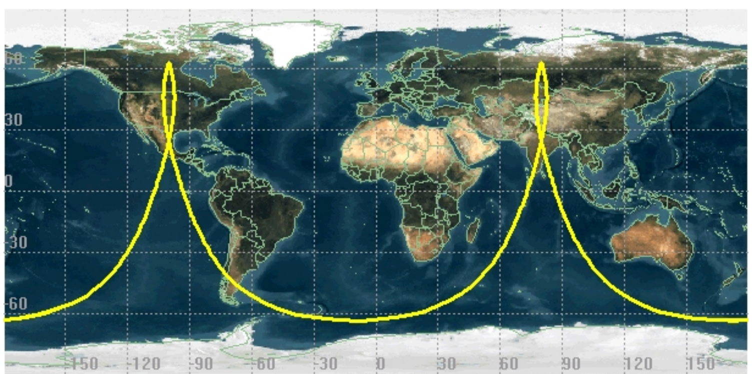


Figure 2-2. Ground track of a Molniya orbit.
Credit : Analytical Graphics Inc.

Figure 2-3. Tandem Molniya satellites
Credit: Canadian Space Agency

A Molniya orbit's inclination of approximately 63.4° is near the critical inclination, the angle at which orbital perturbations from the oblateness of the Earth spheroid are nulled. This prevents precession of the argument of perigee over long time periods. Taken in combination with the orbital period being an integer factor of a sidereal day, it is ensured that the position where the satellite is overhead at apogee remains very nearly constant and station-keeping operations can be kept to a minimum.

To allow 24-hour coverage of a northern area, two Molniya satellites may be flown in tandem as depicted in Figure 2-3. Choosing perpendicular inclinations allows constant coverage, as when one satellite is at perigee over the southern hemisphere the other will be at apogee over the northern hemisphere.

2.3 Geomagnetic Parameters and Relationships

Next we briefly review important concepts relating to geomagnetism which will be relevant in the investigation.

The standard model of the "quiet time" geomagnetic field is the International Geomagnetic Reference Field (IGRF) [6]. The is based on the geomagnetic scalar potential *V(r, θ, φ)* that can be expresses as a spherical harmonic expansion as

$$V(r,\theta,\phi) = R_E \sum_{n=1}^{\infty} \sum_{m=0}^{n} (\frac{R_E}{r})^{n+1} (g_n^m \cos m\phi + h_n^m \sin m\phi) P_n^m (\cos\theta)\,, \tag{2.1}$$

where r is the radial distance from the center of the Earth, ϕ is longitude (east from Greenwich), θ is the geocentric co-latitude and P_m^n is the Schmidt quasi-normalized associated Legendre function of degree n and order m.

Taking the gradient of the scalar potential gives the vector magnetic field. The series expansion is infinite, however, in practice usually only the first ten or thirteen terms in n are taken.

Because the coefficients of the higher terms of the spherical harmonic expansion are small compared to the lower terms, much of the behaviour of the magnetic field can be approximated by taking only the first term ($m = 0$, $n = 1$) leaving:

$$V = R_E (\frac{R_E}{r})^2 g_1^0 \cos\theta\,.$$

This approach yields what is known as the centered dipole model. The dipole axis is centered at the geometric center of the Earth, but is inclined with respect to the geometric axis.

The geomagnetic field lines of a dipole field can be expressed in polar coordinates by the equation:

$$r = L \sin^2\theta = L \cos^2\lambda\,, \tag{2.2}$$

where λ is the magnetic latitude and L is the value of r when λ = 0, that is, at the magnetic equator.

Thus the quantity L can be used to describe a position in space with respect to the magnetic field lines of the Earth; an L value corresponds to a field line which crosses the geomagnetic equator at a distance of L Earth radii. Note that L needs not be an integer. This concept is illustrated in Figure 2-4.

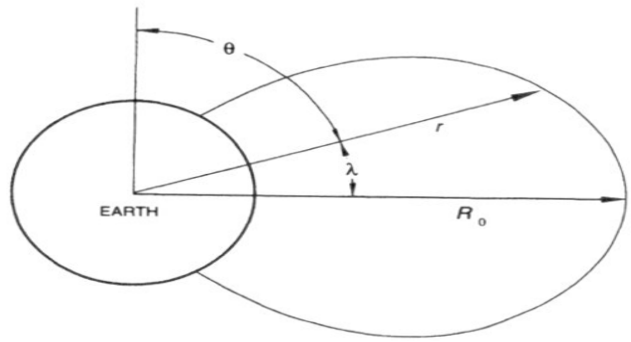


Figure 2-4. L-Shell (R_0), geomagnetic latitude (λ) and co-latitude (θ), radial distance (r). All points on the curved black line have an L value of R_0 [7]

Another important geomagnetic parameter is that of Magnetic Local Time (MLT). Longitude describes the location of a body with respect to the equatorial plane of the Earth and a reference meridian (Greenwich). The analogous geomagnetic quantity is MLT which describes position with respect to the Sun and the magnetic field lines of the Earth.

Magnetic local time is measured not in degrees but hours (1 hour = 15°). The line of geomagnetic longitude intersecting the Earth-Sun line is defined as 12 hours MLT ("magnetic noon") and the line opposite 0/24 hours ("magnetic midnight") (Figure 2-5).

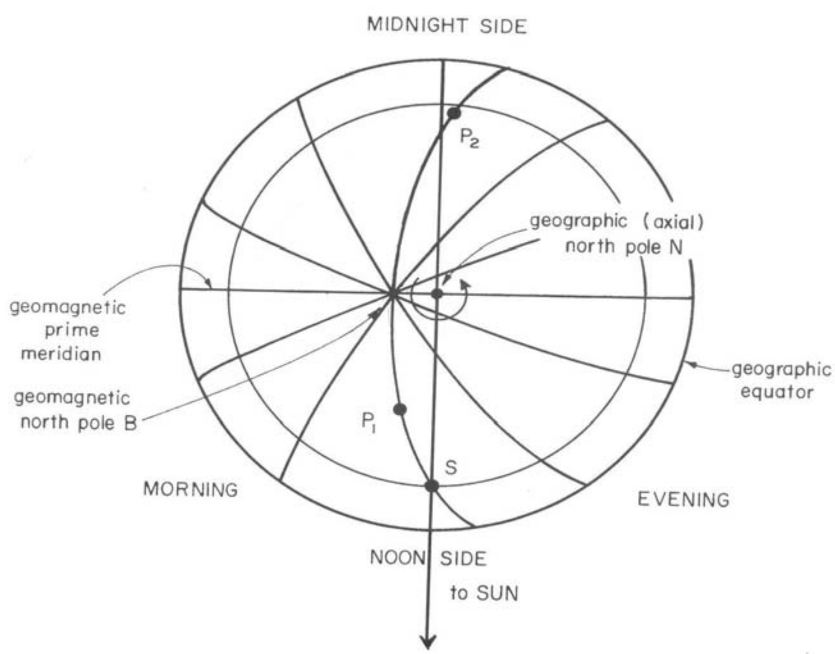


Figure 2-5. Magnetic Local Time (MLT). S and P_1 are at magnetic noon, P_2 is at magnetic midnight [7].

2.4 Orbital reconstruction using the dipole mode of the geomagnetic field

As science was not the primary objective of the HEO missions, certain key information (such as spacecraft position in space) is not publicly available due to political and security considerations. It was therefore necessary to attempt to reconstruct the orbits of the spacecraft using the data that were available. This section outlines the steps that were taken in that process.

The data from the HEO missions provide the following relevant parameters:

- *L*, which is L-Shell (Roeder and McIlwain, IGRF and Olson-Pfitzer models, units: R_E),
- *B*, total local magnetic field strength (IGRF and Olson-Pfitzer, units: nT),
- *MLT*, magnetic local time (IGRF, units: hours),
- *R*, radial distance from center of the Earth (units: R_E),
- *Date (time),* Julian date (units: days).

The code used to calculate the modeled quantities in the data sets is the ONERA-DESP library, a product of The French National Aerospace Research Laboratory [Office National d'Etudes et Recherches Aérospatiales, (ONERA)], and The Aerospace Corporation. It is open-source under the GNU Public License, written in FORTRAN (with modules also available for calling procedures from either IDL or MATLAB), and available at http://craterre.onecert.fr/home.html.

2.4.1. Calculation of Geomagnetic Longitude from Magnetic Local Time

Calculating geographic longitude from magnetic local time presented no major problems as it does not require the assumption of a dipole model. It is useful to first consider the routine calculation of the magnetic local time of a point in a given coordinate system.

Recall that the Geocentric Solar Magnetospheric coordinate system (GSM) is defined with the x-axis as the line from the Earth to the Sun. Thus the Earth-Sun line in the GSM coordinate system is any vector along that axis. Converting from degrees to hours and adding 12 (as the Earth-Sun line is defined to be magnetic noon) gives the magnetic local time. To convert a given *MLT* into geographic longitude, the set of operations is reversed.

Given a magnetic local time, subtracting 12 and converting from hours to degrees (or radians) will give the angle between the line of geomagnetic longitude intersecting the Earth-Sun line and the line of geomagnetic longitude intersecting the original coordinate. Thus, if ϕ is the geomagnetic longitude of the original point, ϕ_s is the geomagnetic longitude of the Earth-Sun line and *MLT* is the magnetic local time, then:

$$\Phi = 15(\mathrm{MLT}-12) + \Phi_s. \qquad (2.3)$$

Geomagnetic longitude can then be transformed into geographic longitude using a regular coordinate transformation if the geomagnetic latitude is known.

2.4.2 Calculation of Geomagnetic Latitude from McIlwain L-Shell and Radial Distance

Converting from McIlwain L-Shell (*L*) and radial distance (*R*) to geomagnetic latitude is straightforward. Using the relationship which was given previously (Section 2.3) we rearrange, $r = L\cos^2\lambda$ giving:

$$\lambda=\cos^{-1}[\pm(r/L)^{1/2}]. \tag{2.4}$$

However, (2.4) returns only positive values for geomagnetic latitude, and this relationship only holds true for the dipole model. The ambiguity here is due to the symmetry of the dipole model. Computation of geomagnetic latitude from a given *L* and *r* and time using the coefficients of the IGRF should be possible numerically but this was not successfully implemented.

2.5 Orbital reconstruction using the Kepler's law

To specify the position of the spacecraft on its orbit more accurately we can use the Kepler's law. Satellite moves along its orbit under the action of the Earth's gravity force. According to the Kepler's law its orbit can be described as an ellipse with the Earth in a focus of the ellipse, and the angular momentum of the satellite is constant while satellite moves along its orbit.

The angular momentum $\boldsymbol{L_p}$ of the satellite is

$$\mathbf{L_p} = \mathbf{r} \text{ x } \mathbf{p} = \mathbf{r} \text{ x } (m\mathbf{v}),$$

where **r** is the radius-vector of the satellite, **p** = m**v** is its impulse, **v** is the speed of the satellite.

The speed **v** is defined as is **v**= d**r**/dt. And the angular momentum is

$$\mathbf{L_p} = \mathbf{r} \text{ x } m\, d\mathbf{r}/dt. \tag{2.5}$$

After the differentiation of both sides of the equation (2.4) with respect to time t we get

$$d\mathbf{L_p}/dt = (\mathbf{r} \text{ x } \mathbf{F}) + (d\mathbf{r}/dt)\text{x } m(d\mathbf{r}/dt) = (\mathbf{r} \text{ x } \mathbf{F}) + (\mathbf{v} \text{ x } \mathbf{p}) = 0,$$

where **F** is the Earth's gravity force. The gravity force **F** is co-directed with the radius-vector **r**, and the vector product (**r**x**F**)=0. The satellite speed **v** and the impulse **p** are also co-directed, so **v** x **p** =0.

The satellite orbit is an ellipse. Let us take the polar coordinates with the pole in the focus of the ellipse (the Earth is in the focus) and the axis which is directed along the major axis of the ellipse (see Figure 2-6).

We can write coordinates *(x,y)* of the satellite as $x = r \cos \varphi$ and $y = r \sin \varphi$,

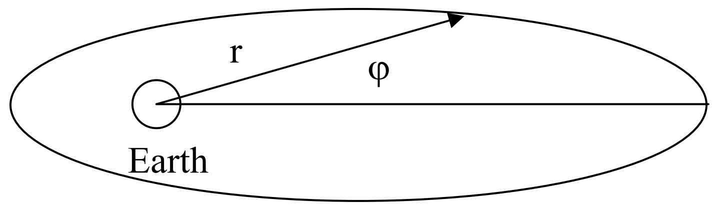


Figure 2-6. (r, φ) coordinates of the satellite orbit

where φ is the angle between the major axe of the ellipse and the radius-vector of the satellite.

$$dx/dt = dr/dt \cos \varphi - r \sin \varphi \, (d\varphi/dt),$$
$$dy/dt = dr/dt \sin \varphi + r \cos \varphi \, (d\varphi/dt).$$

The angular moment of the satellite is

$|\mathbf{L_p}| = |\mathbf{r} \times d\mathbf{r}/dt| =$
$r \cos \varphi \, (dr/dt \sin \varphi + r \cos \varphi \, (d\varphi/dt)) - r \sin\varphi \, (dr/dt \cos \varphi - r \sin \varphi \, (d\varphi/dt)) = r^2 \, d\varphi/dt.$

We know that according to the Kepler's law the angular momentum $\boldsymbol{L_p}$ is constant, so along the orbit

$$r^2 \, d\varphi/dt = \text{constant} = C.$$

The time-dependence of the distance between the satellite and the centre of the Earth is given in HEO data. We can find the φ-coordinate of the satellite on the orbit as a function of time: $\varphi = \varphi(t,C)$, where *C* is a constant

$$\varphi = \varphi_0 + \int (C/r(t)^2) dt \, . \quad (2.6)$$

Distance from the centre of the Earth and time for any point on an orbit is recorded in HEO data. Restoring the orbit we see that the trajectory fits to ellipse (see Figure 2-7).

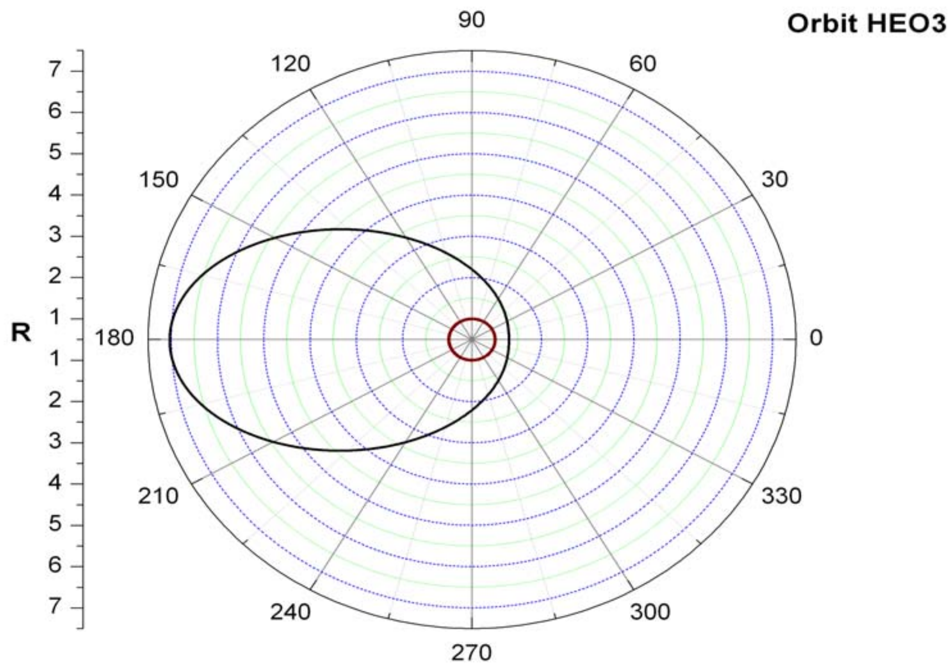


Figure 2-7. The satellite orbit plotted using R-values (HEO3 data) and the angle restored by equation (2.5)

2.6 Evaluation

For the purposes of evaluating the accuracy and quality of the orbital reconstruction methodology, an arbitrary Molniya orbit was created using the AGI Satellite Tool Kit (STK) software (http://www.agi.com/). The parameters used are summarized in Table 8. Further insight may be acquired by examining the original scenario files, either in STK or a text editor.

Table 8. Parameters used for test orbit in Satellite Tool Kit

Parameter	Value
Start Time	2000 January 27 00:00:00 UTC
End Time	2000 January 28 00:00:00 UTC
Semi-major Axis, a	26547.5 km
Eccentricity, e	0.688
Inclination, i	63.4 degrees
Longitude of Ascending Node, Ω	153 degrees
Argument of Perigee, ω	270 degrees
True Anomaly	0 degrees

Positional data generated from the test orbit was then used as input into procedures from the ONERA-DESP library to calculate associated geomagnetic field (*B*), McIlwain L-Shell (*L*) and magnetic local time (*MLT*) values with the IGRF model.

These geomagnetic parameters were then used to calculate the geographic latitude and longitude as described in the previous section, which were then compared with the original values. The results are illustrated in Figure 2-8 - Figure 2-11.

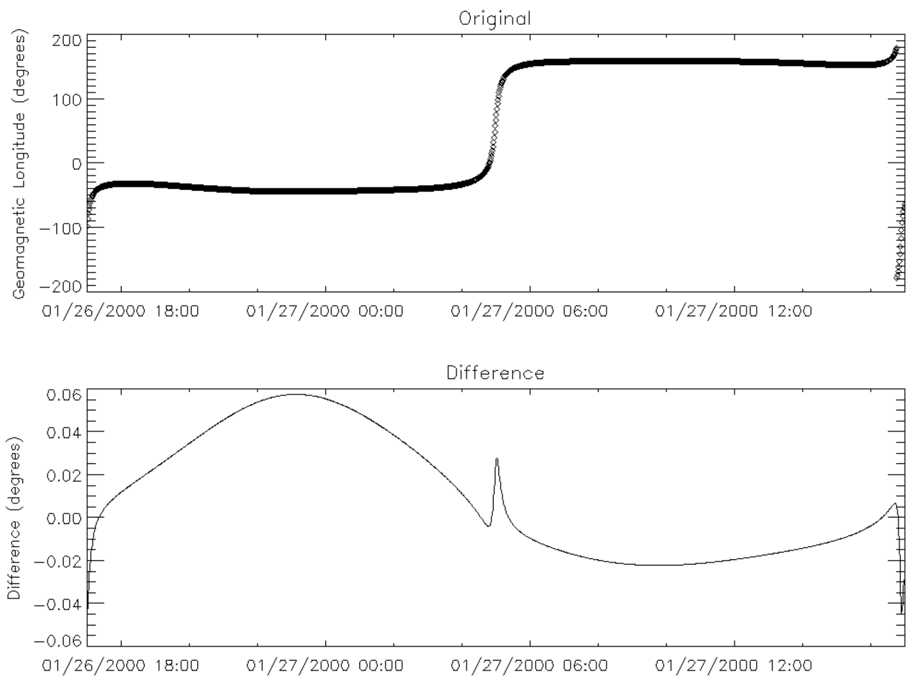


Figure 2-8. Geomagnetic longitude of the test orbit as a function of time (top) Difference between the original values and those calculated using MLT (bottom).

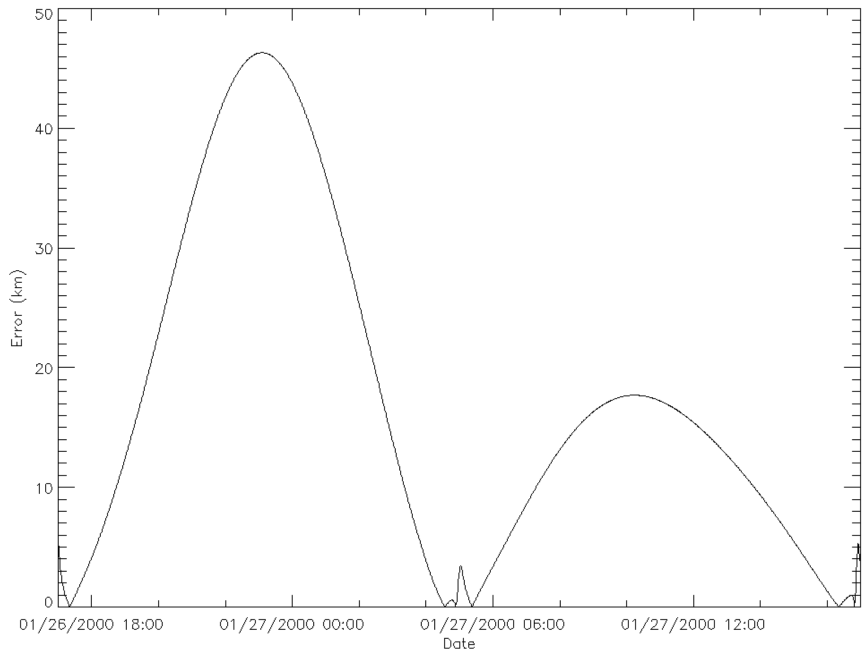


Figure 2-9. Distance from the original position to the calculated position.

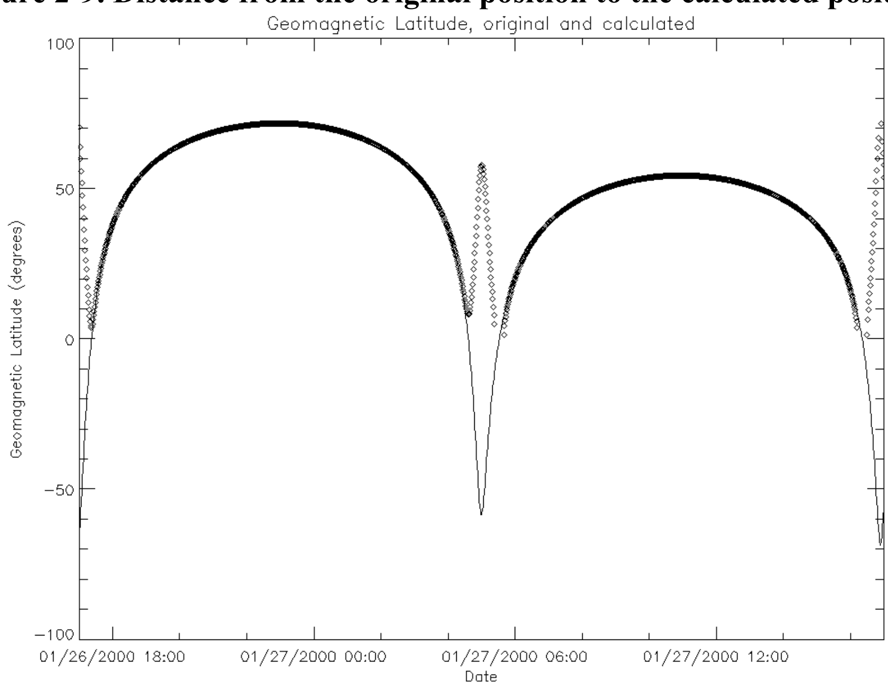


Figure 2-10. Geomagnetic latitude (solid) of the test orbit and that calculated from the HEO data (diamond).

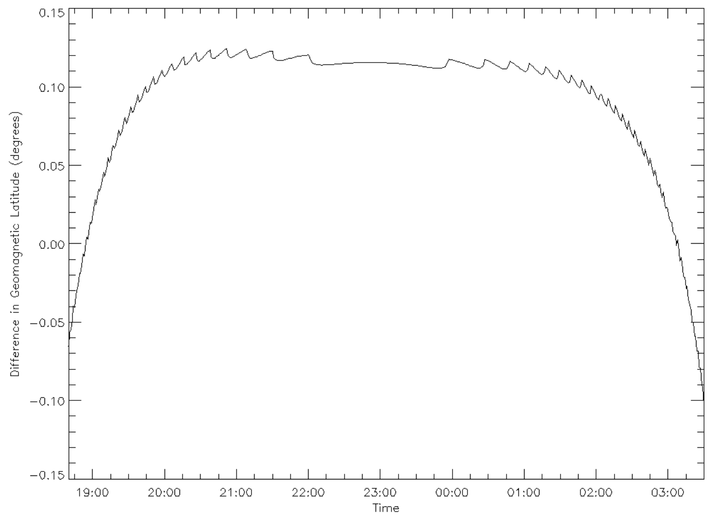


Figure 2-11. Error in calculated geomagnetic latitude values during a segment of orbit.

The geomagnetic longitudes calculated from *MLT* have not been overplotted with the original values as the differences are negligible.

Looking at the simple difference between the original and calculated values in Figure 2-8, we see a maximum error of approximately 0.06°. Considering only this value allows the calculation of the error in kilometers in the xy-plane (in MAG) along an arc $\Delta r = r\Delta\varphi$, where φ is in radians. This value is plotted in Figure 2-9, assuming a mean Earth radius of 6371 kilometers.

The longitude calculations have not introduced any errors due to an assumption of a dipole as this assumption was not made in the calculations; looking at the sequence of steps earlier shows that such an assumption is not necessary. The error in the geomagnetic longitudes calculated at this point is likely due to other smaller errors introduced, such as those from the multiple coordinate conversions required.

Examining Figure 2-10, the sections where the sign of the calculated latitude is correct (apogee sections) appear to be in good agreement with the original values, whereas the values during the perigee segment are inverted in sign due to the symmetry of the dipole. Figure 2-11 illustrates the error between the calculated and original geomagnetic latitudes in the first apogee segment. The oscillation is likely due to the dipole assumption when the *B* and *L* values were calculated using the IGRF; further investigation into the oscillation can be pursued if a more sophisticated method for calculating geomagnetic latitude is implemented.

Putting the original and calculated coordinates together gives the ground tracks as depicted below in Figure 2-12.

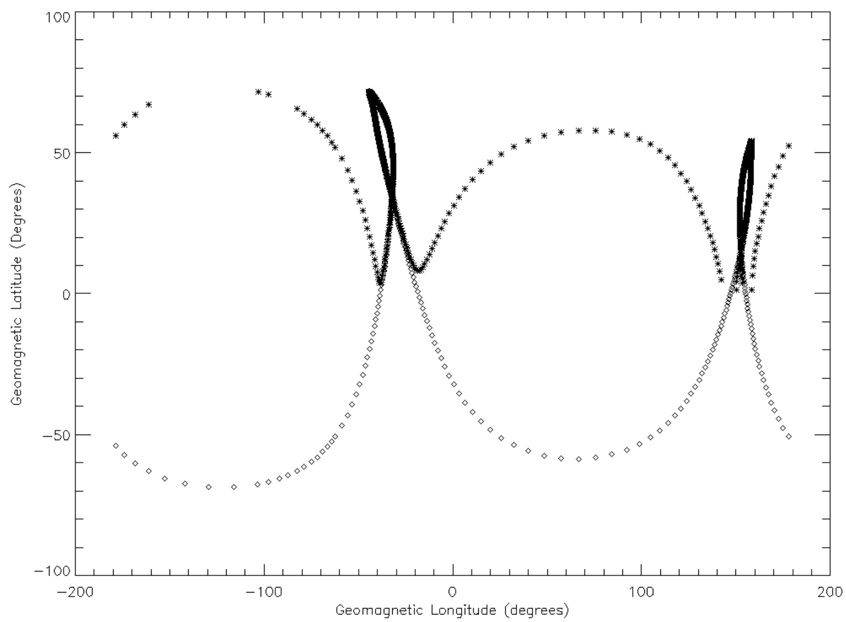


Figure 2-12. Geomagnetic ground tracks.
Original values – diamond, calculated – stars.

2.7 Conclusions to chapter 2

Position of satellite in space is defined by some direct and relevant measurements of its coordinate. We can use HEO-1 and HEO-3 datasets to restore the satellite coordinates. HEO data contain the magnetic field values calculated by IGRF for a given point on the orbit. The IGRF (International Geomagnetic Reference Field) is a global model of the geomagnetic field which allows values of the geomagnetic field vector to be calculated anywhere from the Earth's core out into space. The IGRF is generally revised every five years and is provided as IGRF models for the epoch 1995.0, 2000.0, 2005.0 etc. This value can be considered as a sort of a coordinate to find the position of the satellite because the magnetic field value can be calculated as a function of coordinates. The reverse problem to find coordinates using the magnetic field calculated by IGRF model is not uniform. But we can find a way to restore the magnetic coordinates using our knowledge about the orbit.

In section 2.4 we described how to find an approximate value of the geomagnetic latitude using the dipole model of the magnetic field of the Earth,

$$\cos^2\lambda = r/L, \tag{2.7}$$

where r is the distance from the Earth centre and L is the McIlwain L-Shell. The IGRF model is represented as the sum of infinite number of harmonics, so the λ value which is found by (2.4) is an approximate value of the geomagnetic latitude. We also have to note that the value of $\cos^2\lambda = r/L$ corresponds to 4 points on the orbit where $\cos \lambda = \pm(r/L)^{1/2}$

in different segments of the orbit. To find the right segment of the orbit and to find the accurate value of the geomagnetic latitude we can use the following method.

To define an elliptical orbit we need to know a focus (which is the Earth) and the coordinates for any two points on the orbit. For every point on the orbit we know the radial distance from the Earth centre, an approximate value of the geomagnetic latitude calculated by (2.7), and the geomagnetic longitude which is

$$\Phi = 15(MLT-12) + \Phi_s.$$

Here Φ_s is the geomagnetic longitude of the Earth-Sun line, and MLT is the magnetic local time. So we can parameterize the orbit using the geomagnetic latitudes of any two points as parameters. Variation of these parameters changes the position of the orbit in space and the value of the magnetic field calculated by the IGRF model. Comparing the magnetic field registered in HEO data with the IGRF model values, we will try to minimize the difference and find the actual orbit.

It is important to have all the coordinates for all the points on the orbit to get the statistical distribution of the radiation environment. To be sure that our statistical analysis is applicable to the orbit we need to monitor if the orbit changes its location with time. Usually the orbit moves from one position to another very gradually, because of natural causes, e.g., precession of the Earth. But sometimes the orbit changes its location significantly during the short time period which can be caused artificially. For example, in 2001 the orbit was shifted as it is demonstrated on Figure 2-13. Curve 1 on this plot corresponds to the satellite orbit before 1st of April, 2001, and curve 2 corresponds to the orbit after 10th of May, 2001. This change took approximately 40 days. We have to take this fact into account when we use the statistical methods to find, for example, the average annual distribution of the radiation environment.

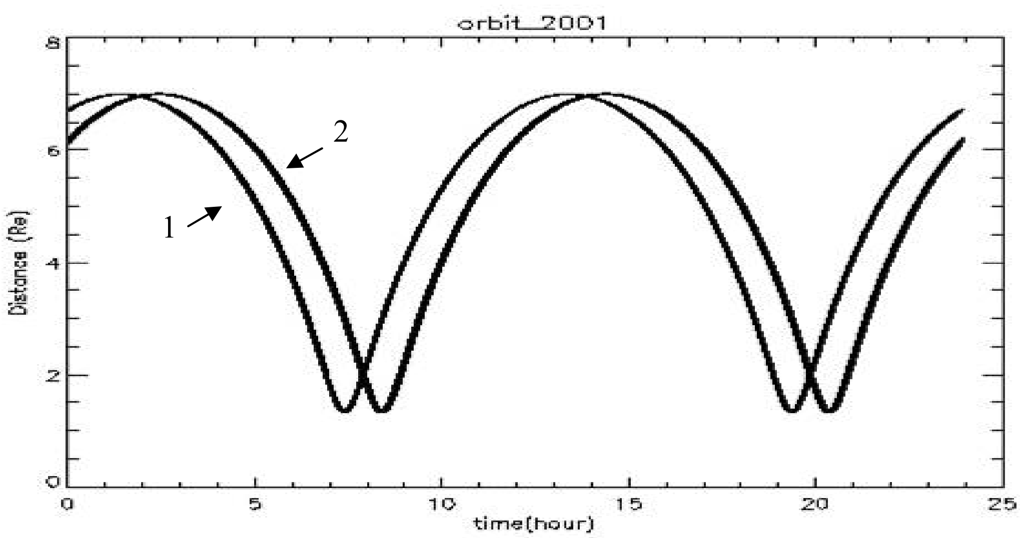


Figure 2-13. Shift of the orbit in 2001. 1 is the orbit before 1st April, 2001, 2 is the orbit after 10 May, 2001

3 Analysis of HEO-1 data

The data recorded by HEO-1 were considered as the start point for our research. They were processing to investigate the energetic particle environment and get the accumulate value of the radiation dose on a highly elliptical orbit.

3.1 Radiation dose data

The data recording in the HEO-1 data sets starts for every orbit when the distance between the satellite and the Earth centre is about 3.7 Re (Re is the Earth's radius) and continues while the satellite moves to the orbit's apogee and moves back downward to the Earth up to the moment where the distance becomes again 3.7-4.0 Re (see Figure 3-1e).

Analysis of one orbit on 9^{th} of January 2000 (it was an arbitrary chosen orbit for a day without magnetic storms) shows that the radiation dose on the first dosimeter sharply increases in the beginning and in the end of the recording time when the satellite passes the radiation belts, at 3.7-4.0 Re from the Earth's centre (Figure 3-1a and 3-1e). We see that the radiation dose on other dosimeters (with shielding levels at 390 Mils, 682 Mils and 950 Mils of Be) changes gradually, and the value of the radiation dose on these dosimeters is an order smaller than at the first dosimeter (Figure 3-1 b,c,d). So we can conclude that the largest radiation dose the satellite obtains is recorded by the first dosimeter and can be shielded by 390 Mils Be.

3.2 Radiation dose for days with and without events

The next step was to figure out if the monthly averaged accumulated radiation dose depends on solar energetic particle events. Graphs for all radiation doses for all months in 2000 based on HEO-1 data are plotted in Appendix 1. Monthly cumulative radiation dose behind 4 shieldings. HEO-1, 2000.The radiation doses were plotted separately for every month. Data recorded by the first dosimeter are of the most interest for the analysis because the first dosimeter is the most sensitive, with shielding level 111 Mils of Be, while other dosimeters have shielding levels at 390 Mils, 682 Mils and 950 Mils respectively.

The analysis of the data shows that the cumulative dose for the first dosimeter varies from 6 to 8 Rads/month. Table 9 presents a cumulative monthly radiation dose from January to December 2000 together with the monthly Ap magnetic index. The table shows that during the year the radiation dose does not change much from one month to another and a correlation between indices of magnetic activity and the monthly radiation dose is not evident. It would be interesting to compare these radiation doses with other geophysical parameters of solar activity in future research.

Table 9. Cumulative Radiation dose (111Mils) for January-December 2000

Month	Cumulative dose (Rads) on Dosimeter 1 (111 Mils Be)	Ap monthly index [3]
January	6.30	13
February	6.65	16
March	6.04	9
April	5.78	15
May	5.77	15
June	6.74	15
July	6.95	21
August	7.45	16
September	6.48	18
October	6.98	18
November	7.03	17
December	6.29	8

The average monthly radiation dose does not change much from one month to another. But daily dose varies significantly when comparing the daily radiation doses recorded on quiet days with those recorded on days with energetic particles events.

We also compared the radiation dose during days with magnetic storms and in quiet days. Here are three examples of the radiation dose for months January, November, and July 2000, behind four different levels of shielding. In January 2000 there were no proton events (Figure 3-2), and the cumulative radiation dose increased smoothly. In July 2000 it was a very strong proton event occurred on July 14, known as the Bastille Day Event, and there was a sharp increase of the cumulative dose behind all shieldings (Figure 3-3). The similar result we get for November radiation dose where the sharp increase of the doze corresponds to the strong magnetic storms on November, 10 (Figure 3-4).

The analysis of the radiation data was undertaken for the magnetic storm on the 10th of November with Kp= 6.5. If to compare two consecutive days, before and during this magnetic storm (i.e., 9 and 10 November) it is obvious that the radiation dose in the day with this magnetic storm (10 November) increases dramatically, approximately 10-100 times comparing that of the previous quiet day and the accumulation of the radiation dose occurs at all distance from the Earth for all dosimeters (see Figure 3-5. and Figure 3-6 to compare the radiation dose for the quiet day on 9th of November and during the magnetic storm on the 10th of November).

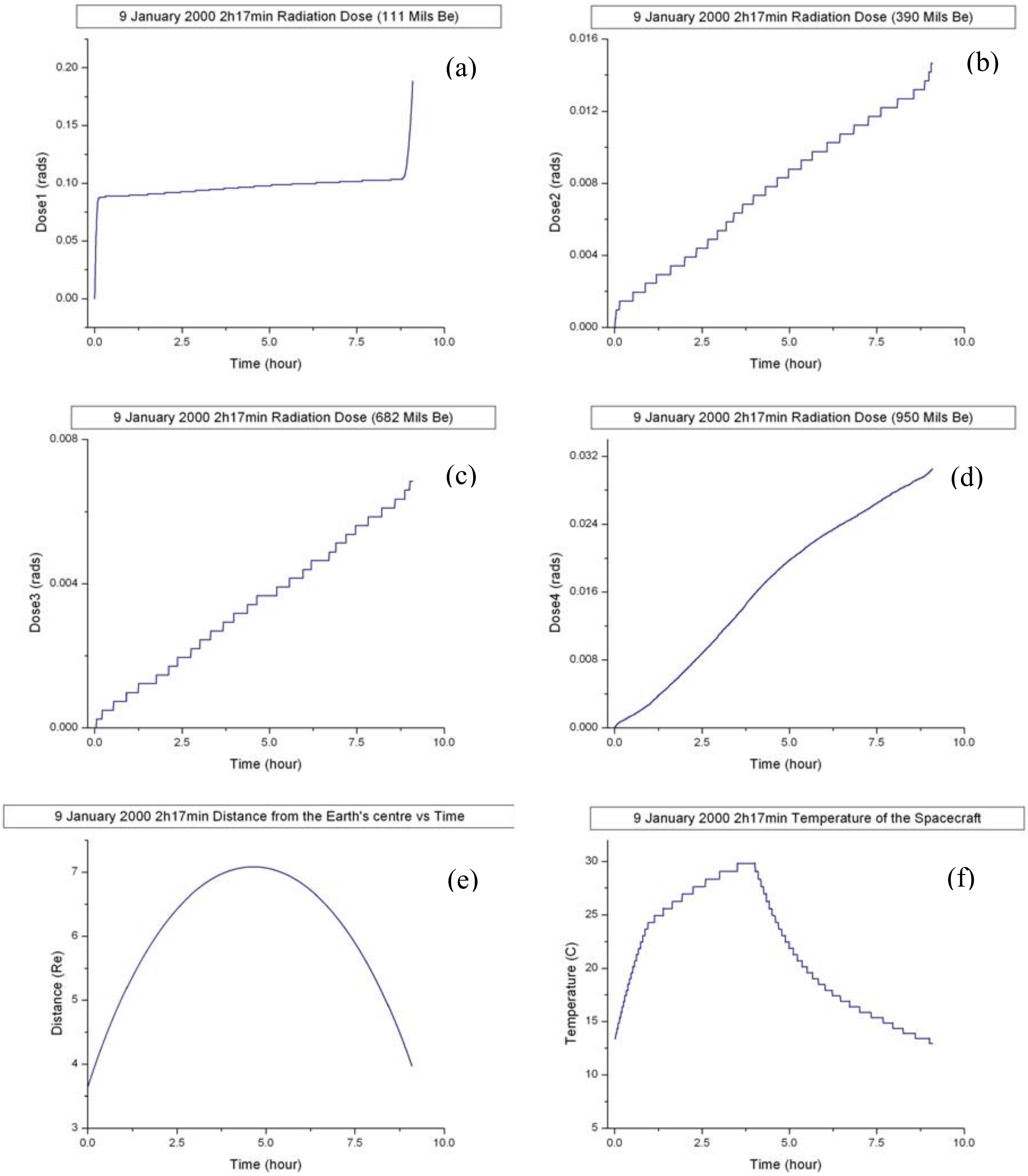


Figure 3-1. Orbit 9 January 2000 02h17min (example of quiet day)
The dose accumulated during 8 hours registered by dosimeters with
a) shielding level 111 Mils Be, b) shielding level 390 Mils Be,
c) shielding level 682 Mils Be, d) shielding level 950 Mils Be.
e) Distance from the Earth (changes from ≈ 3.7 R_E to the apogee and back to ≈ 4Re)
f) Temperature of the spacecraft

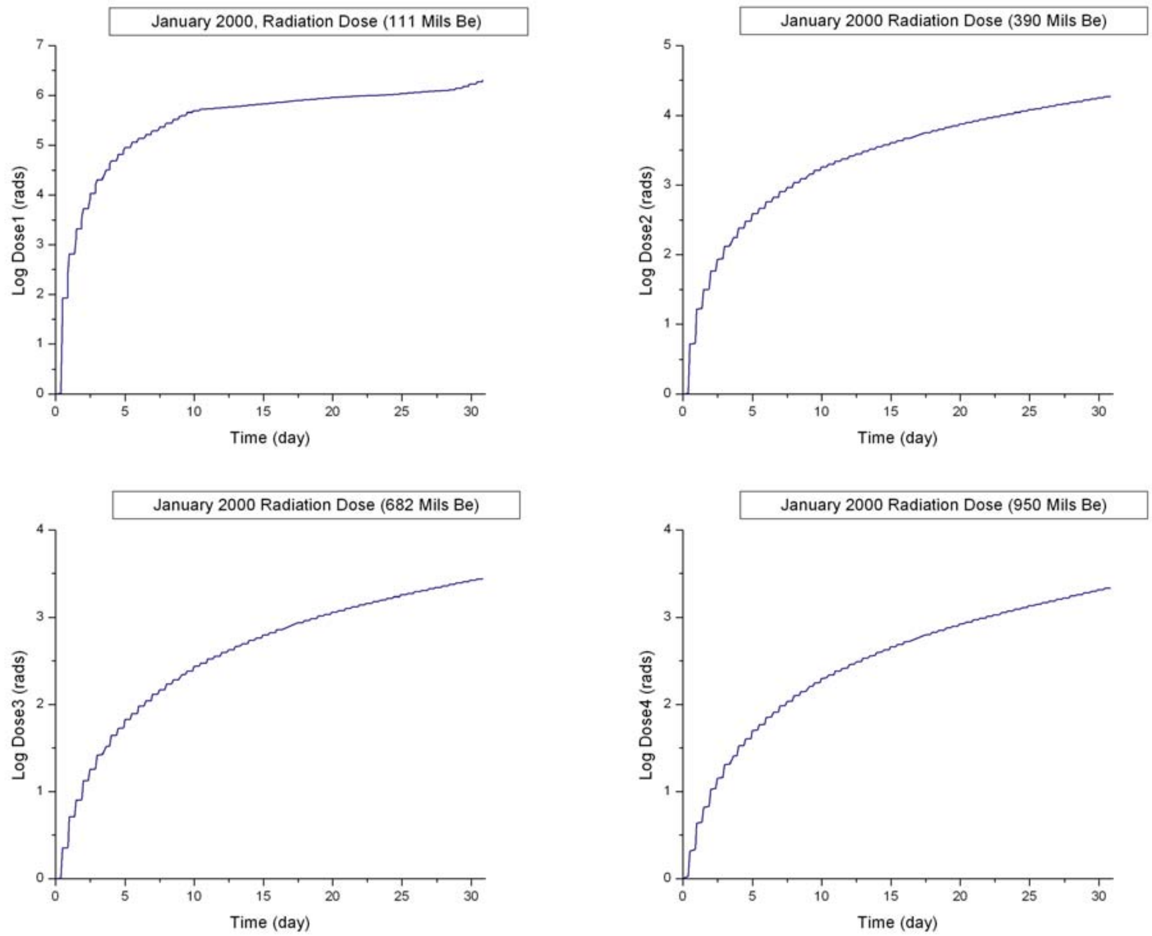


Figure 3-2. Radiation dose accumulated in January 2000
There were no large proton events, and the radiation dose increases gradually.

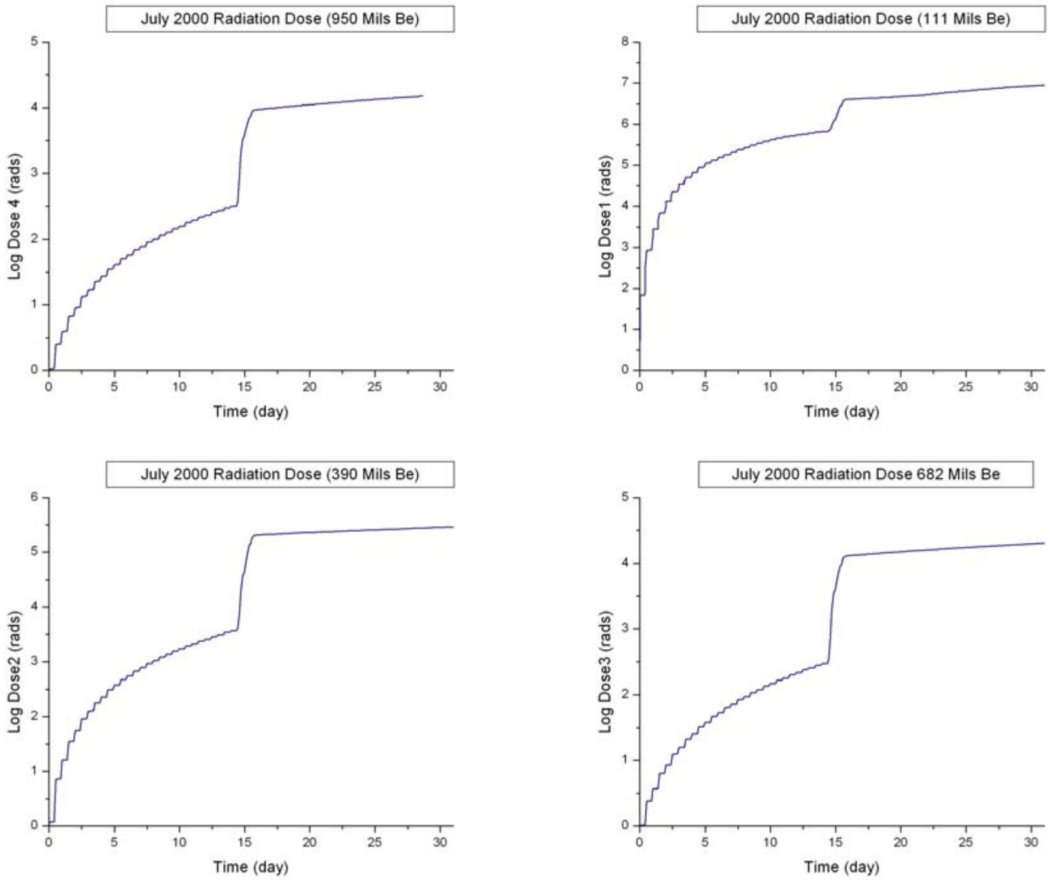


Figure 3-3. Radiation dose accumulated in July 2000.
We see a sharp increase in the accumulated dose during the Bastille Day Event

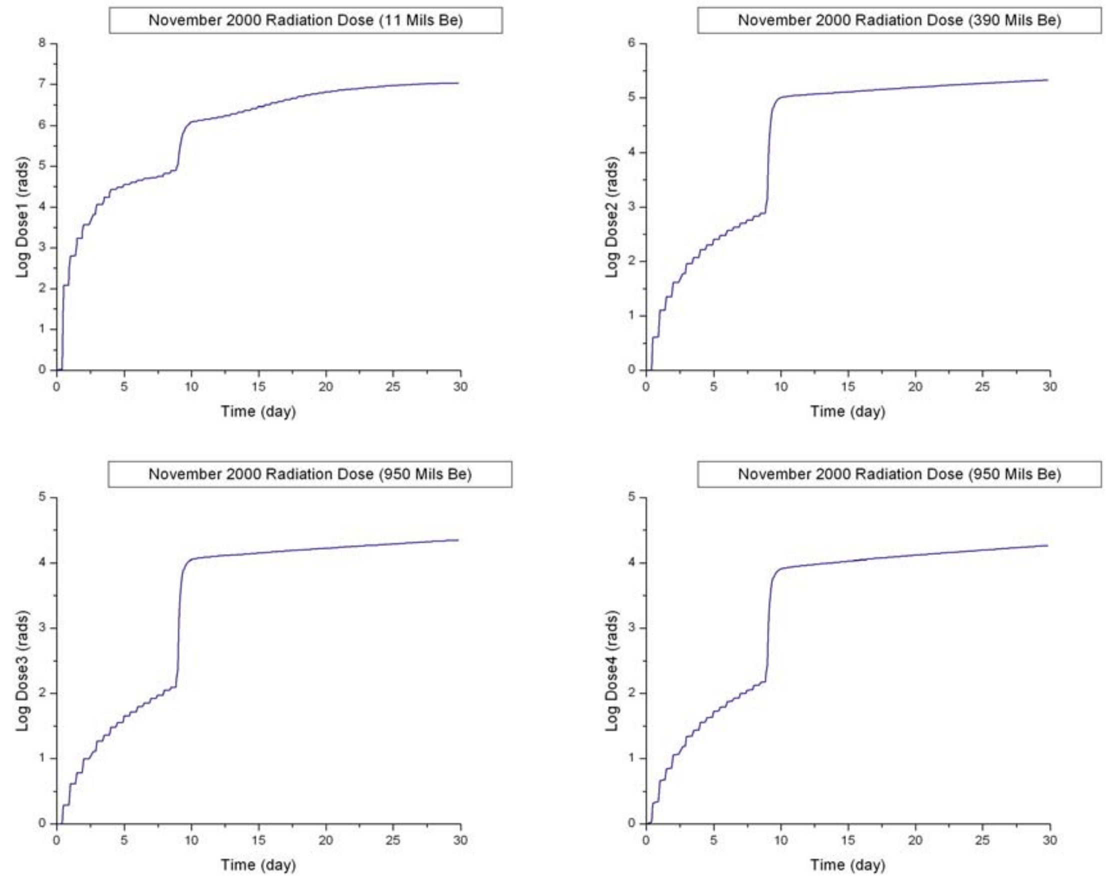
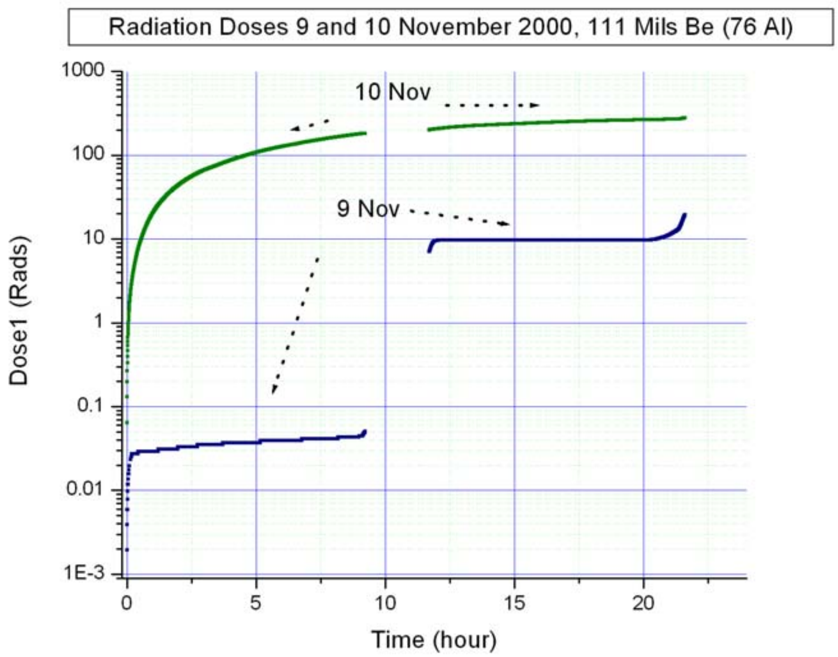


Figure 3-4. Radiation dose accumulated in November 2000, HEO-1



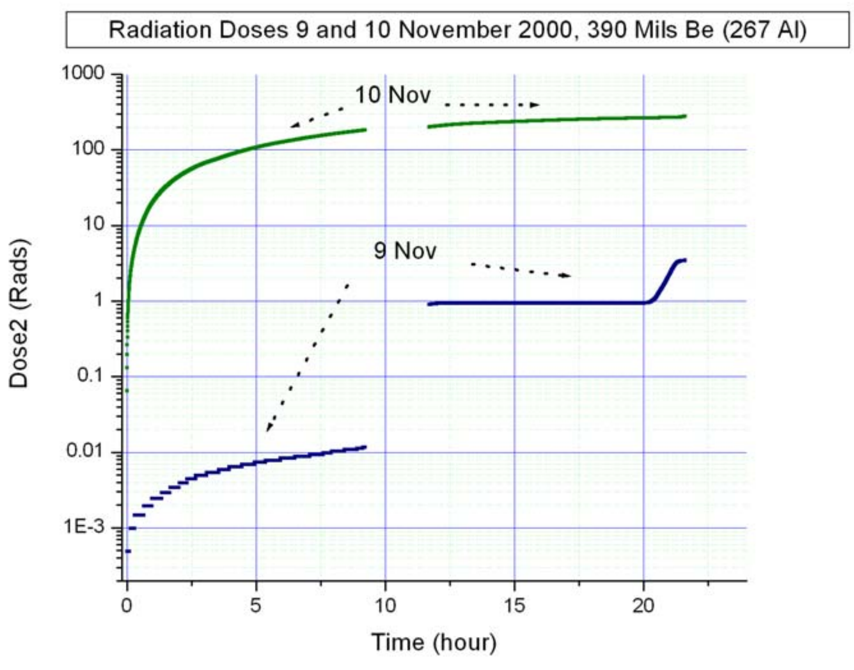


Figure 3-5.
Comparing of the accumulated radiation dose for 2 days: 9 and 10 November, before and during the magnetic storm. Shielding levels 111 and 390 Mils Be

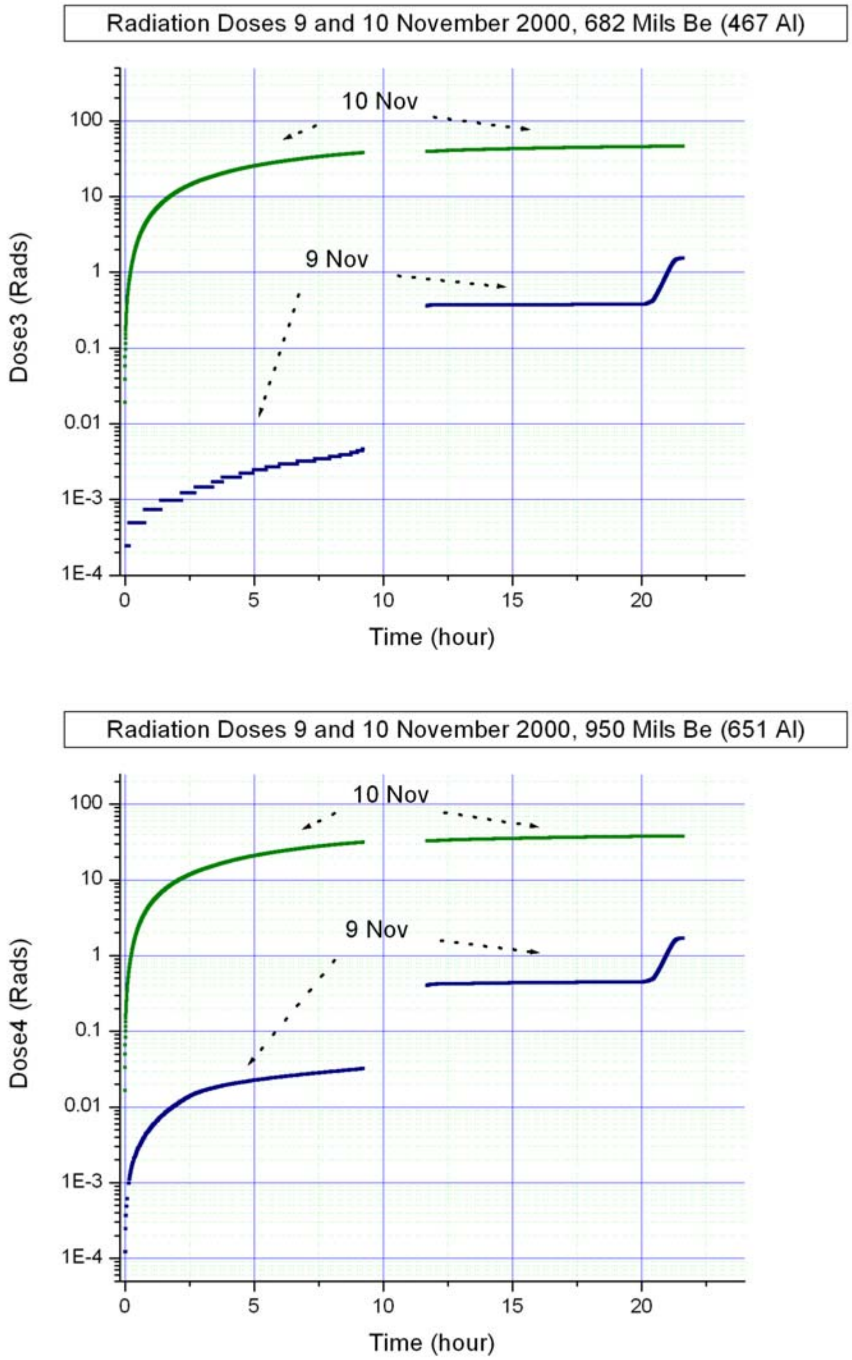


Figure 3-6.
Comparing of the accumulated radiation dose for 2 days: 9 and 10 November, before and during the magnetic storm. Shielding levels 467 and 651 Mils Be.

The comparison of the accumulated dose during event and in quiet days shows that the radiation dose can vary substantially from one day to another and depends on solar energetic particles events.

3.3 Conclusions to chapter 3

The data recording in HEO-1 data do not cover the entire orbit. The data are recorded for distance greater than 3.7 Re from the Earth centre. The dose of radiation on the first dosimeter (shielding level 111 Mils Be) increases sharply in the end and the beginning of the recording time. So, we can conclude that the satellite gets the main dose of radiation in radiation belts of the Earth. In next chapters we shall present statistical analyses of the energetic particles environment at a Molniya orbit based on the data provided by HEO-3 mission.

4 Analysis of HEO-3 data

After the analyses of the radiation environment based on HEO-1 data we processed the analyses of HEO-3 data. The reasons that we switched to HEO-3 data are

- HEO-3 data are more complete. HEO-1 data are recorded when the satellite is at the distance $R \geq 3.7$ Re from the Earth centre. From HEO-1 data we can not get information about, for example, energetic particles inside the inner electron belt at $R \approx 2$Re, or in the slot region between the inner and the outer electron belts. HEO-3 data provide information for the entire orbit in the distance range from the perigee to the apogee;
- Completeness of HEO-3 data allows us to obtain the statistical description of the radiation environment along the orbit as well as to verify the stability of the orbit, the change of the orbit perigee and the orbital period.

4.1 Orbital period

One of the first problems we had to solve was to check the stability of the orbit because the variation of the orbit influences the measurement results. Analysis of the data would allow us to see how the perigee of the orbit changes with time as well as the period of the orbit.

Period of the orbit was defined by idl code **find_period.pro** (see Appendix 5. Codes). In this code the data of a whole year was used to find the orbit period. To calculate the period the iteration procedure of two steps was used. It is known that the Molniya orbit's period should be close to 11h 57min. In the first iteration all the data were separated into different orbits using the approximate value of the period. The data consist of 15 second measurements, and because of satellite's high speed the distance between two consecutive measurements is large, and the points where measurements were made are not well repeatable from one orbit to another.

Table 10. Orbital periods, HEO3 Mission

Year	Period (hour)
1998	11.954335
1999	11.963148
2000	11.963582
2001	11.963487
2002	11.963400
2003	11.963249
2004	11.963159
2005	11.963161
2006	11.963351

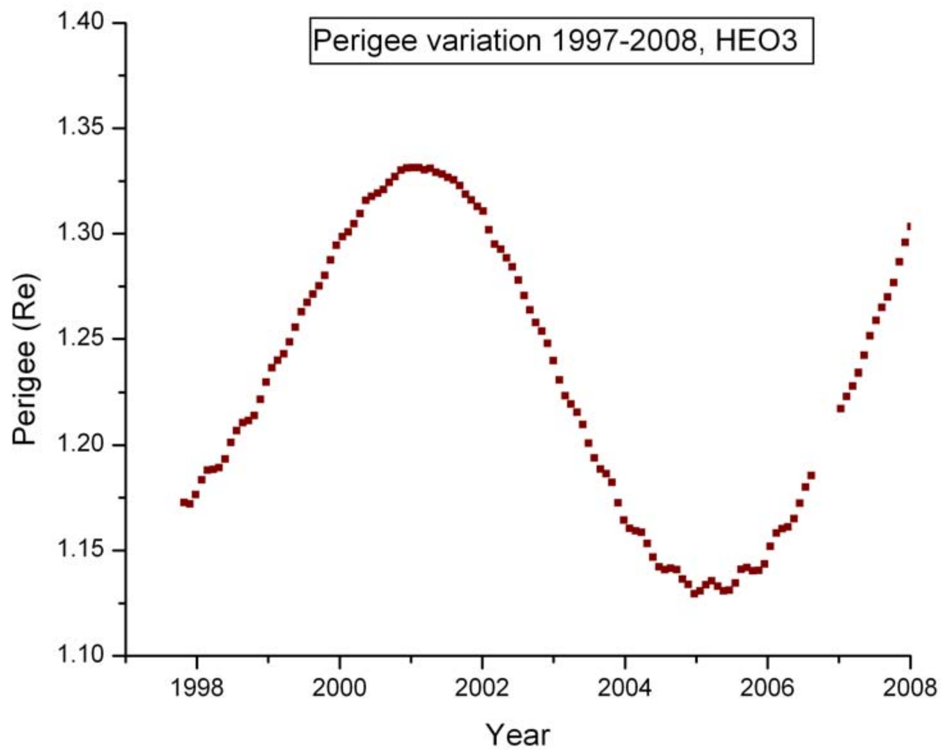


Figure 4-1. Variations in the perigee, HEO3 data, 1998-2008

In the code the points belonging to different orbits with the smallest difference in their locations (with the smallest ΔR) were determined and the period was determined with the simple formula $T=\Delta t/n$ where Δt is the Julian date difference between these two points, and n is the number of orbits the satellite passed between these two measurements. This approximated value for the period was used for the second iteration procedure to find the more accurate value of the period. Table 10 shows orbital periods calculated for several years for the HEO3 mission by using **find_period.pro** (see Appendix 5. Codes).

4.2 Perigee dynamics

To check the stability of the orbit we determined also the orbit perigee dynamics. Idl code **find_perigee.pro** gives the perigee value for every orbit (see Appendix 5. Codes). All the data for several years are divided into separate orbits using the calculated period and for every orbit the minimal value of the radial distance between the satellite and the Earth's centre is determined. Because of small gaps of data, for some orbits the minimal value is far from the real perigee. That is why some obvious outliers were deleted from the data.

The dynamics of the monthly averaged values of the perigee for about ten years is plotted on Figure 4-1.

The perigee dynamics has at least two periods of variation. From Figure 4-1 we can conclude that one period is about 9 years (we consider 10 years time interval and can not rigorously speak about the period of 9 years though) and the perigee changes its location with the speed about 300 km/year. The perigee has also small variations with the period close to several months. The variations of the perigee are most likely associated with the third body orbit perturbations caused by gravity forces of the Sun and the Moon.

In chapter 6 we will compare the perigee dynamics with the dynamics of daily radiation dose, and the dynamics of proton and electron fluencies.

4.3 Even and odd orbits

To use the statistical approach described in the next chapter we had to decide if two orbits per day can be used for the same averaging procedure or they have to be considered separately. Two orbits on the graph for the radial distance from the centre of the Earth (Figure 4-2) look very similar, so to decide if they are enough close or not we plotted the distance difference between the first and the second orbit per day (Figure 4-3).

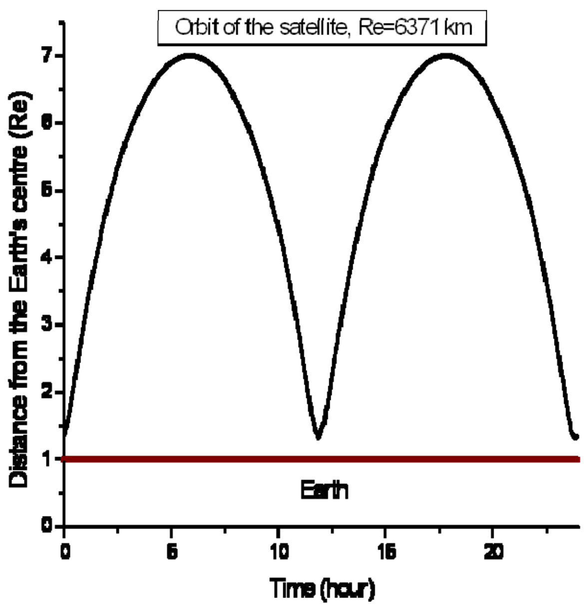


Figure 4-2. Two orbits per day, distance from the Earth's centre, HEO-3, 2000.

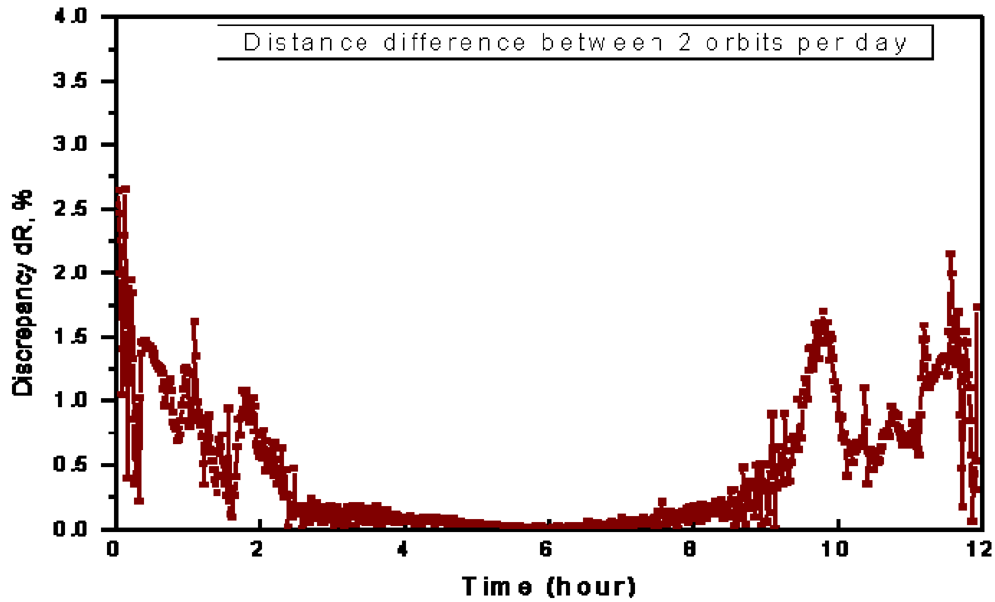


Figure 4-3. Distance between average odd and average even orbits, HEO-3, 2000

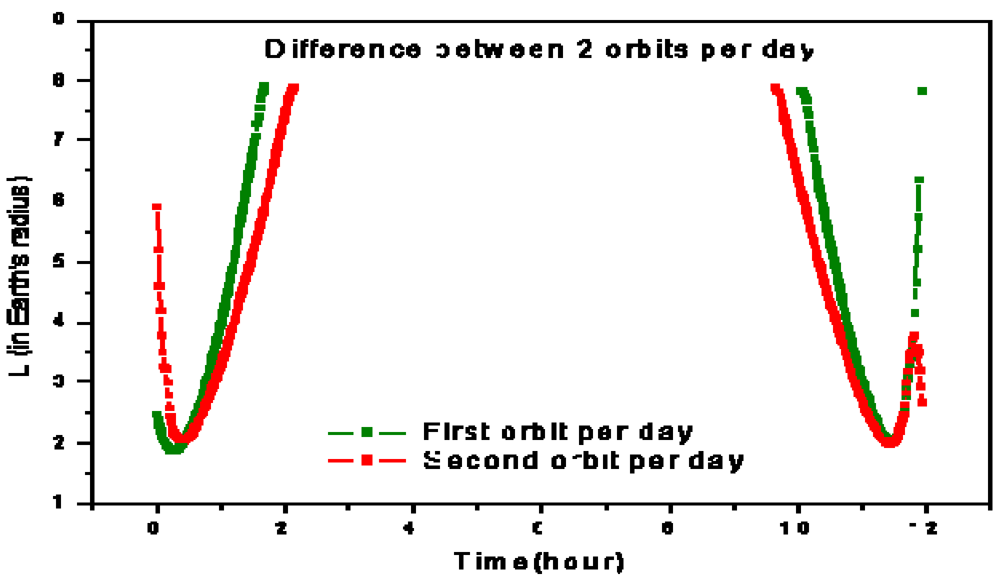


Figure 4-4. Average L-shell for odd and even orbits, HEO-3, 2000

The discrepancy between two orbits achieves 2.5 %. This value is large enough to cause the large error in the radiation dose value. As will be shown in the next section, we shall reduce the distance variability for one bin to 0.75% in order to obtain some reasonable statistics.

The comparison of L-values for two orbits also shows that these two orbits are different (see Figure 4-4). The odd orbit starts with L-shell ≈ 2.5 and the orbit passes through the open magnetic field lines in the end of odd orbits. The even orbits start with large L-values and come back to L ≈ 2.5 in the end of the even orbit. So, for the averaging procedure we decided to use the double period 2*T ≈ 23h 56 min as an averaging time and hence to consider even and odd orbits separately.

4.4 Statistical analysis of the data

When we overlap all the data for one year we see the main features of the radiation dose distribution (code **all_data.pro** in Appendix 5. Codes). For example, Figure 4-5 for proton fluxes with energies 16-40 MeV shows the stable proton belt during the year and the proton fluxes outside the radiation belts which are very changeable. The similar plots for other years of HEO-3 mission are in Appendix 2. Radiation dose rate for years 1998-2008 (HEO-3). Shielding 5 Mils Al (for the radiation dose rate) and in Appendix 3 (for proton fluxes).

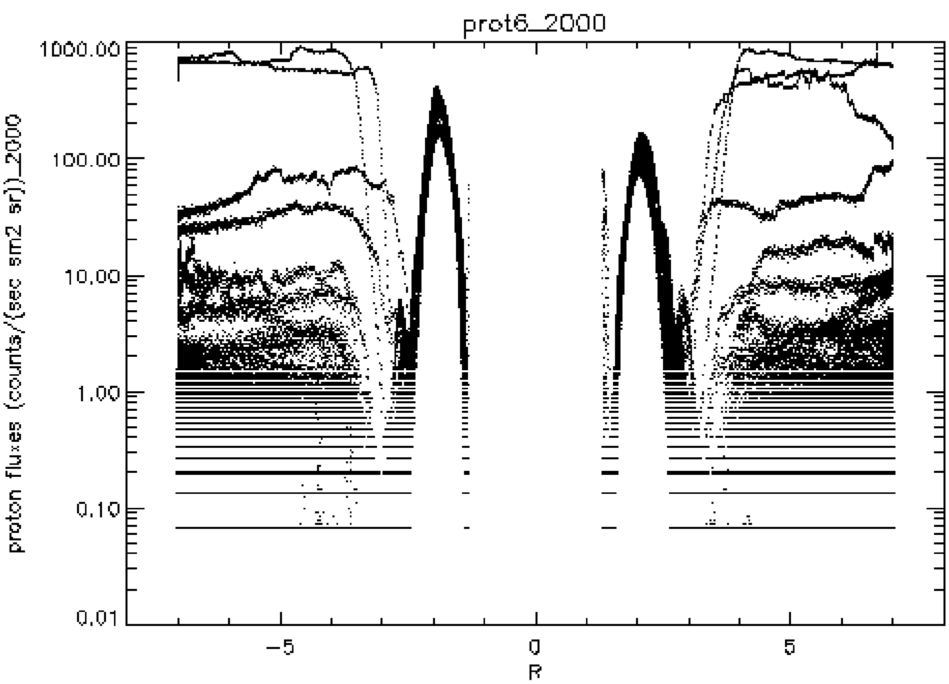


Figure 4-5. Proton fluxes with energies 16-40 MeV, HEO-3, 2000

To estimate average characteristics of the radiation we decided to consider an orbit beginning from the first perigee of the year. To find the average statistics we use all the data for one year. The hypothetical average orbit was broken into small-time intervals (approximately one minute intervals) and the corresponding measurements were binned by the radial distance. All other parameters like the radiation dose rate, proton and electron fluxes, L-shell and the geomagnetic field values were binned in accordance to the radial distance binning.

Before we decided to bin all the data by the radial distance we tried to bin them by time only. But there are only 4 measurements per minute, the radial distance changes very quickly because of the satellite high speed, especially in the vicinity of the orbit's perigee. That is why the 1-minute binning gives sometimes up to 10% error in the radial distance detection, and in this case the average values of the radiation dose changes dramatically, especially in the radiation belts.

Figure 4-6 shows a comparison of three different binning procedures. For Figure 4-6 the data for the radiation dose behind the shielding 5 Mils Al for the whole year were used. In one case we took all the data binned by time, without any restriction for the radial distance error. The corresponding graph is plotted in red. Two other graphs are plotted using both time and the radial distance restrictions. To plot the black graph the radial distance error was taken as large as 1.5%, and for the green graph the distance detection error was 1%. It is evident from the graph that the value of average radiation dose increases sharply with decreasing radial distance error. This is due to the huge gradient value for radiation doses in vicinity of radiation belts. It is clear that the less bin for the distance we take, the more accurate value of the radiation dose we obtain.

That is why in the final version of the code we took the radiation distance error as small as 0.75%. Further decrease of the radial distance bin does not look reasonable because we can substantially decrease the number of observations in the bin and it does not look good from the statistical point of view. The distance error close to 0.75% allows us to keep approximately 200-250 observations from 365 for the whole year.

Another approach is double binning, which includes binning all the data by time (one-minute intervals) and by radial distance. Unfortunately, because of the variability of the orbit we were not able to keep strictly double binning. After 1-2 months, the orbit moves a little bit from its place and sometimes we can not get any observations in bins we used. So, in the end, we decided to give more flexibility to time binning but keep strictly bins for the radial distance because the radial distance from the Earth is more important for the radiation dose detection.

The code **stat_along_orbits_simple.pro** produces the annual distribution of the radiation dose along the orbit (see chapter 5 and Appendix 4. Annual distribution of the dose rate behind shielding 5 Mils Al, HEO3).

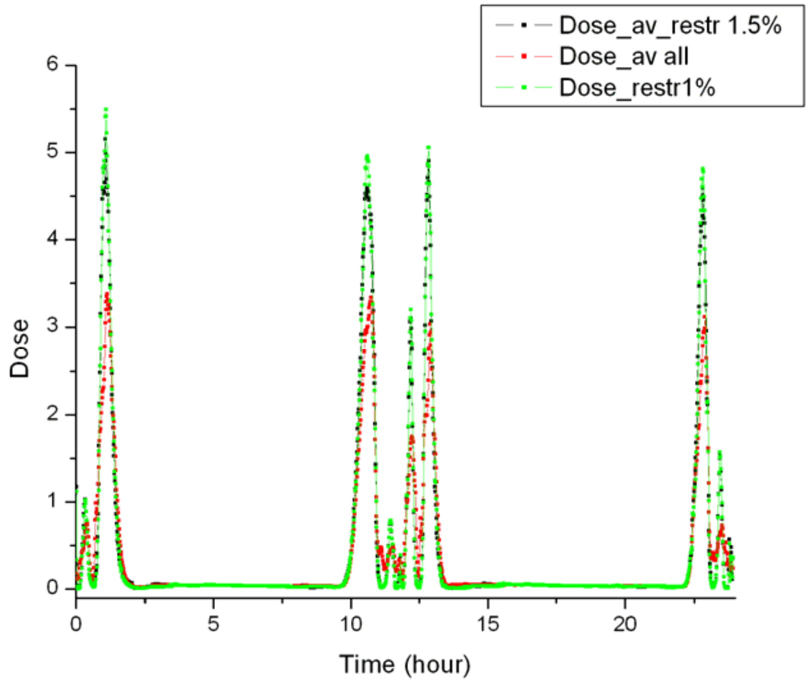


Figure 4-6. Comparison of different binning methods.
Red – binning by time only
Black – binning by time and distance, distance error is 1.5%
Green – binning by time and distance, distance error is 1%

For every one-minute point on the orbit we can plot the radiation dose distribution, the cumulative distribution function, and calculate not only the mean value of the radiation dose but also 50%, 90% and 99.5% values of the dose. The 50% value gives information about the value of the radiation which is not exceeded in 50% of all cases, and 99.5% point define that the radiation can be larger than this value only in 0.5% of all cases, and we can consider this value as the worst case scenario for this location on the orbit. It is demonstrated on the histogram corresponding to the point 23h 32 min after the perigee (see Figure 4-7).

To demonstrate the statistical reliability of our procedure, we consider three points on the orbit which corresponds to t=1h after the first perigee per day, t=10h 23min after the perigee, and t=23h 12min. To check that the data we used for the averaging procedure can be assigned to one point we plotted histograms for the radial distance for these three bins (Figure 4-8-Figure 4-10). The histograms for the radial distance are close to normal and so demonstrate that the data assigned to one bin can be considered as random data and are suitable for the statistical analysis.

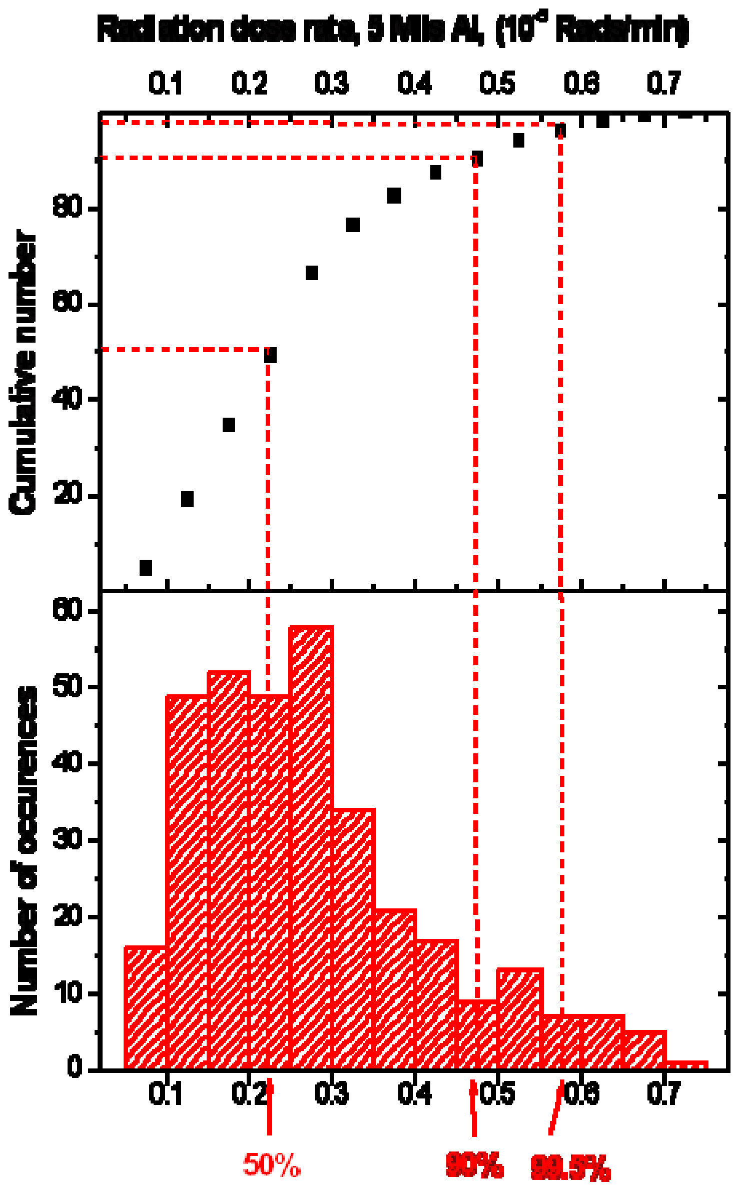


Figure 4-7. The radiation dose distribution behind the shielding 5 Mils Al and its cumulative distribution function. This distribution is plotted for t= 23h 12 min after the first perigee.

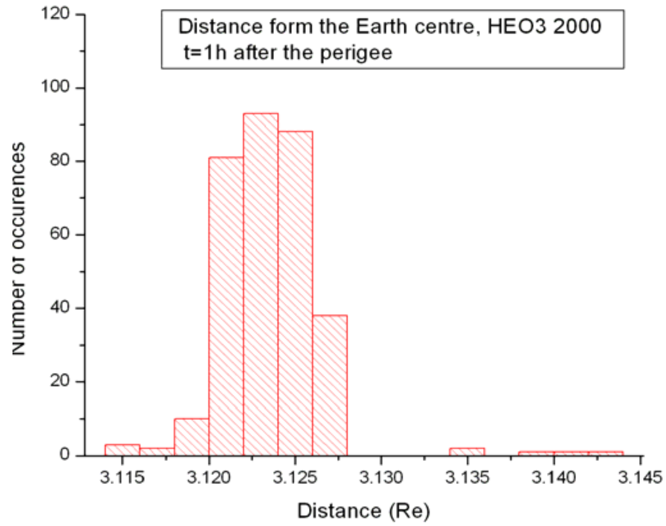


Figure 4-8. Histogram for the radial distance from the Earth's centre. Point location: t=1h after the perigee

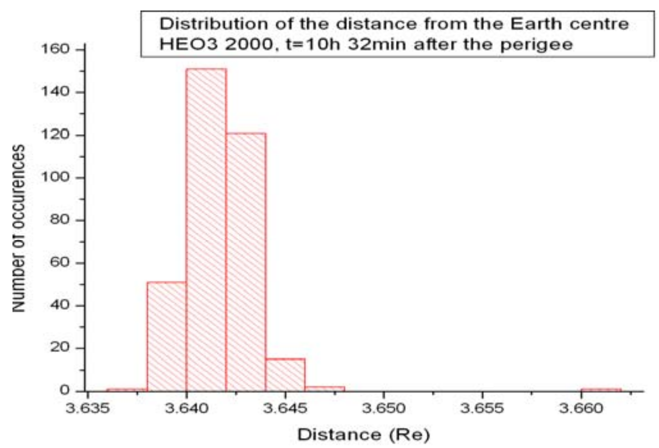


Figure 4-9. Histogram for the radial distance
Point location: 10h 32 min after the perigee

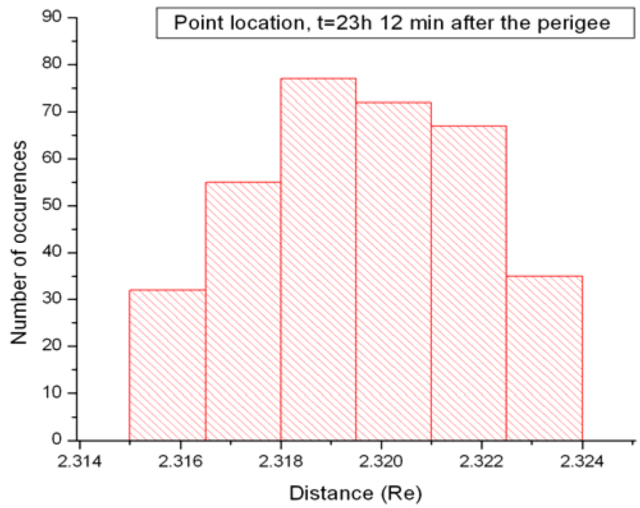


Figure 4-10. Histogram of the radial distance for the point on the orbit corresponding to 23h 12 min after the perigee.

Histograms for the magnetic coordinates also can be used to justify the selected binning procedure. Histograms for L-value and the magnetic field (IGRF model) are close to normal or a uniform distribution (Figure 4-11-Figure 4-13) which means that the data can be considered as random data.

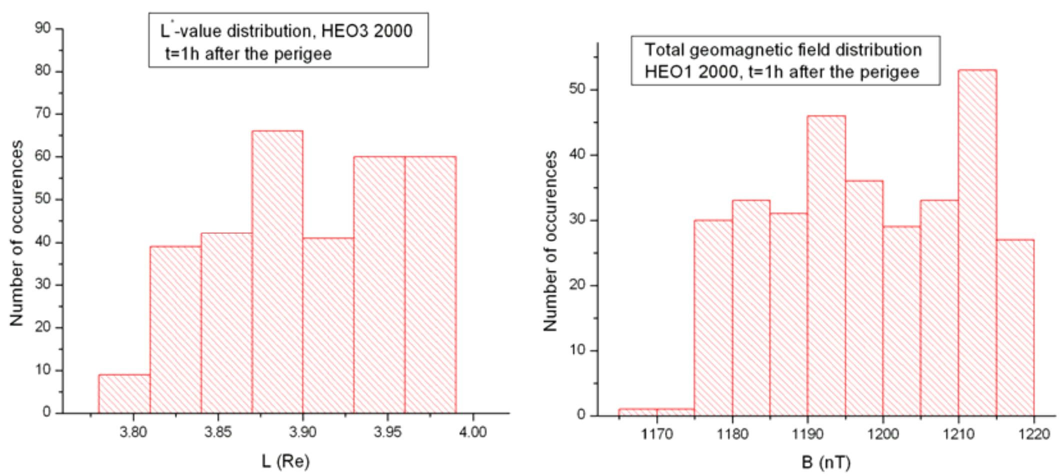


Figure 4-11 Histograms for L=value (Roederer) and geomagnetic fields. Point location: t=1h after the perigee.

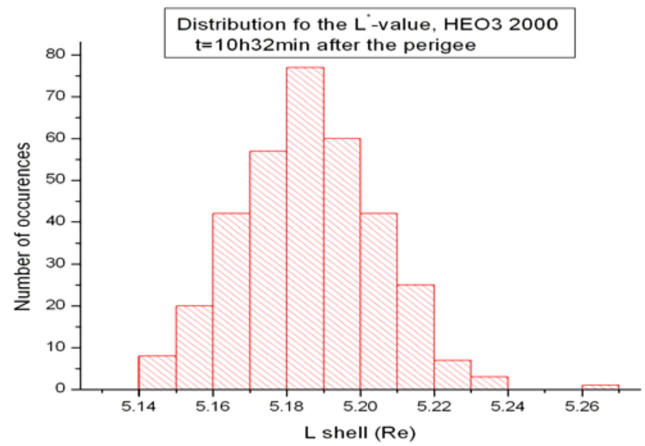
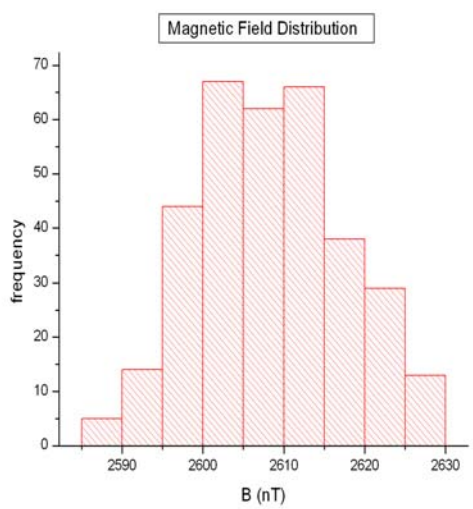


Figure 4-12. Histogram for L-value (Roederer). Point location: 10h 32 min after the perigee



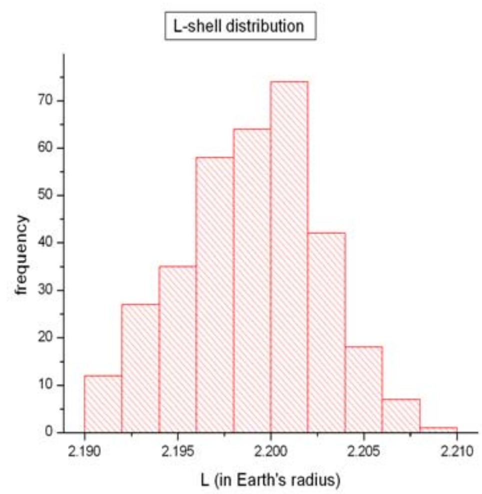


Figure 4-13. Histogram of the geomagnetic field and L=shell (Roederer) for the point on the orbit corresponding to 23h 12 min after the perigee.

To check if the L-shell bin size is appropriate, the radiation dose is plotted as a function of L-value (Figure 4-14). It is evident that there is no correlation between L-value and the radiation dose inside the bin, so the bin size is good for the statistical purposes.

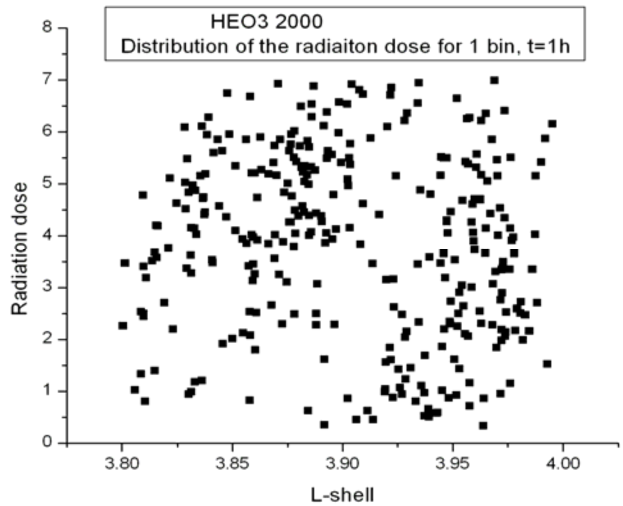


Figure 4-14. Radiation dose depending on L-shell for one L-bin. Shielding level 5 Mils Al, t=1h after the perigee

The radiation dose, proton and electron fluxes have exponential distribution for almost all the points on the orbit (see Figure 4-15. Electron fluxes distribution. T=1h after the perigee-**Figure 4-18. Histogram for the radiation dose, t=10h 32 min after the perigee,**

Shielding 5 Mils Al). Once the level of energetic particles, or the radiation dose rate, increases, its attenuation time should satisfy the diffusion law, and the statistical distribution of energetic particles should depend on the diffusion coefficient. In future, we plan to use the data to find the diffusion coefficient for the radiation dose for different points on the orbit. This coefficient can be used in the diffusion model which will be built specially for a high elliptical orbit.

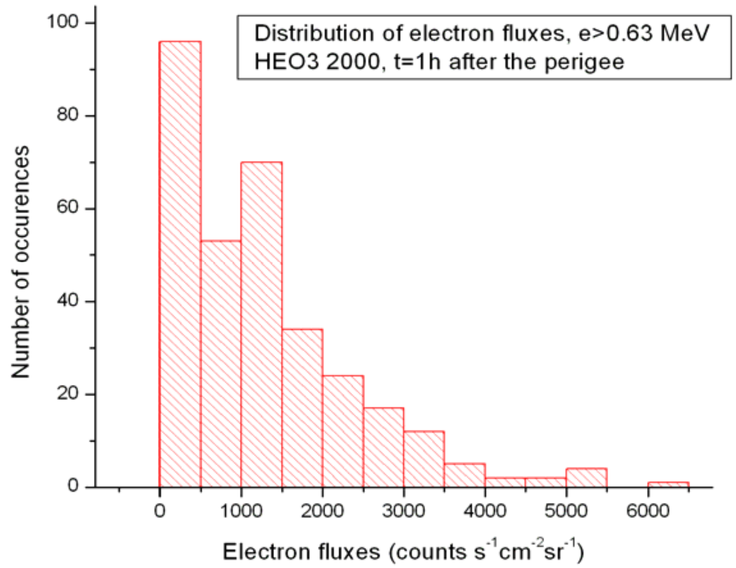
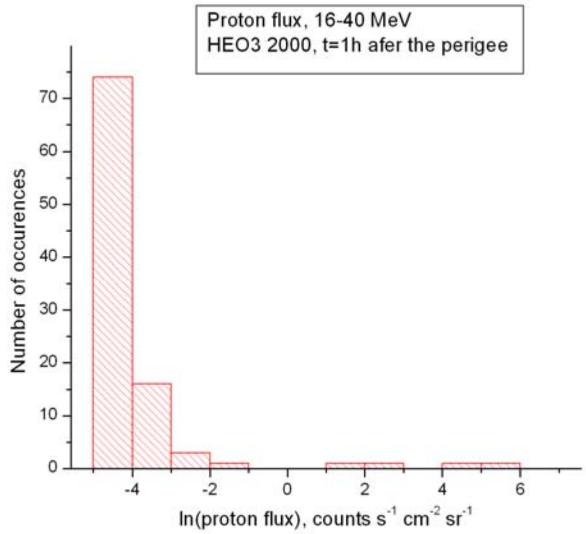


Figure 4-15. Electron fluxes distribution. T=1h after the perigee



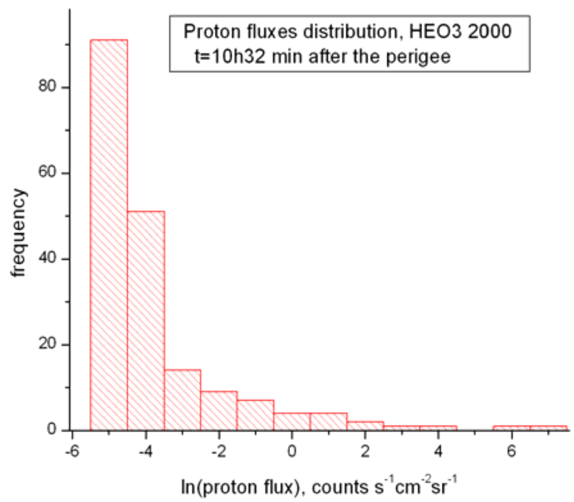


Figure 4-16. Proton fluxes distribution, 16-40 MeV
Point locations: 1h after the perigee and 10h32 min after the perigee

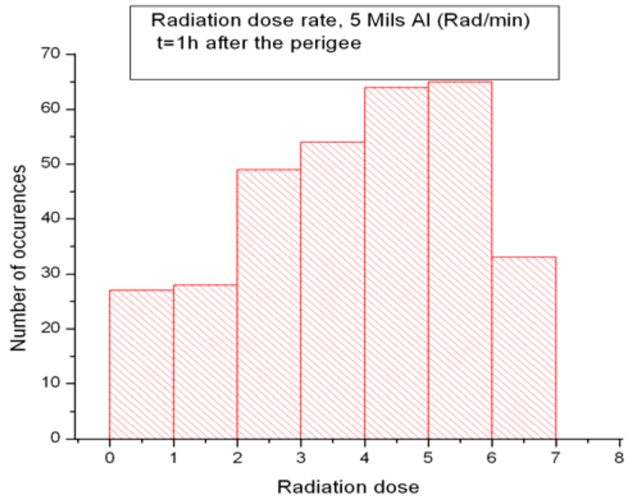


Figure 4-17. Histogram for the radiation dose, t=1h after the perigee, Shielding 5 Mils Al

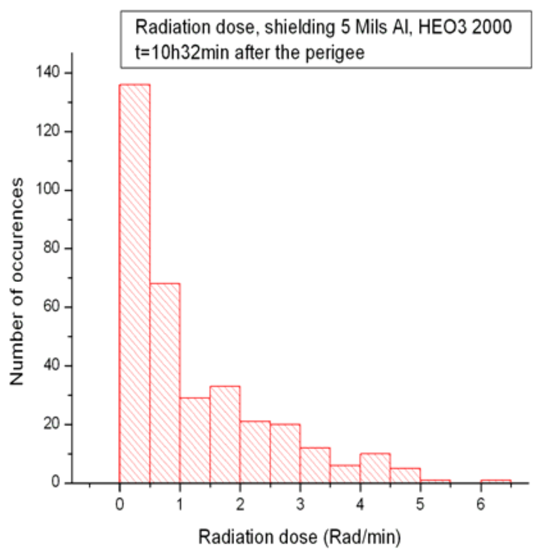


Figure 4-18. Histogram for the radiation dose, t=10h 32 min after the perigee, Shielding 5 Mils Al

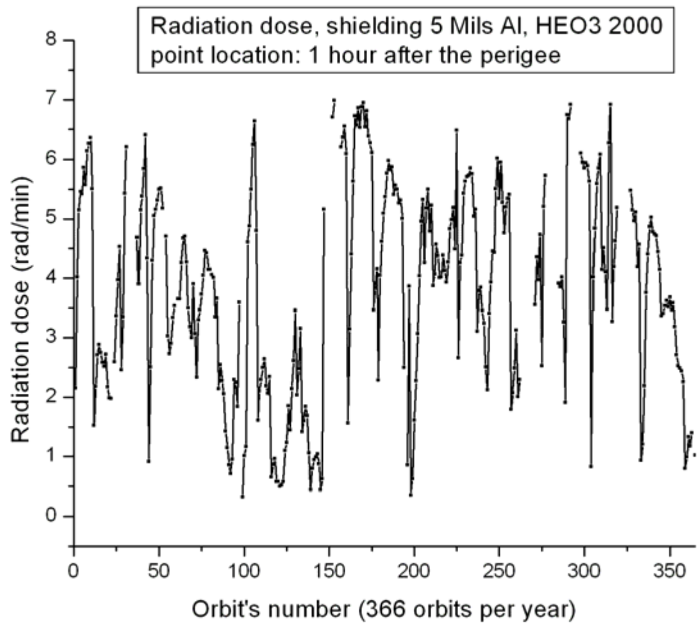


Figure 4-19. Annual dynamics of the radiation dose for 1 point on the orbit, t=1 hour after the perigee, shielding 5 Mils Al

In some cases histograms for the radiation dose are more close to normal distribution than to the exponential distribution (see, e.g., Figure 4-17). If to look at the annual dynamics of the radiation dose for this point (Figure 4-19), it becomes evident that several times per year the radiation dose increases sharply and after that decreases slowly according to the exponential law. So in the histogram corresponding to this point we have the sum of several exponential processes and according to the Central Limit Theorem the sum of several similar processes has a normal distribution if number of processes goes to infinity (usually if the number larger than 30). We can conclude that the closer the distribution is to the normal the more events influenced this point on the orbit during the year.

4.5 Conclusions to chapter 4

Chapter 4 gives the description of the statistical approach we used for data processing. The procedure to obtain the annual distribution for the radiation dose rate and energetic particles along HEO orbit was implemented. To demonstrate the statistical reliability of this approach, histograms of the radial distance and geomagnetic coordinates (L-value and magnetic field) for one bin were plotted to demonstrate that coordinates for observations corresponding to one bin are normally or uniformly distributed around their average value. The result of the statistical analysis comprising the annual distribution of the radiation dose rate, proton and electron fluxes are given in chapter 5 as well as in Appendix 4.

5 Average annual distributions of proton, electron fluxes and radiation doses

Using the statistical approach described in the previous chapter, the average distributions proton, electron fluxes and radiation doses, were plotted in Figure 5-1 - Figure 5-7 for 2000 and in Appendices 3 and 4 for other years. The code for this procedure is **stat_along_orbit_simple.pro.** To estimate the influence of magnetic storms on annual distributions, we plotted 2 sets of graphs. In the first set all the data for a year were used to calculate the average annual distributions. For the second set only quiet days, without magnetic storms were taken into account.

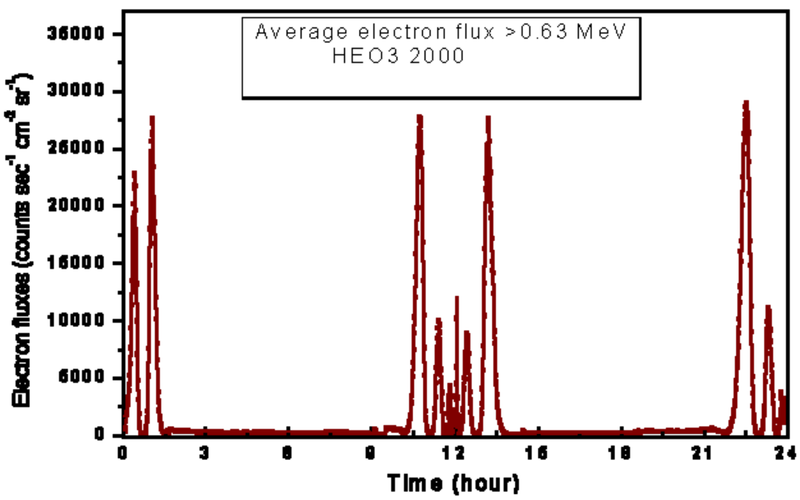


Figure 5-1. Average annual distribution of electron fluxes with energy >0.63 MeV along the average orbit, all data for the year, HEO-3 mission, 2000.

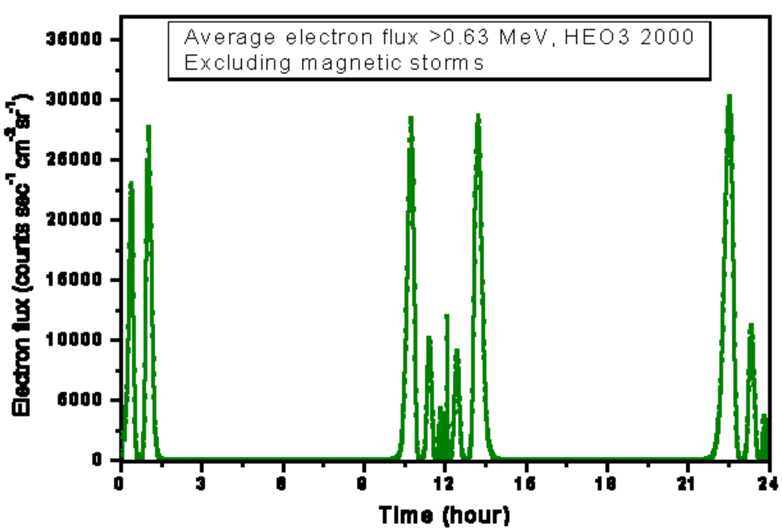


Figure 5-2. Average annual distribution of electron fluxes with energy >0.63 MeV along the average orbit, without magnetic storms, HEO-3 mission, 2000.

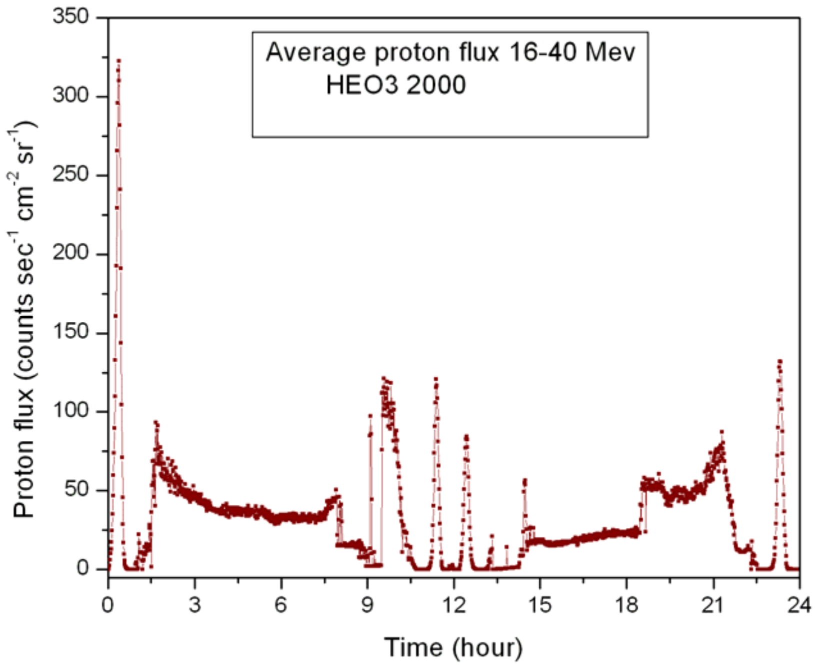


Figure 5-3. Average annual distribution of proton fluxes with energy 16-40 MeV along the average orbit, all data for the year, HEO-3 mission, 2000.

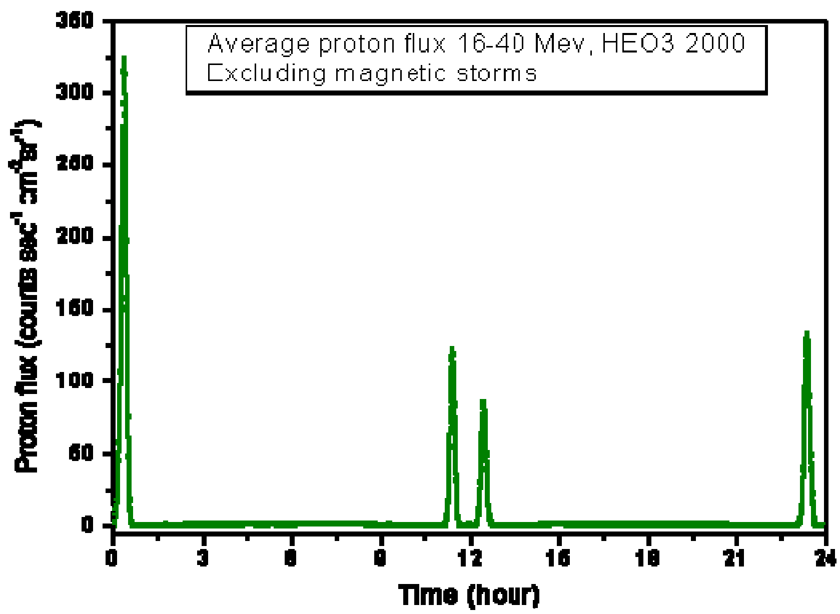


Figure 5-4. Average annual distribution of proton fluxes with energy 16-40 MeV along the average orbit, without magnetic storms, HEO-3 mission, 2000.

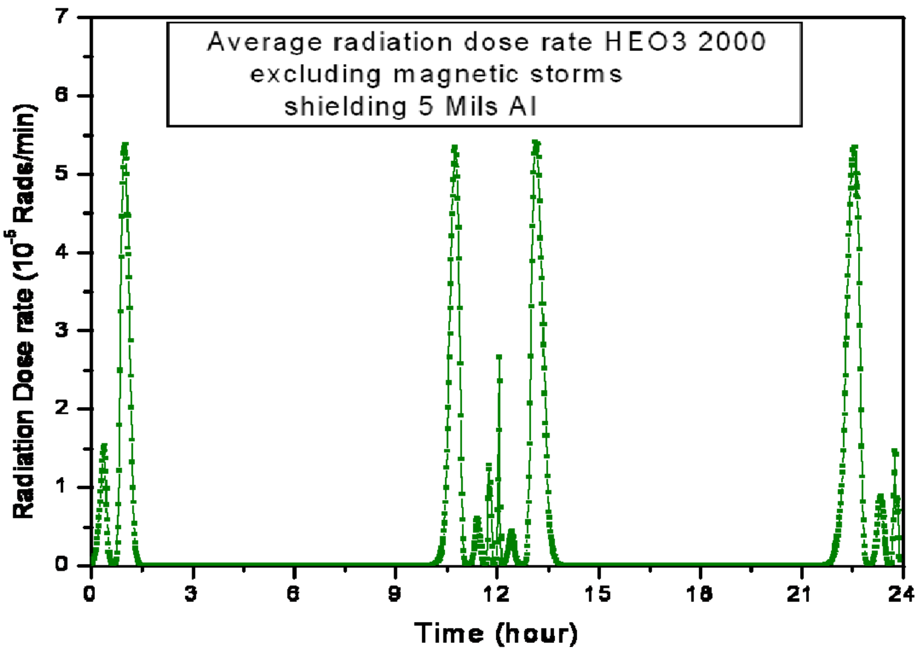
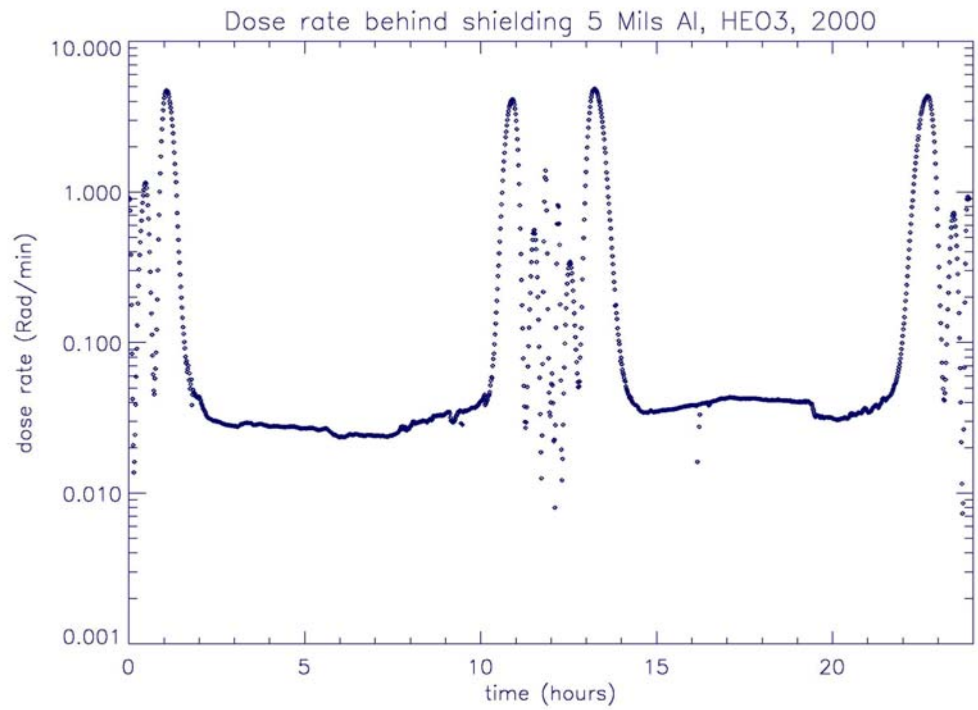


Figure 5-5. Average annual distribution of the radiation dose behind 5 Mils Al, along the average orbit, without magnetic storms. HEO-3 mission, 2000.

Figure 5-1 - Figure 5-5 show HEO-3 data for 2000. Strong magnetic events in this year were registered in July and in November. To find average distributions for quiet days the data for July 14-21 and November 8-15 were excluded.

The annual distributions for the radiation dose rate are plotted on Figure 5-6 for 2000 and on Figure 5-7 for 2006, for all days per year (upper panel) and for quiet days (lower panel). 2006 was a very quiet year and we see that both distributions look very similar. Comparing graphs for 2000 and 2006, we also can conclude that distributions for quiet days do not change much from one year to another. All annual distributions of the radiation dose rate for years 1998-2000 and 2002-2008 are in Appendix 4.

Comparison of the graphs shows that because of the magnetic events the radiation doses, proton and electron fluxes increase, especially at the large distance from the Earth where in the quiet days all the parameters are close to zero values. It appears that the thickness of radiation belts does not increase during the magnetic storm neither average annual values changes significantly because of magnetic storms. However, it is obvious that during the magnetic storm, the radiation environment changes significantly behind the radiation belts, for distance R>3Re.



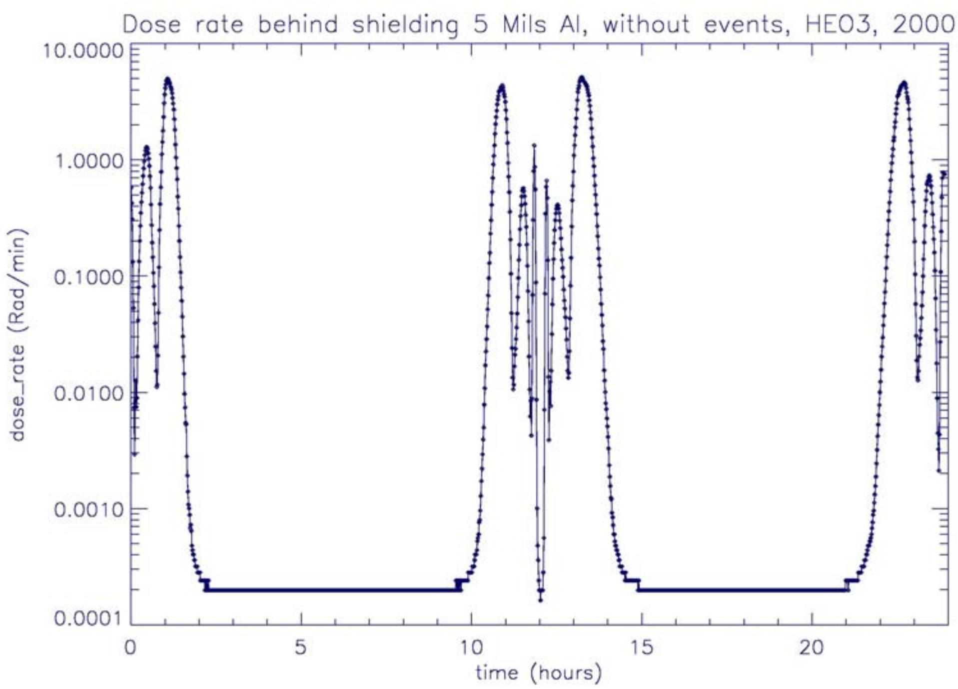
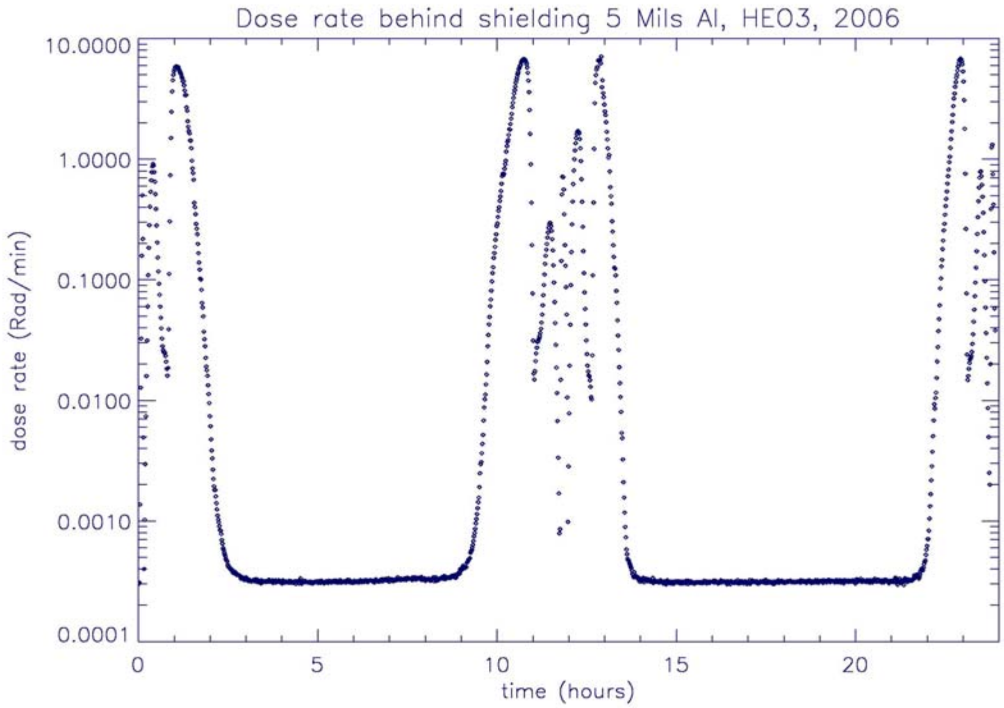


Figure 5-6. Annual distribution for the dose rate for all days (upper plot) and for quiet days (lower plot), HEO-3, 2000.



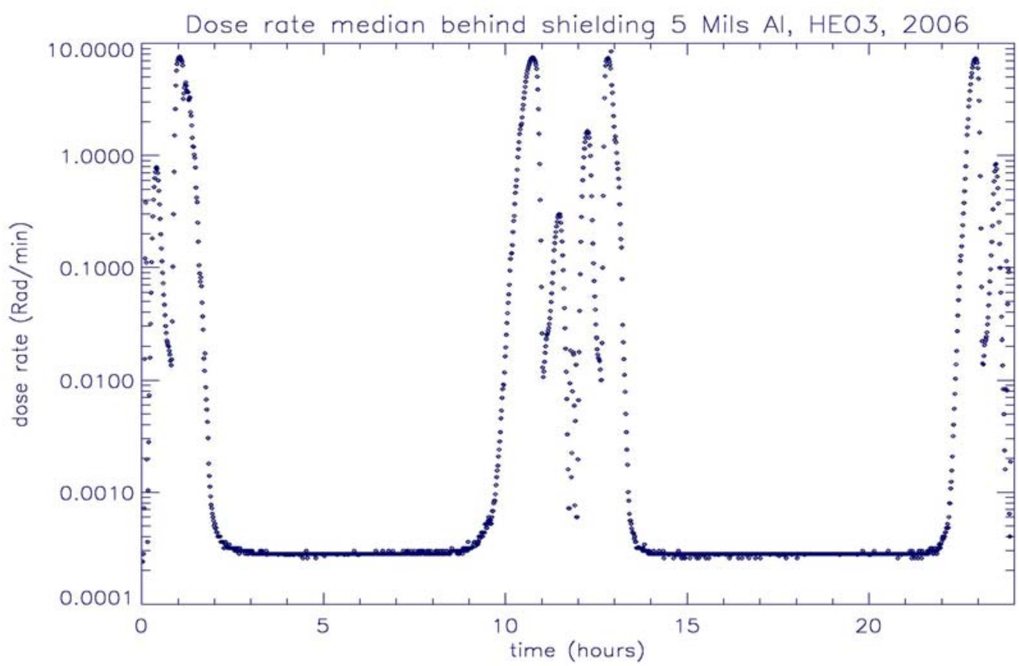


Figure 5-7. Annual distribution for the dose rate for all days (upper plot) and for quiet days (lower plot), HEO-3, 2006.

6 Fluencies and average daily doses

6.1 Annual radiation doses behind shieldings, missions HEO-1 and HEO-3

The average radiation dose behind different shieldings is a very important characteristic of the radiation environment because it can be used to forecast operational time of satellite instruments. The data from two missions HEO-1 and HEO-3 were used to find an average radiation dose per day. The analysis was made for different shielding levels: 76 Mils Al, 267 Mils Al, 467 Mils Al, 651 Mils Al for HEO-1 and 5 Mils Al, 12 Mils Al, 49.5 Mils Al and 125 Mils Al for HEO-3. HEO-1 data cover years 1994 - 2003 and HEO-3 mission covers years 1997 - 2007.

As shown in Figure 6-1 the cumulative radiation dose zeroed out several times per year. A special code was developed to overcome this issue and to calculate the cumulative dose per year and average daily amount. Daily radiation dose was calculated as a difference between the last and the first values of the cumulative radiation dose per day. The code used to determine daily dose is **av_monthly_dose.pro** (see Appendix 5. Codes).

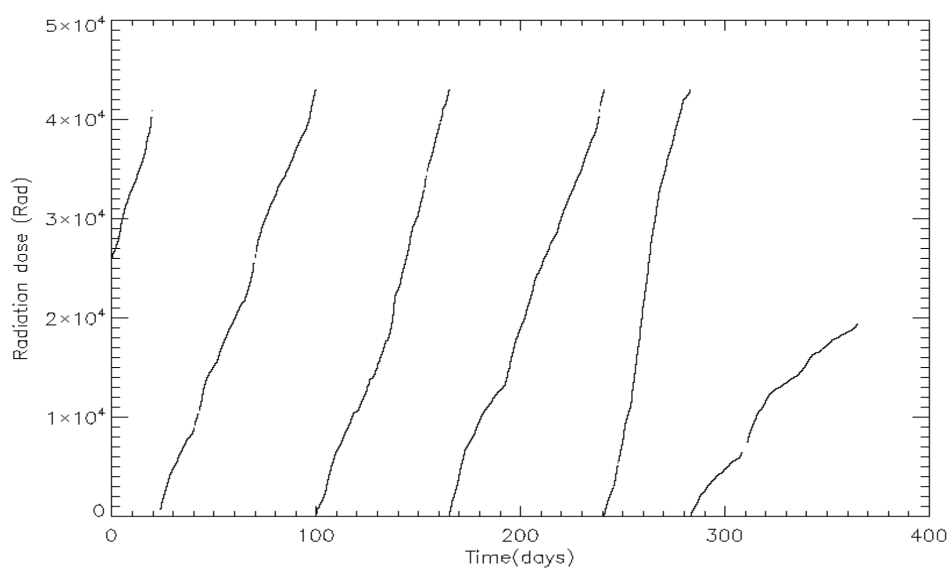


Figure 6-1. The radiation dose behind 5 Mils Al shielding. HEO-3, 2000
The cumulative dose is zeroed out several times per year.
This fact should be taken into account to find the cumulative annual dose.

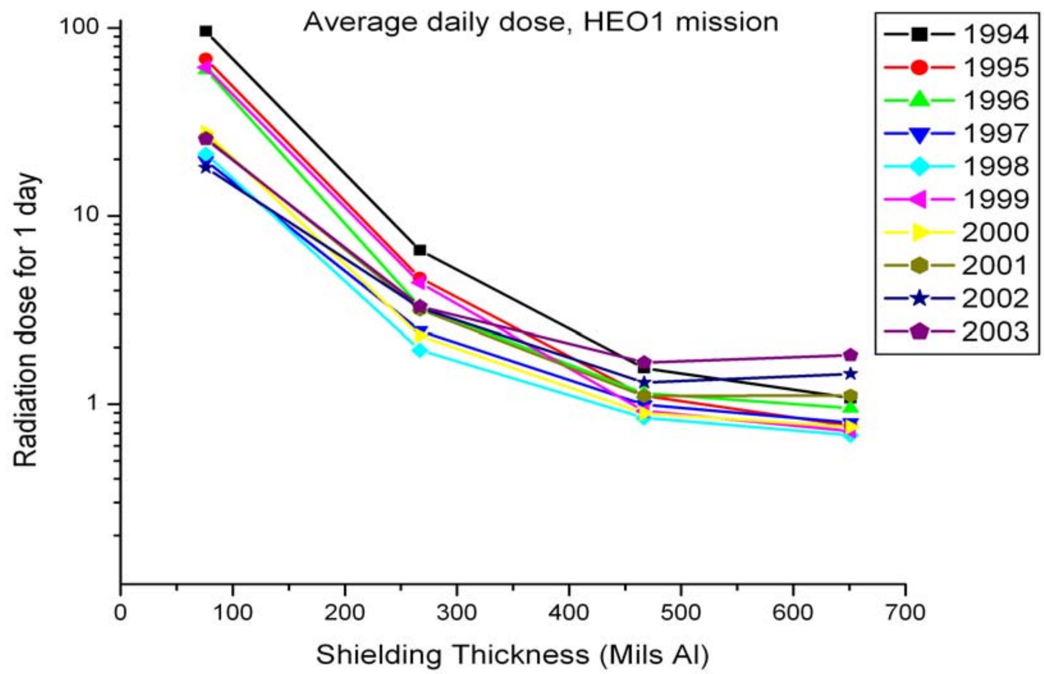


Figure 6-2. Average daily dose for different shieldings, HEO-1 Mission

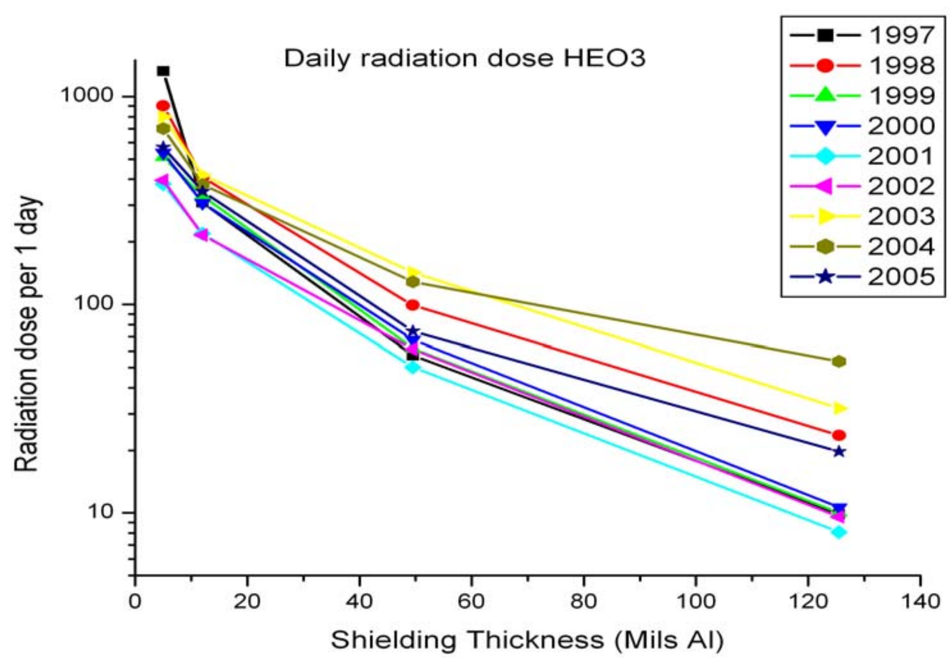


Figure 6-3. Average annual dose for different shieldigs, HEO-3 Mission

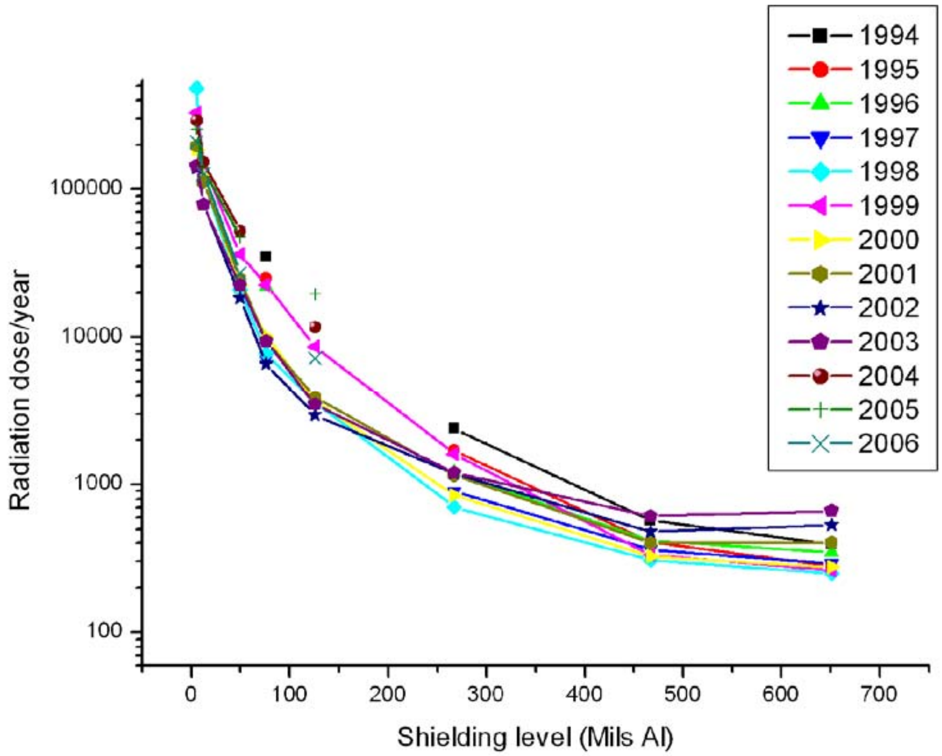


Figure 6-4. Annual radiation dose for HEO-1 (shieldings 76, 267, 467, 651 Mils Al) and HEO-3 (shieldings 5, 12, 49.5, 111 Mils Al).

The distributions of the average radiation dose behind different shielding levels are plotted on Figure 6-2 and Figure 6-3 separately for HEO-1 and HEO-3 missions. We see that the radiation dose decreases exponentially with increasing of shielding level. HEO1 mission covers shieldings 76, 267, 467, 651 Mils Al, HEO3 mission provides data for shieldings 5, 12, 49.5, 125 Mils Al. On Figure 6-4 the data from both missions were plotted on one graph. Trends from both missions are similar and can be approximated by the same exponentially decreasing curve.

6.3. Fluencies of protons and electrons, HEO-3 mission

To find fluencies we used data for electron and proton fluxes. The fluxes are measured in counts per second, and we had to calculate counts per day. So the fluxes were integrated with respect to time for every double orbit. Unfortunately, there are gaps in electron and proton data. If data covered less than 2/3 of the entire orbit we omitted this orbit. The fluencies were calculated for electrons with energy >0.63 MeV and >1.5 MeV, and protons with energy 8.5-35 MeV and 16-40 MeV. The daily radiation dose and the perigee dynamics plots (Figure 6-5 and Figure 6-6) demonstrate that the radiation dose can be influenced by change in the orbit and the perigee location. We see that when the perigee increases the basis line for the radiation dose decreases, and vice versa. However, some features of the radiation dose seem to depend on solar wind speed (Figure 6-6 and Figure 6-7). Thus, in 2004 the behaviour of both parameters is very similar.

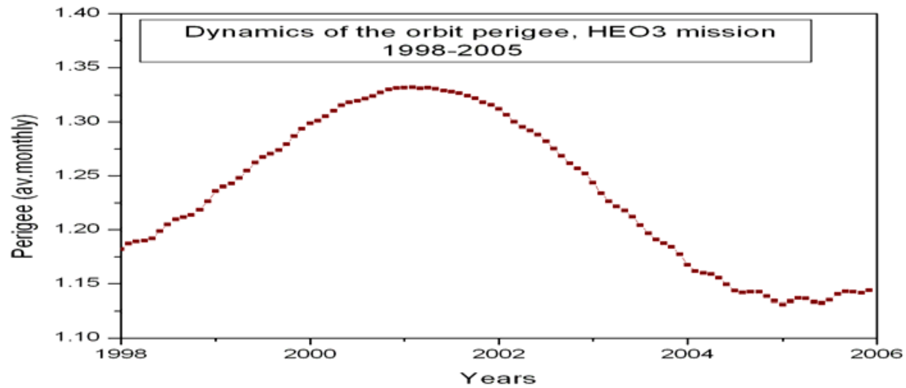


Figure 6-5. Dynamics of the perigee, HEO-3 Mission, 1998-2006

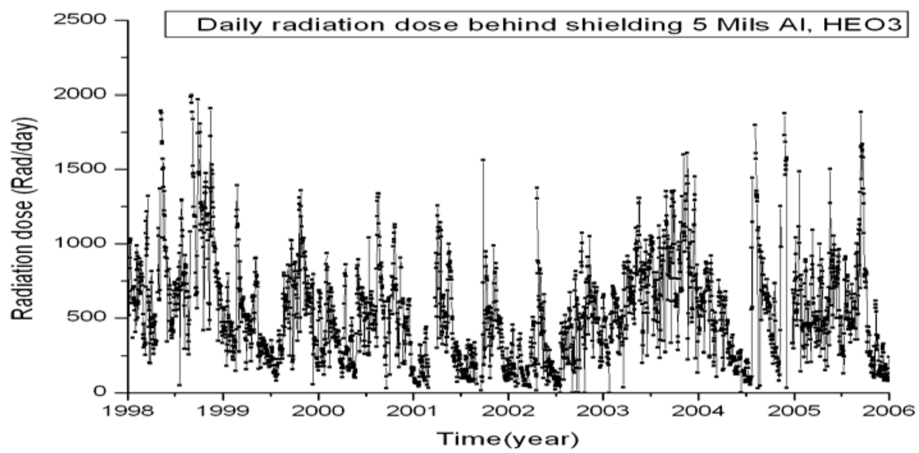


Figure 6-6. Dynamics of the daily radiation dose behind 5 Mils Al, 1998 – 2006

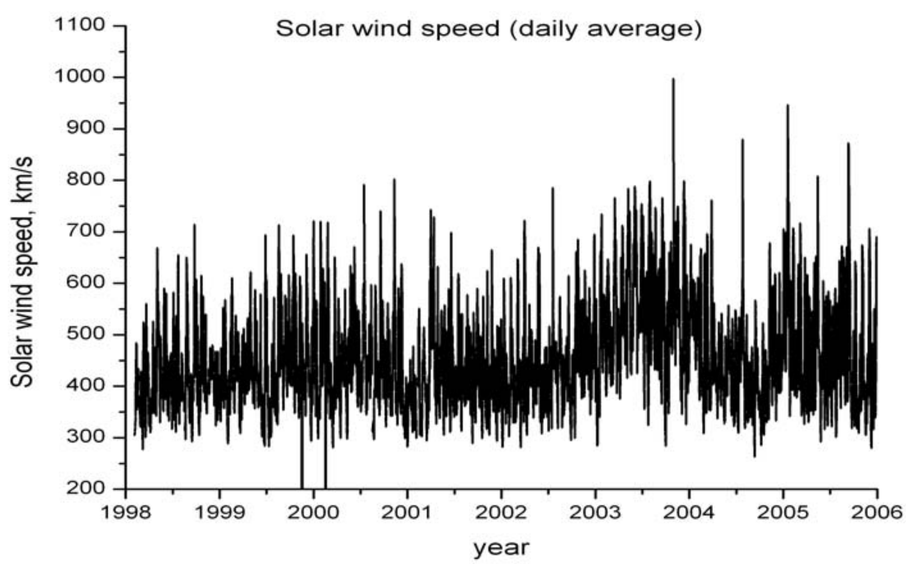


Figure 6-7. Solar wind speed for 1998-2006

Proton and electron fluences also repeat some features of the solar wind in 2004 (Figure 6-8 and Figure 6-9). We can conclude that among other factors the radiation environment depends on the orbit location and on the speed of the solar wind. In future research we can study this effect in detail.

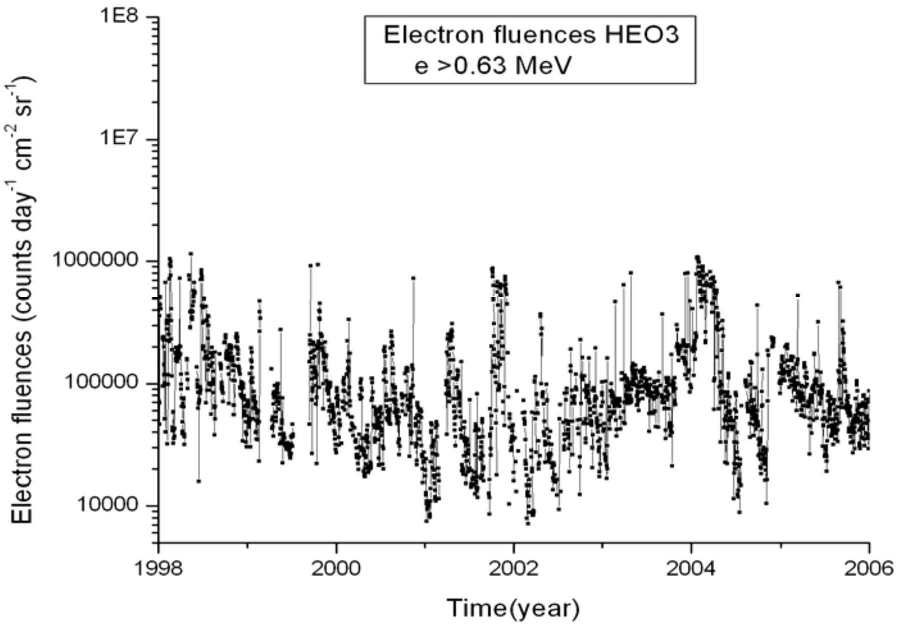


Figure 6-8. Electron fluencies, HEO-3 mission, 1998-2006

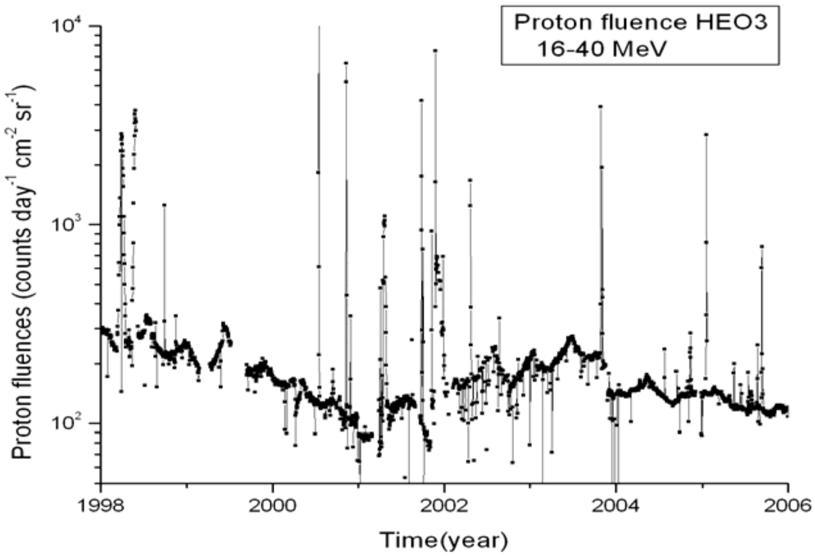


Figure 6-9. Proton fluencies, HEO-3 mission, 1998-2006

Results and discussion

We have carried out a statistical study of the radiation environment data produced by HEO-1 and HEO-3 missions, using data for energetic particles. The main results are

- Using data for HEO-3 mission, the value of the orbital periods for every year was determined.
- Using data for the radial distance for HEO-3 mission 1998-2008, the perigee and dynamics of the perigee during several years was plotted.
- An average orbit for a year was defined. Annual distribution for basic physical characteristics of the radiation environment: radiation dose, proton fluxes, electron fluxes were plotted for the average orbit.
- The stability of the results were checked by plotting

  - histograms of distributions of distance from the Earth's centre,
  - histograms for L-shell (Roederer),
  - histograms for the geomagnetic field B (IGRF) model.

All histograms show normal or uniform distributions, so we can conclude that our approach to data binning is reasonable from the statistical point of view.

- The daily radiation dose for 1998-2006 as well as daily fluencies of protons and electrons were plotted for HEO-3 mission.

- The dynamics of the radiation environment were plotted for several periods of time such as several years, or several days with a magnetic storm.

- The radiation doses behind different shieldings and their average daily value were calculated and plotted using data for both HEO-3 and HEO-1 missions.

For future research we plan to study space weather events and their influence on the radiation environment. For these purposes

- we have to work out statistical methods to define a space weather event,
- using this definition we will obtain a list of space weather events for 1998-2008,
- we plan to study influence of space weather events on short term (several days) and long-term (months) variability of the radiation environment,
- we also plan to obtain a spatial distribution of the radiation environment variability, i.e. inside radiation belts, in the slot region between electron belts, and in the exterior part of the magnetosphere, outside of radiation belts.

References

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[7] Walt, Martin, 1994, *Introduction to Geomagnetically Trapped Radiation.* New York: Cambridge University Press.

Appendicies

Appendix 1. Monthly cumulative radiation dose behind 4 shieldings. HEO-1, 2000.

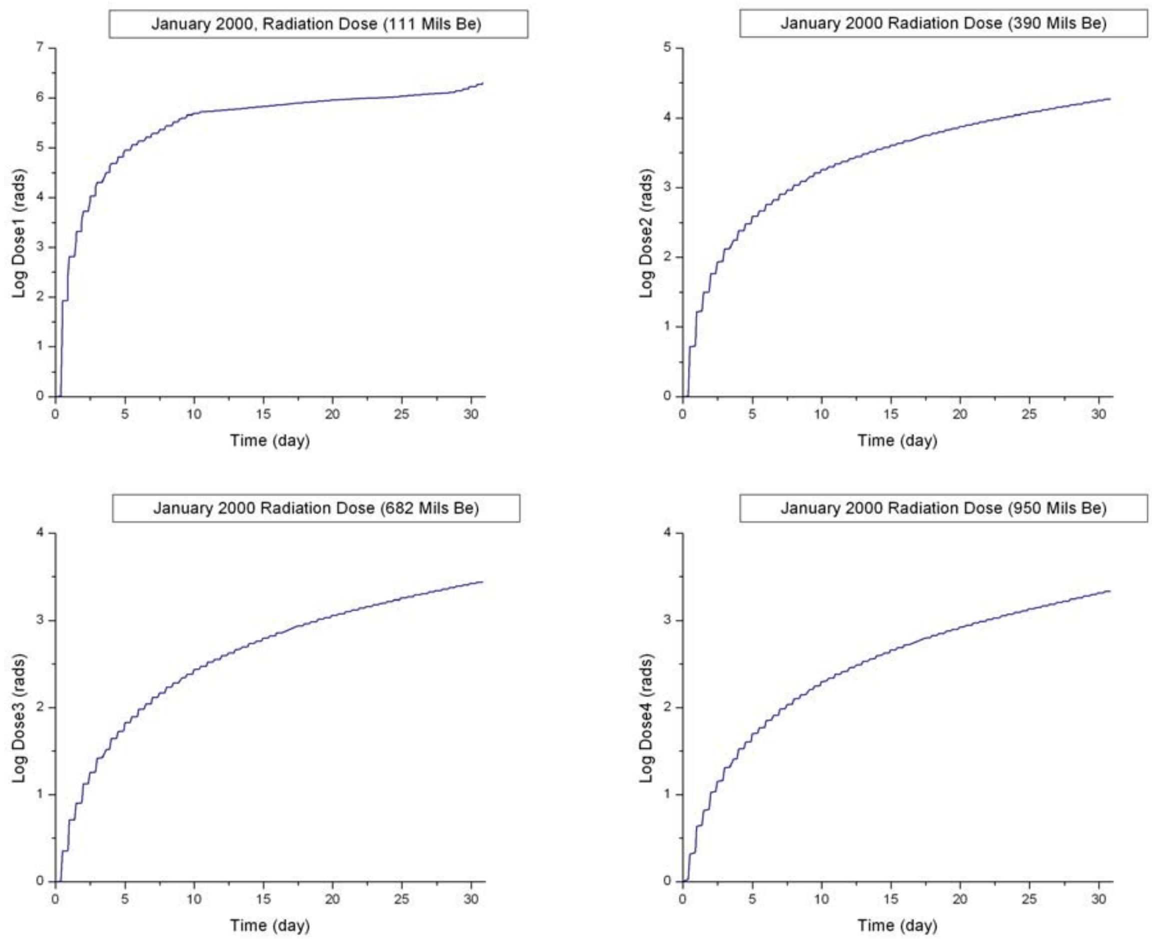


Figure A1-1. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). January 2000, HEO-1

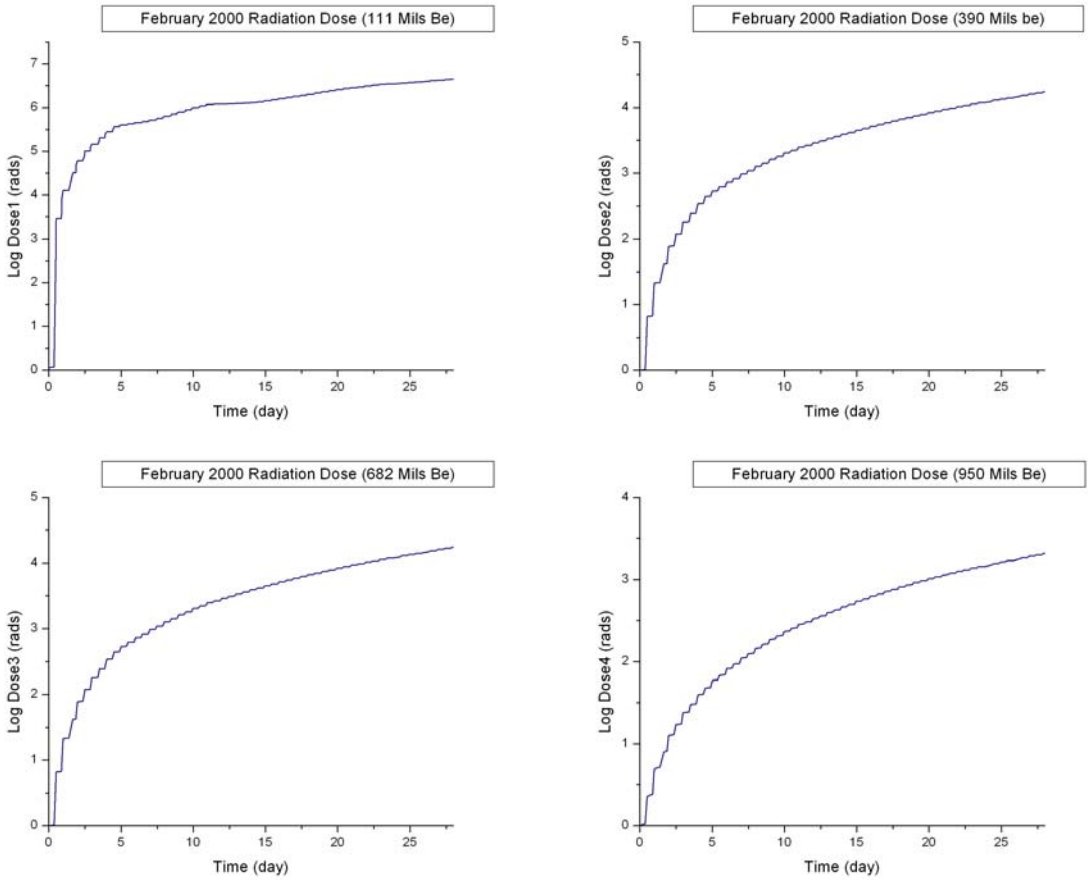


Figure A1-2. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). February 2000, HEO-1

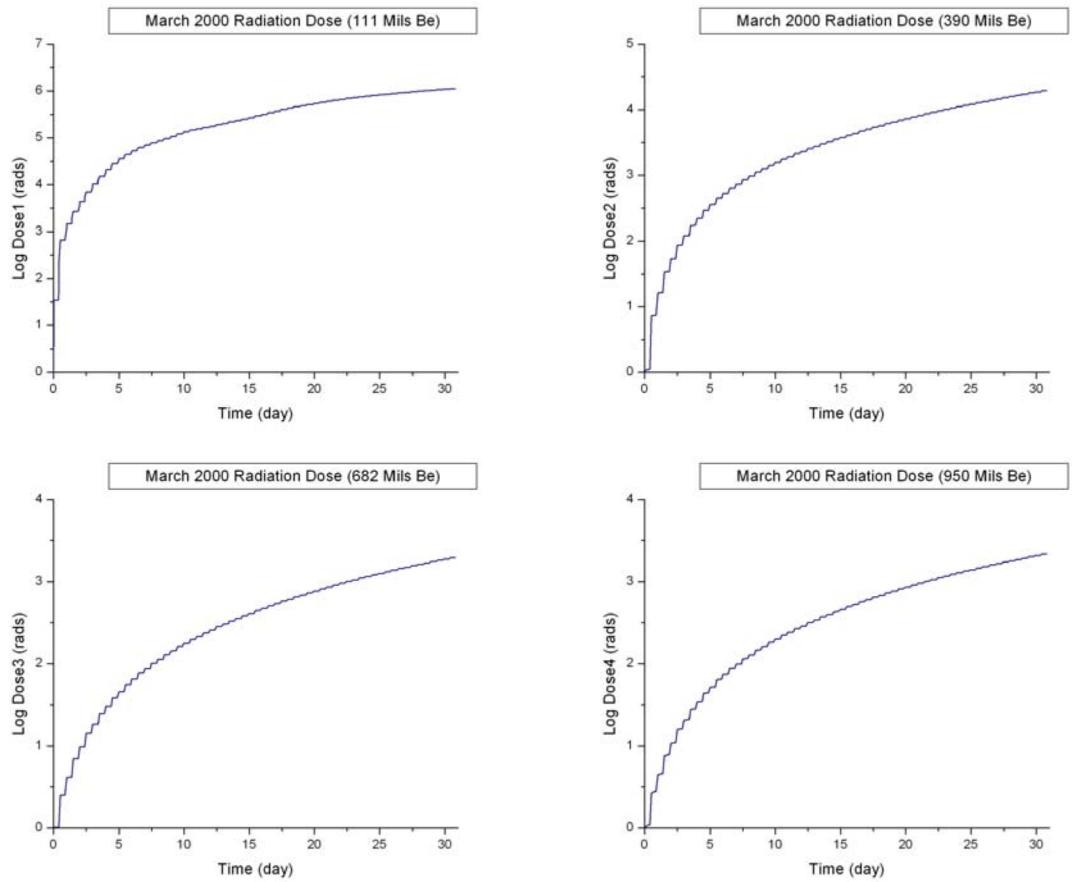


Figure A1-3. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). March 2000, HEO-1

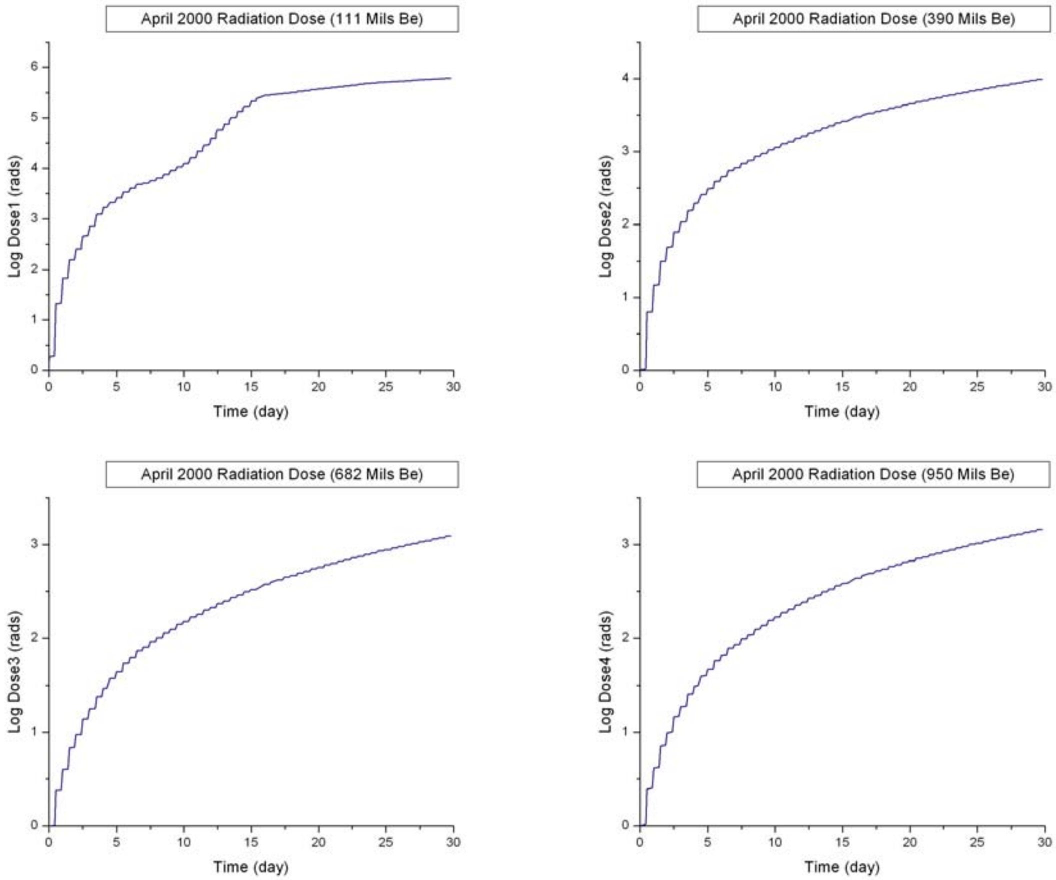


Figure A1-4. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). April 2000, HEO-1

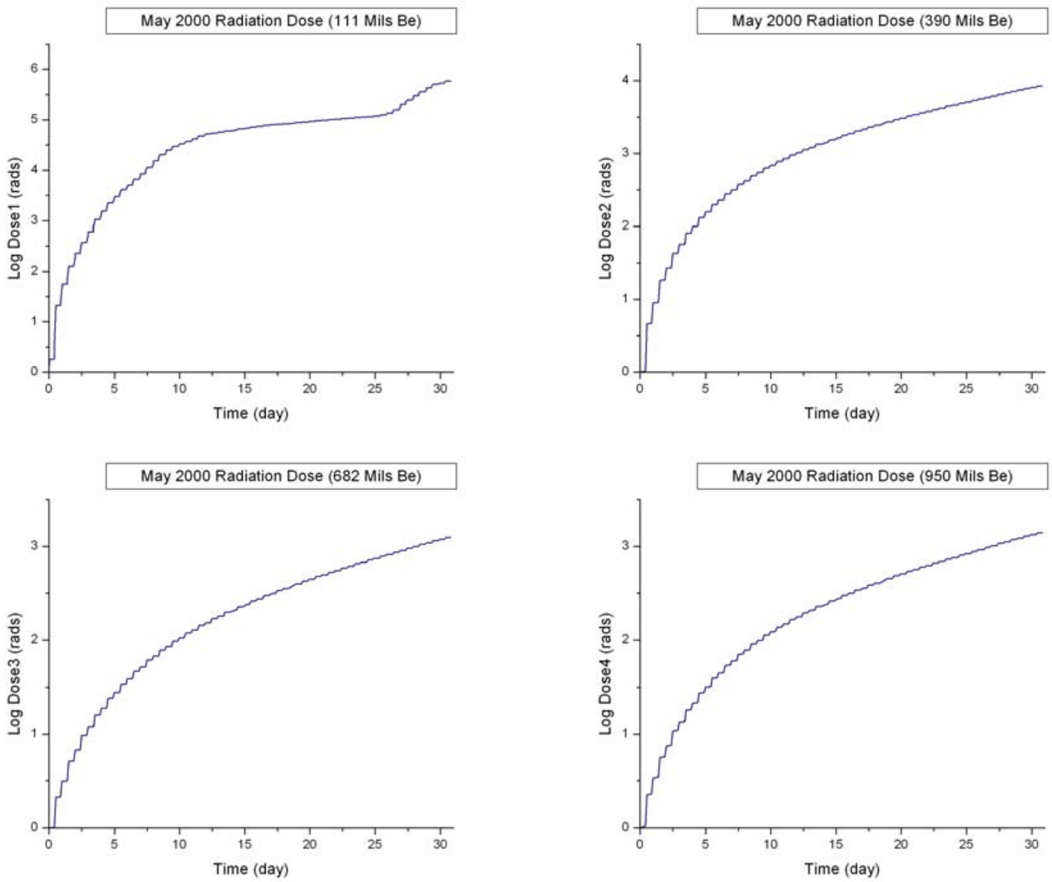


Figure A1-5. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). May 2000, HEO-1

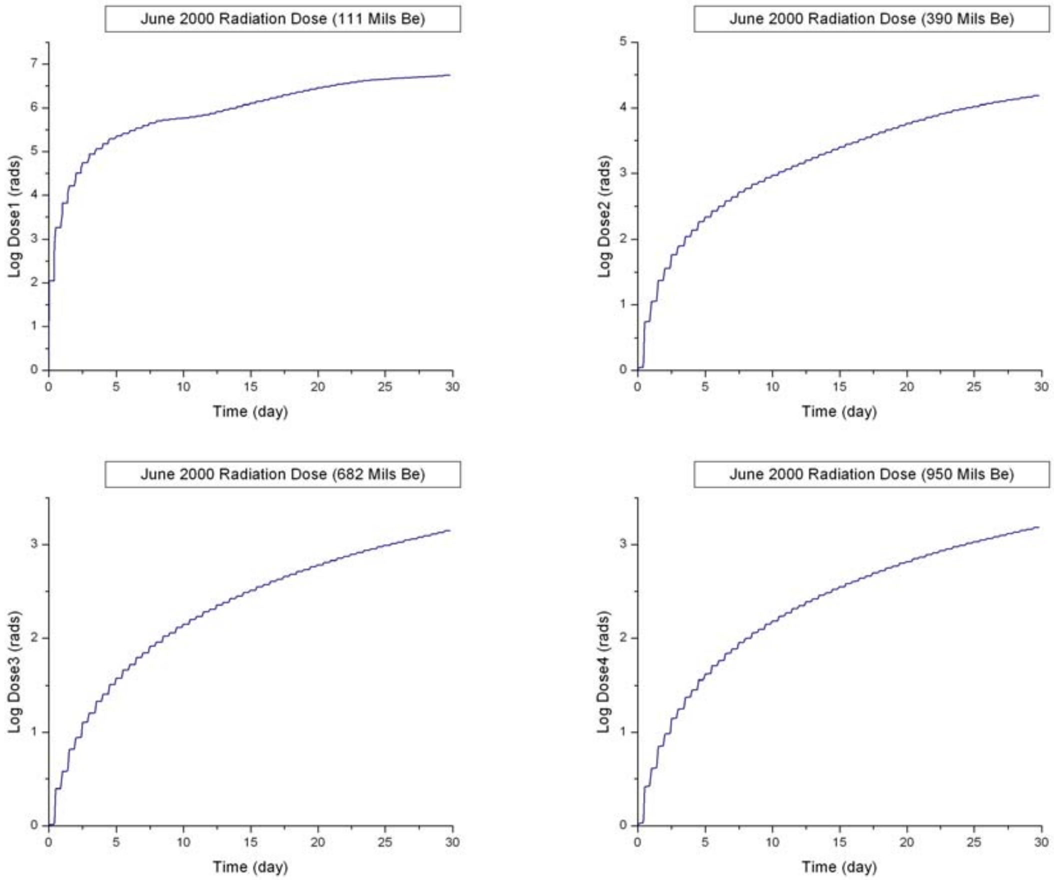


Figure A1-6. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). June 2000, HEO-1

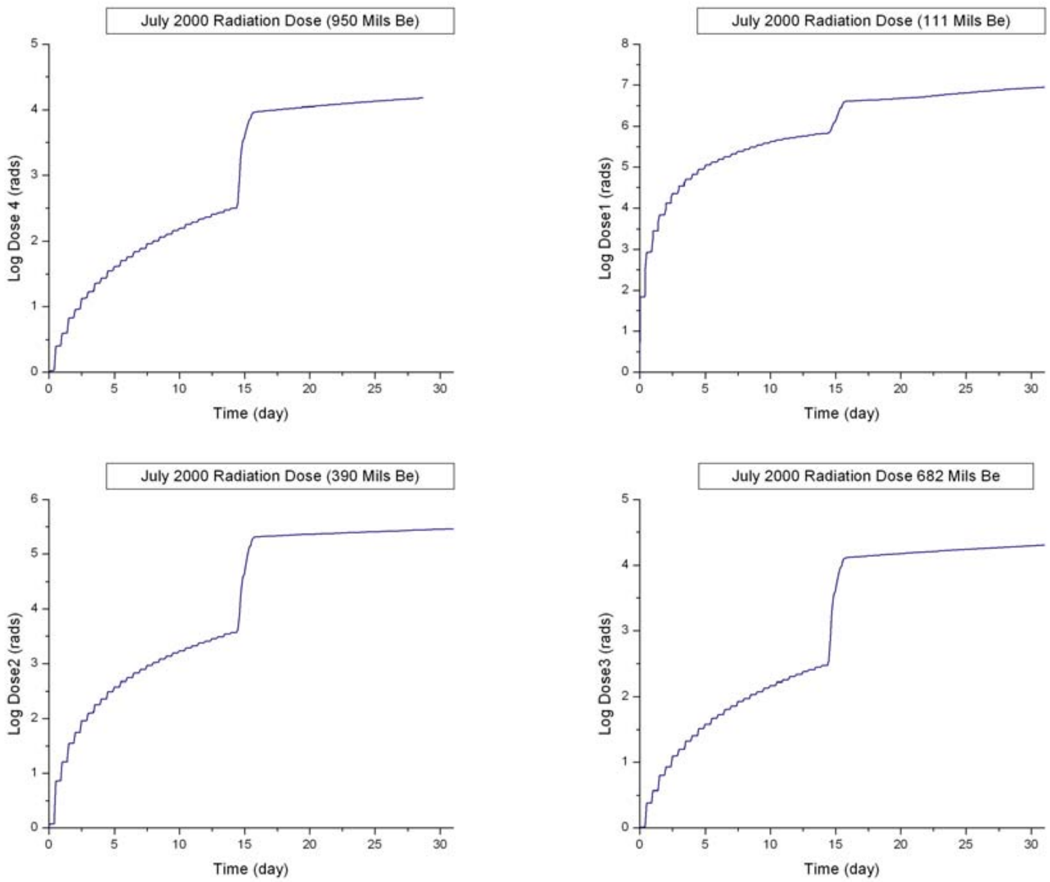


Figure A1-7. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). July 2000, HEO-1

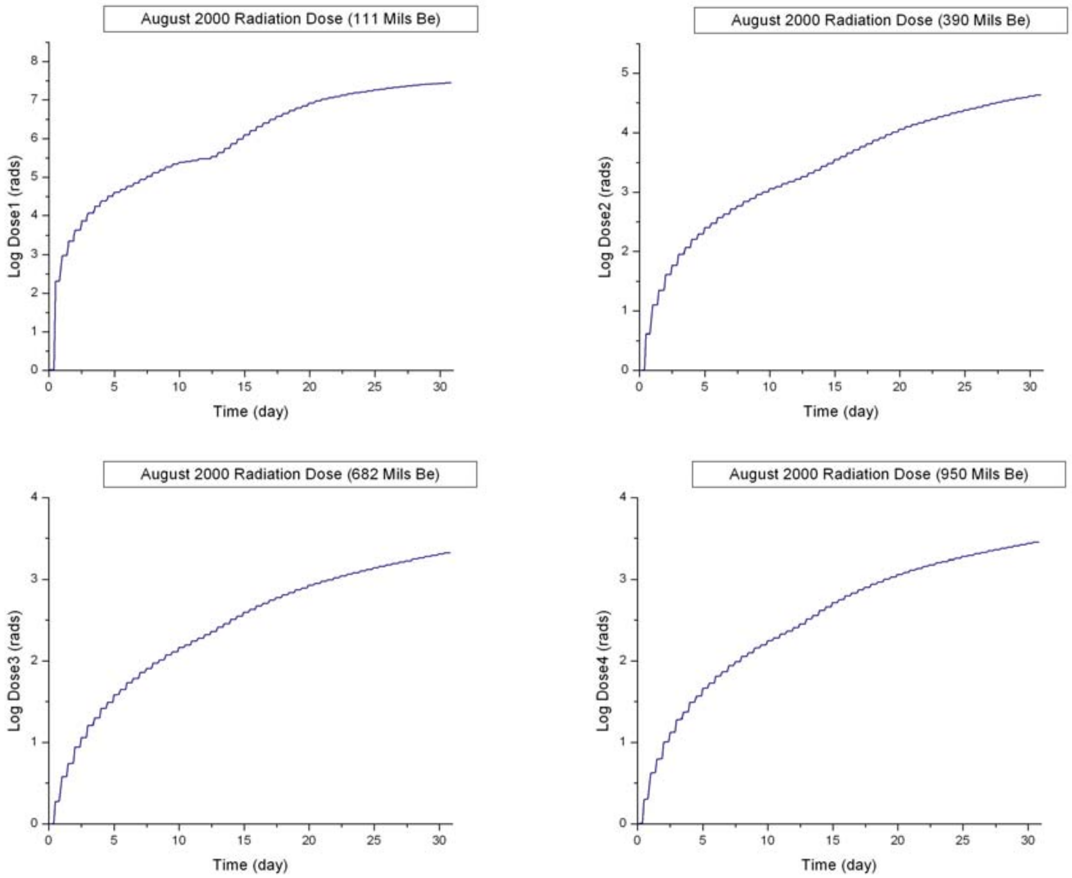


Figure A1-8. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). August 2000, HEO-1

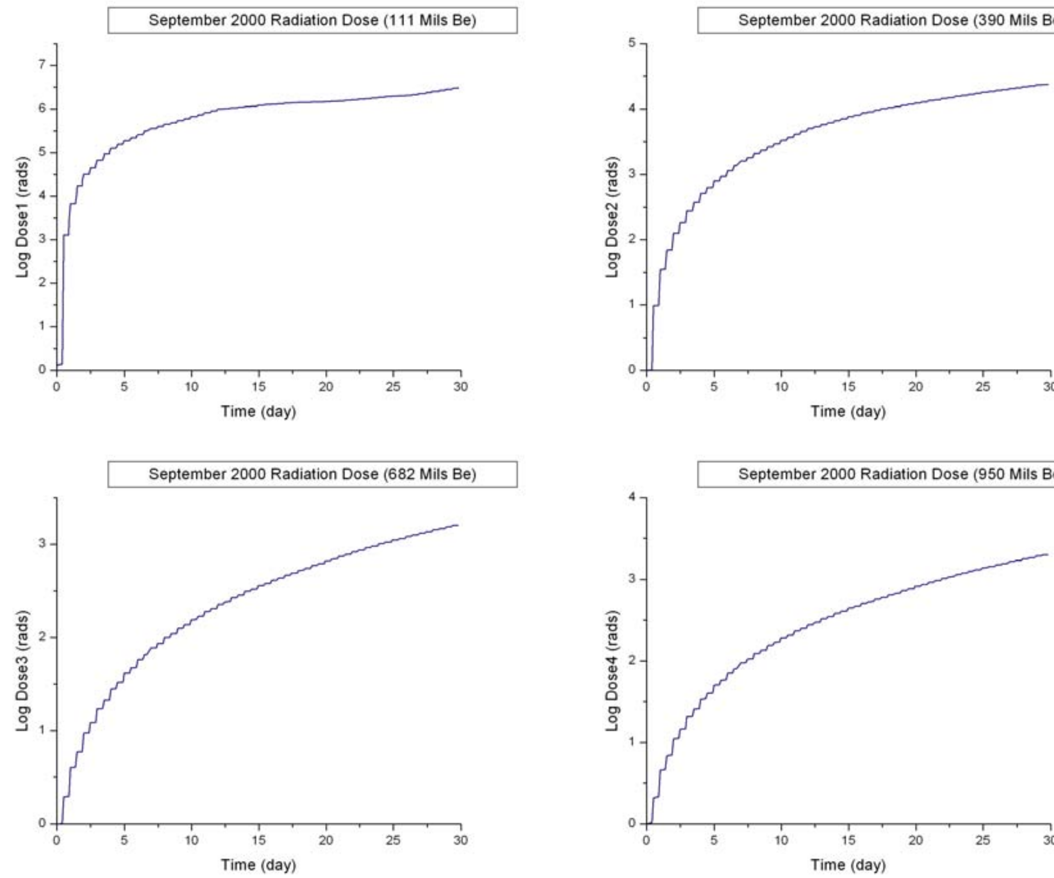


Figure A1-09. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). September 2000, HEO-1

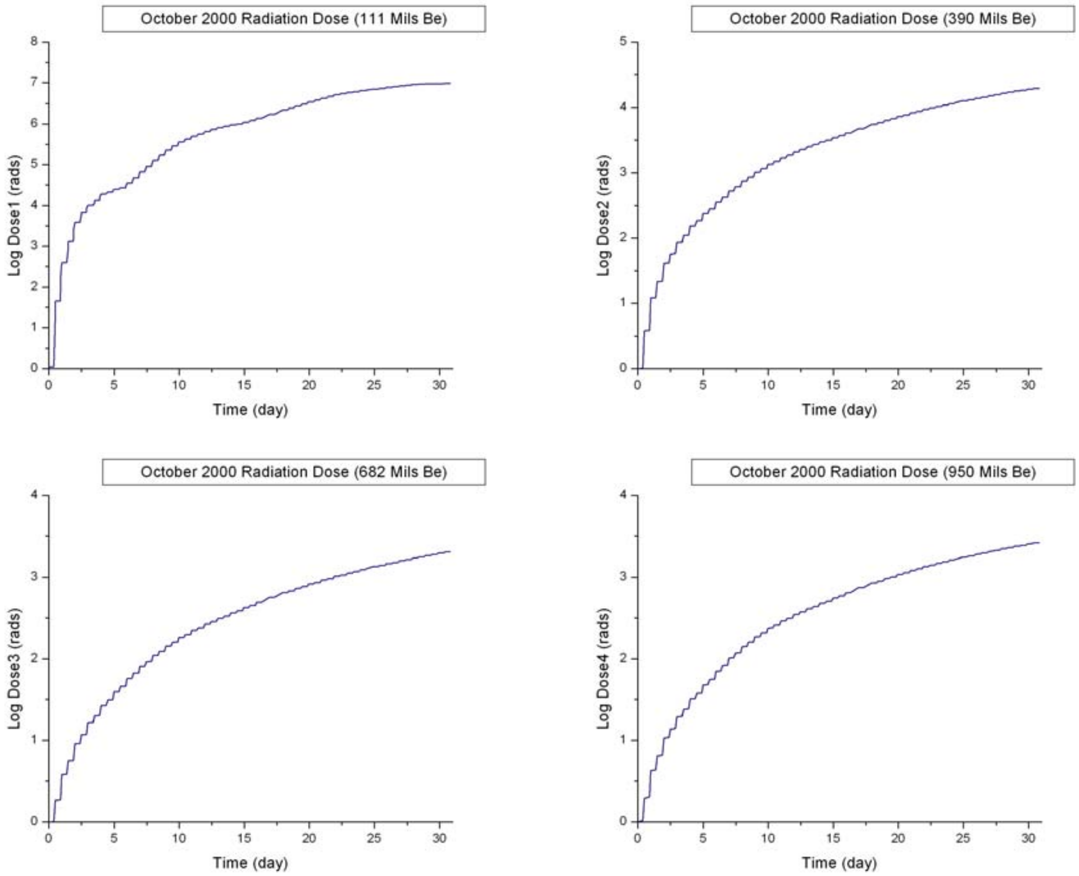


Figure A1-10. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). October 2000, HEO-1

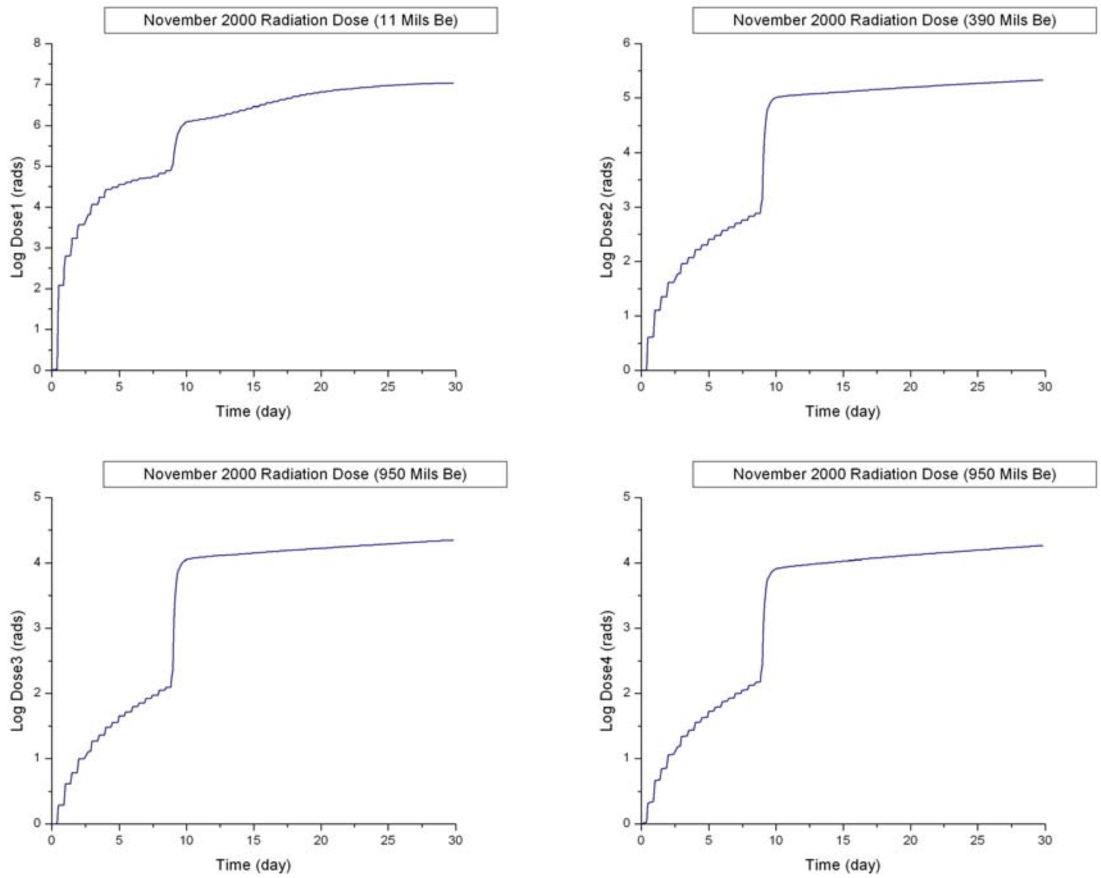


Figure A1-11. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). November 2000, HEO-1

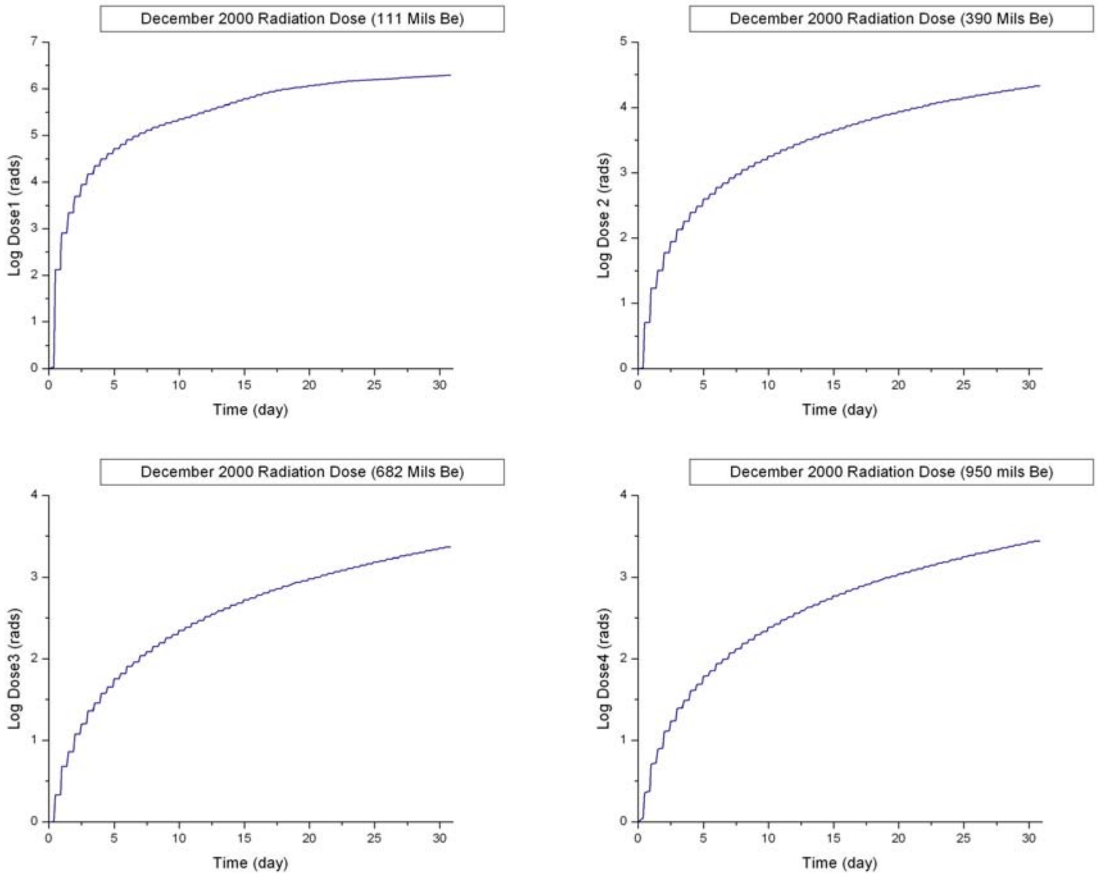


Figure A1-12. Monthly cumulative radiation at 4 dosimeters (shielding levels 111 Mils Be, 390 Mils Be, 682 Mils Be, 950 Mils Be). December 2000, HEO-1

Appendix 2. Radiation dose rate for years 1998-2008 (HEO-3). Shielding 5 Mils Al

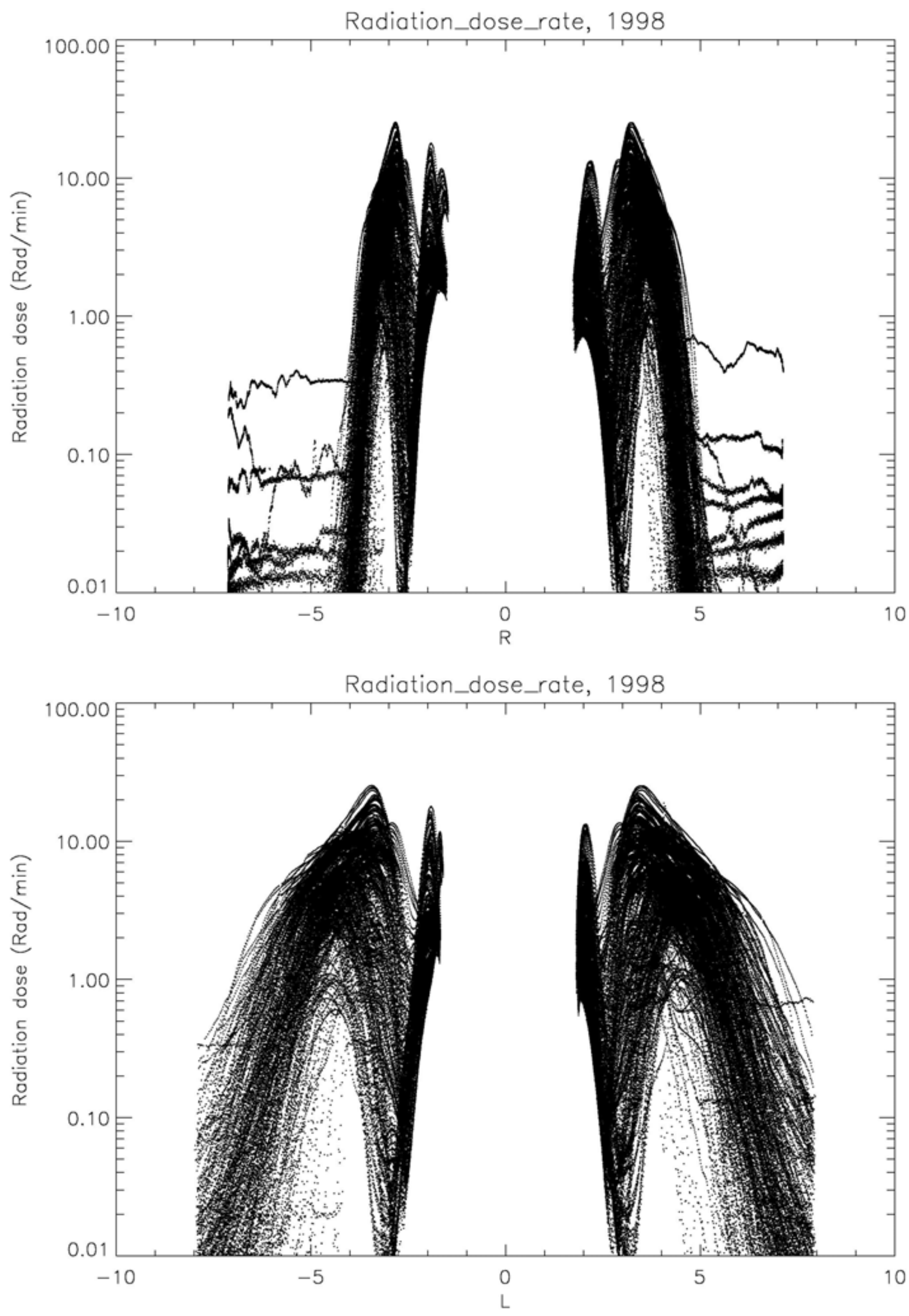


Figure A2-1. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs Radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO-3 1998

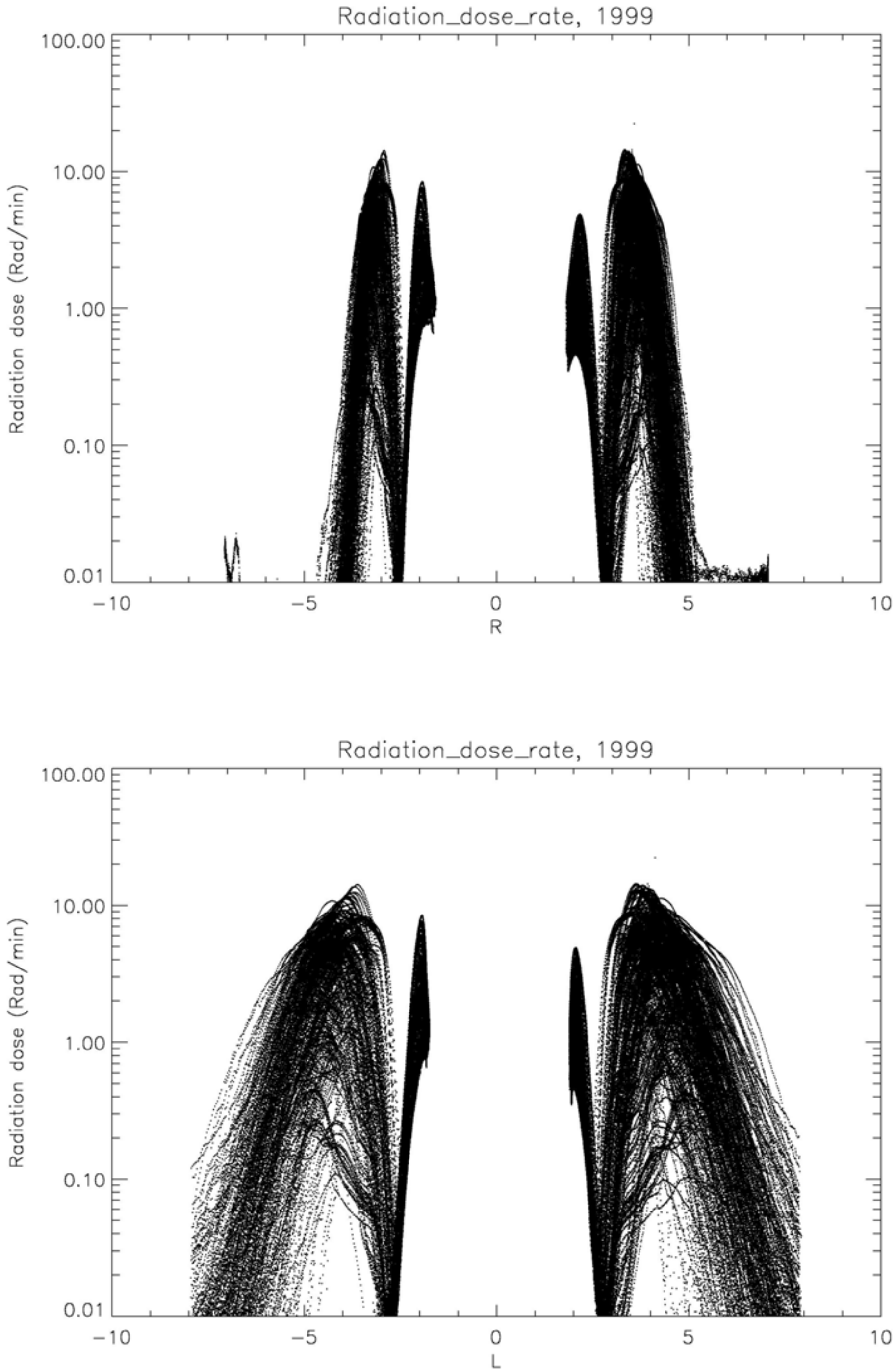


Figure A2-2. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO-3 1999

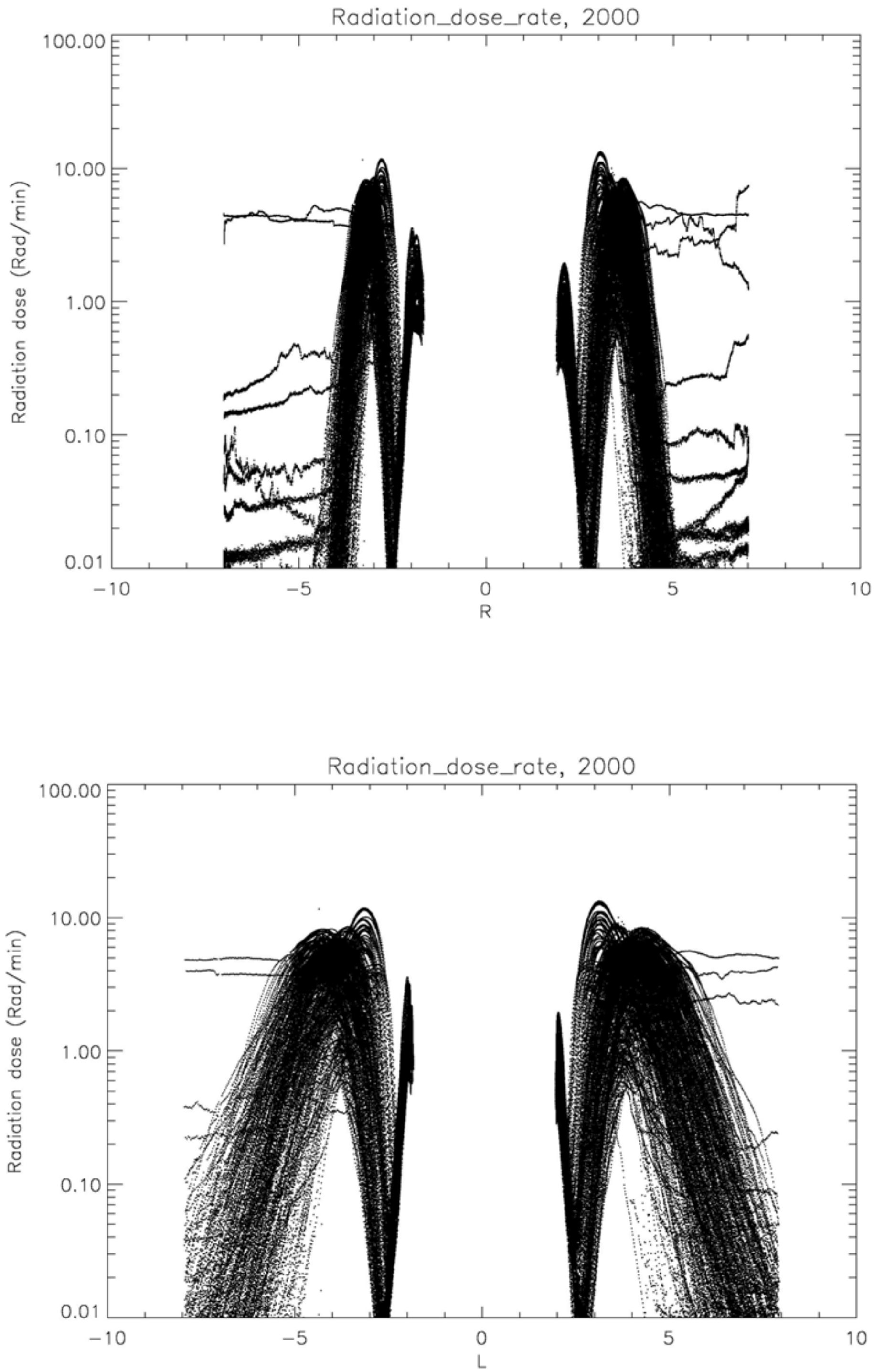


Figure A2-3. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs Radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO-3 2000

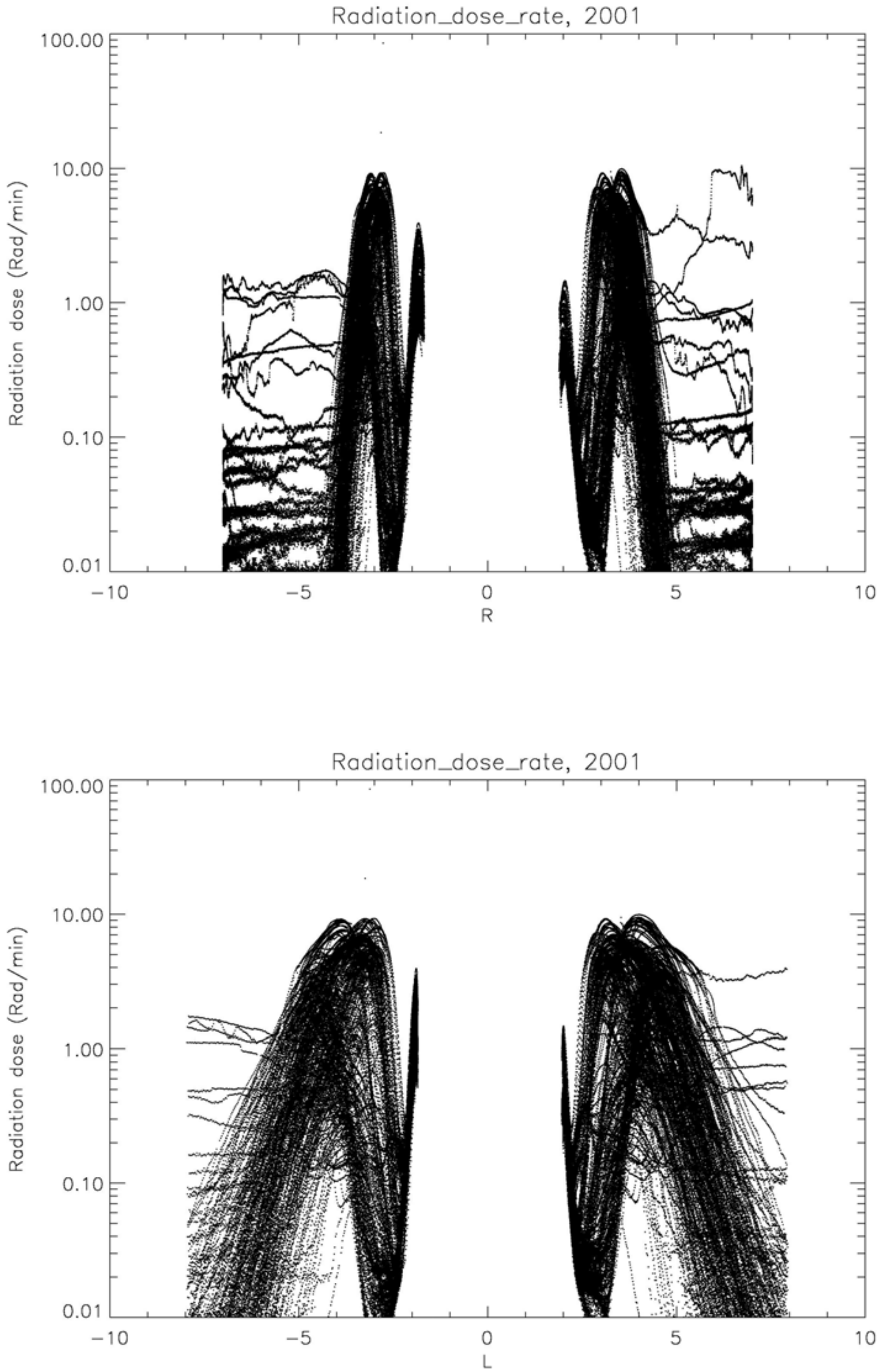


Figure A2-4. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO-3 2001

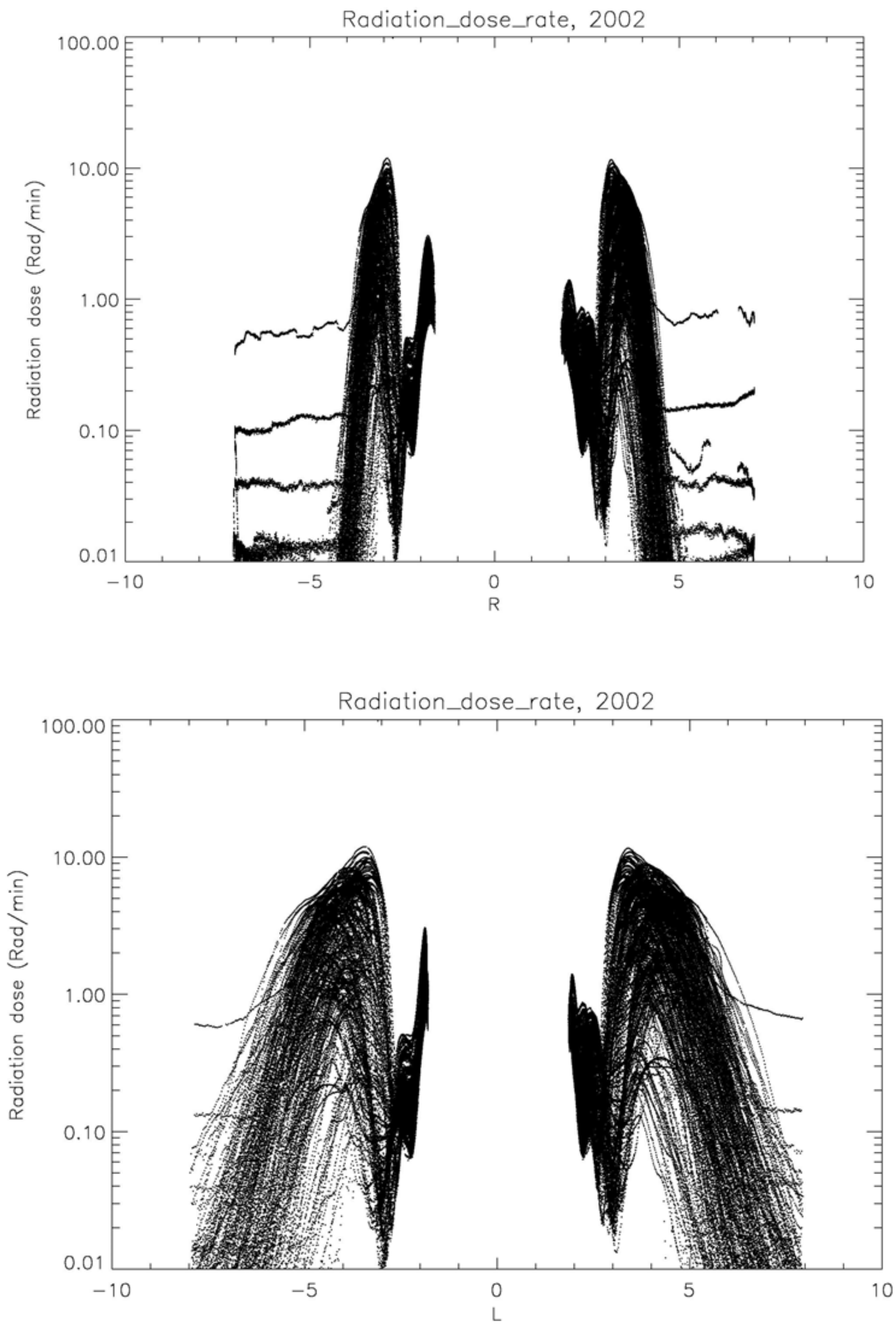


Figure A2-5. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO-3 2002

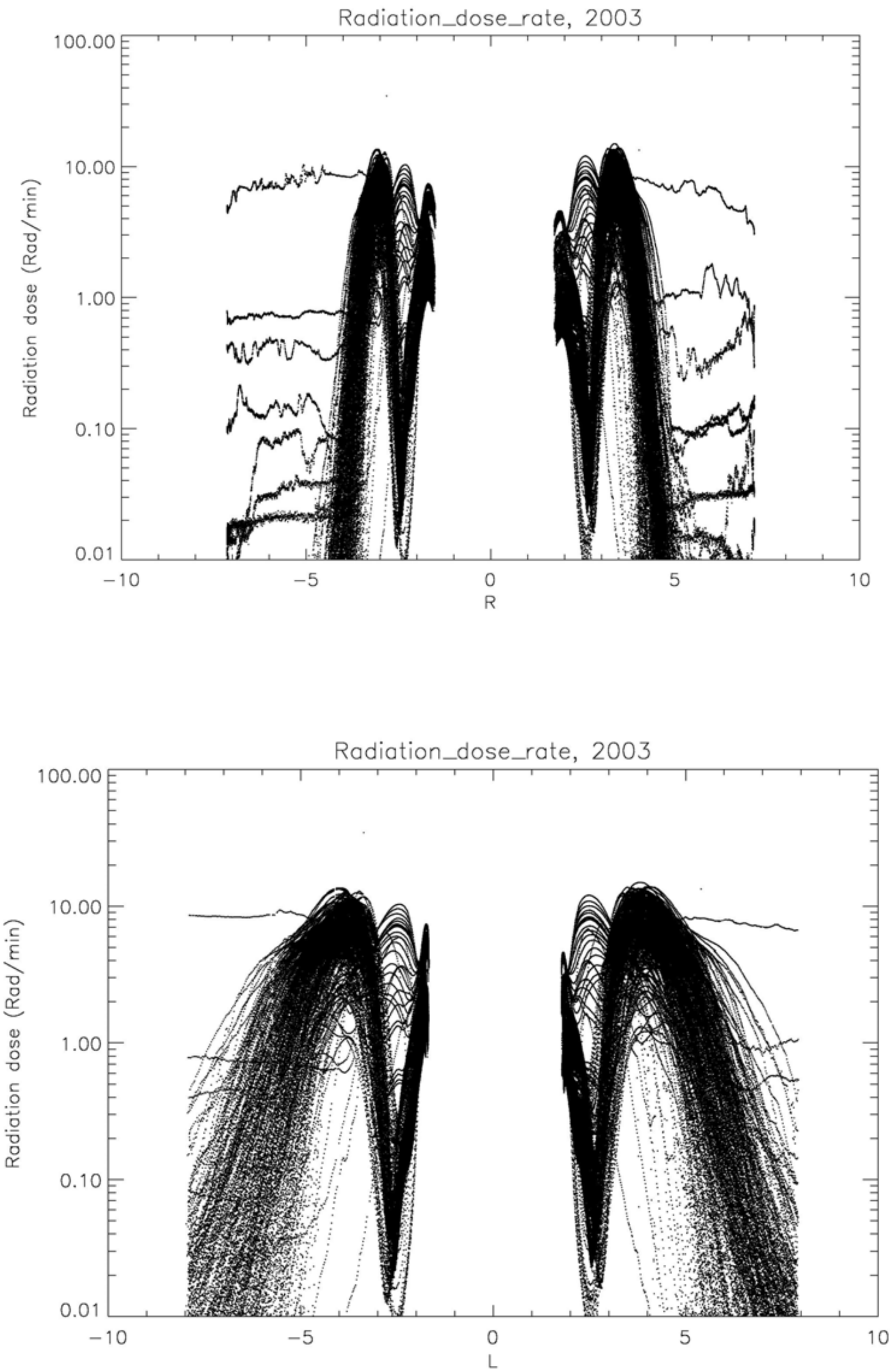


Figure A2-6. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO-3 2003

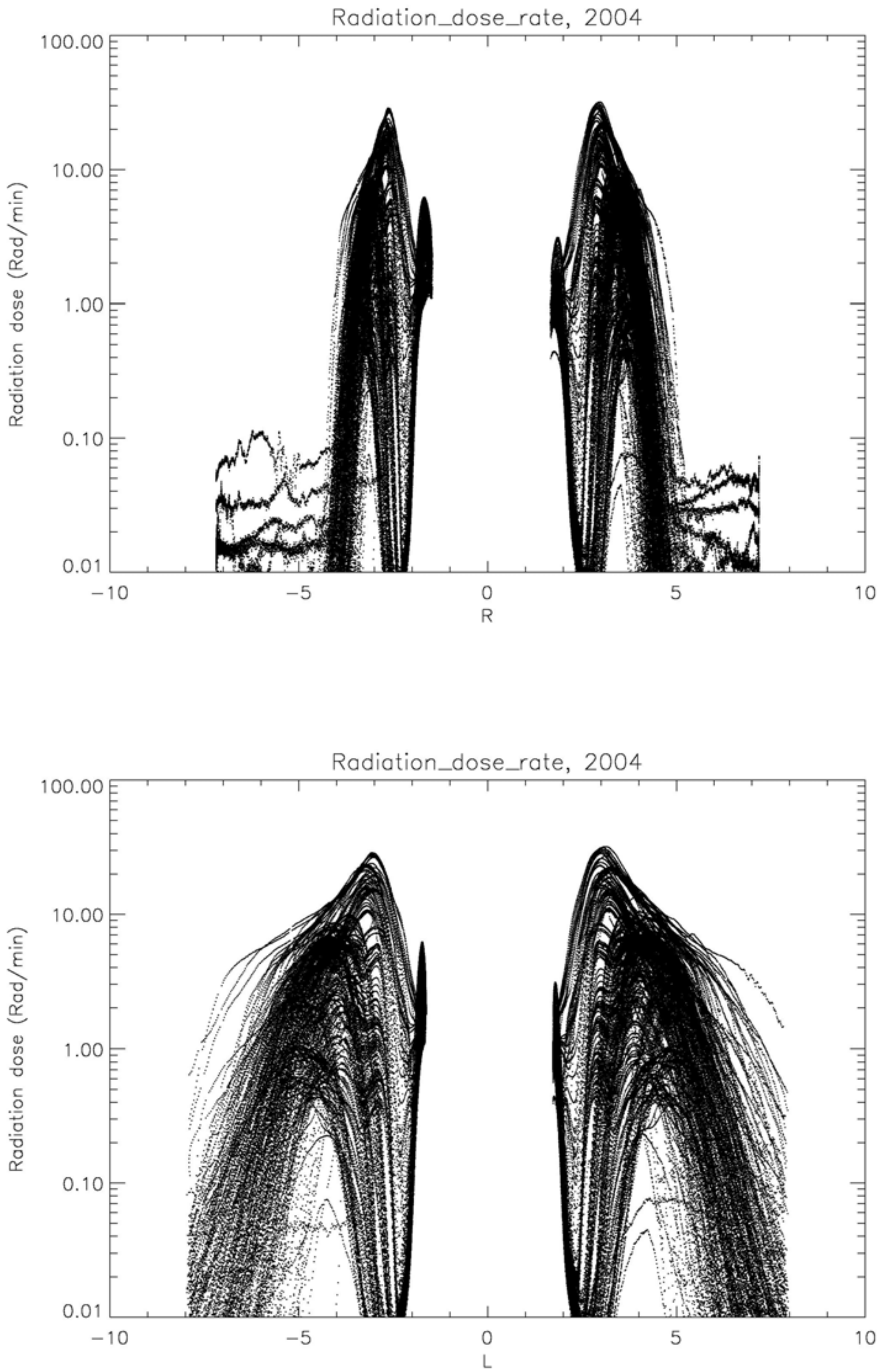


Figure A2-7. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO-3 2004

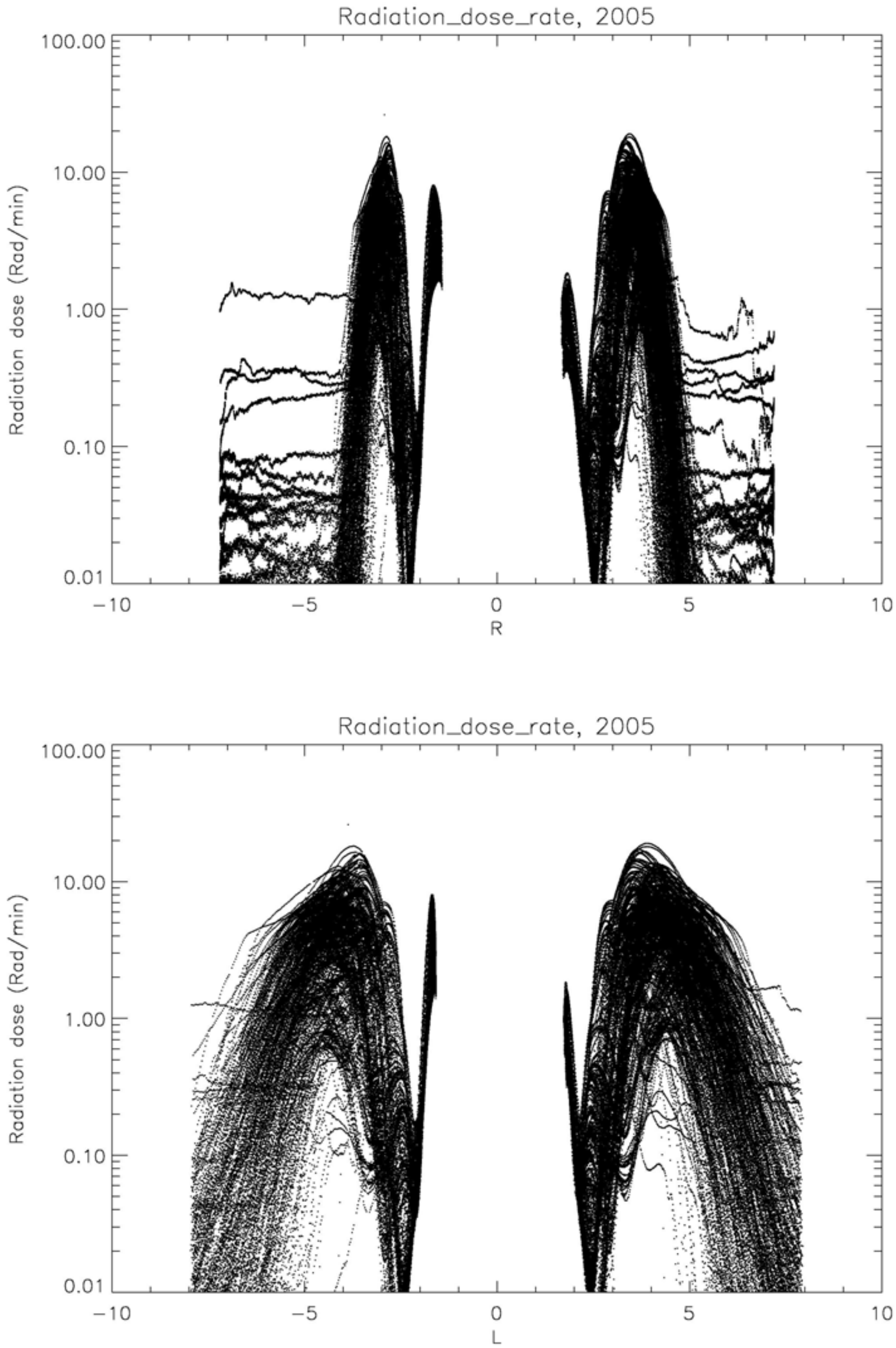


Figure A2-8. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO-3 2005

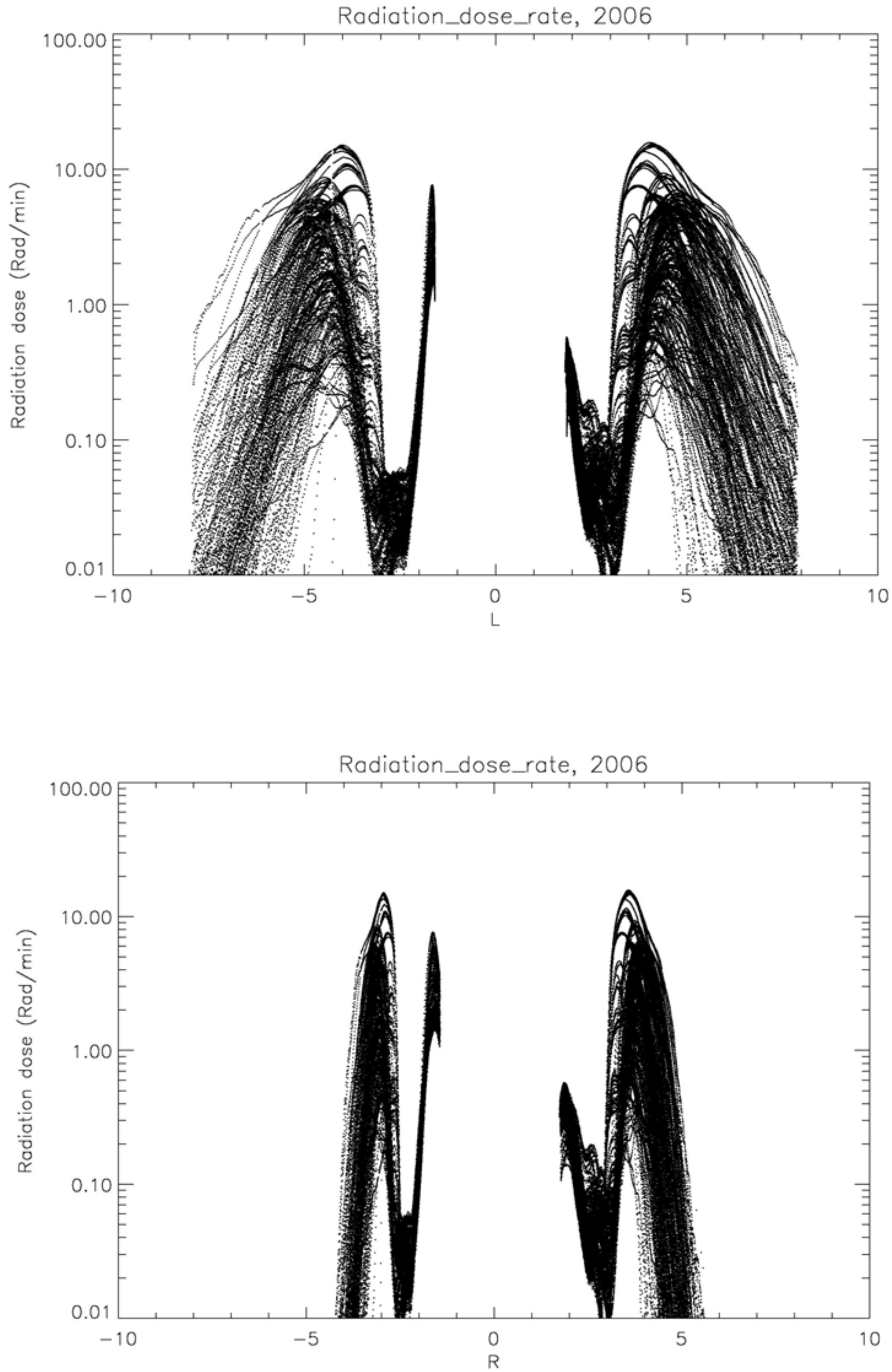


Figure A2-9. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO-3 2006

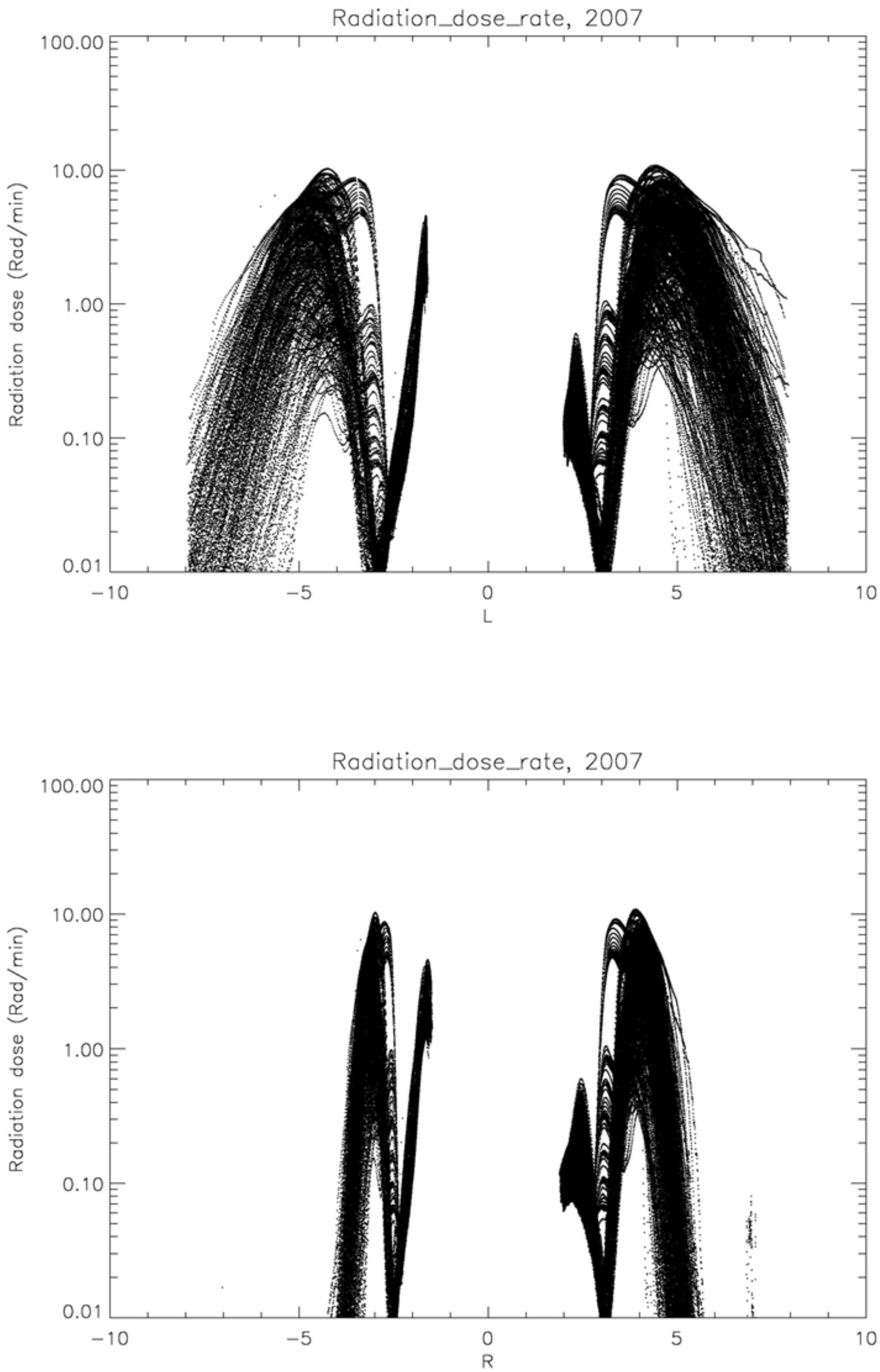


Figure A2-10. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO-3 2007

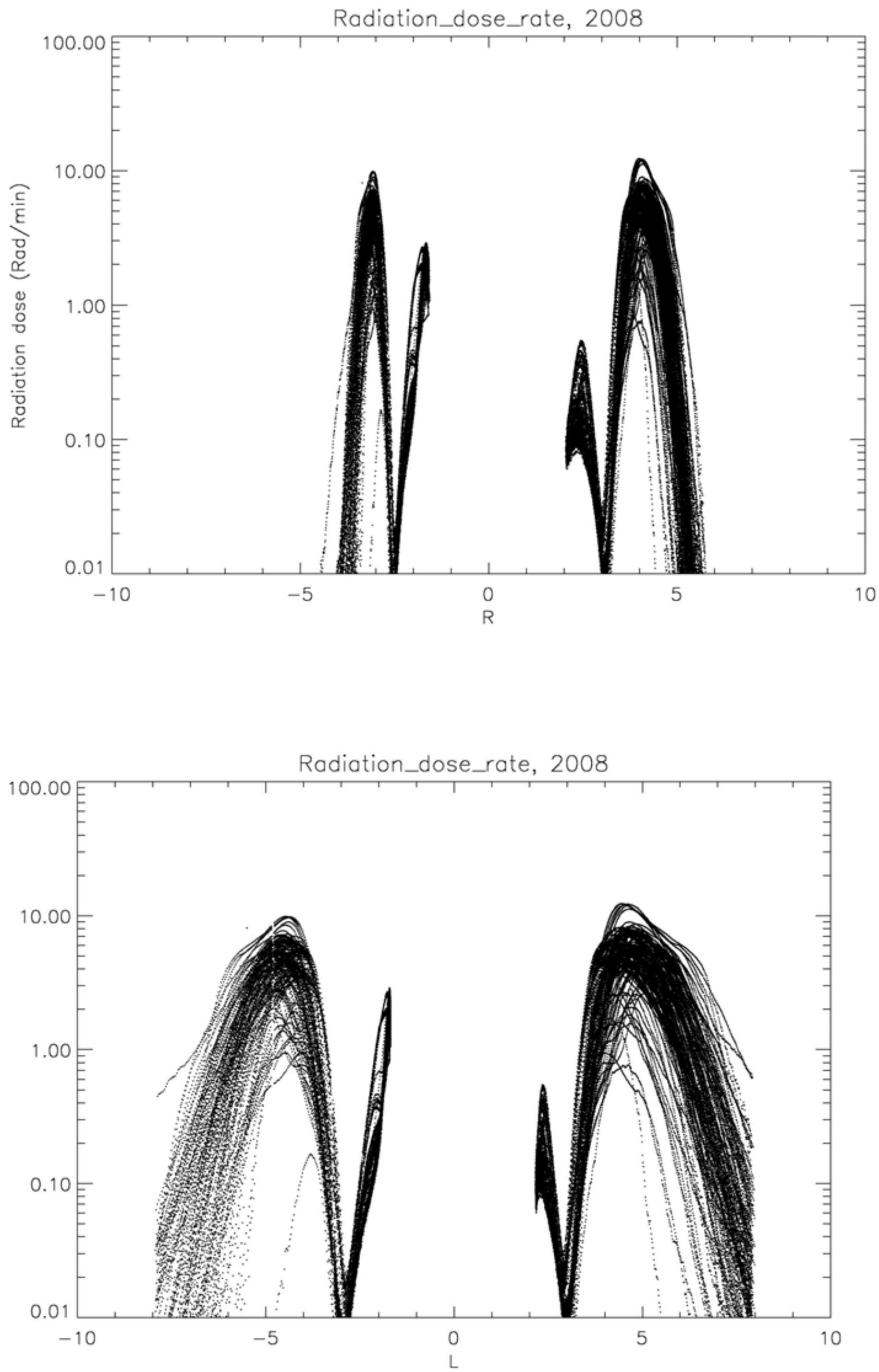


Figure A2-11. Radiation dose rate behind shielding 5 Mils Al. Dose rate vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 2008

Appendix 3. Proton fluxes for years 1998-2008 (HEO 3)

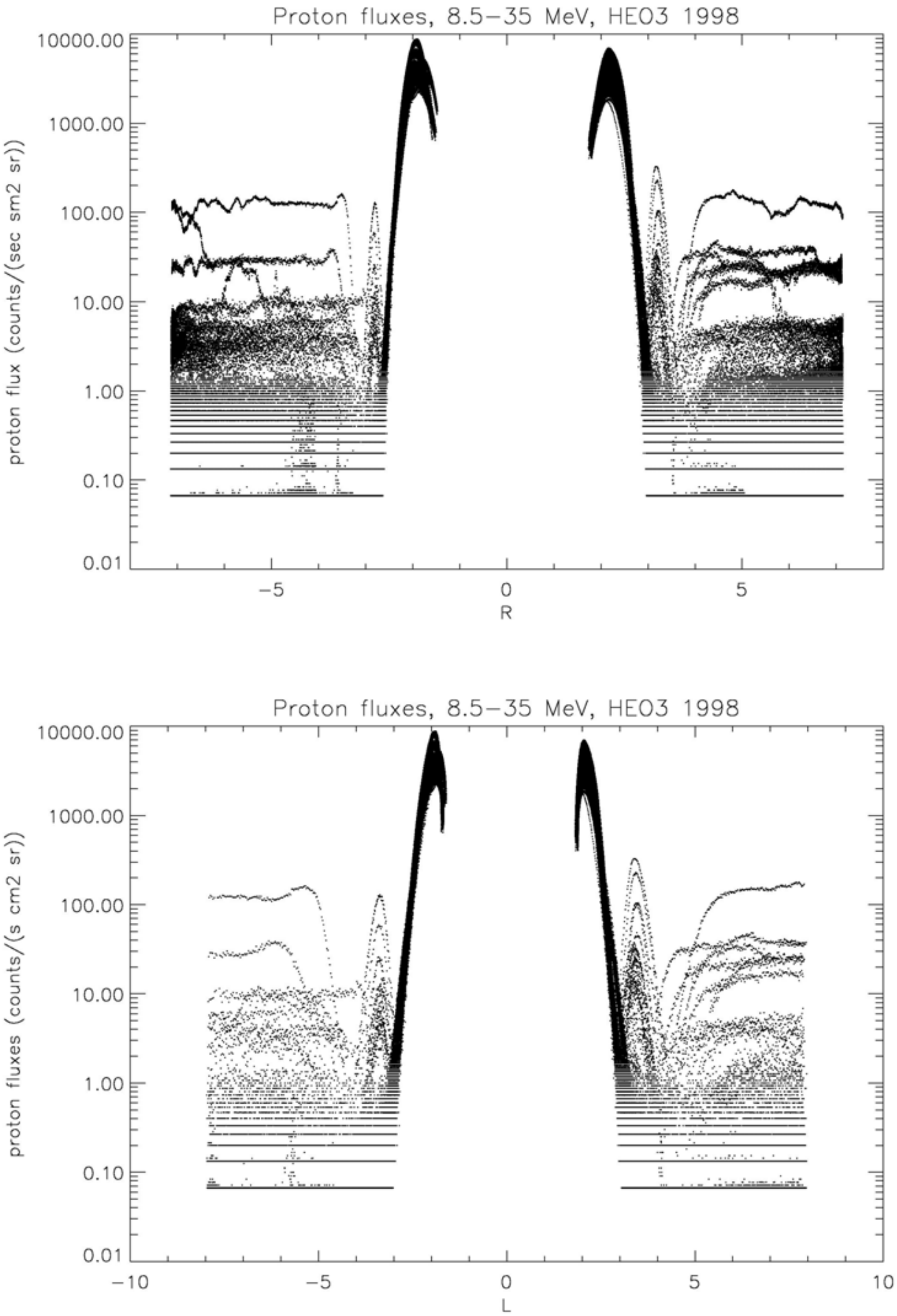
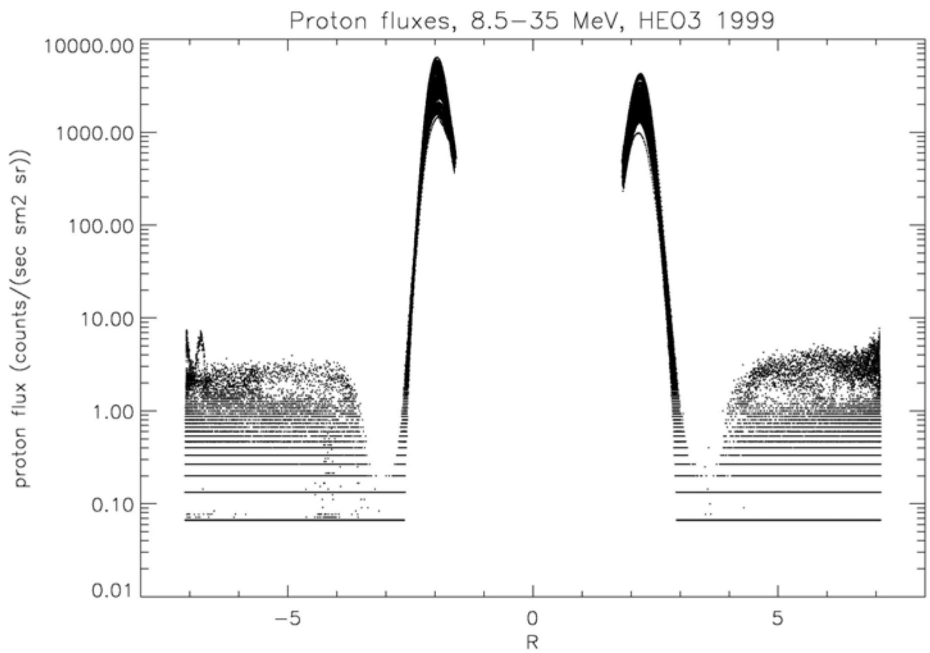


Figure A3-1. Proton fluxes, 8.5-35 MeV. Proton fluxes vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 1998



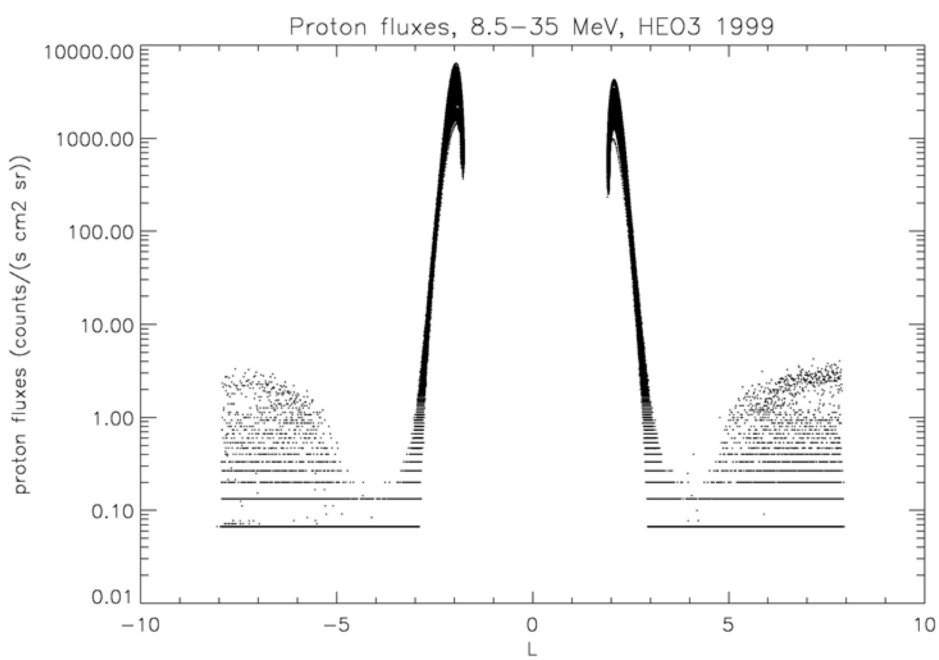
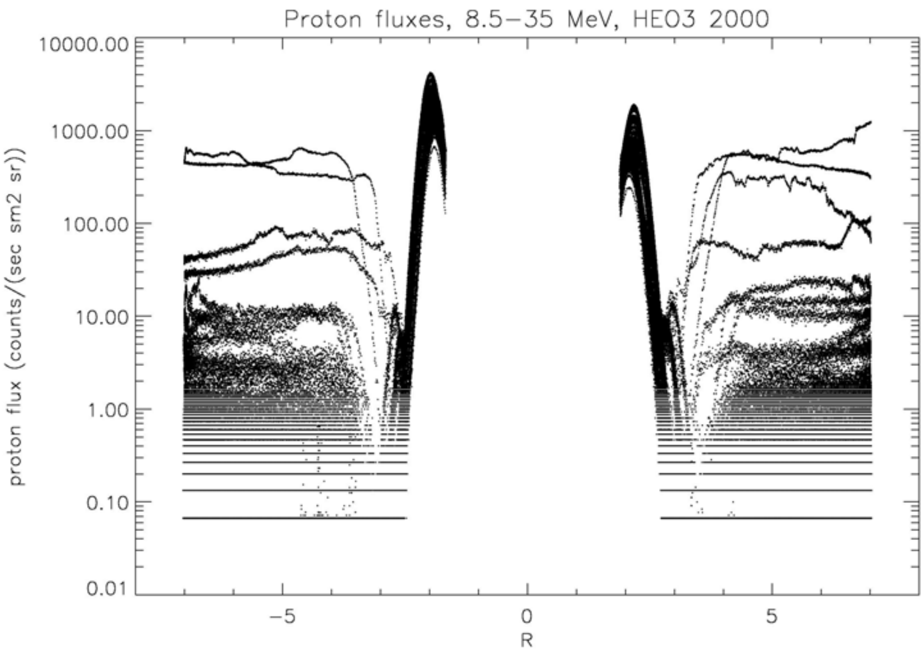


Figure A3-2. Proton fluxes, 8.5-35 MeV. Proton fluxes vs Radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 1999



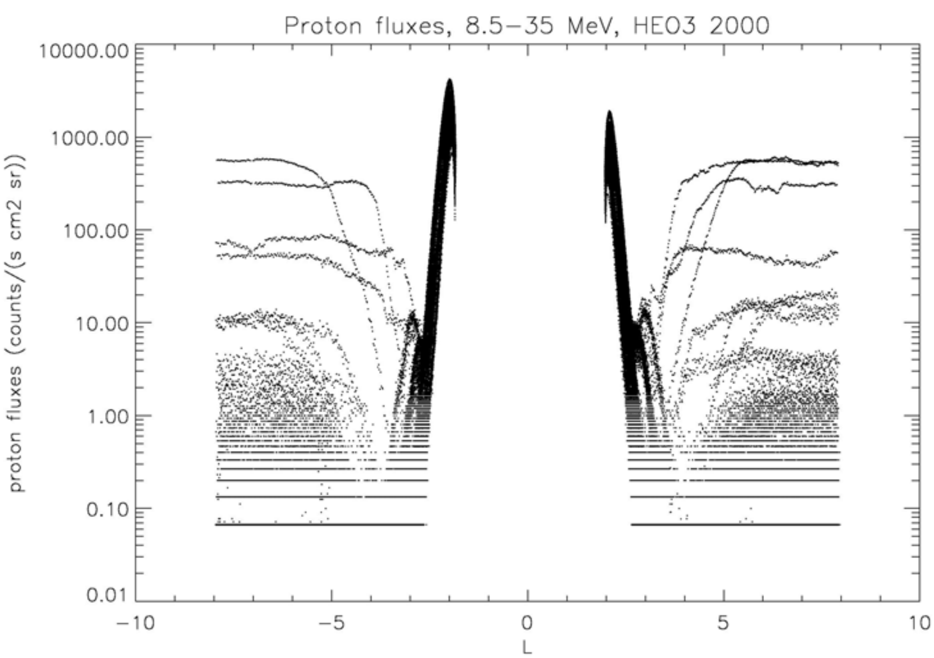


Figure A3-3. Proton fluxes, 8.5-35 MeV. Proton fluxes vs Radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 2000

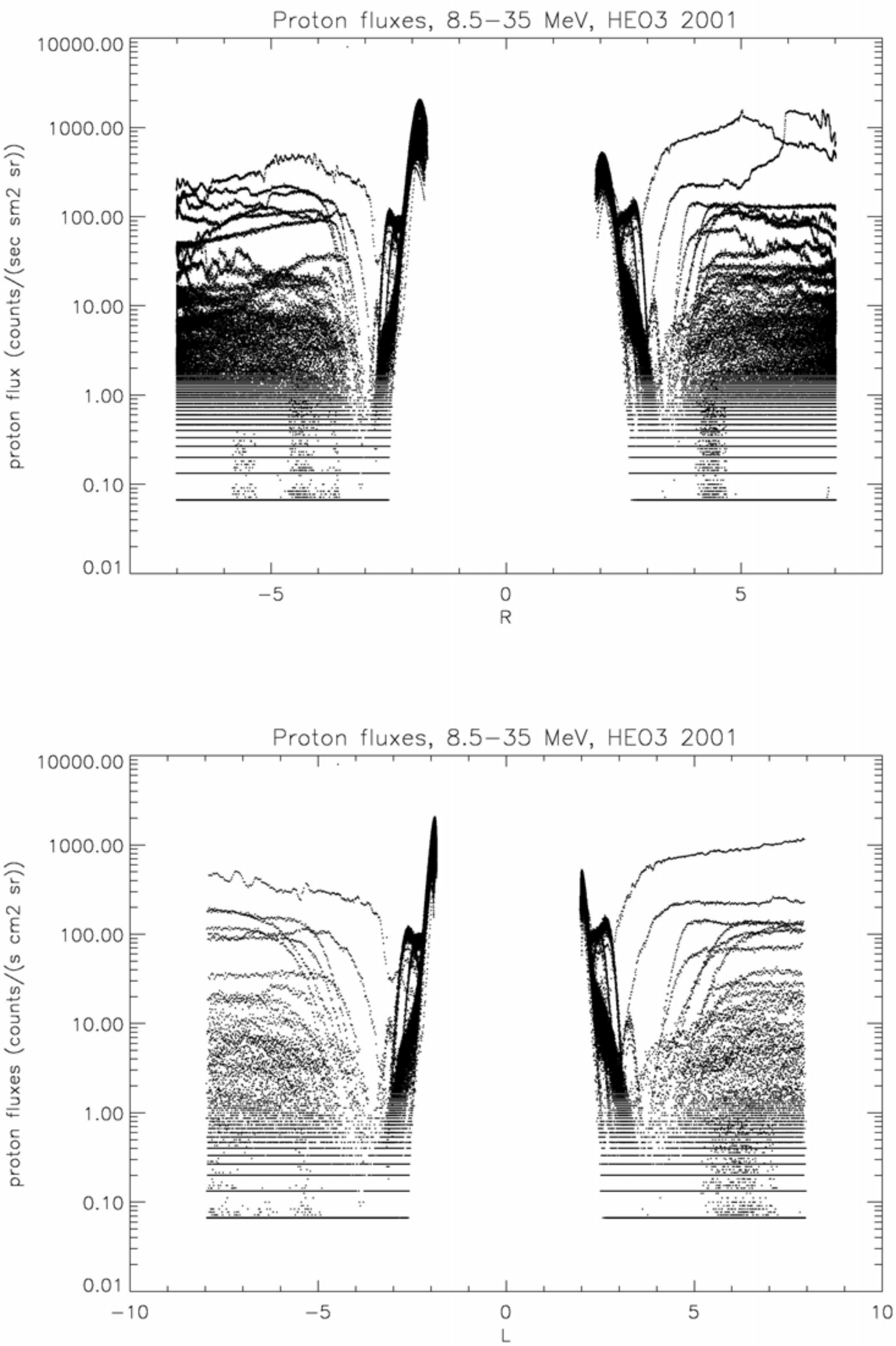


Figure A3-4. Proton fluxes, 8.5-35 MeV. Proton fluxes vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 2001

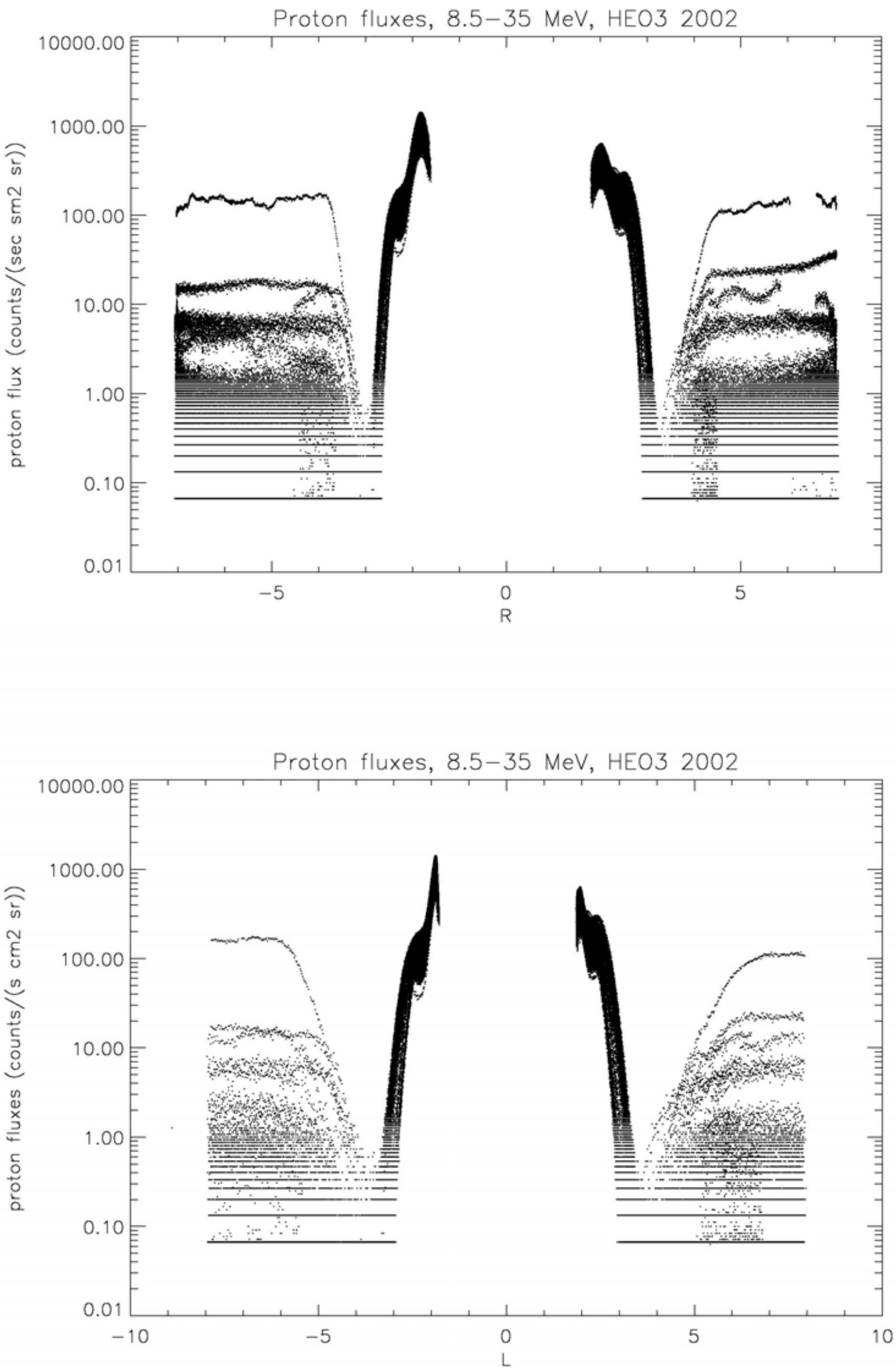
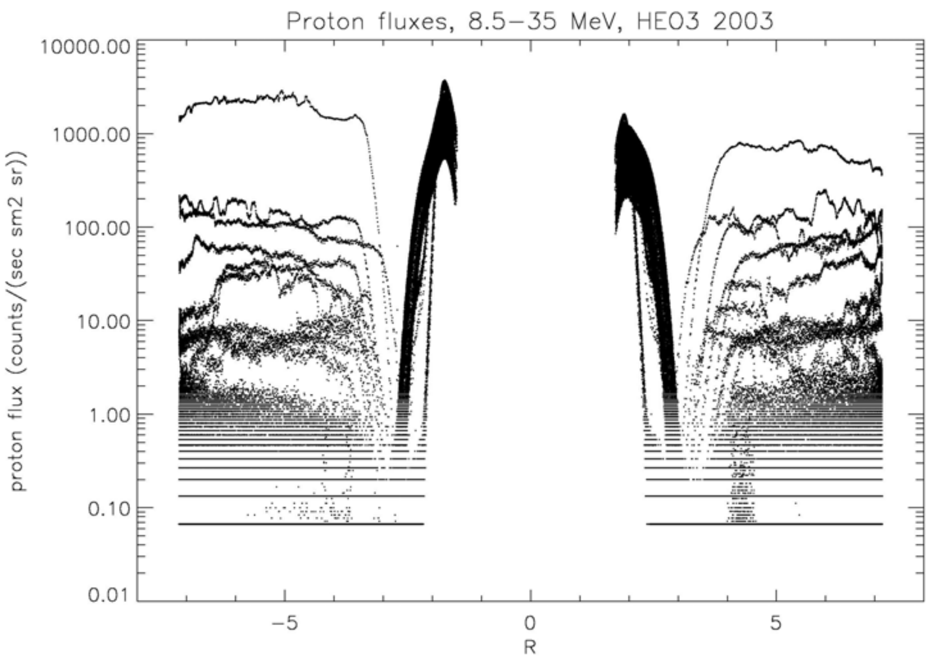


Figure A3-5. Proton fluxes, 8.5-35 MeV. Proton fluxes vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 2002



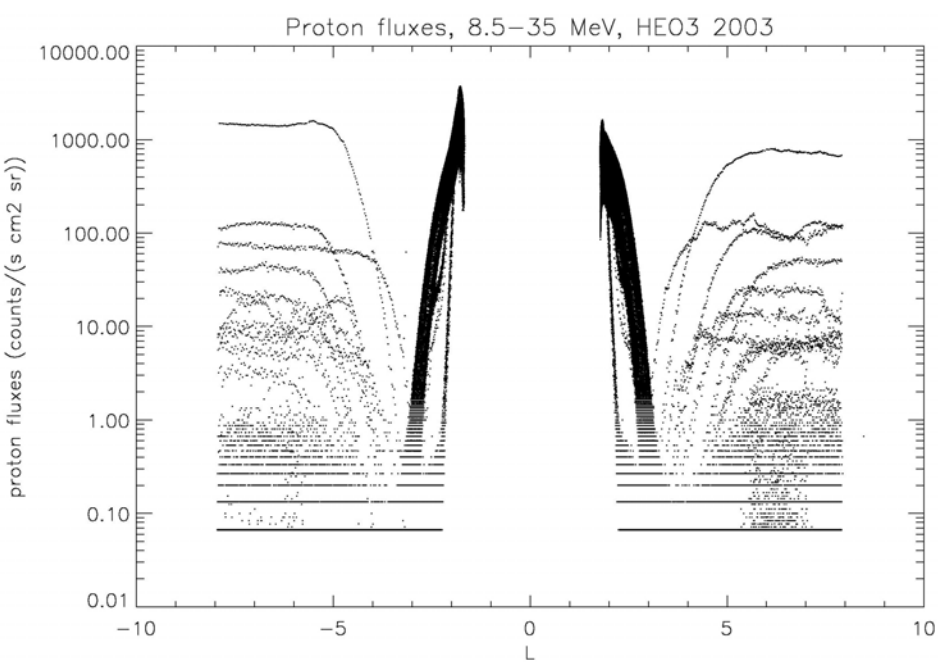


Figure A3-6. Proton fluxes, 8.5-35 MeV. Proton fluxes vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 2003

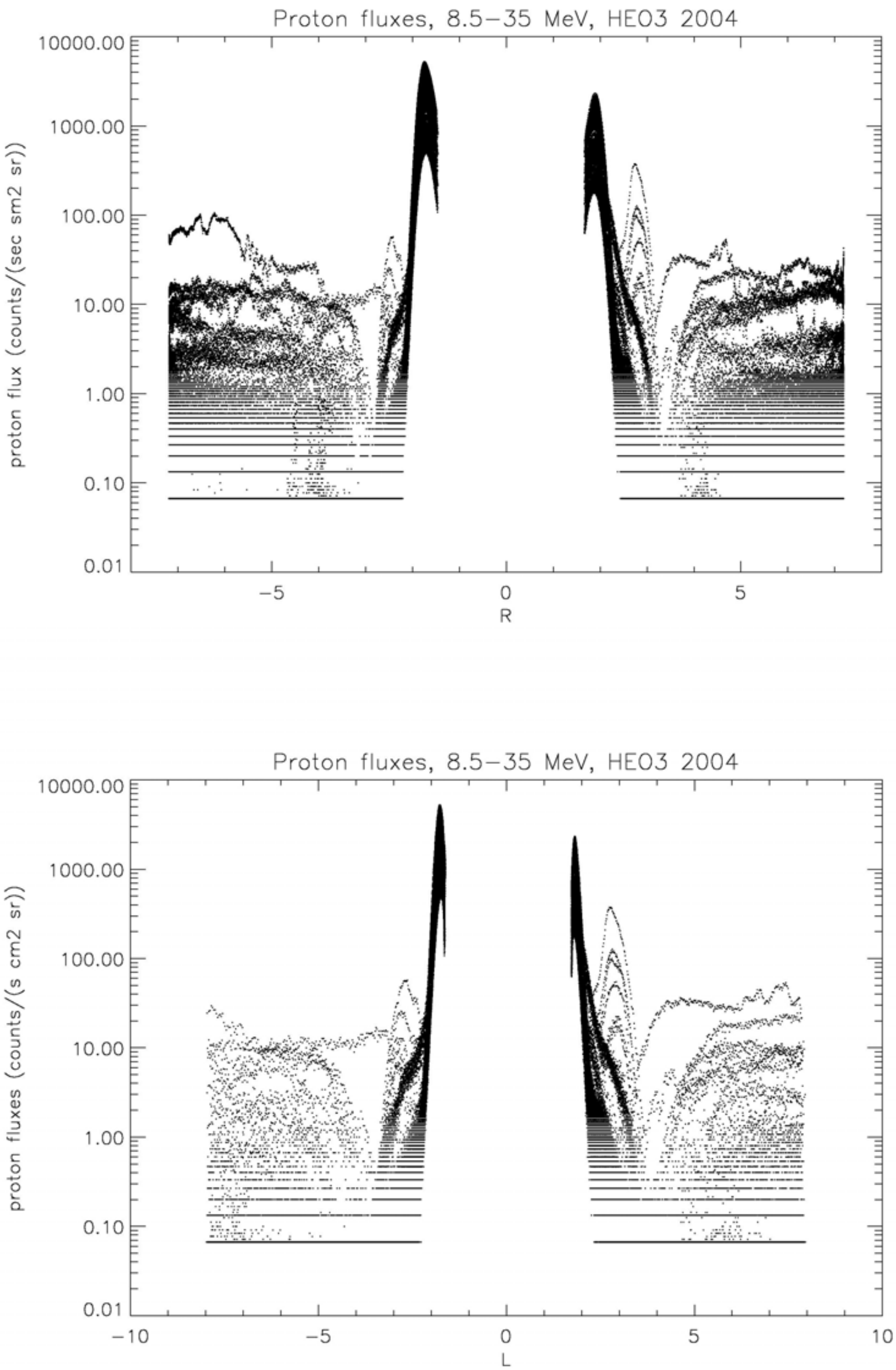


Figure A3-7. Proton fluxes, 8.5-35 MeV. Proton fluxes vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 2004

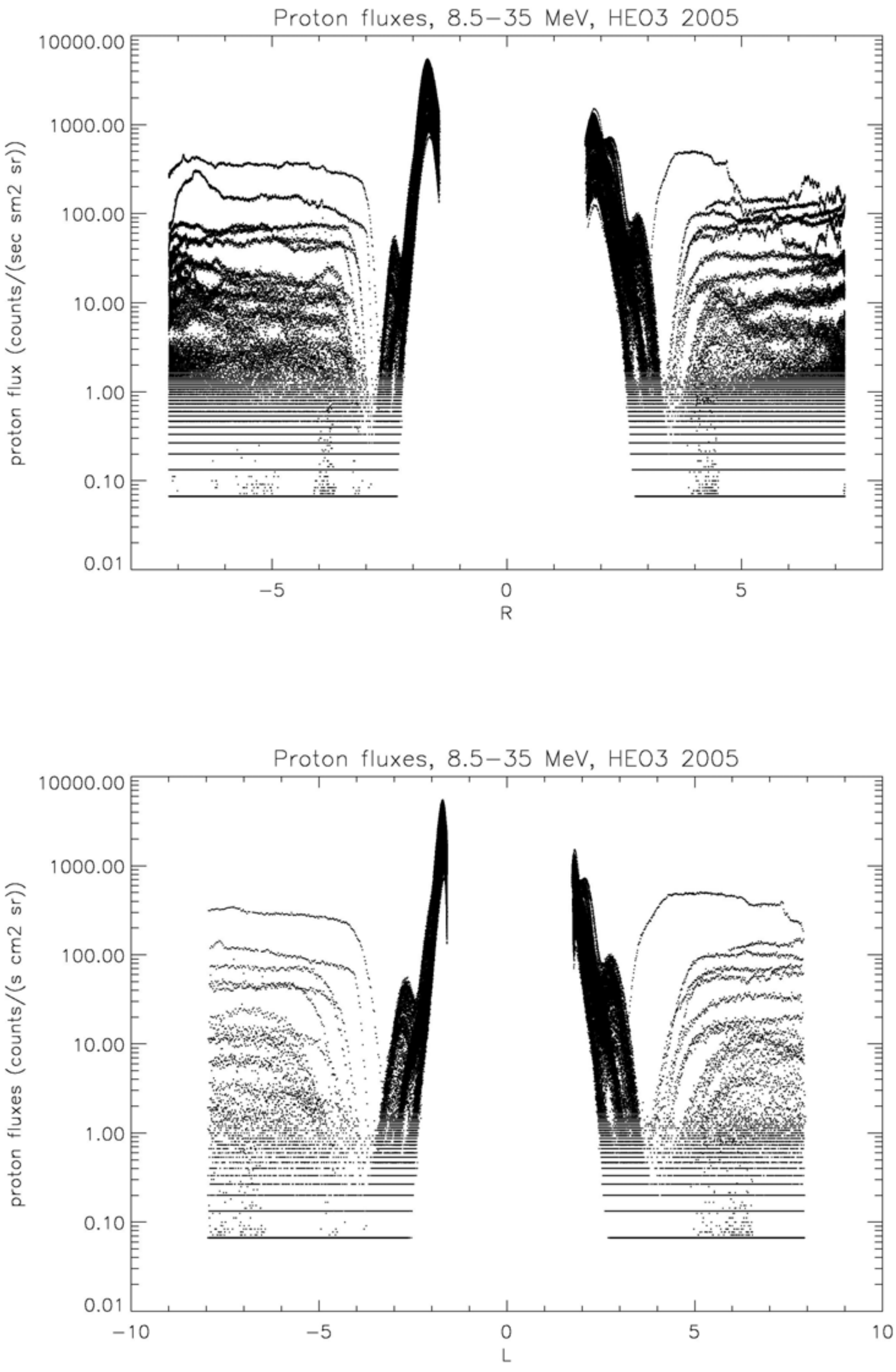
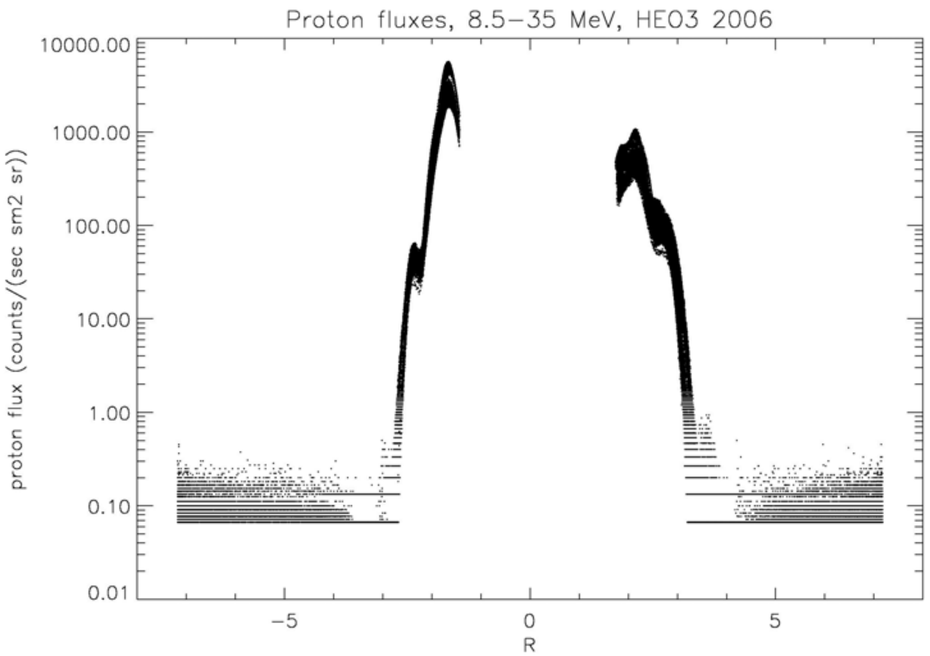


Figure A3-8. Proton fluxes, 8.5-35 MeV. Proton fluxes vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 2005



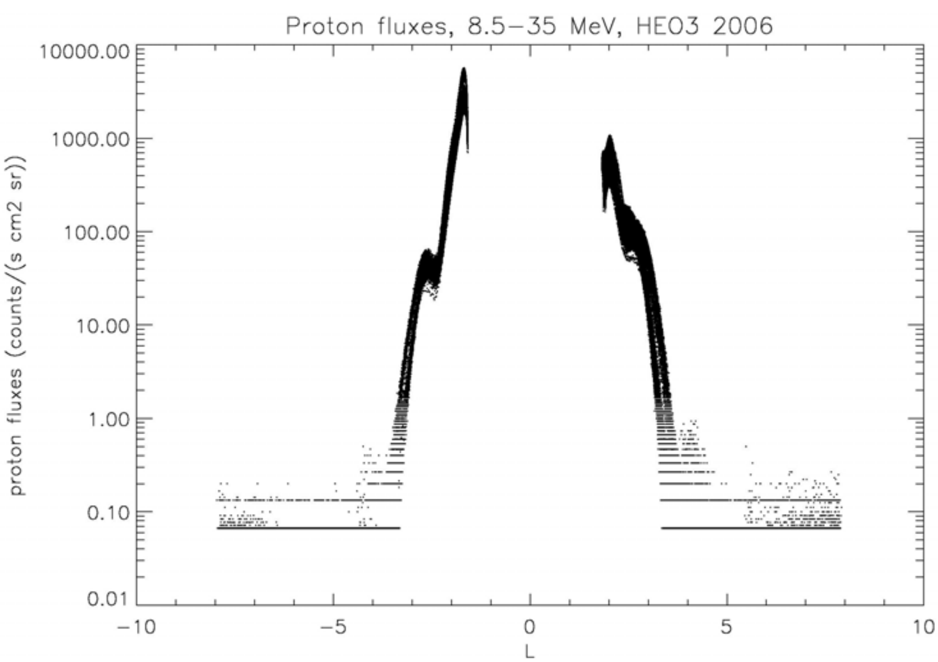


Figure A3-9. Proton fluxes, 8.5-35 MeV. Proton fluxes vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 2006

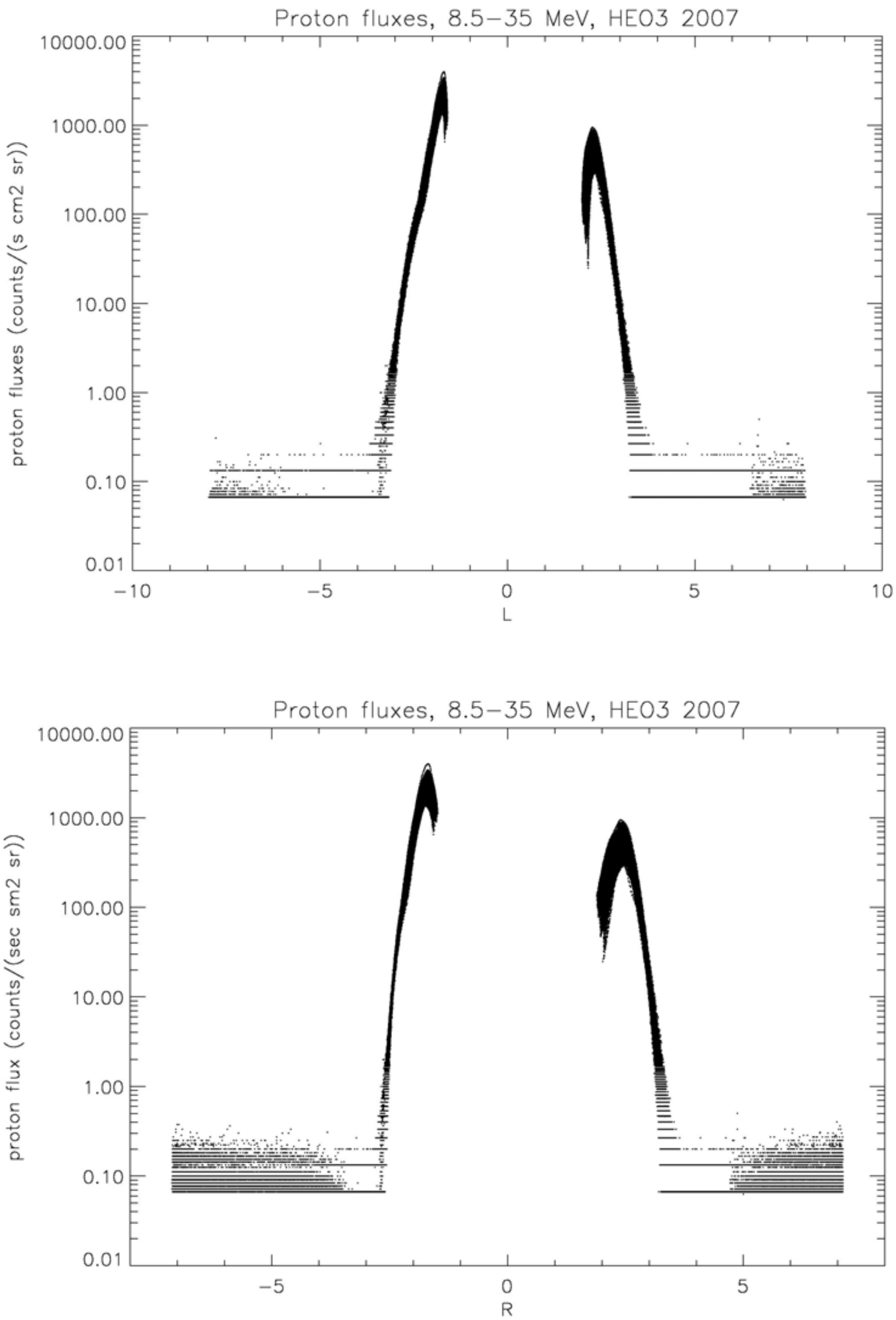


Figure A3-10. Proton fluxes, 8.5-35 MeV. Proton fluxes vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 2007

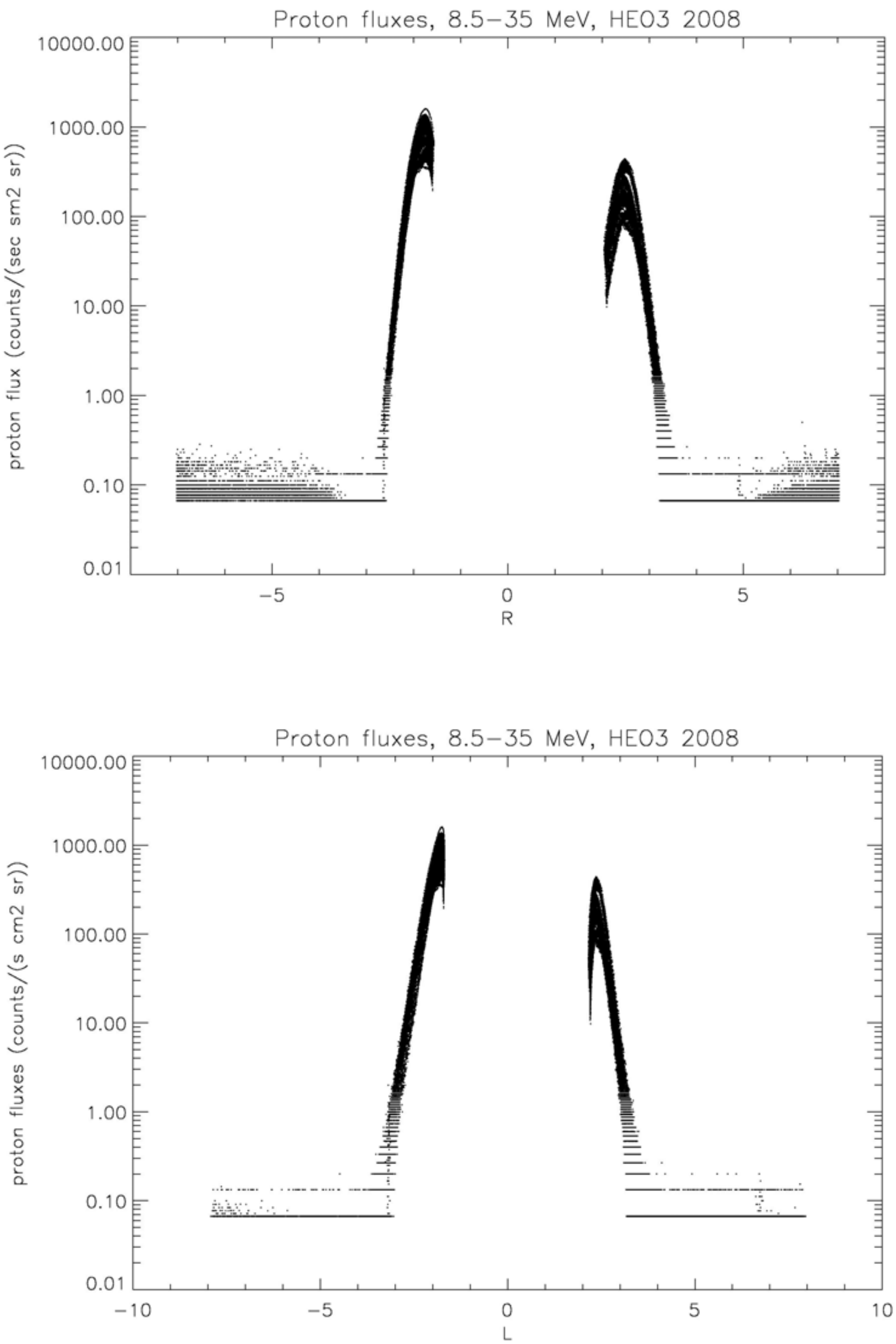
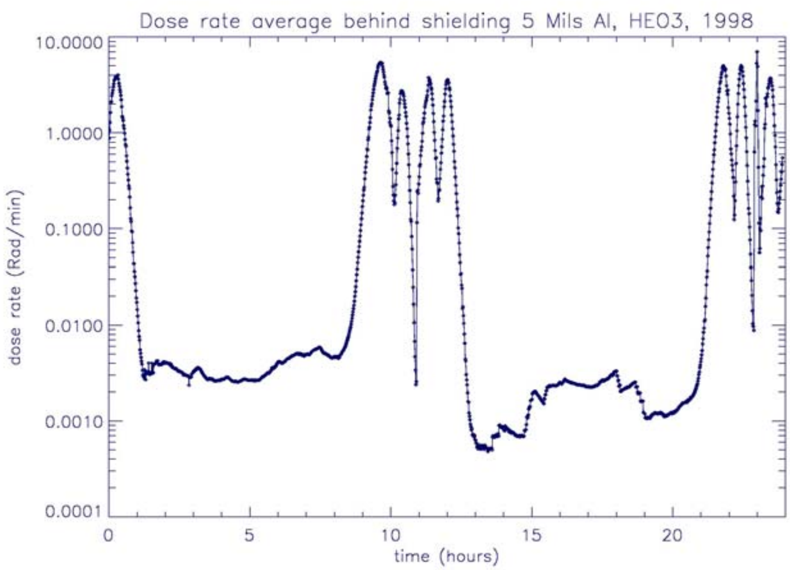


Figure A3-11. Proton fluxes, 8.5-35 MeV. Proton fluxes vs radial distance from the centre of the Earth (on the top panel) and dose rate vs L-shell value (bottom panel). HEO3 2008

Appendix 4. Annual distribution of the dose rate behind shielding 5 Mils Al, HEO3



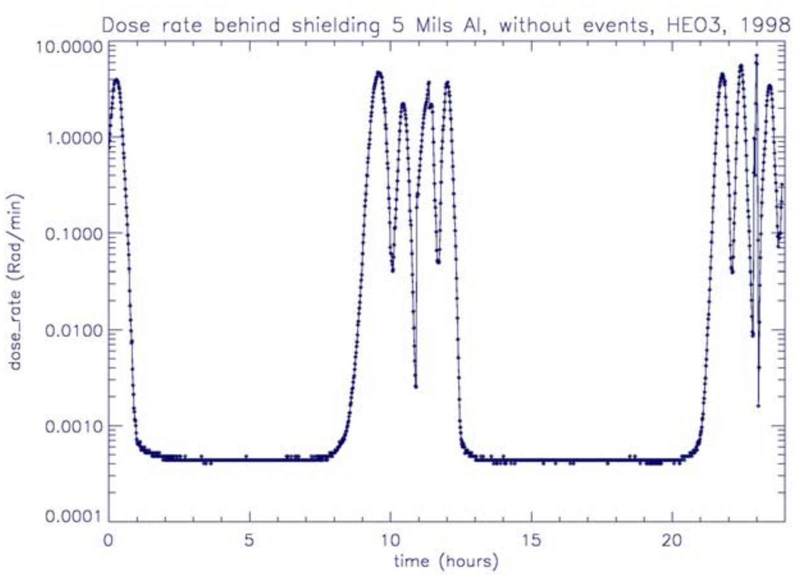


Figure A4-1. Dose rate behind shielding 5 Mils Al, the annual distribution. All the data (on the top panel) and without events (bottom panel). HEO3 1998

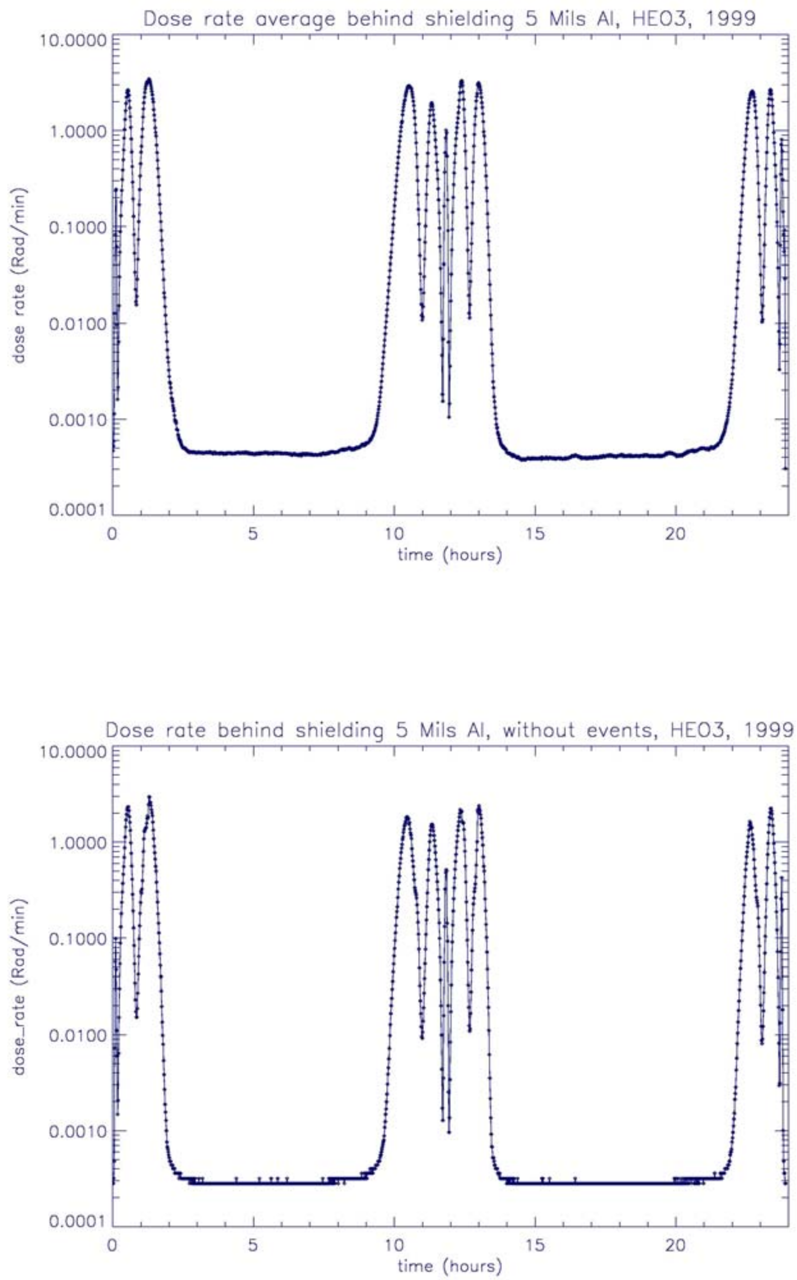


Figure A4-2. Dose rate behind shielding 5 Mils Al, the annual distribution. All the data (on the top panel) and without events (bottom panel). HEO3 1999

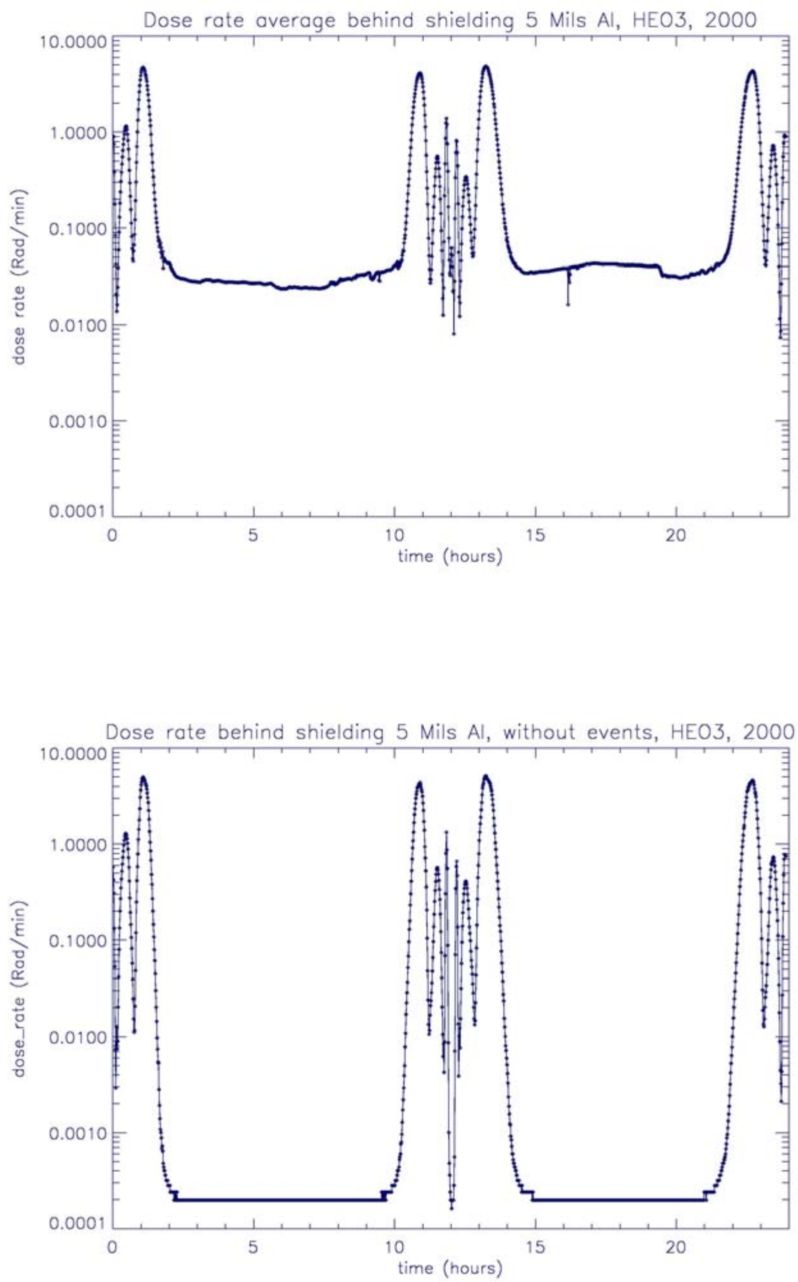
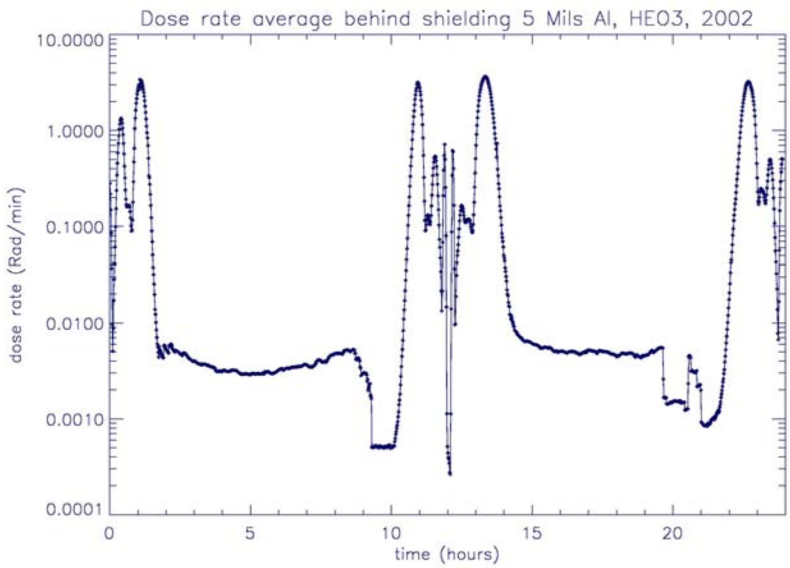


Figure A4-3. Dose rate behind shielding 5 Mils Al, the annual distribution. All the data (on the top panel) and without events (bottom panel). HEO3 2000



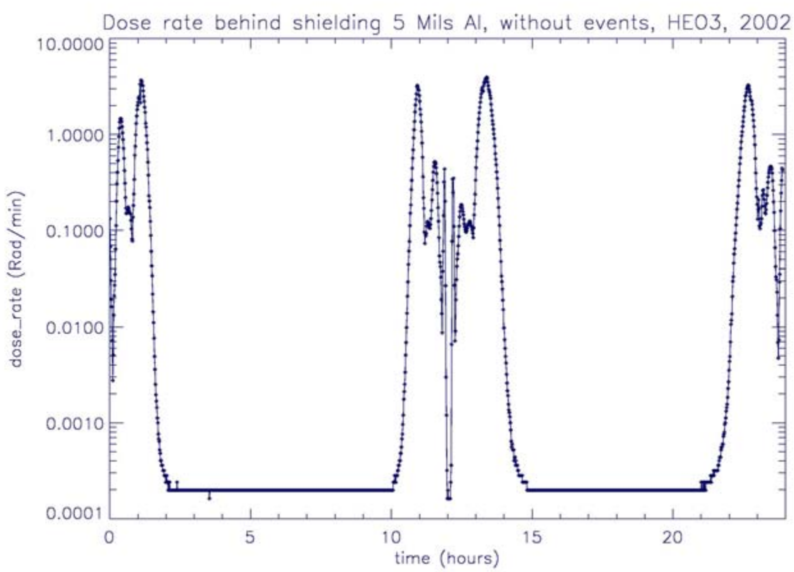
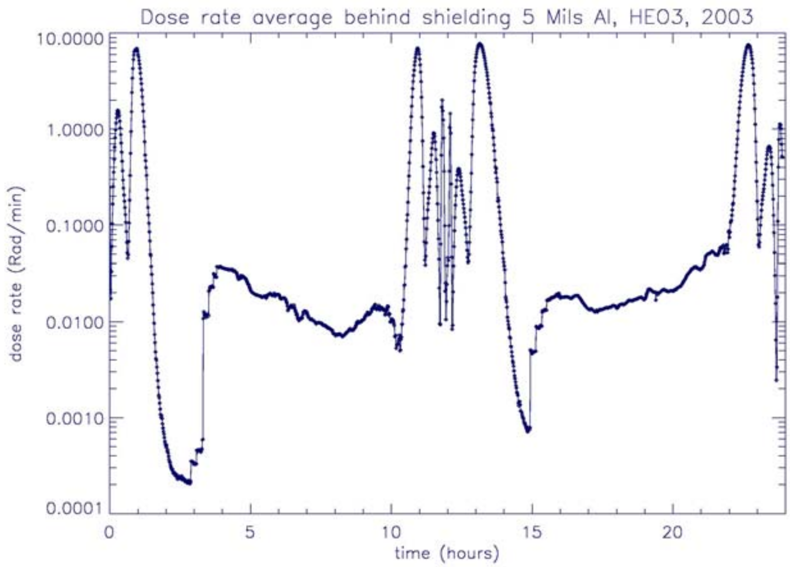


Figure A4-4. Dose rate behind shielding 5 Mils Al, the annual distribution. All the data (on the top panel) and without events (bottom panel). HEO3 2002



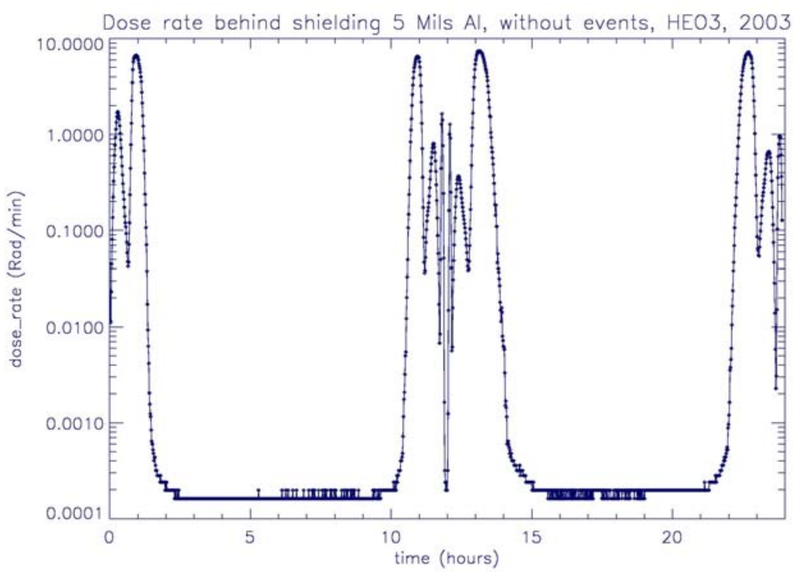


Figure A4-5. Dose rate behind shielding 5 Mils Al, the annual distribution. All the data (on the top panel) and without events (bottom panel). HEO3 2003

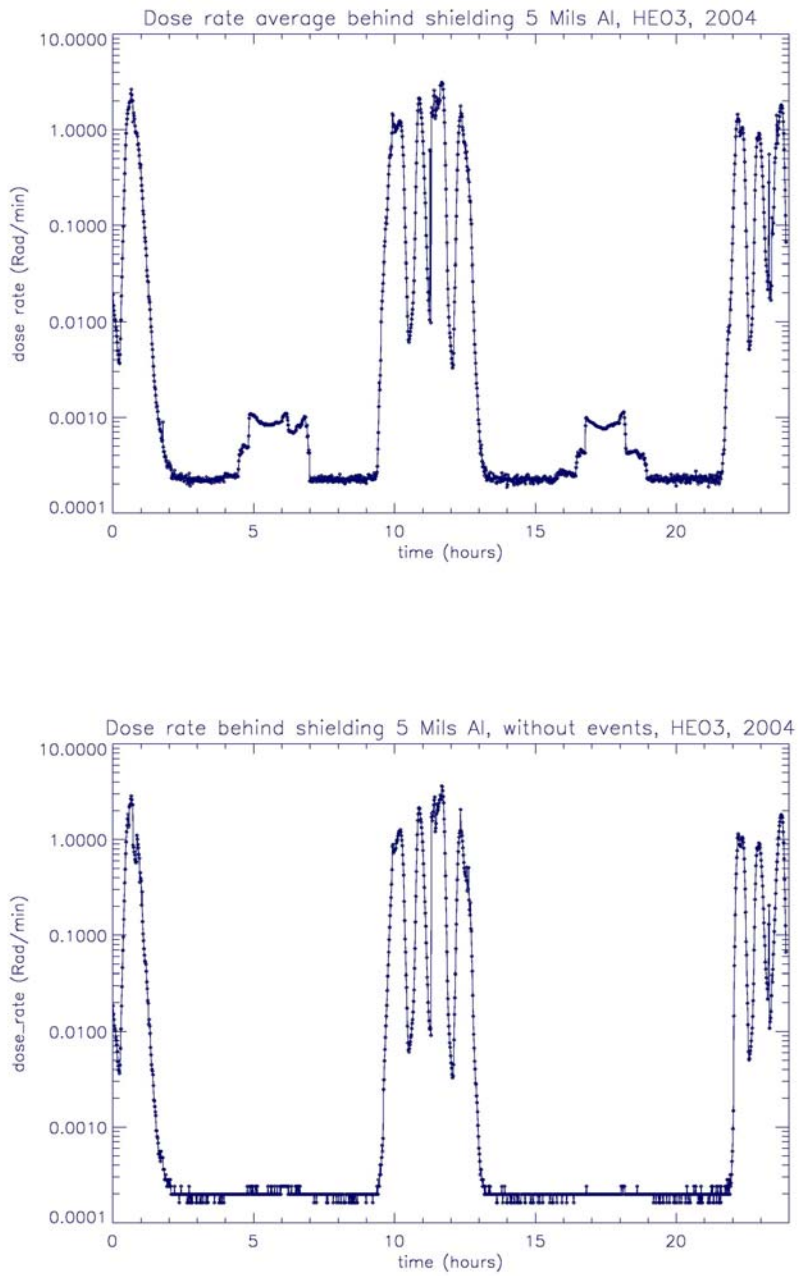
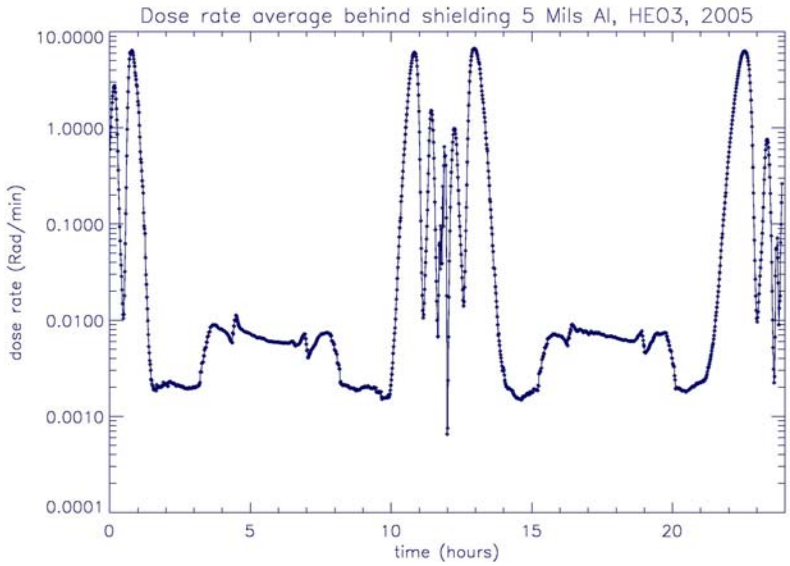


Figure A4-6. Dose rate behind shielding 5 Mils Al, the annual distribution. All the data (on the top panel) and without events (bottom panel). HEO3 2004



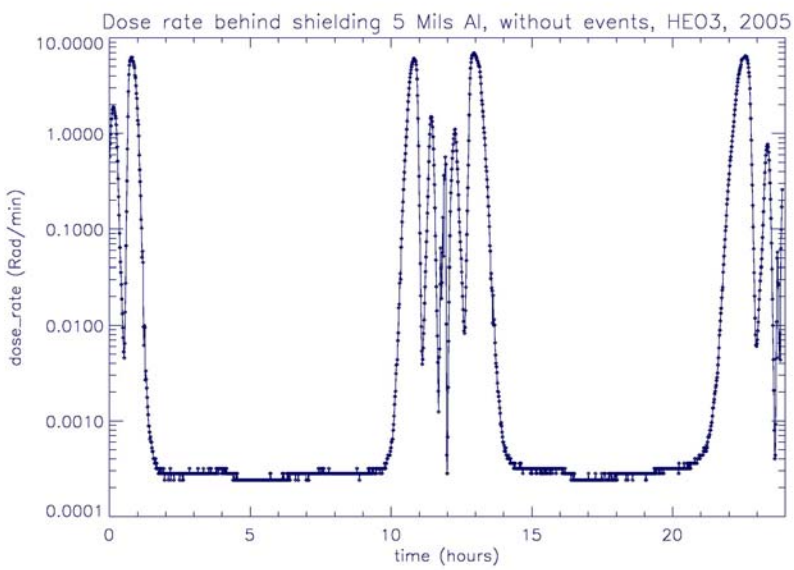
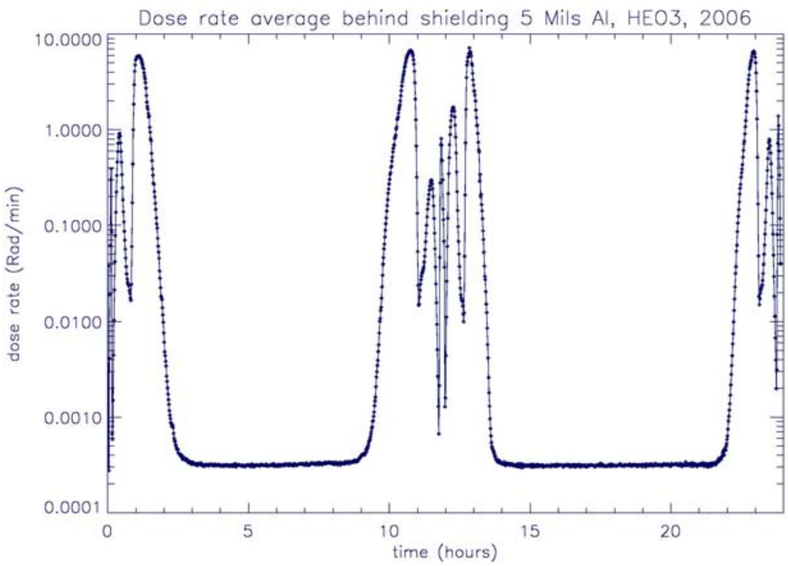


Figure A4-7. Dose rate behind shielding 5 Mils Al, the annual distribution. All the data (on the top panel) and without events (bottom panel). HEO3 2005



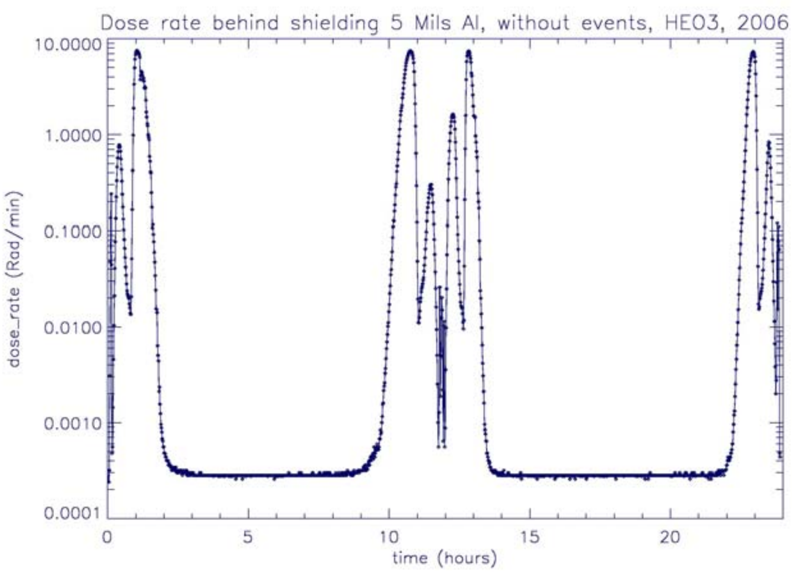
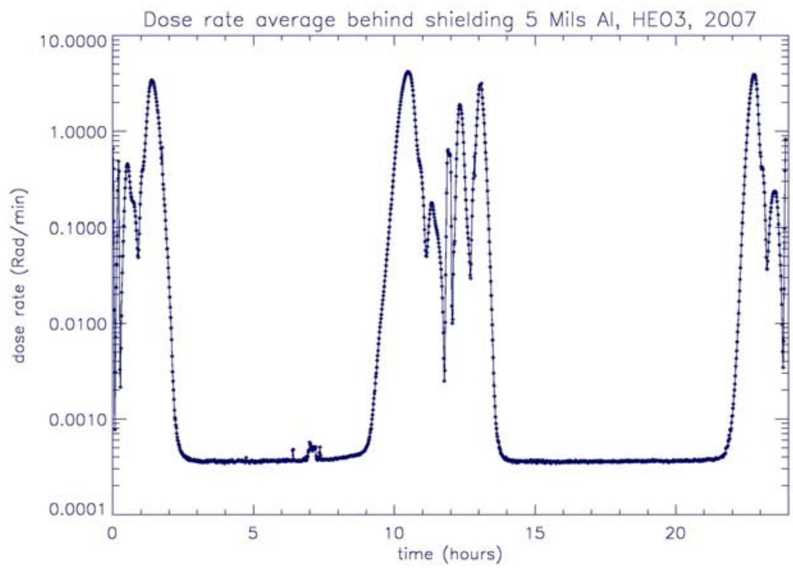


Figure A4-8. Dose rate behind shielding 5 Mils Al, the annual distribution. All the data (on the top panel) and without events (bottom panel). HEO3 2006



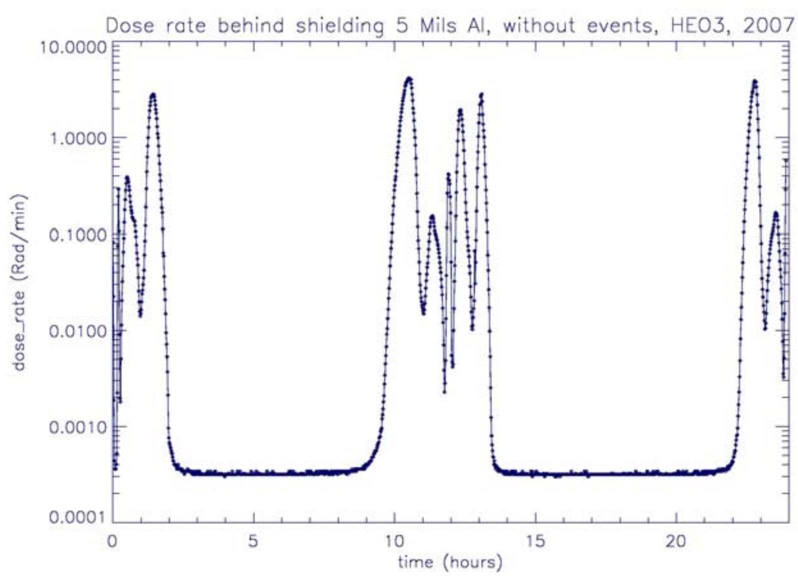
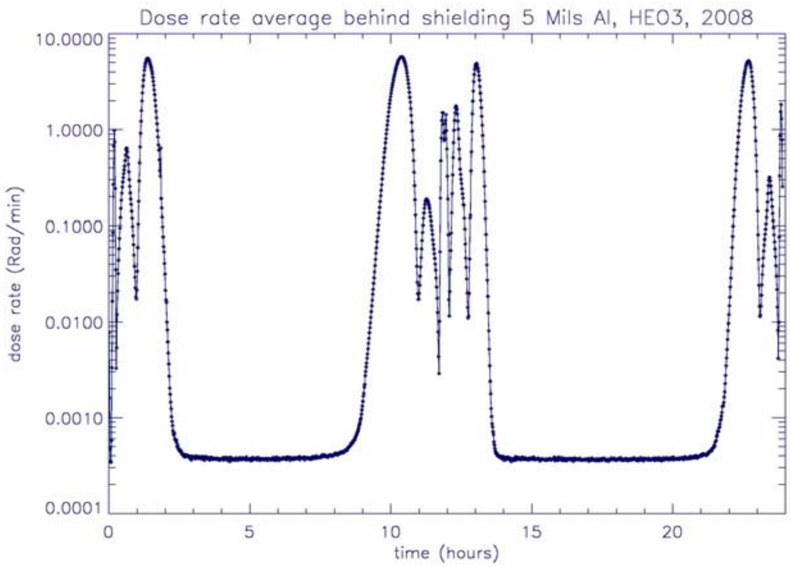


Figure A4-9. Dose rate behind shielding 5 Mils Al, the annual distribution. All the data (on the top panel) and without events (bottom panel). HEO3 2007



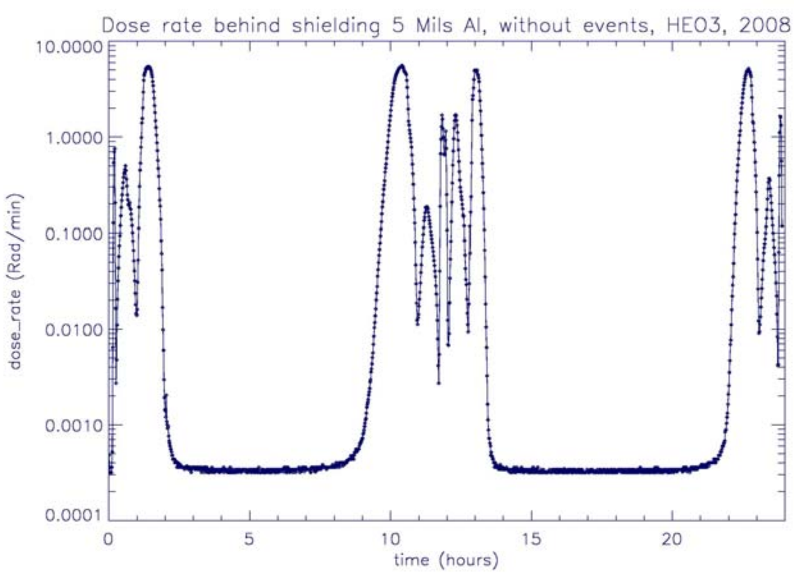


Figure A4-10. Dose rate behind shielding 5 Mils Al, the annual distribution. All the data (on the top panel) and without events (bottom panel). HEO3 2008

Appendix 5.

Appendix 5. Codes

clean_data.pro

```
; HEO1 and HEO3 Data Reading and Cleaning Procedures
; -------------------------------------------------
;
; Myles Harrison
; Geomagnetic Laboratory, Natural Resources Canada
; 2617 Anderson Road, Ottawa, ON K1A0Y3
; Contact: myharris@nrcan.gc.ca
;
; Modification History:
; May 2010 - Merged seperated procedures into one file
; June 2010 - Rewrote and read_lbin_multi and read_exp_multi to call read_lbin and read_exp as
sub-procedures
;
; -------------------------------------------------
;
; heo_cdf.pro
; -----------
;
; Author: Myles Harrison
; Date: July 2009
; Modified: November 2009 - Implemented reading indicated variables into structure array to
allow use in HEO plotting procedures
;           January 2010 - Changed handling of input parameter zvar to allow specification with
numbers as well as strings (var names)
;           March 2010 - Changed handling parameter zvar to allow substrings of variable
names as input (pattern search/match)
;                        - Added QUIET keyword to suppress output messages
;           June 2010 - Removed variable 'cdf' from procedure parameters (useless)
;           July 12, 2010 - Added TAGS and INDEX keywords (as in get_struct_field.pro)
; Inputs: file - a scalar string variable specifying the path of a HEO Sat CDF file to be read
; Outputs: zvar - a string array of the variable names in the CDF file
;          records - the data read from the CDF as specified by the "zvar" keyword. Not used
unless the latter is specified.
; Keywords: year - scalar integer for specifying only one year of variable to be read into "data".
;           TAGS - optional named variable which will be filled with a string array of the zvar
names returned from 'file' / tag names in 'records'
;           INDEX - optional named variable which will be filled with a int array of the zvar
indices returned from 'file'
;           LIST - optional boolean flag specifying that the procedure only list the z-variables in
'file' and return. With this flag set,
;                 only the 'file' parameter is required to call the procedure.
;           QUIET - boolean flag to suppress output messages
```

```
PRO heo_cdf, file, zvar, records, year=year_kw, TAGS=tags_kw, INDEX=index_kw,
LIST=list_KW, QUIET=quiet_kw

; If used incorrectly, print usage message and exit
IF N_PARAMS() LT 3 AND N_ELEMENTS(list_KW) EQ 0 THEN BEGIN
	PRINT, 'Usage: HEO_cdf, file, zvar, records, (year=year, /LIST)'
	RETURN
ENDIF

; If file not specified, prompt with a dialog
IF N_ELEMENTS(file) EQ 0 THEN file =
DIALOG_PICKFILE(PATH='/home/lidia/HEO_Sat/data/')

; Open the CDF file
cdf = CDF_OPEN(file)

; Find number of variables and initialize string array
nzvars = (CDF_INQUIRE(cdf)).nzvars
vars = STRARR(nzvars)

; Create a string array of the variable names
FOR i=0, nzvars-1 DO BEGIN
	cdfinfo = CDF_VARINQ(cdf, i, /ZVAR)
	vars[i] = cdfinfo.name
ENDFOR

; Print a listing of the variables in the CDF file and exit if keyword set
IF ARG_PRESENT(list_kw) NE 0 OR N_ELEMENTS(list_kw) NE 0 THEN BEGIN
	FOR i=0, nzvars-1 DO PRINT, i, ' ', vars[i]
	list_kw = vars
	RETURN
ENDIF

IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'READING CDF FILE:', file

CDF_CONTROL, cdf, variable=0, GET_VAR_INFO=var_info, /ZVARIABLE ; Get metadata
; Grab all records of variable by default
rec_start = 0
rec_count = var_info.maxrecs

; Find which records to grab if the year keyword is set
IF N_ELEMENTS(year_kw) NE 0 THEN BEGIN
	year_index = WHERE(STRPOS(STRUPCASE(vars), 'YEAR') GT 0, count) ; Determine
which variable contains the year information
	IF count LE 0 THEN MESSAGE, 'Error - no year variable found.' ; Should never
happen...
	CDF_VARGET, cdf, year_index, years, REC_START=0,
REC_COUNT=var_info.maxrecs, /ZVARIABLE ; Get year variable into array
	rec_year_index = WHERE(years EQ year_kw)
	rec_start = MIN(rec_year_index)
```

```
        rec_count = N_ELEMENTS(rec_year_index)
ENDIF

IF N_ELEMENTS(zvar) EQ 0 THEN zvar = vars

zvar_match = ''
index_kw = -1

; If zvar is not of type string, then assume numerical and grab names of zvars for those # from
variable list
IF SIZE(zvar, /TYPE) NE 7 THEN BEGIN
        zvar_match = vars[zvar]
ENDIF ELSE BEGIN
        ; Search for matching zvar variable names
        ; Loop through the variable search expressions as STRPOS is a scalar valued function
        FOR k=0, N_ELEMENTS(zvar)-1 DO BEGIN
                ; Look for variable name matching expression, make upper case to remove case
sensitivity
                index = STRPOS(STRUPCASE(vars), STRUPCASE(zvar[k]))
                var_index = WHERE(index NE -1, count)
                IF count GT 0 THEN BEGIN
                        zvar_match = [zvar_match, vars[var_index]]
                        index_kw = [index_kw, var_index]
                ENDIF
        ENDFOR
        zvar_match = zvar_match[WHERE(zvar_match NE '')]
        index_kw = index_kw[1:*]
        ; Populate the TAGS keywords
        tags_kw = zvar_match
ENDELSE

record = CREATE_STRUCT(zvar_match[0], 0D)

; Create the empty records structure array with proper tagnames
FOR i=1, N_ELEMENTS(zvar_match)-1 DO record = CREATE_STRUCT(record,
zvar_match[i], 0D)
records = REPLICATE(record, rec_count)

; Populate the records structure
FOR j=0, N_ELEMENTS(zvar_match)-1 DO BEGIN
        IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Reading ', zvar_match[j], '......'
        CDF_VARGET, cdf, zvar_match[j], data, REC_START=rec_start,
REC_COUNT=rec_count
        records.(j) = REFORM(data)
ENDFOR


IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'READ ', file, ' - DONE.'

END
```

```
; read_exp.pro
; -------------
;
; Author: Myles Harrison
; Date: July 2009
;
; Inputs: file - a scalar string specifying the location of a 15-second .exp file
(fn_yyyy__all_vnn.exp[.gz])
; Outputs: records - structure of the satellite data
; Keywords: QUIET - supress output messages

PRO read_exp, file, records, QUIET=QUIET_kw

IF N_ELEMENTS(file) EQ 0 THEN file =
DIALOG_PICKFILE(PATH='/home/lidia/HEO_Sat/data/') ; If file not specified, prompt iwht a
dialog

IF STRMID(file, 1, 3, /REVERSE_OFFSET) EQ 'gz' THEN COMPRESS=1 ; Set compress flag
depending on extension

; Find the number of lines in the file
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Tallying number of records in file....'
n_records = file_lines(file, COMPRESS=COMPRESS)-1
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, STRING(n_records, FORMAT='(I0)'), '
records total.'

IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Creating data structure......'
; Create a record structure for reading in the data
IF STRMID(file_basename(file), 0, 2) EQ 'f1' THEN BEGIN ; F1
	record = {HEO1_year_exp:0, HEO1_month_exp:0, HEO1_day_exp:0,
HEO1_decday_exp:0D, HEO1_nSeconds_exp:0, HEO1_Elec1_exp:0.0, HEO1_Elec2_exp:0.0,
HEO1_Elec3_exp:0.0, HEO1_Elec4_exp:0.0, HEO1_Elec5_exp:0.0, HEO1_Elec6_exp:0.0,$
		HEO1_Prot1_exp:0.0, HEO1_Prot2_exp:0.0, HEO1_Prot3_exp:0.0,
HEO1_Prot4_exp:0.0, HEO1_Prot5_exp:0.0, HEO1_Prot6_exp:0.0, HEO1_Prot7_exp:0.0,
HEO1_Dose1_exp:0.0, HEO1_Dose2_exp:0.0, HEO1_Dose3_exp:0.0,$
		HEO1_Dose4_exp:0.0, HEO1_Dose1_rate_exp:0.0, HEO1_Dose2_rate_exp:0.0,
HEO1_Dose3_rate_exp:0.0, HEO1_Dose4_rate_exp:0.0, HEO1_SC_Temp_exp:0.0,
HEO1_JulDate_exp:0D, HEO1_Orbit_Status_IGRF_exp:0,$
		HEO1_Orbit_Status_OP_exp:0, HEO1_TiltAngle_exp:0.0,
HEO1_RadDist_exp:0.0, HEO1_nDose_Seconds_exp:0, HEO1_dose_Toffset_exp:0.0,
HEO1_Lstar_IGRF_ONERA_exp:0.0, HEO1_Lm_IGRF_ONERA_exp:0.0,$
		HEO1_Btot_IGRF_ONERA_exp:0.0, HEO1_Bequ_IGRF_ONERA_exp:0.0,
HEO1_MLT_IGRF_ONERA_exp:0.0, HEO1_I_IGRF_ONERA_exp:0.0,
HEO1_Lstar_OP_exp:0.0, HEO1_Lm_OP_exp:0.0, HEO1_Btot_OP_exp:0.0,
HEO1_Beq_OP_exp:0.0, HEO1_I_OP_exp:0.0}
	format_code='((3I0, D0, I0, 13E0.6, 8F0, F0, D0, 2I0, 2E0.6, 2F0, 11E0.6))'
ENDIF ELSE IF STRMID(file_basename(file), 0, 2) EQ 'f3' THEN BEGIN ; F3
	record = {HEO3_year_exp:0, HEO3_month_exp:0, HEO3_day_exp:0,
HEO3_decday_exp:0D, HEO3_nSeconds_exp:0, HEO3_Elec1_exp:0.0, HEO3_Elec2_exp:0.0,
HEO3_Elec3_exp:0.0, HEO3_Elec4_exp:0.0, HEO3_Elec5_exp:0.0, HEO3_Elec6_exp:0.0,$
```

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                    HEO3_Prot1_exp:0.0, HEO3_Prot2_exp:0.0, HEO3_Prot3_exp:0.0,
HEO3_Prot4_exp:0.0, HEO3_Prot5_exp:0.0, HEO3_Prot6_exp:0.0, HEO3_Prot7_exp:0.0,
HEO3_Dose1_exp:0.0, HEO3_Dose2_exp:0.0, HEO3_Dose3_exp:0.0, HEO3_Dose4_exp:0.0,$
                    HEO3_Dose1_rate_exp:0.0, HEO3_Dose2_rate_exp:0.0,
HEO3_Dose3_rate_exp:0.0, HEO3_Dose4_rate_exp:0.0, HEO3_cElec3_exp:0.0,
HEO3_cElec4_exp:0.0, HEO3_cElec5_exp:0.0, HEO3_cElec6_exp:0.0,$
                    HEO3_SC_Temp_exp:0.0, HEO3_JulDate_exp:0D,
HEO3_Orbit_Status_IGRF_exp:0, HEO3_Orbit_Status_OP_exp:0, HEO3_TiltAngle_exp:0.0,
HEO3_RadDist_exp:0.0, HEO3_nDose_Seconds_exp:0,$
                    HEO3_dose_Toffset_exp:0.0, HEO3_Lstar_IGRF_ONERA_exp:0.0,
HEO3_Lm_IGRF_ONERA_exp:0.0, HEO3_Btot_IGRF_ONERA_exp:0.0,
HEO3_Bequ_IGRF_ONERA_exp:0.0, HEO3_MLT_IGRF_ONERA_exp:0.0,
HEO3_I_IGRF_ONERA_exp:0.0, HEO3_Lstar_OP_ONERA_exp:0.0,
HEO3_Lm_OP_ONERA_exp:0.0,$
                    HEO3_Btot_OP_ONERA_exp:0.0, Beq_OP_ONERA_exp:0.0,
I_OP_ONERA_exp:0.0}
          format_code='((3I0, D0, I0, 13E0.6, 8F0, 4E0.6, F0, D0, 2I0, 2E0.6, 2F0, 11E0.6))'
ENDIF

records = replicate(record, n_records)

; Open the file and read in the data
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Reading ' + file + '.....'
OPENR, lun, file, /GET_LUN, COMPRESS=COMPRESS
SKIP_LUN, lun, 1, /LINES
READF, lun, records, FORMAT=format_code
CLOSE, lun
FREE_LUN, lun

END


; read_exp_multi.pro
; -------------
;
; Author: Myles Harrison
; Date: July 2009
;
; Inputs: files - a string array specifying the location of a 15-second .exp file
(fn_yyyy__all_vnn.exp[.gz])
; Outputs: records - structure of the satellite data
; Keywords: QUIET - supress output messages

PRO read_exp_multi, files, records, QUIET=QUIET_kw

IF N_ELEMENTS(files) EQ 0 THEN files =
DIALOG_PICKFILE(PATH='/home/lidia/HEO_Sat/', /MULTI) ; If file not specified, prompt
iwht a dialog

filenames = FILE_BASENAME(files)
```

```
IF STRMID(files[0], 1, 3, /REVERSE_OFFSET) EQ 'gz' THEN COMPRESS=1 ; Set compress
flag depending on extension

; Find the number of lines in the file
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Tallying number of records in file....'
n_records = file_lines(files, COMPRESS=COMPRESS)-1
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, STRING(n_records, FORMAT='(I0)'), '
records total.'

prefixes = STRMID(file_basename(files), 0, 2)
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Creating data structure......'
; Create a record structure for reading in the data
IF N_ELEMENTS(WHERE((prefixes EQ 'f1'))) EQ N_ELEMENTS(files) THEN BEGIN ; F1
        record = {HEO1_year_exp:0, HEO1_month_exp:0, HEO1_day_exp:0,
HEO1_decday_exp:0D, HEO1_nSeconds_exp:0, HEO1_Elec1_exp:0.0, HEO1_Elec2_exp:0.0,
HEO1_Elec3_exp:0.0, HEO1_Elec4_exp:0.0, HEO1_Elec5_exp:0.0, HEO1_Elec6_exp:0.0,$
                HEO1_Prot1_exp:0.0, HEO1_Prot2_exp:0.0, HEO1_Prot3_exp:0.0,
HEO1_Prot4_exp:0.0, HEO1_Prot5_exp:0.0, HEO1_Prot6_exp:0.0, HEO1_Prot7_exp:0.0,
HEO1_Dose1_exp:0.0, HEO1_Dose2_exp:0.0, HEO1_Dose3_exp:0.0,$
                HEO1_Dose4_exp:0.0, HEO1_Dose1_rate_exp:0.0, HEO1_Dose2_rate_exp:0.0,
HEO1_Dose3_rate_exp:0.0, HEO1_Dose4_rate_exp:0.0, HEO1_SC_Temp_exp:0.0,
HEO1_JulDate_exp:0D, HEO1_Orbit_Status_IGRF_exp:0,$
                HEO1_Orbit_Status_OP_exp:0, HEO1_TiltAngle_exp:0.0,
HEO1_RadDist_exp:0.0, HEO1_nDose_Seconds_exp:0, HEO1_dose_Toffset_exp:0.0,
HEO1_Lstar_IGRF_ONERA_exp:0.0, HEO1_Lm_IGRF_ONERA_exp:0.0,$
                HEO1_Btot_IGRF_ONERA_exp:0.0, HEO1_Bequ_IGRF_ONERA_exp:0.0,
HEO1_MLT_IGRF_ONERA_exp:0.0, HEO1_I_IGRF_ONERA_exp:0.0,
HEO1_Lstar_OP_exp:0.0, HEO1_Lm_OP_exp:0.0, HEO1_Btot_OP_exp:0.0,
HEO1_Beq_OP_exp:0.0, HEO1_I_OP_exp:0.0}
        format_code='((3I0, D0, I0, 13E0.6, 8F0, F0, D0, 2I0, 2E0.6, 2F0, 11E0.6))'
ENDIF ELSE IF N_ELEMENTS(WHERE((prefixes EQ 'f3'))) EQ N_ELEMENTS(files) THEN
BEGIN ; F3
        record = {HEO3_year_exp:0, HEO3_month_exp:0, HEO3_day_exp:0,
HEO3_decday_exp:0D, HEO3_nSeconds_exp:0, HEO3_Elec1_exp:0.0, HEO3_Elec2_exp:0.0,
HEO3_Elec3_exp:0.0, HEO3_Elec4_exp:0.0, HEO3_Elec5_exp:0.0, HEO3_Elec6_exp:0.0,$
                HEO3_Prot1_exp:0.0, HEO3_Prot2_exp:0.0, HEO3_Prot3_exp:0.0,
HEO3_Prot4_exp:0.0, HEO3_Prot5_exp:0.0, HEO3_Prot6_exp:0.0, HEO3_Prot7_exp:0.0,
HEO3_Dose1_exp:0.0, HEO3_Dose2_exp:0.0, HEO3_Dose3_exp:0.0, HEO3_Dose4_exp:0.0,$
                HEO3_Dose1_rate_exp:0.0, HEO3_Dose2_rate_exp:0.0,
HEO3_Dose3_rate_exp:0.0, HEO3_Dose4_rate_exp:0.0, HEO3_cElec3_exp:0.0,
HEO3_cElec4_exp:0.0, HEO3_cElec5_exp:0.0, HEO3_cElec6_exp:0.0,$
                HEO3_SC_Temp_exp:0.0, HEO3_JulDate_exp:0D,
HEO3_Orbit_Status_IGRF_exp:0, HEO3_Orbit_Status_OP_exp:0, HEO3_TiltAngle_exp:0.0,
HEO3_RadDist_exp:0.0, HEO3_nDose_Seconds_exp:0,$
                HEO3_dose_Toffset_exp:0.0, HEO3_Lstar_IGRF_ONERA_exp:0.0,
HEO3_Lm_IGRF_ONERA_exp:0.0, HEO3_Btot_IGRF_ONERA_exp:0.0,
HEO3_Bequ_IGRF_ONERA_exp:0.0, HEO3_MLT_IGRF_ONERA_exp:0.0,
HEO3_I_IGRF_ONERA_exp:0.0, HEO3_Lstar_OP_ONERA_exp:0.0,
HEO3_Lm_OP_ONERA_exp:0.0,$
```

```
                HEO3_Btot_OP_ONERA_exp:0.0, Beq_OP_ONERA_exp:0.0,
I_OP_ONERA_exp:0.0}
        format_code='((3I0, D0, I0, 13E0.6, 8F0, 4E0.6, F0, D0, 2I0, 2E0.6, 2F0, 11E0.6))'
ENDIF ELSE MESSAGE, 'Error - all files must be for same flight (f1 or f3). Aborting!'

; Determine the total number of file lines and initialize the array
file_lines = FILE_LINES(files, COMPRESS=COMPRESS)-1
file_lines = [0, file_lines]
total_lines = TOTAL(file_lines, /CUMULATIVE)
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Total ', STRING(MAX(total_lines),
FORMAT='(I0)'), ' records.'

records = replicate(record, MAX(total_lines))

; Loop through the array of files
FOR j=0, N_ELEMENTS(files) - 1 DO BEGIN
        loop_file = files[j]
        temp_records = replicate(record, file_lines[j+1])
        ;; Open the file and read in the data
        IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Reading ', loop_file, '......'
        ; Read the data and insert the data into the array
        read_exp, loop_file, temp_records, /QUIET
        records[total_lines[j]:total_lines[j+1]-1] = temp_records
        ;CLOSE, lun
        ;FREE_LUN, lun
ENDFOR


END


; read_lbin.pro
; -------------
;
; Author: Myles Harrison
; Date: July 2009
;
; Inputs: file - a scalar string specifying the location of an l-binned file
(fn_yyyy_lbinIGRF_all_vnn.exp)
; Outputs: records - structure of the data
; Keywords: QUIET - boolean flag to suppress output messages

PRO read_lbin, file, records, QUIET=QUIET_kw

IF N_ELEMENTS(file) EQ 0 THEN file =
DIALOG_PICKFILE(PATH='/home/lidia/HEO_Sat/') ; If file not specified, prompt with a dialog

IF STRMID(file, 1, 3, /REVERSE_OFFSET) EQ 'gz' THEN COMPRESS=1 ; If compressed, set
flag

; Find the number of lines in the file
```

```
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Tallying number of records in file....'
n_records = file_lines(file, COMPRESS=COMPRESS)-1
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, STRING(n_records, FORMAT='(I0)'), '
records total.'

IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Creating data structure......'
; Create a record structure for reading in the data
IF STRMID(file_basename(file), 0, 2) EQ 'f1' THEN BEGIN ; F1
        record = {HEO1_year_lbin_IGRF:0, HEO1_doy_lbin_IGRF:0D,
HEO1_Lshell_lbin_IGRF:0.0, HEO1_Orbit_Status_lbin_IGRF:0,
HEO1_nSeconds_lbin_IGRF:0, HEO1_Elec1_lbin_IGRF:0.0, HEO1_Elec2_lbin_IGRF:0.0,
HEO1_Elec3_lbin_IGRF:0.0, HEO1_Elec4_lbin_IGRF:0.0, HEO1_Elec5_lbin_IGRF:0.0,
HEO1_Elec6_lbin_IGRF:0.0,$
                HEO1_Prot1_lbin_IGRF:0.0, HEO1_Prot2_lbin_IGRF:0.0,
HEO1_Prot3_lbin_IGRF:0.0, HEO1_Prot4_lbin_IGRF:0.0, HEO1_Prot5_lbin_IGRF:0.0,
HEO1_Prot6_lbin_IGRF:0.0, HEO1_Prot7_lbin_IGRF:0.0, HEO1_Dose1_rate_lbin_IGRF:0.0,
HEO1_Dose2_rate_lbin_IGRF:0.0, HEO1_Dose3_rate_lbin_IGRF:0.0,$
                HEO1_Dose4_rate_lbin_IGRF:0.0, HEO1_JulDate_lbin_IGRF:0D,
HEO1_Lshell_IGRF_lbin_IGRF:0.0, HEO1_Lstar_IGRF_lbin_IGRF:0.0,
HEO1_Btot_IGRF_lbin_IGRF:0.0, HEO1_Bequ_IGRF_lbin_IGRF:0.0,
HEO1_MLT_IGRF_lbin_IGRF:0.0, HEO1_I_IGRF_lbin_IGRF:0.0,$
                HEO1_RadDist_lbin_IGRF:0.0, HEO1_nDose_seconds_lbin_IGRF:0}
        format_code = '((I0, D0, F0, 2I0, 17E0.6, D0, 6E0.6, F0, I0))'
ENDIF ELSE IF STRMID(file_basename(file), 0, 2) EQ 'f3' THEN BEGIN ; F3
        record = {HEO3_year_lbin_IGRF:0, HEO3_doy_lbin_IGRF:0D,
HEO3_Lshell_lbin_IGRF:0.0, HEO3_Orbit_Status_lbin_IGRF:0,
HEO3_nSeconds_lbin_IGRF:0, HEO3_Elec1_lbin_IGRF:0.0, HEO3_Elec2_lbin_IGRF:0.0,
HEO3_Elec3_lbin_IGRF:0.0, HEO3_Elec4_lbin_IGRF:0.0, HEO3_Elec5_lbin_IGRF:0.0,
HEO3_Elec6_lbin_IGRF:0.0,$
                HEO3_Prot1_lbin_IGRF:0.0, HEO3_Prot2_lbin_IGRF:0.0,
HEO3_Prot3_lbin_IGRF:0.0, HEO3_Prot4_lbin_IGRF:0.0, HEO3_Prot5_lbin_IGRF:0.0,
HEO3_Prot6_lbin_IGRF:0.0, HEO3_Prot7_lbin_IGRF:0.0, HEO3_Dose1_rate_lbin_IGRF:0.0,
HEO3_Dose2_rate_lbin_IGRF:0.0,$
                HEO3_Dose3_rate_lbin_IGRF:0.0, HEO3_Dose4_rate_lbin_IGRF:0.0,
HEO3_cElec3_lbin_IGRF:0.0, HEO3_cElec4_lbin_IGRF:0.0, HEO3_cElec5_lbin_IGRF:0.0,
HEO3_cElec6_lbin_IGRF:0.0, HEO3_JulDate_lbin_IGRF:0D,
HEO3_Lshell_IGRF_lbin_IGRF:0.0, HEO3_Lstar_IGRF_lbin_IGRF:0.0,$
                HEO3_Btot_IGRF_lbin_IGRF:0.0, HEO3_Bequ_IGRF_lbin_IGRF:0.0,
HEO3_MLT_IGRF_lbin_IGRF:0.0, HEO3_I_IGRF_lbin_IGRF:0.0,
HEO3_RadDist_lbin_IGRF:0.0, HEO3_nDose_seconds_lbin_IGRF:0}
        format_code = '((I0, D0, F0, 2I0, 21E0.6, D0, 6E0.6, F0, I0))'
ENDIF

records = replicate(record, n_records)

; Open the file and read in the data
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Reading ' + file + '.....'
OPENR, lun, file, /GET_LUN, COMPRESS=COMPRESS
SKIP_LUN, lun, 1, /LINES
READF, lun, records, FORMAT=format_code
```

```
CLOSE, lun
FREE_LUN, lun

END


; read_lbin_multi.pro
; -------------
;
; Author: Myles Harrison
; Date: July 2009
;
; Inputs: files - a scalar string or string array specifying the location(s) of l-binned file(s)
(fn_yyyy_lbinIGRF_all_vnn.exp)
; Outputs: records - structure of the data

PRO read_lbin_multi, files, records, QUIET=QUIET_kw

IF N_ELEMENTS(files) EQ 0 THEN files =
DIALOG_PICKFILE(PATH='/home/lidia/HEO_Sat/', /MULTI) ; If file not specified, prompt
iwht a dialog

; Check consistency of data type for all records
prefixes = STRMID(file_basename(files), 0, 2)
IF N_ELEMENTS(WHERE((prefixes EQ 'f1'))) EQ N_ELEMENTS(files) THEN BEGIN ; F1
	record = {HEO1_year_lbin_IGRF:0, HEO1_doy_lbin_IGRF:0D,
HEO1_Lshell_lbin_IGRF:0.0, HEO1_Orbit_Status_lbin_IGRF:0,
HEO1_nSeconds_lbin_IGRF:0, HEO1_Elec1_lbin_IGRF:0.0, HEO1_Elec2_lbin_IGRF:0.0,
HEO1_Elec3_lbin_IGRF:0.0, HEO1_Elec4_lbin_IGRF:0.0, HEO1_Elec5_lbin_IGRF:0.0,
HEO1_Elec6_lbin_IGRF:0.0,$
		HEO1_Prot1_lbin_IGRF:0.0, HEO1_Prot2_lbin_IGRF:0.0,
HEO1_Prot3_lbin_IGRF:0.0, HEO1_Prot4_lbin_IGRF:0.0, HEO1_Prot5_lbin_IGRF:0.0,
HEO1_Prot6_lbin_IGRF:0.0, HEO1_Prot7_lbin_IGRF:0.0, HEO1_Dose1_rate_lbin_IGRF:0.0,
HEO1_Dose2_rate_lbin_IGRF:0.0, HEO1_Dose3_rate_lbin_IGRF:0.0,$
		HEO1_Dose4_rate_lbin_IGRF:0.0, HEO1_JulDate_lbin_IGRF:0D,
HEO1_Lshell_IGRF_lbin_IGRF:0.0, HEO1_Lstar_IGRF_lbin_IGRF:0.0,
HEO1_Btot_IGRF_lbin_IGRF:0.0, HEO1_Bequ_IGRF_lbin_IGRF:0.0,
HEO1_MLT_IGRF_lbin_IGRF:0.0, HEO1_I_IGRF_lbin_IGRF:0.0,$
		HEO1_RadDist_lbin_IGRF:0.0, HEO1_nDose_seconds_lbin_IGRF:0}
	format_code = '((I0, D0, F0, 2I0, 17E0.6, D0, 6E0.6, F0, I0))'
ENDIF ELSE IF N_ELEMENTS(WHERE((prefixes EQ 'f3'))) EQ N_ELEMENTS(files) THEN
BEGIN ; F3
	record = {HEO3_year_lbin_IGRF:0, HEO3_doy_lbin_IGRF:0D,
HEO3_Lshell_lbin_IGRF:0.0, HEO3_Orbit_Status_lbin_IGRF:0,
HEO3_nSeconds_lbin_IGRF:0, HEO3_Elec1_lbin_IGRF:0.0, HEO3_Elec2_lbin_IGRF:0.0,
HEO3_Elec3_lbin_IGRF:0.0, HEO3_Elec4_lbin_IGRF:0.0, HEO3_Elec5_lbin_IGRF:0.0,
HEO3_Elec6_lbin_IGRF:0.0,$
		HEO3_Prot1_lbin_IGRF:0.0, HEO3_Prot2_lbin_IGRF:0.0,
HEO3_Prot3_lbin_IGRF:0.0, HEO3_Prot4_lbin_IGRF:0.0, HEO3_Prot5_lbin_IGRF:0.0,
HEO3_Prot6_lbin_IGRF:0.0, HEO3_Prot7_lbin_IGRF:0.0, HEO3_Dose1_rate_lbin_IGRF:0.0,
HEO3_Dose2_rate_lbin_IGRF:0.0,$
```

```
                        HEO3_Dose3_rate_lbin_IGRF:0.0, HEO3_Dose4_rate_lbin_IGRF:0.0,
HEO3_cElec3_lbin_IGRF:0.0, HEO3_cElec4_lbin_IGRF:0.0, HEO3_cElec5_lbin_IGRF:0.0,
HEO3_cElec6_lbin_IGRF:0.0, HEO3_JulDate_lbin_IGRF:0D,
HEO3_Lshell_IGRF_lbin_IGRF:0.0, HEO3_Lstar_IGRF_lbin_IGRF:0.0,$
                        HEO3_Btot_IGRF_lbin_IGRF:0.0, HEO3_Bequ_IGRF_lbin_IGRF:0.0,
HEO3_MLT_IGRF_lbin_IGRF:0.0, HEO3_I_IGRF_lbin_IGRF:0.0,
HEO3_RadDist_lbin_IGRF:0.0, HEO3_nDose_seconds_lbin_IGRF:0}
            format_code = '((I0, D0, F0, 2I0, 21E0.6, D0, 6E0.6, F0, I0))'
ENDIF ELSE MESSAGE, 'Error - all files must be for same flight (f1 or f3). Aborting!'

; Determine the total number of file lines and initialize the array
file_lines = FILE_LINES(files, /COMPRESS)-1
file_lines = [0, file_lines]
total_lines = TOTAL(file_lines, /CUMULATIVE)
IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Total ', STRING(MAX(total_lines),
FORMAT='(I0)'), ' records.'

records = replicate(record, MAX(total_lines))

; Loop through the array of files
FOR j=0, N_ELEMENTS(files) - 1 DO BEGIN
            loop_file = files[j]
            temp_records = replicate(record, file_lines[j+1])
            ; Open the file and read in the data
            IF ~KEYWORD_SET(QUIET_kw) THEN PRINT, 'Reading ', loop_file, '......'
            ; Insert the data into the array
            read_lbin, loop_file, temp_records, /QUIET
            records[total_lines[j]:total_lines[j+1]-1] = temp_records
ENDFOR

END

; clean_data.pro
; -------------
;
; Author: Myles Harrison
; Date: July 2009
; Modified: March 2010 - Fixed counts in records trimmed, tidied up
;               April 2010 - Fixed no QUIET keyword inheritance in calls to read_exp, read_lbin, etc.
;
; Inputs: file - a scalar or array of string(s) specifying the location of a 15-sec or lbinned file.
;                       If unspecified, a file is chosen with a dialog.
; Outputs: records - a structure of satellite data
; Keywords: QUIET - boolean flag to suppress output messages
;               NOCLEAN - boolean flag to suppress cleaning of data
; Dependencies: read_exp.pro, read_exp_multi.pro, read_lbin.pro, read_lbin_multi.pro
;
; Umbrella procedure to read file(s) of type .exp

PRO clean_data, file, records, QUIET=QUIET_kw, NOCLEAN=noclean_kw
```

```
; %%%%%%% KEYWORD DEFAULTS IF UNSET %%%%%%%

; If file is not specified, prompt with a dialog
IF N_ELEMENTS(file) EQ 0 THEN file = DIALOG_PICKFILE(/MULTI,
PATH='/home/lidia/HEO_Sat/')
IF N_ELEMENTS(QUIET_kw) EQ 0 THEN QUIET_kw = 0

filename = FILE_BASENAME(file)
n = N_ELEMENTS(file)

; Read in the data
IF N_ELEMENTS(file) GT 1 THEN BEGIN
	IF STRPOS(file[0], 'lbin') EQ -1 THEN read_exp_multi, file, records,
QUIET=QUIET_kw ELSE read_lbin_multi, file, records, QUIET=QUIET_kw
ENDIF ELSE BEGIN
	IF STRPOS(file, 'lbin') EQ -1 THEN read_exp, file, records, QUIET=QUIET_kw ELSE
read_lbin, file, records, QUIET=QUIET_kw
ENDELSE

; Get the year from the filename
start_year = FIX(STRMID(filename[0], 3, 4))
end_year = FIX(STRMID(filename[n-1], 3, 4))

n1 = N_ELEMENTS(records)
tags = TAG_NAMES(records)
jul_ind = WHERE(STRPOS(tags, 'JULDATE') NE -1);

n2 = 0.0

IF ~KEYWORD_SET(noclean_kw) THEN BEGIN ; Clean data if not specified otherwise
	; Trim out Julian dates which are not within the year specified in the file
	index = WHERE(records.(jul_ind) GE JULDAY(1, 1, start_year, 0, 0, 0) AND $
		records.(jul_ind) LE JULDAY(1, 1, end_year+1, 0, 0, 0), count,
NCOMPLEMENT=trimcount) ; Must add zeroes for double precision
	IF count GT 0 THEN BEGIN
		records = records[index]
		n2 += trimcount
	ENDIF ELSE MESSAGE, 'Julian date error'

	; NaN nonsensical values for proton counts, electron counts and dose quantities
	; Create array of structure tags
	ind = WHERE(STRPOS(tags, 'PROT') NE -1) ; Proton tags
	ind2 = WHERE(STRPOS(tags, 'ELEC') NE -1) ; Electron tags
	ind3 = WHERE(STRPOS(tags, 'DOSE') NE -1) ; Dose tags
	ind = [ind, ind2, ind3]
	; 'NaN'ed count
	n3 = 0.0

	; Loop through structure tags and remove values < 0
	FOR i=0, N_ELEMENTS(ind)-1 DO BEGIN
```

```
        index = WHERE(records.(ind[i]) LT 0, count)
        IF count GT 0 THEN records[index].(ind[i]) = !VALUES.F_NAN
        n3 += count
    ENDFOR

    ; Print message
    IF ~KEYWORD_SET(QUIET_kw) THEN BEGIN
        PRINT, STRING(n2, FORMAT='(I0)'), ' records trimmed.'
        PRINT, STRING(n3, FORMAT='(I0)'), ' bad sensor values set to NaN'
        PRINT, STRING(n1-n2, FORMAT='(I0)'), ' records total.'
    ENDIF
ENDIF

END
```

angle.pro

```
; Author: Lidia Nikitina
; Date: January 2011
;
;Inputs: records - a structure of sattelite data
;outputs: angle - polar coordinate along an elliptical orbit
; Keywords: juldate - scalar numeric specifying Julian Data (in hours from the first
obseravation on this orbit)
;         dist - distance from the Earth's centre in Re (Earth's Radius Re=6378.14 km)

PRO angle
restore, 'records_2000.dat'
a=records
C=1
juldatenr = a.HEO3_JulDate_exp
juldate=juldatenr-2451544.5

d = a.HEO3_RadDist_exp
b11=where(juldate ge 1 and juldate lt 1.5, count)
dist1=min(d(b11), imin1)
juldate11=juldate(b11)
b12=where(juldate ge 1.5 and juldate lt 2, count)
dist1=min(d(b12), imin2)
juldate12=juldate(b12)
moment1=juldate11(imin1)
```

```
print, moment1
moment2=juldate12(imin2)
print, moment2

dist2=shift(d,-1)
juldate2=shift(juldate, -1)

b3=where(juldate ge moment1 and juldate lt moment2)
d1=d(b3)
;print, d1
d2=dist2(b3)
deltat=juldate2(b3)-juldate(b3)

delta_angle=C*.5*((d1)^(-2)+(d2)^(-2))*deltat

ndist=SIZE(delta_angle, /N_elements)

angle = fltarr(ndist)
angle(0)=0
for j=1l, ndist-1 do begin
angle(j)=angle(j-1)+delta_angle(j-1)
endfor
pi=3.1416

print, max(abs(angle))
angle_phi=2*pi*(angle/max(abs(angle)))

;angle_phi=(angle_phi MOD max(angle_phi))*2*pi

;openW, lun, 'Angle_C_500.dat',/Get_lun, Width=12
;PrintF, lun, angle_phi
;Free_Lun, lun
;
;openW, lun, 'Dist_C_500.dat',/Get_lun, Width=12
;PrintF, lun, dist1
;Free_Lun, lun
;
;openW, lun, 'Time_C_500.dat',/Get_lun, Width=12
;PrintF, lun, juldate
;Free_Lun, lun

SET_PLOT, 'ps'
Device, filename='orbit.ps'
plot, d1, angle_phi, psym=3, /POLAR
DEVICE, /CLOSE
openW, lun, 'angle_dist.dat', /Get_lun ;, Width=100
```

```
printF, lun, 'dist, angle'
Thisformat='(2(F12.4))'
for j=0l, ndist-1 do begin
printF, lun, d1(j), angle_phi(j), format=Thisformat
endfor
Free_lun, lun

END
```

find_perigee.pro

```
pro perigee_all_years
restore, 'raddist_1997-2008.dat'
restore, 'time_1997-2008.dat'

time=time-2450449.5 ;1997

M=146 ;365*12/30
step=30./365

raddist_min=fltarr(M)
time_min=fltarr(M)

for j=0l, M-2 do begin
	b=where(time gt 30*j and time lt 30*(j+1), count)
	if count ne 0 then begin
raddist_min(j)=min(raddist(b), /NaN)

time_min(j)=1997+step*j
;print, time_min(j)
endif
endfor
print, 'raddist_min=', raddist_min
print, 'time_min=', time_min

set_plot, 'ps'
Device, filename='perigee_all_years.ps'
plot, time_min, raddist_min, psym=3, xrange=[1997, 2009], xstyle=1, yrange=[1.1,
1.4], ystyle=1, Xtitle='Year', Ytitle='perigee'
Device, /Close_file

openW, lun, 'perigee_1997-2008.dat', /Get_lun, Width=100
printF, lun, 'time, perigee'
```

```
Thisformat='(2(F12.4))'
for j=0, M-2 do begin
        printF, lun, time_min(j), raddist_min(j), format=Thisformat
endfor
Free_lun, lun
end
```

pro stat_along_orbits_simple

```
;Author:Lidia_Nikitina
;Date: February_April_December 2011
;input: satellite data for the specified year
;       dist1 specifies the distance between the satellite and the Earth's centre
;       dose1 specifies the cumulatuve radiation dose behind the shielding (1 - 5 Mils
Al, 2 - 12 Mils Al, 3 - 49.5 Mils Al, 4 - 125.5 Mils Al)
;       elec/prot specify fluxes (counts/(sec cm^2 sr)) for electrones and protons of
different energies
;       elec4, e>0.63 MeV
;       elec5, e >1.5 MeV
;       elec6, e >3.0 MeV
;       prot5, 8.5-35 MeV
;       prot6, 16-40 MeV
;       L-star specifies the L_value (Roederer), in Earth radii (Re=6371. km)
;       Btot - total geomagnetic field, in nT
;       Bequ - geomagnetic field in the equatorial plane
;       T1 is the period of the orbit depending on the year
;
;approach:to plot histograms of the radiation dose all the data were binned by
distance corresponding to average distance for every minute on the orbit.
;       After that the second binning was made by imposing the requirement that the
the radial deviation from the average distance dR/R for specific bins
;       is less than 0.75%
;       Dose rate was calculated as a difference between doses in two consecutive 15-
sec meausurements if the doses values are available and were recalculeted to get an
average dose rate in rad/min
;       Dose rate was binned by distance like all other parameters.
;       To check the stability of the point on the orbit we can use the statistical
approach and plot histograms of the point characterictics, such as radial distance,
;       L-value (Roederer), magnetic field (IGRF)
;output: dose_av specifies average dose value depending on the point location,
;        elec4_av/prot3_av specifies average electron/proton fluxes for the point
;        dist_av specifies average distance for the point locations (approximately every
minute)
;        L-shell_av specifies average L-value (Roederer) for the point location
;        B_tot_av specifies average values of the magnetic field for the point location
```

```
;       time_av specifies time from the perigee to the point location
;to exclude magnetic events: line
;                   bs=where((juldate le 194*T1) or ((juldate ge 203*T1) and (juldate le 311*T1)) or (juldate ge 320*T1))
;       excludes 2 magnetic storms with significant increase in proton levels in July 14-21 and November 8-15.
;to take into account all the data take the line
;                   bs = where(juldate le 366*T1)

;Changes made in December 2011
;Dose rate is taken now from the HEO data and is not calculated using dose data.
;Dose rate is calculated for all the days in the year, for days without events and for days with events only. File 'eventdays_200....dat' is used to find the start of events and the end of events.
; Code     calculate values of average dose rate per every 30 minutes. Number of large average dose rate per day is detected in file 'eventdays_200...dat'

;arg=command_line_args(count=n)
;file_num=arg(0)
;fileName="records_"+strtrim(file_num, 2)+".dat"

;restore,filename   ; 'records_2000.dat'

restore, 'records_2007.dat'

a = records
time = a.HEO3_JulDate_exp
dist1 = a.HEO3_RadDist_exp
dose1 = a.HEO3_Dose1_exp
dose1_rate=a.HEO3_Dose1_rate_exp
prot4=a.HEO3_prot4_exp
elec4=a.HEO3_elec4_exp
;ndist=SIZE(dist1, /N_elements)
L_star=a.HEO3_Lstar_IGRF_ONERA_exp
B_tot = a.HEO3_Bequ_IGRF_ONERA_exp
status=a.HEO3_Orbit_Status_OP_exp
;t0 is perigee

dose1_rate=dose1_rate*60
bbs=where (dose1_rate lt 90)
time=time(bbs)
dist1=dist1(bbs)
ndist=size(dist1, /N_elements)
dose1=dose1(bbs)
dose1_rate=dose1_rate(bbs)
```

```
prot4=prot4(bbs)
elec4=elec4(bbs)
L_star=L_star(bbs)
B_tot=B_tot(bbs)
status=status(bbs)

;deltad1=a.HEO3_dose1_rate_exp*60
;boutliers=where(deltad1 gt 100, count3) ;2001
;boutliers=where(deltad1 gt 20, count3)
;if count3 ne 0 then deltad1(boutliers)='NaN'

;start of the year corresponds to time=0
;time_in=time-2450814.5 ;1998
;time_in=time-2451179.5 ;1999
;time_in=time-2451544.5 ;2000
;time_in=time-2451544.5-0.131 ;2000 to match orbit with 2001
;time_in=time-2451910.5  ;2001
;time_in=time-2452060.5 ;2001 starting day150
;time_in=time-2452275.5;2002
;time_in=time-2452640.5;2003
;time_in=time-2453005.5;2004
;time_in=time-2453371.5 ;2005
;time_in=time-2453736.5; 2006
time_in=time-2454101.5 ; 2007
;time_in=time-2454466.5; 2008

juldate= time_in*24+24
juldate2=juldate
juldate_day=round(time_in+1)
b1=where (time_in+1 lt round(time_in+1), count5)
if count5 ne 0 then juldate_day(b1)=round(time_in(b1))-1

T10=11.9633 ;2000
;T10=11.9633 ;2001
;T10=11.9633 ;2002
;T10=11.9632;2003
;T10=11.96175 ;2004
;T10=11.9628 ;2005
;T10 = 11.963351 ;2006

T1=T10*2

;b1=where(juldate le min((juldate)+2)) ;2000
b1=where(juldate le min((juldate)+64)) ;2007
;b1=where(juldate le min(juldate) + 12) ; 2001
;b1=where(juldate le min((juldate)+18) and dist1 gt 1.33) ;2003 2004 1999
```

```
;b1=where(juldate le min(juldate)+5 and dist1 gt 1.19)
dist_per1=dist1(b1)
print, min(dist_per1, i0)
dist_per2=shift(dist_per1,-1)

;b2=where((dist_per1-dist_per2) gt 0)

;i0=max(b2)+1

print, i0
print, dist1(i0)
t0=juldate(i0)
;t0 = juldate(i0)
;t01=juldate(i0)
print, t0
;i0=306, dist(i0)=1.29725 for 2000

print, 'status=', status(i0+5)
juldate=juldate-juldate(i0)
;n- number of points on the trajectory, n1 is the number of points per hour
;n1=60*4
n1=60

n=round(n1*T1); 2 orbits per day
if (n gt n1*T1) then n=round(n1*T1)-1

;n=round(n1*T1/4); quater of orbit
;if (n gt n1*T1) then n=round(n1*T1/4)-1


;t_l=fltarr(n+1)
t_l = findgen(n+1)*(1./n1)

;t_l(n)=T1/4 ;half of orbit
t_l(n)=T1 ;2 orbits per day

deltad1 = fltarr(ndist+1)
;deltad1(*)='NaN'

dist_av= fltarr(n+1)
error_distance = fltarr(n+1)
;d_rate_av = fltarr(n+1)

dist_av(*)= 'NaN'
error_distance(*) = 'NaN'
```

```
deltad1=dose1_rate
juldate1=juldate MOD T1

bs = where(juldate le 366*T1)
;bs=where(juldate le 5*T1)
print, n_elements(bs)

;nk=size(k, /N_elements)
;knew=k*0.2/0.2
;for j=1, nk-2 do begin
;       if (knew(j) eq 1 and knew(j-1) eq 0 and knew(j+1) eq 0) then knew(j)=0
;endfor
;for j=1, nk-1 do begin
;       if ((knew(j) gt knew(j-1)) and (knew(j-1) eq 0)) then begin
;       knew(j-1)=knew(j-1)+0.5
;       endif
;
;endfor
;for j=1, nk-1 do begin
;       if ((knew(j) lt knew(j-1)) and ((knew(j) eq 0) or (knew(j) eq 0.5))) then
knew(j)=knew(j)-0.5
;endfor
;
;bevents_start=where(knew eq 0.5, count_start)+1
;bevents_finish=where(knew eq -0.5, count_finish)+2
;
;numberofevents=size(bevents_start, /N_elements)
;
;if size(bevents_finish, /N_elements) lt numberofevents then
bevents_finish=[bevents_finish, round(max(juldate0))]
;if size(bevents_start, /N_elements) lt size(bevents_finish, /N_elements) then
bevents_start=[round(min(juldate)), bevents_start]
;print, bevents_start
;print, bevents_finish
;
;for j=0, numberofevents-1 do begin
;bsevents=where(juldate_day ge bevents_start(j) and juldate_day le
bevents_finish(j), countbsevents)
; if countbsevents ne 0 then juldate2(bsevents)=0
;endfor
;
;bswevents=where (juldate2 ne 0, countbswevents)
;print, n_elements(bswevents)
;bsevents1=where (juldate2 eq 0)
;print, n_elements(bsevents1)
```

```
N_max=n+1
d_rate_av=fltarr(N_max-1)
d_rate_median=fltarr(N_max-1)
dist_avi=fltarr(N_max-1)
time_avi=fltarr(N_max-1)
number_of_points=fltarr(N_max-1)

elec4_av=fltarr(N_max-1)
elec4_median=fltarr(N_max-1)

;elec4_st_dev=fltarr(N_max-1)

prot4_av=fltarr(N_max-1)
prot4_median=fltarr(N_max-1)

;prot4_st_dev=fltarr(N_max-1)

L_star_av=fltarr(N_max-1)
B_tot_av=fltarr(N_max-1)

;for k1=0, 2 do begin

dist1_part = dist1(bs)
deltad1_part = deltad1(bs)

juldate_part = juldate(bs)
juldate1_part =juldate1(bs)

L_star_part=L_star(bs)
B_tot_part=B_tot(bs)

elec4_part=elec4(bs)
prot4_part=prot4(bs)
time_in_part=time_in(bs)

bs1=where ((L_star_part eq -1), count)
if count ne 0 then begin
L_star_part(bs1) = 'NaN'
B_tot_part (bs1) = 'NaN'
endif

for k3=0l, N_max-3 do begin
i=(k3+1)*1  ;
;b3 = where ((juldate1_part lt t_l(i)) and (juldate1_part ge t_l(i-1)) and
```

```
(finite(deltad1_part) eq 1), count)
b3 = where ((juldate1_part lt t_l(i)) and (juldate1_part ge t_l(i-1)) and
(finite(deltad1_part)) and ((juldate_part ge 0*T1) or (juldate_part lt 365*T1)), count)
if count ne 0 then begin
;b3 = where ((juldate1 lt t_l(i)) and (juldate1 ge t_l(i-1)) and (finite(deltad1) eq 1))

dist_i0 = dist1_part(b3)
deltad1_i0 = deltad1_part(b3)
juldate_i0 = juldate_part(b3)
time_i0 =juldate1_part(b3)
L_star_i0=L_star_part(b3)
B_tot_i0=B_tot_part(b3)
elec4_i0=elec4_part(b3)
prot4_i0=prot4_part(b3)
time_doy_i0=time_in_part(b3)

endif


;endif

dist_av(k3)=mean(dist_i0, /NaN)
;dose_rate_av(i)=mean(deltad1_i0, /NaN)
error=fltarr(size(dist_i0, /N_elements))
error(*)='NaN'
error=100*(dist_i0-dist_av(k3))/dist_av(k3)
b30=where (abs(error) lt 0.75, count)
;if ((dist_av(k3) ge 3) and (dist_av(k3) lt 4)) then b30=where (abs(error) lt 4, count)
;if dist_av(k3) ge 5 then b30=where(abs(error) lt 3, count)
;if dist_av(k3) lt 10 then b30=where(abs(error) lt 0.75, count)

if count ne 0 then begin
number_of_points(k3)=count

deltad1_i1 = deltad1_i0(b30)
dist_i1=dist_i0(b30)

time_i1=time_i0(b30)
juldate_i1 = juldate_i0(b30)
time_doy_i1 =time_doy_i0(b30)

L_star_i1=L_star_i0(b30)
B_tot_i1=B_tot_i0(b30)

elec4_i1=elec4_i0(b30)
prot4_i1=prot4_i0(b30)
```

```
L_star_av(k3)=mean(L_star_i1, /NaN)
B_tot_av(k3)=mean(B_tot_i1, /NaN)

elec4_av(k3)=mean(elec4_i1, /NaN)
elec4_median(k3)=median(elec4_i1)
prot4_av(k3)=mean(prot4_i1, /NaN)
prot4_median(k3)=median(prot4_i1)

d_rate_av(k3)=mean(deltad1_i1, /NaN)
d_rate_median(k3)=median(deltad1_i1)

b4=where(finite(deltad1_i1))
;if n_elements(b4) gt 1 then begin
;d_rate_st_dev(k3)=stddev(deltad1_i1, /NaN)
;elec4_st_dev(k3)=stddev(elec4_i1, /NaN)
;prot4_st_dev(k3)=stddev(prot4_i1, /NaN)
;endif

dist_avi(k3)=mean(dist_i1, /Nan)
time_avi(k3)=mean(time_i1, /NaN)

;dist_avi(k3)=median(dist_i1)
;time_avi(k3)=mean(time_i1, /NaN)

endif
endfor

print, max(d_rate_median)

loadct, 5
set_plot, 'ps'
;!p.multi=[0,4,4]
!p.multi=0

;bslarge=where(dist_avi gt 1.9)
;bssmall=where(dist_avi le 1.9)

Device, /color, filename= 'dose_rate_day_av_2007.ps'

plot, time_avi, d_rate_median,  xtitle='time (hours)', ytitle='dose rate (Rad/min)',
xrange=[0,24], xstyle=1, yrange=[0.0001, 10],  Title='Dose rate median behind
shielding 5 Mils Al, HEO3, 2007', psym=4, symsize=0.3, color=20, /ylog
plot, time_avi, d_rate_median,  xtitle='time (hours)', ytitle='dose_rate(Rad/min)',
xrange=[0,24], xstyle=1, yrange=[0.0001, 10],  Title='Dose rate median behind
```

```
shielding 5 Mils Al, HEO3, 2007', psym=-4, symsize=0.3, color=20, /ylog
plot, time_avi, dist_avi, xtitle='time (hours)', ytitle='Dist', xrange=[0,24], xstyle=1
;plot, time_avi_wevents, d_rate_av_wevents, xtitle='time', xrange=[0,24],
yrange=[0.0001, 15], Title='Dose_rate_without events_2000', psym=3, /ylog
;plot, time_avi_only_events, d_rate_av_only_events, xtitle='time', xrange=[0,24],
yrange=[0.0001, 15], Title='Dose_rate_only_events_2000', psym=3, /ylog
Device, /Close_File

end
```

find_period.pro

```
PRO period, records, results

;Author: Lidia Nikitina
;Date:June 2011
;Inputs: records of the satellite data for one year
;Depending on the year the perigee should be changed
;Results: Perigee, daily values
;        Perigee_av, monthly averaged values
;        Error_perigee, standard deviation of daily perigee values for a month

;arg=command_line_args(count=n)
;file_num=arg(0)
;fileName="records_"+strtrim(file_num, 2)+".dat"

;restore,filename   ; 'records_2000.dat'

restore, 'records_1998.dat'

a = records
juldate = a.HEO3_JulDate_exp
dist1 = a.HEO3_RadDist_exp

ndist=SIZE(dist1, /N_elements)
;t0 is perigee

juldate = (juldate-juldate(0))*24


T10=11.954335 ;?? ;1998
;T10=11.963148 ; 1999
;T10=11.963582   ;2000
;T10=11.963487   ;2001
;T10=11.963400  ;2002
;T1=11.963584*2
;T10=11.963249 ;2003
;T10 = 11.963159 ;2004
;T10 = 11.963161 ;2005
;T10 = 11.963351 ;2006

T1=T10*2

;b1=where(juldate le 2)
```

```
;dist_per1=dist1(b1)
;dist_per2=shift(dist_per1,-1)
;b2=where((dist_per1-dist_per2) gt 0)
;i0=max(b2)+1
;print, i0
;print, dist1(i0)
;t0 = juldate(i0)
;;i0=306, dist(i0)=1.29725 for 2000


j_max= round(max(juldate)/T1)
if (j_max ge round(max(juldate)/T1)) then j_max=j_max-1

print, j_max

perigee = fltarr(j_max+1)
perigee(*)='NaN'
period = fltarr(j_max)
time=fltarr(j_max+1)


b_0 = where ((juldate lt T1), count3)
if (count3 ne 0) then begin
        dist1_0=dist1(b_0)
        juldate1=juldate(b_0)

perigee(0)=min(dist1(b_0),mi0 )
time(0)=juldate1(mi0)
endif
print, time(0)
juldate=juldate-time(0)

for j=1, j_max do begin
        b_j = where((juldate ge j*T1+21)and (juldate lt (j+1)*T1+3), count)
        if count ne 0 then begin
        dist1_j=dist1(b_j)
        juldate_j=juldate(b_j)
        perigee(j)=min(dist1_j, mi)
        time(j)=juldate_j(mi)

        ;if (period (j-1) lt 11.93 or period(j-1) gt 11.98) then period(j-1)=12.2
        if (finite(perigee(j)) eq 1) and (finite(perigee(j-1))  eq 1) and ((perigee(j)-
perigee(j-1)) gt 0.01) then begin
        perigee(j)='NaN'

       endif
```

```
        endif
endfor
for j=1, j_max do period(j-1)=(time(j)-time(j-1))

histper=histogram(period, nbins=37, min=23.90, max=23.99, /NaN)
dt=0.09/36
a=max(histper, k0)
k1=where((period ge 23.90+k0*dt) and (period lt 23.90+(k0+1)*dt), count4)
if count4 ne 0 then period_true= mean(period(k1), /NaN)
print, period_true/2
;perigee_av = fltarr(12)
;error_p=fltarr(12)


;j1=findgen(j_max)
;for k=0, 11 do begin
;b_k=where ((j1 ge k*30) and (j1 le (k+1)*30))
;perigee_av(k)=mean(perigee(b_k), /NaN)
;perigee_k=perigee(b_k)
;
;b_outliers=where(((perigee_k-perigee_av(k))/perigee_av(k) gt 0.05),
count_b_outliers)
;if count_b_outliers ne 0 then begin
;       perigee_k(b_outliers)='NaN'
;       perigee(b_k)=perigee_k
;       perigee_av(k)=mean(perigee_k, /NaN)
;endif
;perigee_av(k)=mean(perigee(b_k), /NaN)
;error_p(k) = sqrt( variance(perigee(b_k), /NaN))

;endfor

set_plot, 'ps'
Device, filename='period_1998.ps'
plot, period, psym=3, xrange=[0,365], yrange=[23.90,23.97], Xtitle='day per year',
Ytitle='period_1998(hours)'
Device, /Close_file


;openW, lun, 'HEO3_2000_perigee.dat',/Get_lun, Width=12
;PrintF, lun, perigee
;Free_Lun, lun
;
;openW, lun, 'HEO3_2000_period.dat',/Get_lun, Width=12
;PrintF, lun, period
```

```
;Free_Lun, lun

;openW, lun, 'HEO3_2006_error_perigee.dat',/Get_lun, Width=12
;PrintF, lun, error_p
;Free_Lun, lun

end
```

av_monthly_dose.pro

```
pro dose_average

restore, 'time_1997-2008.dat'  ;time
restore, 'raddist_1997-2008.dat' ;raddist
restore, 'dose_rate1_1997-2008.dat' ;dose1
;restore, 'elec4_1997-2008.dat';elec4
;restore, 'dose_rate2_1997-2008.dat' ;dose2
;restore, 'dose_rate3_1997-2008.dat' ;dose3
;restore, 'dose_rate4_1997-2008.dat' ;dose4

;dose1=elec4

b21=where(dose1 lt 1.2, count1)
if count1 ne 0 then dose1=dose1(b21)*60

;dose2=dose2(b2)*60
;dose3=dose3(b2)*60
;dose4=dose4(b2)*60

raddist=raddist(b21)
time=time(b21)

time_in=time-2450449.5 ;1997
;time_in=time-2450814.5; 1998
;time_in=time-2451179.5 ;1999
;time_in=time-2451544.5 ;2000
;time_in=time-2451544.5-0.131 ;2000 to match orbit with 2001
;time_in=time-2451910.5  ;2001
;time_in=time-2452275.5;2002
;time_in=time-2452640.5;2003
;time_in=time-2453005.5;2004
;time_in=time-2453371.5 ;2005
;time_in=time-2453736.5 ; 2006
;time_in=time-2454101.5 ; 2007
;time_in=time-2454466.5; 2008
```

```
years=[2450449.5, 2450814.5, 2451179.5, 2451544.5, 2451910.5, 2452275.5,
2452640.5, 2453005.5, 2453371.5, 2453736.5, 2454101.5, 2454466.5, 2454832.5]

juldate=time_in*24

;T10=11.9633 ;?? ;1998
T10=11.9633 ; 1999
;T10=11.9633   ;2000
;T10=11.9633  ;2001
;T10=11.9633  ;2002
;T10=11.9632 ;2003
;T10 = 11.96175 ;2004
;T10 = 11.9628 ;2005
;T10 = 11.96275 ;2006

T1=T10*2

j_max= round(max(juldate, /NaN)/T1)
if (j_max ge round(max(juldate, /NaN)/T1)) then j_max=j_max-1

print, j_max


k_max=12
;k_max=round(j_max/90)+1

dose_av1=fltarr(k_max)
dose_av2=fltarr(k_max)
dose_av3=fltarr(k_max)
dose_av4=fltarr(k_max)
date=fltarr(k_max)
dose_median1=fltarr(k_max)
dose_median2=fltarr(k_max)
dose_median3=fltarr(k_max)
dose_median4=fltarr(k_max)
date(*)='NaN'



for k=0, k_max-1 do begin
bj=where((time gt years(k) and time lt years(k+1)) and (raddist gt 5 and raddist lt 8),
count)

if count ne 0 then begin
```

```
        time1=time(bj)
        dose_av1(k)=mean(dose1(bj), /NaN)*24*60
        date(k)=1997+k
        dose_median1(k)=median(dose1(bj))
;dose_median2(k)=median(dose2(bj))
;dose_median3(k)=median(dose3(bj))
;dose_median4(k)=median(dose4(bj))
endif
endfor
print, dose_av1
print, date

;for k=1l, k_max-1 do begin
;bj=where((juldate gt k*720 and juldate lt (k+1)*720) and (raddist gt 1.2 and raddist
lt 3), count)
;
;if count ne 0 then begin
;       juldate1=juldate(bj)
;       time1=time(bj)
;       dose_av1(k)=mean(dose1(bj), /NaN)
;       date(k)=mean(time1, /Nan)
;       dose_median1(k)=median(dose1(bj))
;;dose_median2(k)=median(dose2(bj))
;;dose_median3(k)=median(dose3(bj))
;;dose_median4(k)=median(dose4(bj))
;endif
;endfor

;print, 'dose_av1=', dose_av1
;print, 'dose_av2=', dose_av2
;print, 'dose_av3=', dose_av3
;print, 'dose_av4=', dose_av4
;
;print, 'dose_median1=', dose_median1
;print, 'dose_median2=', dose_median2
;print, 'dose_median3=', dose_median3
;print, 'dose_median4=', dose_median4

set_plot, 'ps'
;Device, filename='dose_rate_2000.ps'
;plot, juldate/24, dose1_min, psym=3, Title='dose1_rate/min_2000', xrange=[1,3],
/ylog ;, yrange=[0,100]
;plot, juldate/24, dose2_min, psym=3, Title='dose2_rate/min_2000', xrange=[1,3],
/ylog ;, yrange=[0,100]
;plot, juldate/24, dose3_min, psym=3, Title='dose3_rate/min_2000', xrange=[1,3],
/ylog ;, yrange=[0,100]
```

```
;plot, juldate/24, dose4_min, psym=3, Title='dose4_rate/min_2000', xrange=[1,3],
/ylog ;, yrange=[0,100]
;Device, /Close_file

date_label = LABEL_DATE(DATE_FORMAT = ['%M!C%Y'])

Device, Filename='dose_rate_1997-2008.ps'
plot, date, dose_av1, Title='dose1_rate/day_monthly_averaged, R>5', xstyle=1,
xrange=[2450449.5,2454832.5], XTICKFORMAT = 'Label_date'
;;plot, date, dose_av2, psym=4, Title='dose2_rate/min_monthly_averaged',
XTICKFORMAT = 'LABEL_DATE'
;;plot, date, dose_av3, psym=4,
Title='dose3_rate/min_monthlyDevice,Device_averaged', XTICKFORMAT =
'LABEL_DATE'
;
;;plot, date, dose_av4, psym=4, Title='dose4_rate/min_monthly_averaged',
XTICKFORMAT = 'LABEL_DATE'
;
plot, date, dose_median1, Title='dose1_median/day_monthly_averaged, R>5',
xstyle=1, xrange=[2450449.5,2454832.5], XTICKFORMAT = 'LABEL_DATE'
;
;;plot, date, dose_median2, psym=4, Title='dose2_median/min_monthly_averaged',
XTICKFORMAT = 'LABEL_DATE'
;;
;;plot, date, dose_median3, psym=4, Title='dose3_median/min_monthly_averaged',
XTICKFORMAT = 'LABEL_DATE'
;;
;;plot, date, dose_median4, psym=4, Title='dose4_median/min_monthly_averaged',
XTICKFORMAT = 'LABEL_DATE'

;Device, Filename='elec4_1997-2008.ps'
;plot, date, dose_av1, psym=4, Title='elec4_monthly_averaged_fluences', xstyle=1,
xrange=[2450449.5,2454832.5], XTICKFORMAT = 'Label_date'
;plot, date, dose_median1, psym=4, Title='elec4_median/averaged fluences',
xstyle=1, xrange=[2450449.5,2454832.5], XTICKFORMAT = 'LABEL_DATE'
;;
;;;plot, date, dose_median2, psym=4, Title='dose2_median/min_monthly_averaged',
XTICKFORMAT = 'LABEL_DATE'
;;;
;;;plot, date, dose_median3, psym=4, Title='dose3_median/min_monthly_averaged',
XTICKFORMAT = 'LABEL_DATE'
;;;
;;;plot, date, dose_median4, psym=4, Title='dose4_median/min_monthly_averaged',
XTICKFORMAT = 'LABEL_DATE'
Device, /Close_file
```

end

pro all_data

```
;to get an overlapped picture of dose, or proton/electrone fluencies for the whole
year

Restore, 'records_2004.dat'
a=records
status_in=a.HEO3_orbit_status_IGRF_exp
L_in=a.HEO3_Lstar_IGRF_Onera_exp
R_in=a.HEO3_Raddist_exp
Temp_in=a.HEO3_SC_TEMP_exp
time=a.HEO3_Juldate_exp

;time_in=time-2450449.5 ;1997
;time_in=time-2450814.5; 1998
;time_in=time-2451179.5 ;1999
;time_in=time-2451544.5 ;2000
;time_in=time-2451544.5-0.131 ;2000 to match orbit with 2001
;time_in=time-2451910.5  ;2001
;time_in=time-2452275.5;2002
;time_in=time-2452640.5;2003
time_in=time-2453005.5;2004
;time_in=time-2453371.5 ;2005
;time_in=time-2453736.5 ; 2006
;time_in=time-2454101.5 ; 2007
;time_in=time-2454466.5; 2008

;D1=a.HEO3_Dose1_Exp
;D2=shift(d1, -1)
;Deltad1_in=(d2-d1)*4
;print, max(deltad1_in)
;b4=where(((deltad1_in gt 30) or (deltad1_in lt 0)), count)
;if count ne 0 then deltad1_in(b4)='NaN'

;deltad1_in=a.HEO3_Dose1_Rate_exp*60
;b4=where(deltad1_in gt 100, count)
;if count ne 0 then begin
;deltad1_in(b4)='NaN'
;endif

b23=where(L_in eq -1 or L_in gt 9, count7)
if count7 ne 0 then L_in(b23)='NaN'

;MLT_in=records.HEO3_MLT_IGRF_Onera_exp
;prot4_in=records.HEO3_Prot4_exp
```

```
;prot3_in=records.HEO3_Prot3_exp
prot5_in=records.HEO3_Prot5_exp
prot6_in=records.HEO3_Prot6_exp
prot7_in=records.HEO3_Prot7_exp
;elec3_in=records.HEO3_Elec3_exp
elec4_in=records.HEO3_Elec4_exp
elec5_in=records.HEO3_Elec5_exp
elec6_in=records.HEO3_Elec6_exp

;b1=where(((status_in eq 3) or (status_in eq 7)) and ((Temp_in lt 25) and (Temp_in
gt 0)));for R
b1=where(status_in eq 3)
;MLT1=MLT_in(b1)
;prot31=prot3_in(b1)
;prot41=prot4_in(b1)
prot51=prot5_in(b1)
prot61=prot6_in(b1)
prot71=prot7_in(b1)
;elec31=elec3_in(b1)
elec41=elec4_in(b1)
elec51=elec5_in(b1)
elec61=elec6_in(b1)
;deltad11=deltad1_in(b1)
R1=R_in(b1)
L1=L_in(b1)
time1=time_in(b1)
temp1=temp_in(b1)
status1=status_in(b1)

;b2=where(((status_in eq 0) or (status_in eq 4)) and ((Temp_in lt 25) and (Temp_in
gt 0))) ;for R
b2=where(status_in eq 0)
;MLT2=MLT_in(b2)
;prot32=prot3_in(b2)
;prot42=prot4_in(b2)
prot52=prot5_in(b2)
prot62=prot6_in(b2)
prot72=prot7_in(b2)
;elec32=elec3_in(b2)
elec42=elec4_in(b2)
elec52=elec5_in(b2)
elec62=elec6_in(b2)
;deltad12=deltad1_in(b2)
R2=(-1)*R_in(b2)
L2=L_in(b2)
```

```
b22=where((finite(L2) eq 1), count5)
if count5 ne 0 then L2(b22)=(-1)*L2(b22)

time2=time_in(b1)
temp2=temp_in(b1)
status2=status_in(b1)

T10=11.9633/24 ;2000
;T10=11.9633/24 ;2001
;T10=11.9633/24 ;2002
;T10=11.9632/24;2003
;T10=11.96175/24 ;2004
;T10=11.9628/24 ;2005
;T10=11.96275/24 ;2005

T1=T10*2
;b0=where((time le 194) or ((time ge 203) and (time le 311)) or (time ge 320)) ;2000
b0=where(time1 le 365)
b01=where(time2 le 365)
;b0=where((time1 lt 80) or (time1 gt 130));2001
;b01=where((time2 lt 80) or (time2 gt 130));2001
;b0=where((time lt 134) or ((time ge 135) and (time lt 266)) or ((time gt 270) and
(time lt 273)) or ((time gt 274) and (time lt 306)) or $
;((time ge 311*24) and (time lt 325*24)) or (time gt 329*24))  ;2001
;time_per_orbit=(time MOD T1)*24
time_per_orbit=(time_in MOD T1)*24

;b_2001=where((time_in lt 95) or (time_in gt 130));2001
b_2000=where(time_in lt 365)
;MLT_all=[MLT1(b0), MLT2(b0)]
R_all=[R1(b0), R2(b01)]
;prot3_all=[prot31(b0), prot32(b01)]
;prot4_all=[prot41(b0), prot42(b01)]
prot5_all=[prot51(b0), prot52(b01)]
prot6_all=[prot61(b0), prot62(b01)]
prot7_all=[prot71(b0), prot72(b01)]
;
;elec3_all=[elec31(b0), elec32(b01)]
elec4_all=[elec41(b0), elec42(b01)]
elec5_all=[elec51(b0), elec52(b01)]
elec6_all=[elec61(b0), elec62(b01)]
L_all=[L1(b0),L2(b01)]
;deltad1_all=[deltad11(b0), deltad12(b01)]

;loadct
```

```
set_plot, 'ps'
Device, filename='prot-elec_overlapped_2004.ps'
;plot, time_per_orbit(b_2001), R_in(b_2001), psym=3, yrange=[1,8], xrange=[0,24],
Xtitle='time(hour)', ytitle='Distance (Re)', Title='orbit_2000'
;plot, R_all, MLT_all, xrange=[-8,8], psym=3, yrange=[0,24], Xtitle='R',
Title='MLT_odd_outband_even_inband_orbit_2000'
;plot, R_all, prot3_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,50000],
Xtitle='R', Title='prot3_odd_outband_even_inband_orbit_2000'
;plot, R_all, prot4_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,15000],
Xtitle='R', Title='prot4_odd_outband_even_inband_orbit_2006'
plot, R_all, prot5_all, /ylog, xrange=[-8,8], xstyle=1, psym=3, yrange=[0.01,5000],
Xtitle='R', ytitle='proton flux (counts/(sec sm2 sr))', title='Proton fluxes, 8.5-35
MeV, HEO3 2004'
plot, R_all, prot6_all, /ylog, xrange=[-8,8], xstyle=1, psym=3, yrange=[0.01,1000],
Xtitle='R', ytitle='proton flux (counts/(sec sm2 sr)), ', Title='Proton fluxes, 16-40
MeV, HEO3 2004 '
plot, R_all, prot7_all, /ylog, xrange=[-8,8], xstyle=1, psym=3, yrange=[0.01,1000],
Xtitle='R', ytitle='proton flux (counts/(sec sm2 sr))', Title='Proton fluxes, 27-45
MeV, HEO3 2004'


plot, R_all, elec4_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,80000],
Xtitle='R', ytitle='electron flux (counts/(s cm2 sr))', Title='electron fluxes, 0.63 MeV,
HEO3 2004'
plot, R_all, elec5_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,90000],
Xtitle='R', ytitle='electron flux (counts/(s cm2 sr))', Title='electron fluxes, 1.5 MeV,
HEO3 2004'
plot, R_all, elec6_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,30000],
Xtitle='R', ytitle='electron flux (counts/(s cm2 sr))', Title='electron fluxes, 3 MeV,
HEO3 2004'
;plot, R_all, deltad1_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,100],
Xtitle='R', ytitle='Radiation dose (Rad/min)', Title='Radiation_dose_rate, 1999'


;plot, L_all, prot3_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,50000],
Xtitle='L', Title='prot3_odd_outband_even_inband_orbit_2000'
;plot, L_all, prot4_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,15000],
Xtitle='L', Title='prot4_odd_outband_even_inband_orbit_2000'
plot, L_all, prot5_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,5000], Xtitle='L',
ytitle='proton fluxes (counts/(s cm2 sr))', Title='Proton fluxes, 8.5-35 MeV, HEO3
2004'
plot, L_all, prot6_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,1000], Xtitle='L',
ytitle='proton fluxes (counts/(s cm2 sr))',  Title='Proton fluxes, 16-40 MeV, HEO3
2004'
plot, L_all, prot7_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,1000], Xtitle='L',
```

```
ytitle='proton fluxes (counts/(s cm2 sr))',  Title='Proton fluxes, 27-45 MeV, HEO3
2004'

plot, L_all, elec4_all, xrange=[-8,8], psym=3, yrange=[0.01,120000], Xtitle='L',
ytitle='electron flux (counts/(s cm2 sr))', Title='electron fluxes, 0.63 MeV, HEO3
2004'
plot, L_all, elec5_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,90000], Xtitle='L',
ytitle='electron flux (counts/(s cm2 sr))', Title='electron fluxes, 1.5 MeV, HEO3
2004'
plot, L_all, elec6_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,30000], Xtitle='L',
ytitle='electron flux (counts/(s cm2 sr))', Title='electron fluxes, 3 MeV, HEO3 2004'
;plot, L_all, deltad1_all, /ylog, xrange=[-8,8], psym=3, yrange=[0.01,100],
Xtitle='L', ytitle='Radiation dose (Rad/min)', Title='Radiation_dose_rate, 1999'

;plot, R(b0), prot4(b0),xrange=[1,8], psym=3, yrange=[0,7000],
Xtitle='R',Title='prot4_odd_outband_orbit_2000'
;plot, R(b0), prot5(b0),xrange=[1,8], psym=3, yrange=[0,5000],  Xtitle='R',
Title='prot5_odd_outband_orbit_2000'
;plot, R(b0), prot6(b0),xrange=[1,8], psym=3, yrange=[0,1000], Xtitle='R',
Title='prot6_odd_outband_orbit_2000'
;plot, R(b0), deltad1(b0), xrange=[1,8], psym=3, yrange=[0,30], Xtitle='R',
Title='dose1_odd_outband_orbit_2000'
;plot, R(b0), elec4(b0), xrange=[1,8], psym=3, yrange=[0, 80000], Xtitle='R',
Title='elec4_odd_outband_orbit_2000'
;plot, R(b0), elec5(b0), xrange=[1,8], psym=3, yrange=[0, 80000], Xtitle='R',
Title='elec5_odd_outband_orbit_2000'
;plot, R(b0), elec6(b0), xrange=[1,8], psym=3, yrange=[0, 80000], Xtitle='R',
Title='elec6_odd_outband_orbit_2000'

Device, /Close_file

end
```