APEXRAD: Low Altitude Orbit Dose as a Function of Inclination, Magnetic Activity and Solar Cycle

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Abstract

Dosimeter data from the low altitude, high inclination satellite, APEX, flying from 1994-1996 are used to create low altitude dose models for four aluminum shielding thicknesses. These models are appropriately applied to solar minimum conditions. One model is made using the entire data set. The data are also ordered by magnetic activity from which five models are made to show variations in the outer zone electron contribution to dose. The models are imported into a computer utility called APEXRAD such that dose for user-selected orbits and run times may be calculated. The variation of dose with satellite inclination, altitude, solar cycle and magnetic activity is examined using APEXRAD.

I. INTRODUCTION

Two years ago we presented high spatial resolution proton dose models of the inner edge of the inner radiation belt using the APEX (PASP+), DMSP and CRRES dose data [1]. The models were also used to specify dose variation for different periods in the solar cycle. Since that time we have added more data (the full APEX data set) to the APEX model, extended the model to high latitudes to include the contribution to dose from outer zone electrons, and incorporated the model into a personal computer (PC) utility similar to that of CRRESRAD [2]. The new utility is called APEXRAD. Initial results from the PC utility may be found in a preliminary report on the construction of these models [3]. Here we summarize the final construction of the models and use the PC utility to investigate the variability of dose with inclination, altitude, solar cycle and magnetic activity for low altitude orbits such as Space Station.

II. APEX ORBIT AND DOSIMETER

The orbit of the APEX satellite has 70° inclination, 362 km perigee and 2544 km apogee. The satellite was launched in August, 1994, and ceased operations in May, 1996. Due to satellite difficulties the dosimeter on APEX was turned off approximately 40% of this time interval. The period of APEX operations is just prior to solar minimum (solar maximum for Solar Cycle 22 was in July, 1989; solar minimum, September, 1986; and solar minimum, starting Solar Cycle 23, has yet to be determined, but appears to have been in Fall, 1996).

A complete description of the APEX dosimeter [4] will not be given, only a brief characterization of those instrumental features pertinent to the dose maps is included. Previous APEX reports give additional information [1,3]. The APEX dosimeter consists of sensitive elements placed underneath four aluminum shieldings, each of which has a different thickness. The aluminum thicknesses are 4.29, 82.5, 232.5 and 457.5 mils. The thinnest shield is a slab; the remaining three are hemispherical. The shielding determines an energy threshold for protons and electrons that can penetrate and strike the sensitive element. For electrons the threshold energies, in order of increasing shielding thickness, are: 0.15, 1.0, 2.5, and 5.0 MeV; and for protons: 5, 20, 35, 52 MeV. Underneath the shielding the particle dose is detected in two LET ranges: a low LET range (LOLET), which measures particles depositing 50 keV-1 MeV; and a high LET range (HILET), which measures particles depositing 1-10 MeV. Contributors to LOLET dose are electrons whose energies exceed the shielding threshold, and very high energy protons, that is, protons with energies exceeding 80, 115, 120 and 125 MeV (in order of increasing shield thickness). Contributors to HILET are protons in the energy ranges: 5-80, 20-115, 35-120, and 52-125 MeV (again, in order of increasing shield thickness).

The dosimeter returns an accumulated dose measurement every 6 s. However, for our maps, we use a 24 s interval to calculate the difference in accumulated dose and create a delta dose data base. The coarser data base is obtained in a much more straight-forward manner and is easier to process. We have run sample maps with both the 6 s and 24 s data and find no difference in mean values.

The accuracy of the dose measurement is checked periodically in-flight by means of a calibrated alpha-source installed in each of the four detectors. The source provides a constant background which must be subtracted from the measured dose to obtain the environmental dose. There is another source of constant dose (or, more specifically, near-constant over the mission lifetime), namely galactic cosmic rays. There is a slow galactic cosmic ray dose variation over solar cycle. It has been our practice in producing dose maps from DMSP and CRRES to subtract all constant background sources from the measured dose, e.g., the alpha source and the galactic cosmic ray source. An average background value is determined for each detector in regions of lowest dose, that is, underneath the radiation belts. Table 1 gives the background values measured in-flight which were subtracted from the LOLET and HILET dose of each detector, and their standard deviations. These differ slightly from those reported earlier [3] because a larger data base was used to calculate the

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in-flight background. Included, as well, in Table 1 are the dose rates from the alpha-source as measured pre-flight.

Table 1
Dose in rads (Si)/s from backgrounds.

Shield Thickness in mils Al	Pre-flight alpha source calibration	In-flight measured background
	LOLET	
4.29	2.66 10^{-7}	$(5.64 \pm 1.52)10^{-7}$
82.5	2.43 10^{-7}	$(3.17 \pm 0.41)10^{-7}$
232.5	1.07 10^{-7}	$(1.48 \pm 0.25)10^{-7}$
457.5	1.38 10^{-8}	$(5.33 \pm 0.60)10^{-8}$
	HILET	
4.29	1.12 10^{-5}	$(1.03 \pm 0.09)10^{-5}$
82.5	1.41 10^{-5}	$(1.50 \pm 0.07)10^{-5}$
232.5	8.75 10^{-6}	$(9.04 \pm 0.48)10^{-6}$
457.5	9.01 10^{-7}	$(9.45 \pm 0.38)10^{-7}$

III. Dose Maps

The dosimeter data on APEX consists of ~ 1 million 24-s data points for each of the 8 values used in the dose maps (4 HILET and 4 LOLET channels). The dosimeter data were sorted into bins in the two-dimensional McIlwain L-parameter and B/B_0 space (see below) and averaged. The number of data points in the average and the standard deviation were retained. A second pass through the data was made keeping only points that fall within 3 standard deviations of the average value. The number of points discarded was between 0.5 and 1.5 % of the original number of points. One set of maps includes the entire data of the mission (minus the discarded points). For this set of maps the average number of observations per bin was ~130. In order to study the magnetic activity dependence of the outer zone electrons, five additional sets of maps were made by sorting the data according to a 15-day running average of A_P, offset by one day (designated A_{P15}). A_P is a 3-hour index of magnetic activity, measured at selected ground magnetometer stations distributed world-wide to monitor the major magnetospheric current systems. It is a linear index. We sort the data by A_{P15} in imitation of the successful ordering of the outer zone electron data taken onboard CRRES [5]. For the APEX maps we used five combinations of the CRRES A_{P15} intervals from A_{P15} 5 to 25. Not enough data were available for models outside this range. The A_{P15} values that characterize the three models (with the percentage of the total data base represented) are: A_{P15} = 5-7.5 (14%); 7.5-10 (27%); 10-15 (35%); 15-20 (12%); and 20-25 (7%). The missing 5% of the data was either discarded for falling outside the three-sigma requirement, or occurred for activity levels above or below those of the five map sets. The five A_{P15} ranges represent quiet to active levels of magnetospheric magnetic activity.

The model grid is in L and B/B_0. Both quantities are calculated using the IGRF 95 internal field model extrapolated to the time the data were taken. The internal field model is updated from that used earlier [1,3]. No external field model was used. L, in a dipole field, is the distance on the magnetic equator (in Earth radii) to the magnetic shell to which the measured particles are confined. It is similarly defined for non-dipole fields, and becomes dependent on particle pitch angle, the more so the greater the deviation from dipolar. Dose measurements give no direct information on the pitch angle distribution. Therefore, the L calculation we make is for locally mirroring particles, where the flux maximizes in most cases. B is the magnitude of the magnetic field at the point of the measurement, and B_0 is the value of the magnetic field at the magnetic equator when the point of measurement is traced along the field line. The grid size for the models is 1/100th of an Earth radius in L, and each degree of the arcsin of $(B/B_0)^{-1/2}$ (approximately 64 km in altitude by 3/4° in magnetic latitude). This gives a grid size about 20 times smaller than used for the original CRRES dose maps.

Figures 1a and 1b show the models for total dose (LOLET + HILET) for two shielding thicknesses, 4 mils Al (slab) and 232 mils Al (hemispheric), respectively, made using data from the entire APEX mission. The dose accumulated per second is given by the color scale. An Earth-centered dipole field is used for the display. In each map there is complete coverage (within the altitude range sampled) of the inner radiation belt, composed of both electrons and protons, and reasonable coverage of the horns of the outer belt (electrons only) that extend to low altitude. The inner edge of the inner belt is well-defined and sharp near the equator in both maps, but becomes less so with increasing magnetic latitude until attenuated outer zone electrons are seen extending nearly to the surface of the Earth. The shape of contours of constant dose in the inner belt are quite different for the thinner shield compared to the thicker shield. This is due to keV electrons that contribute to dose behind the thinner shield and are continually being injected into low L-values.

IV. APEXRAD

CRRESRAD [2] is a personal computer utility designed for the CRRES dose models. For a user-specified orbit and run time, the utility calculates the time spent in each L-B/B_0 bin. L and B/B_0 are calculated using the Olson-Pfitzer quiet external magnetic field model and the IGRF 85 internal magnetic field model extrapolated to the time requested by the user. It then combines the dose rate in the CRRES dose models for each bin with the appropriate dwell time, and accumulates the dose over the total run time. A simple multiplicative conversion projects the dose per run time to dose per year. For APEXRAD the utility is modified to use the low altitude APEX dose models. The major change is a refinement of the time steps taken as the orbit is followed through the dose maps. These are made much smaller because of the smaller grid size, in order to maintain the same degree of accuracy found in CRRESRAD. A second

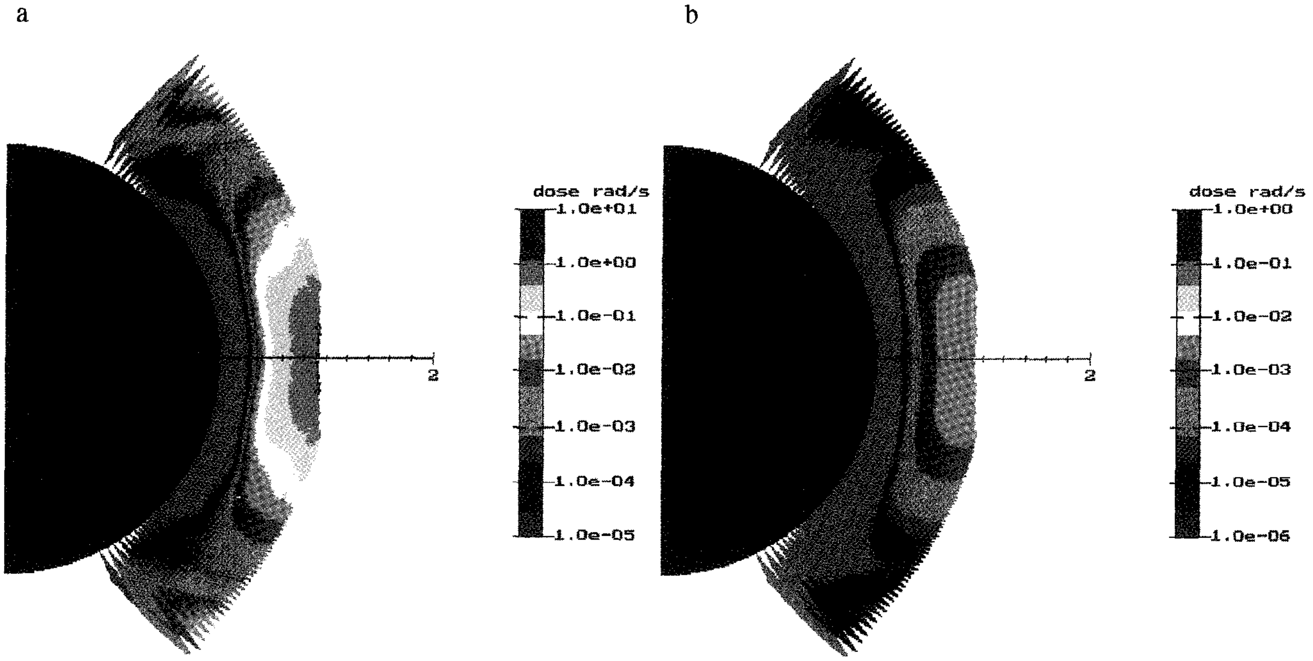

Figure 1: Low altitude total dose maps in Earth-centered dipole coordinates using data from the entire APEX mission for a) slab shield of 4 mils Al and b) hemisphere shield of 232 mils Al. The dose rate is color-coded according to the scales shown to the right.

change is that the IGRF models from 1985 to 1995 are made available for calculating L and B/B_0 for the user-specified orbit. Interpolation is used for times between IGRF models. We tested APEXRAD by running the exact APEX ephemeris and comparing the daily results to the measured daily dose [3]. The agreement is excellent for channels measuring proton dose since the proton belts vary so slowly. The outer zone electrons, however, show high variability, increasing by an order of magnitude or more over several hours, and maintaining elevated flux levels for days on end. We do not expect the mission-averaged model to follow these changes. Instead, it follows the background level, but at a higher value. To demonstrate here the accuracy of our modeling methods and APEXRAD, we use a different technique, one that sheds some light on the comparison of two solar minima, for cycles 22 and 23, and between solar minimum and solar maximum conditions.

The dosimeter data from the DMSP F7 satellite which flew from December 1983 to October 1987 was used to examine dose variations in a high inclination, circular orbit at altitude 840 km as solar minimum in solar cycle 22 was approached and passed [6]. In that study we discovered, using monthly averages of dose, that the maximum proton dose did not occur in the month of solar minimum, but continued to rise, albeit, slowly, and had not shown a clear fall-off some 13 months after solar minimum, when the data were discontinued. The electron dose variation was not so regular, and, in fact, appears to reach a minimum in the year following solar minimum. Taking the DMSP data from 1987 we created dose models exactly as we created those using the APEX data. Importing the DMSP87 model into the APEXRAD PC utility we found the predicted yearly dose for the DMSP orbit using an orbit run time of 1 day. The predicted total dose is shown in Figure 2 (x's) along with the average dose measured onboard the DMSP satellite for 1987 (triangles). Except for the thinnest shielding the model dose given by the PC utility is uniformly higher than the measured dose, by from 2-5%. The DMSP87 model dose for the thinnest shield is some 33% lower than the measured dose. This difference is entirely due to electrons, or LOLET dose, and is expected, since the model average will smooth out the high outer zone flux episodes. From this comparison we conclude that the PC utility gives faithful rendering of the model data to the 5% level.

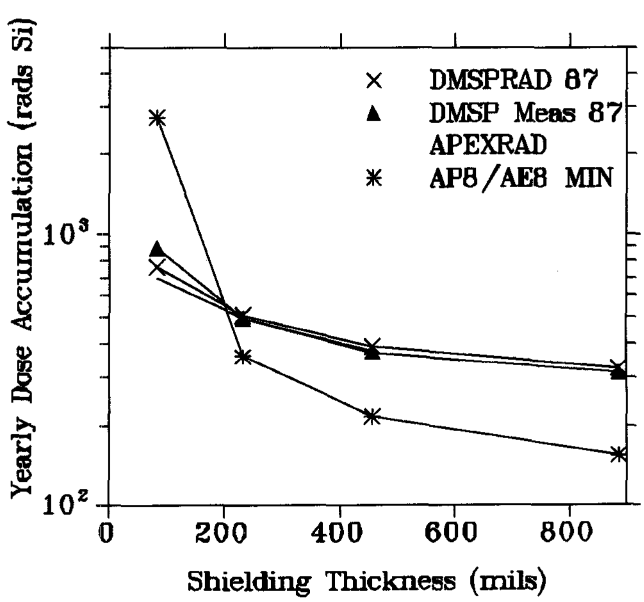

Figure 2: Dose-depth curves for the DMSP orbit (840 km circular) for measured and model values under solar minimum conditions.

In Figure 2 we also show the result of running the DMSP orbit through APEXRAD (circles) using a 1 day run time. APEXRAD gives dose values lower than DMSPRAD87 by 2-10%. For HILET (proton) dose the APEXRAD values are more uniformly lower than DMSPRAD87 by 8-10%. The APEX data are all taken prior to solar minimum. Comparison to measured DMSP dose values for the same position in the previous solar cycle, namely 1983-1985, gives APEXRAD HILET values some 8-21% higher than the measured doses (not shown). This indicates that the solar cycle 23 minimum will, in retrospect, be even deeper than that of solar cycle 22, and the proton dose correspondingly higher.

For comparison we have put the total dose estimates for the DMSP orbit from the NASA AP8MIN and AE8MIN models (stars). To obtain these values we have used the magnetic field models in the epochs in which the data were taken, namely 1964 and 1975, respectively [7]. The differences shown here have been discussed before [5,8,9,10]. The high dose behind the thin shield reflects an excessive electron flux in the NASA models, and the lower values for the three highest shields, approximately a factor of 2, an underestimate in the high energy proton flux values. We note here, however, that it is increasingly difficult to make comparisons using the AP8 and AE8 models the more distant in time the applications are from the acquisition of the AP8 and AE8 data. The low altitude "fixes" are simply that, and we suggest they be compared to actual low altitude dose data taken in more recent epochs whenever possible.

In addition to putting DMSP dose models into the APEX utility, we also rebinned the CRRES dose models, taken near solar maximum, in the finer grid for low altitudes. The CRRES data are confined to within 30° of the magnetic equator, so there is no contribution from outer zone electrons

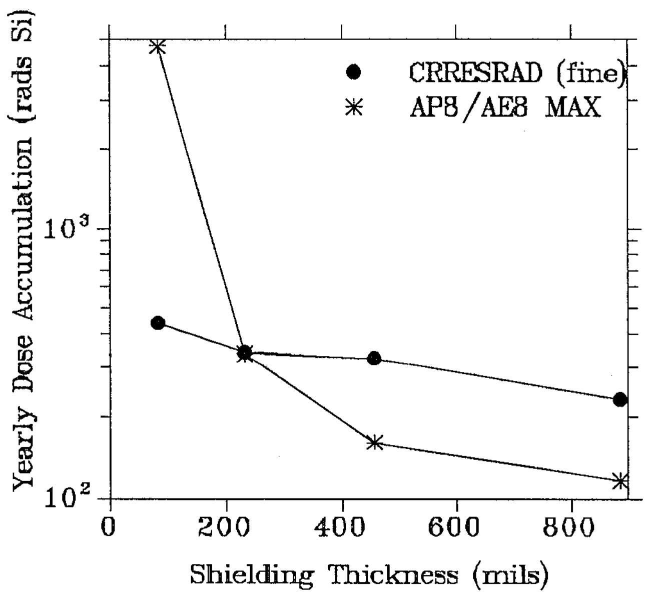

Figure 3: Dose-depth curves for the DMSP orbit (840 km circular) for solar maximum model values.

Table 2
Yearly total dose accumulation in rads (Si) for the DMSP orbit for solar minimum conditions (DMSP87) and for solar maximum conditions (CRRESRAD-fine).

Shield Thickness in mils Al	DMSP87	CRRESRAD (fine)	% Difference
82.5	760	439	73
232.5	507	341	49
457.5	391	325	20
886.5	326	230	42

The % differences take the solar maximum (CRRESRAD) values as the standard.

for low altitude orbits. Figure 3 shows the total dose-depth curves for a DMSP orbit using the CRRES average model and a run time of 1 day. We have also included the AP8 and AE8 solar maximum model values. These bear the same relationship to the CRRES values as their counterparts do for solar minimum to the APEX and DMSP values. Comparison of the CRRES dose to the DMSP dose in Figure 2 gives an upper bound on the range in total dose that can be expected in the DMSP orbit for the extremes of the solar cycle. Table 2 gives the total yearly dose in the DMSP orbit using two models: DMSP87, representing solar minimum, and CRRESRAD (fine grid), representing solar maximum. The differences run from 20-73%. The highest variation of 73% occurs because electrons are important for thin shields and the outer zone electron contribution is absent in CRRESRAD; the HILET differences between solar maximum and solar minimum run consistently near 50%. Thus, at DMSP altitudes (840 km) the difference between solar minimum and solar maximum is well below a factor of 2 (e.g., 100% difference) for aluminum shielding greater than about 1/4 in.

We have cautioned against using the CRRESRAD utility with the original grid sizes for low altitude orbits, since they are so coarse (1/20 RE ~ 300 km) [2]. Indeed, in comparing the two CRRESRAD models, fine and coarse gridding, there is a rather uniform increase in dose of ~12% at DMSP altitudes in using the coarse grid.

V. Dose for Low Altitude Circular Orbits as a Function of Altitude and Inclination

APEXRAD was used to determine the dose for low altitude circular orbits for every 5° increment in inclination. To complete the ephemeris selection the right ascending node = 280.1757°, the argument of perigee = 180°, the mean anomaly = 180°, and mean motion = 15.90814 rev/day. The ephemeris is specified for 1 Jan 1995 at 0 hours, and the run time is 5 days, starting at that time. The results for orbits with altitudes 300 km, 500 km, and 1000 km are shown in Figure 4 for each shielding thickness of the APEX dosimeter. In each panel the yearly dose accumulation in rads (Si), projected from the 5 day run time, is shown as a function of inclination. Different symbols are used to show LOLET,

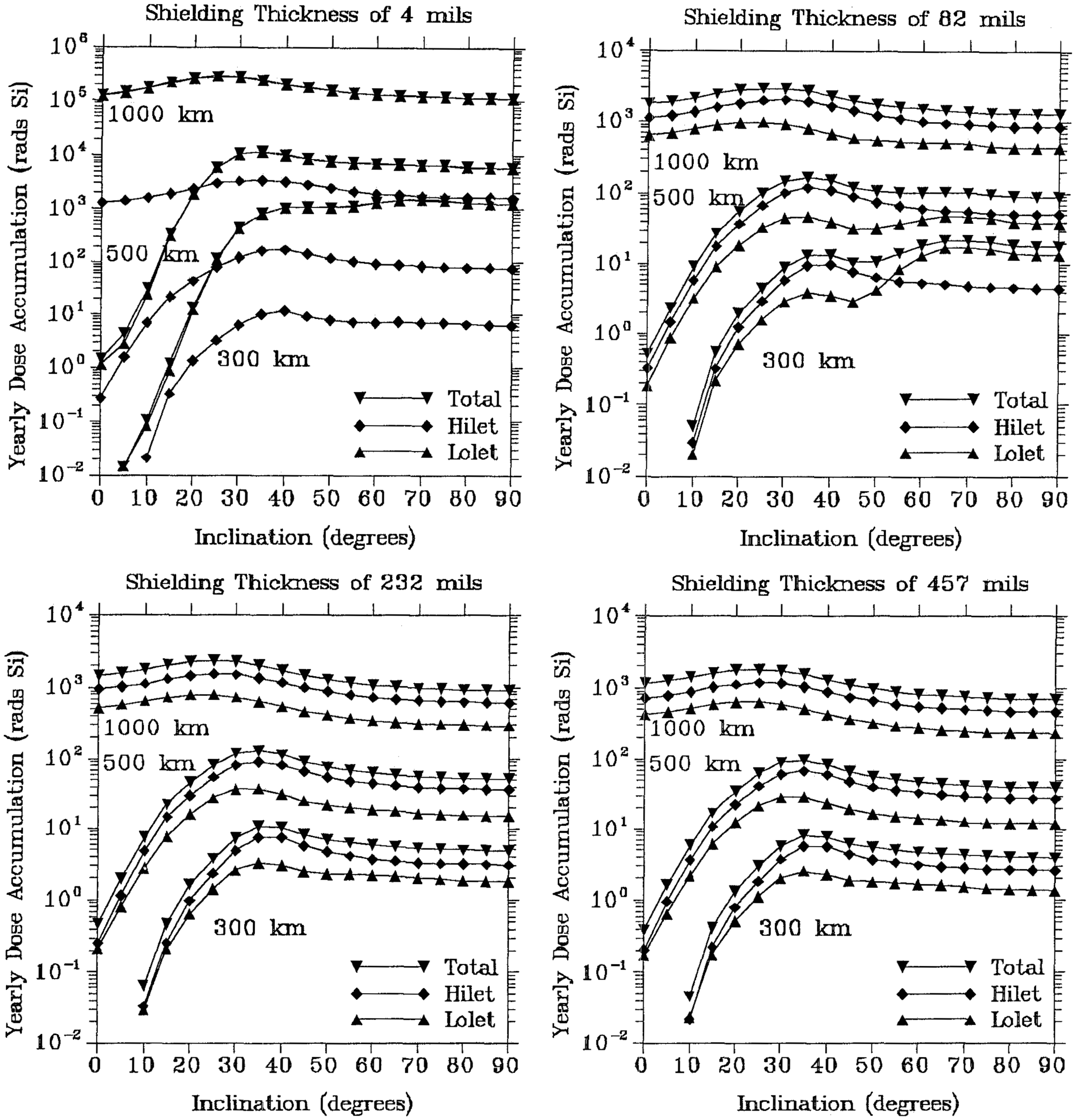

Figure 4: Yearly dose accumulation for low altitude (300, 500 and 1000 km), circular orbits as a function of orbit inclination for the four shielding thicknesses of the APEX dosimeter. LOLET, HILET and total contributions to dose are separately given.

HILET and total dose. The scales for dose are the same in all panels except the first, which extends upward an additional two orders of magnitude. We note that for 4 mils Al thickness, the LOLET and total dose are indistinguishable, the HILET dose being insignificant by comparison.

Figure 4 shows the following:

a) As a function of increasing inclination, total dose rises at low inclinations (very sharply for the two lowest altitude orbits) to a maximum value, and then falls off slowly at the highest inclinations. The dose for 1000 km orbits peaks at an inclination of 25°; for 500 km orbits and behind the two thickest shields in the 300 km orbits, the dose peaks at 35° inclination. At 300 km, and for the two thin shields the dose peaks at inclinations between 60° and 70°. Below 500 km and 35° inclination, the dose drops very quickly with decreasing inclination as the orbit moves almost entirely underneath the radiation belts, with less and less possibility of intersecting it in the South Atlantic Anomaly (SAA) due to the offset dipole of the Earth's magnetic field. At these low inclinations, increasing altitude moves the orbit up the steep gradient of the inner belt with the spacecraft spending less time underneath the inner belt. By 1000 km the orbit is entirely engulfed in the inner belt at the magnetic equator and the variation of total dose over the full inclination range is less than a factor of 5. Thus, when the peak dose occurs at the lower inclinations it can be shown to result from inner belt protons. For the 300 km altitude orbits, however, the outer zone electrons can dominate the total dose causing the dose peak to form at high inclinations. At this altitude the dose peak inclination is a function of shielding thickness.

b) At inclinations above ~35° the dose increases more or less an order of magnitude for the altitude increases given in Figure 4. Thus, the yearly dose behind 0.5 in. Al for a 1000 km orbit is less than 3000 rads (Si), for 500 km, less than 200 rads (Si) and for 300 km, less than 20 rads (Si), regardless of inclination. At lower inclinations the increases in dose with altitude are larger.

c) As a function of particle type (electron versus proton) we see that for the thinnest shield (4 mils), the electrons dominate the dose at all inclinations and altitudes. For the two thickest shields (232 and 457 mils Al) protons contribute more. For a shield of 82 mils Al, depending on both altitude and inclination, either protons or outer zone electrons can make the greater contribution to dose.

d) Recall that a background subtraction was performed, to remove the contribution from the alpha source, which also removed the average contribution from galactic cosmic rays. Dose measured aboard the MIR satellite, in low Earth orbit [11], showed that during the period APEX was collecting data the cosmic ray dose was ~5 rads per year for shielding thickness comparable to the thickest shield on APEX. The galactic cosmic ray contribution to dose, then, provides a real lower bound for very low inclination, low altitude satellite orbits, as well as for interplanetary orbits.

The values of dose shown in Figure 4 were determined for a specific set of six parameters that specify the orbit, plus a time tag for the ephemeris and a start and end time for the orbit run. We have shown the effect of changing altitude and inclination. Changing the other factors will also change the yearly dose accumulations shown in Figure 4. These factors and changes are: 1) The orbit run time: Technically speaking, the yearly dose should be obtained by running APEXRAD for one year, instead of 5 days and projecting to one year. Running APEXRAD for one year for each of these orbits would take a fair fraction of a day on a PC. We have checked the change in yearly dose as a function of run time. Varying the orbit run time from 1, 2, 3, 5, 10, 30, 100 days and comparing the projected yearly dose from each leads to variations up to 3%, and comparing 5 to 100 days, results in less than a 2% variation. However, using only 1/2 a day can give large errors: a factor of 2 or more. This is particularly true for orbits that receive most dose in a small region, such as very low altitude orbits that only intersect the inner proton belt in the SAA. In these cases one third or so of consecutive orbits in a day can escape the effects of the SAA, while another consecutive one third pass through its heart. The initial ephemeris determines how the high and low dose orbits are sequenced in the day. 2) The local time of maximum latitude: Holding all other parameters constant, and changing the local time of maximum latitude leads to variations as large as 10%. 3) The time tag (month, day, year) for the ephemeris and the start time of the orbit run: For the 1000 km orbit at 30° inclination, sampling changes in the ephemeris time tag over a three-year period (while keeping every other parameter the same, including the start of the orbit run time) leads to variations as large as 24%. Generally speaking, the values in Figure 4 are near the high end of the overall variability we sampled, but we do not claim to have covered the full range of all the variables.

VI. Dose-Depth Curves as a Function of Altitude

Figures 5a, b show the total dose-depth curves for 300, 500 and 1000 km circular orbits, with inclination of 35° and 70°, respectively. Again, the yearly dose is obtained by APEXRAD which multiplies the dose from a 5 day orbit-run by 365/5 = 73. The depth-dose curves demonstrate the lack of effectiveness of shielding beyond ~100 mils Al for low inclination orbits and beyond 250 mils Al for high inclination orbits. Essentially, shielding is effective for electrons, but not for inner belt protons below 1000 km. Doubling the shielding from 250 to 500 mils Al decreases the dose by about 30%.

There is considerable interest in being able to accurately predict dose for the Space Station orbit. Toward this end, an analysis of data taken onboard the MIR spacecraft over a six year period was recently completed which organizes the highly fluctuating data by atmospheric density with some success [11]. Although we have organized the APEX data by L and B/B_0 we can use APEXRAD to give dose-depth curves for the MIR (Space Station) orbit for solar minimum conditions and compare these results to those taken on MIR over the same time period and for comparable shielding. Figure 6 gives the dose-depth curves for LOLET, HILET and total dose for an orbit with inclination 51.65, perigee of 370 km, apogee of 470 km, and right ascending node of 280.1449°. The total dose accumulated for one year behind ~.5 in. Al is 25 Rads (Si). Over the time period that coincides with the APEX data, the measured dose on MIR fluctuated considerably. The dose from the same proton and electron energy range as that measured behind the thickest shield on APEX, and extrapolated to a yearly accumulation was found to range from 7.3 to 22 rads/yr. These numbers exclude the contribution from galactic cosmic rays. The agreement is reasonably good (certainly within a factor of 2) since no adjustment has been made for differences in the response curves of the detectors or shielding details.

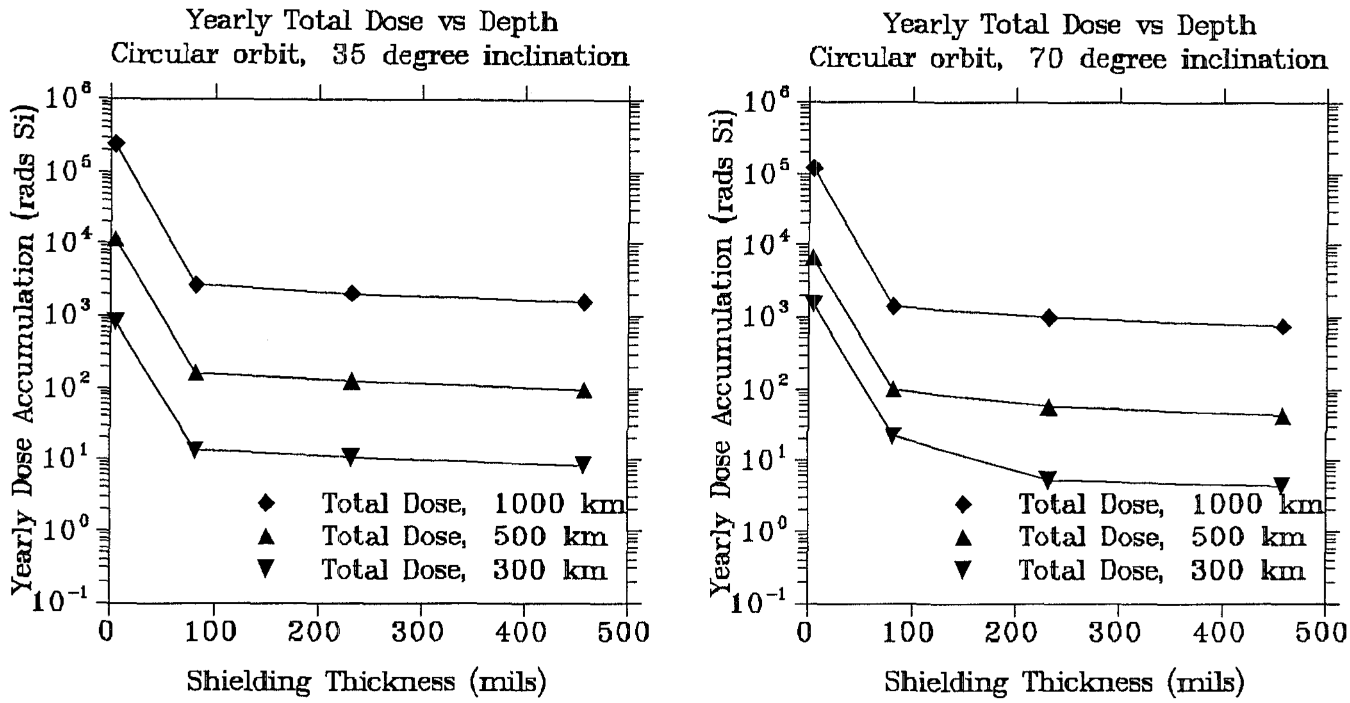

Figure 5: Dose-depth curves from APEXRAD for low altitude (300, 500 and 1000 km) orbits and for a) 35° and b) 70° orbit inclinations.

VII. Electron Outer Belt Dose as a Function of Magnetic Activity

Although electron dose can be effectively shielded, >100 keV electrons present another hazard to space missions, namely that from deep dielectric discharging [12]. The outer zone electron population is highly variable and, despite the fact that it has been monitored for years, the physical mechanisms that drive the variations are poorly understood. An intermediate step to a fully dynamic model of the outer zone electrons is ordering them by the magnetic activity index A_{P15} [5].

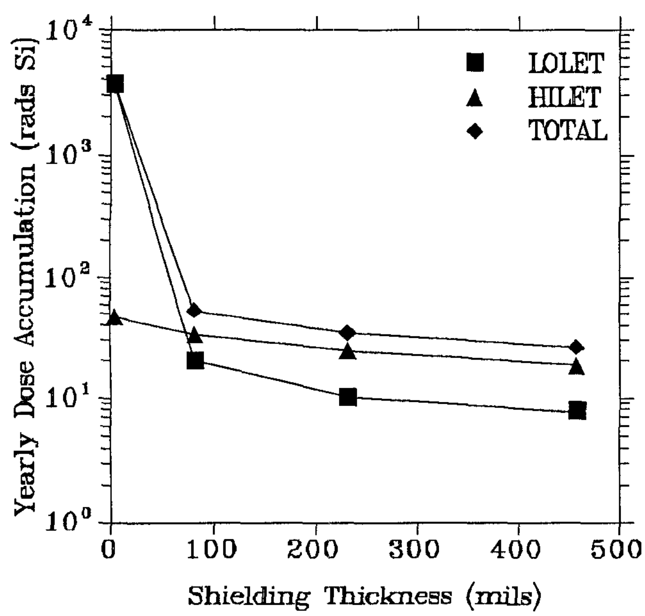

Figure 6: Dose-depth curves from APEXRAD for the MIR orbit.

As we have seen in Figure 4, the outer zone electrons play a dominant role in contributing to total dose only for high inclination, circular orbits below about 500 km and for shielding less than ~1/4 in. Al. For such orbits it is useful to anticipate the range in flux or dose that will be contributed by outer zone electrons. Figure 7 shows the dependence of yearly dose accumulation for the 500 km circular orbit as a function of inclination and magnetic activity behind 82 mils Al. The two lowest activity models have been combined because they differ so little one from the other, and including them separately renders the figure less clear. Figure 7 shows that for high inclinations the dose for 82 mils Al shielding increases systematically as magnetic activity increases. The variation from low magnetic activity to high magnetic activity can be as large as a factor of 8 at a given inclination. Figure 7 also shows that for low inclination orbits, the variation in LOLET dose with magnetic activity, albeit small, is in the reverse order of that for high inclination orbits. Since the LOLET dose for these orbits is almost entirely from inner belt protons, there seems to be a systematic decrease in this population with increasing magnetic activity. The same variation is found in the HILET dose, to a lesser degree (not shown). We can suggest two reasons why this is the case: 1) increased magnetic activity leads to greater heating of the atmosphere from precipitating particles in the auroral regions, and this increases the atmospheric scale-height; and 2) increased magnetic activity is generally accompanied by an increase in wave activity. Both effects increase loss rates for inner zone particles.

VIII. Summary

In this report we have shown that APEXRAD is a reliable model for determining dose for low altitude spacecraft between 300 and 1000 km altitudes. Sample orbit runs through APEXRAD at 300, 500 and 1000 km as a function of inclination show that maximum dose occurs between 30° and 40° inclination for all cases except the 4 and 82 mil Al shieldings at/or below 500 km altitude. In these cases, the higher inclination outer belt electron dose can dominate. For the thinnest shield (4 mils Al), electrons, either from the inner or outer belts dominate at all altitudes. For shielding greater than about 150 mils Al and for altitudes up to 1000 km, inner belt protons dominate. Therefore, for many cases, the outer belt electrons are not a major contribution to total dose and can be ignored. Where outer belt electrons contribute significant total dose, magnetic activity must be considered to obtain accurate total dose levels since outer zone electron dose can vary by more than a factor of 8 between magnetically quiet and disturbed conditions.

To best serve mission planners and those who have an interest in dose variability in low altitude orbits, APEXRAD may be obtained upon request. The request should be made to co-author E.G. Mullen (address given on title page), accompanied by a statement of intended use. The request may be made by E-mail (Mullen@plh.AF.mil) or by FAX (617 377 3160). APEXRAD is not appropriate for satellites whose orbits fall outside the altitude range of APEX, e.g., beyond 2544 km. The peak fluxes of both the inner and outer radiation belts lie at higher altitudes, so one can count on missing significant dose contributions for orbits outside the APEXRAD range. Also APEXRAD is constructed with data taken just prior to solar minimum. The trapped proton contribution to dose peaks near solar minimum. Thus, APEXRAD gives a near "worst case" for trapped proton dose.

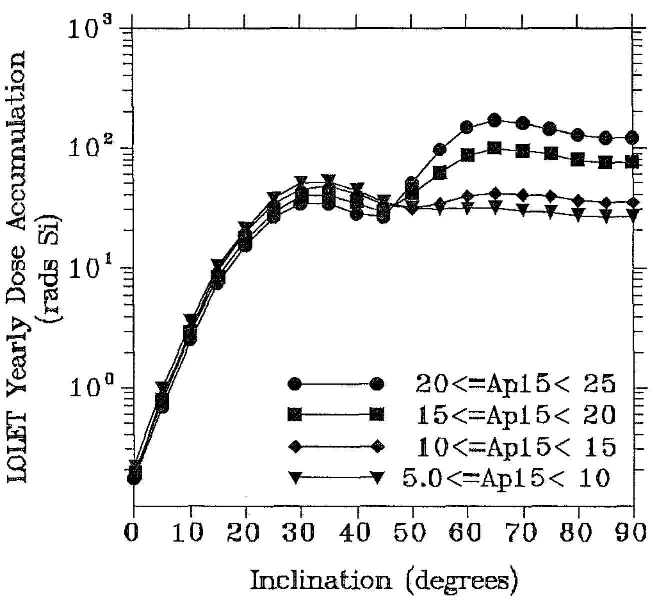

Figure 7: Dependence of LOLET dose on magnetic activity, behind 82 mils Al for a 500 km circular orbit, as given by APEXRAD.

On the other hand, the electron outer zone population has few large episodes during the APEX mission. To better simulate solar maximum conditions using APEXRAD, a different distribution of the outer zone activity-dependent models could be constructed by the user instead of using the mission average model.

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