The Trapped Proton Environment in Medium Earth Orbit (MEO)

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The Trapped Proton Environment in Medium Earth Orbit (MEO)

Gregory P. Ginet, Stuart L. Huston, C. J. Roth, T. Paul O’Brien, and Timothy B. Guild

Abstract—Energetic proton flux maps of the differential flux intensity in the medium-Earth orbit (MEO) regime (altitudes \( \sim 7000 \text{ -- } 15,000 \text{ km} \)) are developed from measurements taken by detectors aboard the Combined Release and Radiation Effects Satellite (CRRES), HEO-F1, HEO-F3 and ICO satellites. Measurement errors have been estimated by cross-calibrating to a standard sensor aboard the GOES satellite during solar proton events. Spectral inversion techniques were employed to derive differential flux spectra from the HEO and ICO integral channel dosimeters. Two methods for combining the four different satellite data sets on a standard energy and coordinate grid are presented and the ramifications due to limited spatial and temporal coverage are explored. Comparison to the NASA AP-8 models shows the new model median flux maps to be of approximately equivalent or lower magnitude in the slot region while new model 95th percentile maps are always higher. Implications for the proton dose received by MEO satellites are discussed.

Index Terms—Environmental radiation effects, extraterrestrial measurements, radiation belts.

I. INTRODUCTION

T he need for a new trapped proton model to replace the venerable workhorse AP-8 [1] has been recognized by the engineering community for some time [2]–[4]. One area of particular concern is the medium Earth orbit (MEO) region corresponding to altitudes of approximately 7000 to 15 000 km. This region is of interest for many operational reasons, and it lies in the so-called “slot” region of the radiation belts, above the main proton belt and below the main electron belt, resulting in what is presumed to be a local minimum in dose rate. However, this region has been poorly mapped and knowledge of the fluxes and dose rates contain large uncertainties. Aggravating the situation have been measurements of large transient increases in the flux lasting for many months [5], [6]. A prime example of this was the creation in March 1991 of a new proton belt which lasted for over a year and was well above the AP-8 slot region intensity specifications – a feature that was captured in the “Active” CRRESPRO proton model [7]. However, the CRRESPRO model was constructed with only 18 months of data from one phase of the solar cycle, a statistical shortcoming which has limited its application.

A significant effort is under way to develop the next-generation trapped proton and electron models for satellite design, AP-9 and AE-9, respectively [8]. The primary objectives of the effort are to: 1) improve the overall accuracy of the models; 2) provide indicators of the uncertainty in the model due to natural variability and instrument uncertainty; 3) cover a broad energy range including hot plasma, relativistic electrons and highly energetic protons; and 4) provide complete spatial coverage. As part of this effort, maps of the energetic proton flux in the slot region are being developed which will reduce the uncertainty in the MEO regime.

In this paper, an overview of the data sets, analysis techniques and resultant proton flux maps in the energy range 10–100 MeV will be presented. Attention is focused on data from satellites directly traversing the MEO slot region and does not include other data in AP-9, e.g., that from the TSX-5 satellite in the low-Earth orbit regime [9]. Table I summarizes the MEO satellites, the specific orbit parameters, time period of coverage (with percent of total database in parenthesis), instrument type (with # of channels in parenthesis) and proton energy range measured. In particular, data was used from the Proton Telescope (PROTEL) on the Combined Release and Radiation Effects Satellite (CRRES) in a geostationary transfer orbit, dosimeters on two satellites in highly elliptical orbit (HEO) and a dosimeter on the ICO satellite in a 10,000 km circular orbit. Overall there are over 6600 satellite-days of data over an 18 year time span. Although

Table I: Data Sets Used in Construction of the MEO Maps.

<table>
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<tr>
<th>Spacecraft</th>
<th>Orbit</th>
<th>Dates (% of database)</th>
<th>Instrument (# channels)</th>
<th>Energy Range (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRRES</td>
<td>350 km x 36000 km x 18°</td>
<td>7/1990 – 10/1991</td>
<td>PROTEL (19 differential)</td>
<td>1 – 86</td>
</tr>
<tr>
<td>HEO-F3</td>
<td>500 km x 39000 km x 63°</td>
<td>11/1997 – 7/2007</td>
<td>Dosimeter (3 integral)</td>
<td>&gt;5, &gt;16, &gt;27</td>
</tr>
<tr>
<td>HEO-F1</td>
<td>500 km x 39000 km x 63°</td>
<td>5/1994 – 7/2007</td>
<td>Dosimeter (4 integral)</td>
<td>&gt;20, &gt;40, &gt;55, &gt;66</td>
</tr>
<tr>
<td>ICO</td>
<td>Circular 10000 km x 45°</td>
<td>6/2001 – 12/2007</td>
<td>Dosimeter (4 integral)</td>
<td>&gt;24, &gt;33, &gt;44, &gt;54</td>
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HEO-F1 has the longest operational time, telemetry issues limited the amount of data actually returned as indicated by the small percentage of the full model data base that HEO-F1 comprises. Methods of data reduction for each detector are explained in Section II, the flux maps and selected profiles are presented in Section III, and the results summarized in Sections IV and V.

II. DATA REDUCTION

The initial data from each detector is a set of count rates as a function of spacecraft position and time recorded in well-defined channels unique to each instrument and designed to be responsive to different portions of the incident particle distribution. Each measurement is integrated over a period of the order of tens of seconds. Analysis must be performed to transform the measurements into directional differential flux $j$ (units of $# \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{MeV}^{-1}$) in a common coordinate system to allow for combination into a single set of energy dependent flux maps.

The intensity of energetic particles trapped in the Earth’s radiation belts at a point $x$ is best represented in magnetic coordinates, historically the particle energy $E$, the McIlwain $L$-shell ($L_m$) [10] and the ratio $(B/B_0)$ of the local magnetic strength $(B)$ to the magnetic field strength at the magnetic equator $(B_0)$ along a magnetic field line attached to $x$. For this work, the coordinates $(E, K, \Phi)$ have been employed where the latter two quantities are related to the so-called second and third adiabatic invariants [11]. $K$ can be thought of as a distance along a magnetic field line in a manner similar to $B/B_0 (K = 0$ at the magnetic equator and takes positive values for particles that bounce away from the equator) and for locally mirroring particles each point in space has a unique value determined by the magnetic field model but independent of energy [12]. The inverse of $\Phi$ is proportional to the Roederer $L$-shell ($L^*$), i.e., $L^* = -\mu_0 M_E/(2D_R B_0)$, where $M_E$ is the Earth magnetic dipole moment, $\mu_0$ is the permeability of free space and $D_R$ is the radius of the Earth. $L^*$ is similar in concept and magnitude to $L_m$, i.e., the approximate radial distance to the equatorial crossing of a magnetic field line. Values of $(K, \Phi)$ were determined for each satellite time history data set by using the magnetic field line and drift-shell tracing routines available from the International Radiation Belt Environment Modeling (iRBEM) library [13] together with the International Geophysical Reference Field (IGRF) [14] and the Olson–Pfitzer 1977 Quiet [15] models for the internal and external magnetic fields.

Data from two types of detectors will be analyzed. The first type is the relatively sophisticated proton telescope (PROTEL) with high energy resolution and a narrow field of view able to resolve pitch-angle distributions when mounted on a spinning satellite, as was the case with CRRES. The second type comprises dosimeters that have only a few integral energy channels and measure essentially the omnidirectional distribution.

A. Protel on CRRES

The PROTEL data from the CRRES satellite has been used extensively for both climatological modeling, e.g., the CRRES-SPRO model [16], and for studies of radiation belt dynamics [17], [18]. Details of the instrument have been described previously [19] as have methods to determine local pitch-angle distributions and correct the data from contamination by high-energy protons entering from the side when deep within the inner belt [20], [21]. A similar data reduction path was followed here to produce a database consisting of the time history of 1 minute-averaged values of $j(E, K, \Phi)$ for the set of $(K, \Phi)$ sampled by the 19 PROTEL energy channels along the CRRES orbit.

Ever-present measurement errors in particle detectors arise from imperfect electronics, inadequate calibration and response modeling, and effects due to particle contamination and secondary emission. Corrections for some of these effects can be applied during processing (e.g., electronic dead-time and count pile-up), but others depend on complex interactions of the often unknown environment with parts of the detector or satellite bus which might not be well modeled (e.g., anomalous energy deposition from particles penetrating from outside the field-of-view) and can only be approximately estimated from first principles, if at all. Consequently, a more statistical approach will be taken to derive measurement error estimates. The method is based on the presence of independent detectors nominally measuring the same quantity, e.g., differential flux at 30 MeV, all simultaneously recording the same event. If a large number of events are compared, a systematic error (i.e., the difference of the averages over all events) and residual error (i.e., the standard deviation of the difference once the systematic difference has been corrected for) can be determined between two or more detectors. Designating one detector as a “standard,” the residual error of another detector as determined by comparison to the standard can be used as an estimate for the nonstandard detector’s error bar. Typically, the magnitude of the residual error is significantly greater than the systematic error. When no detector can be deemed better than another, the average of the residual errors for all detector comparisons can be used as an error bar for all the detectors. Such a statistically derived error estimate should encompass all the sources of uncertainty provided the detectors are exposed uniformly to enough independent events of appropriate intensity and spectral range.

Fortunately for the calibration of proton detectors in near-Earth orbit, the Sun provides intermittent solar particle events (SPEs) which are nearly spatially uniform in intensity with respect to energetic protons when observed at high latitudes ($> 65^\circ$) or high altitudes ($> 25,000 \text{km}$). A series of Geostationary Operational Environmental Satellites (GOES) has hosted Space Environment Monitor (SEM) particle detectors since 1976 [22]. This package was adopted as the standard sensor from which to determine the variance of the detectors used in this study. A correction has been made to the published GOES/SEM differential fluxes in the form of a revised differential energy value designated for each channel. Instead of using the midpoint energy between the upper and lower channel boundary, the value of energy defining the median of the estimated counts in the channel was used. This value was computed assuming a power-law differential flux spectrum with index $-2.5$ (determined from examining many SPE spectra) and a constant detector response across the channel. Using these median energy values for each channel gave much better agreement than using the midpoint energies when compared with spectra from the Proton and Electron Telescope (PET) detector on the SAMPEX satellite during SPEs [23].
The error for the PROTEL data was estimated by comparing to GOES-7 data for six solar proton events over the CRRES mission. PROTEL channels were combined and interpolated in energy to create composite channels matching the five SEM channels between 5–100 MeV at the 5 min SEM measurement cadence. For each channel the systematic error was computed by averaging the data when the CRRES altitude was greater than 25,000 km during the SPEs. The simulated PROTEL channels were then adjusted by the systematic offset, and histograms were made of the number of measurements over all SPEs as a function of the value of the natural log of the ratio of the PROTEL to SEM measurement values. Assuming a lognormal error distribution, the standard error of the values of \( \ln(j) \) as measured by the PROTEL detector channels was estimated as the average of the ratio value at the 34th and 68th percentile. The error values for the composite PROTEL channels were then assigned directly to the original PROTEL channels comprising the composites and ranged from 0.18 for five channels (1–4 MeV), 0.11 for nine channels (6–47 MeV), and 0.08 for three channels (55–82 MeV).

### B. Dosimeters on HEO-F1, HEO-F3, and ICO

With broad integral energy channels and a wide field-of-view the dosimeters aboard the HEO and ICO satellites produce data which requires nontrivial spectral inversion and angle-response modeling to yield \( j[K, \Phi] \) values that can be meaningfully compared and combined. Crucial to the analysis is knowledge of the spectral response of the integral dosimeter channels. Ideally, this information is obtained by preflight calibration with particle accelerators and modeling of the energy deposition using Monte-Carlo codes such as GEANT4. For the instruments on HEO and ICO this type of information on the proton response was limited. However, Guild, et al. [24] have performed a postflight cross-calibration to determine the best fit geometric factor and residual error in the integral flux for each of the HEO and ICO dosimeter channels. In a manner similar to the statistical determination of the PROTEL channel variances, the dosimeter data was compared to GOES/SEM data during SPEs when the subject satellites were at high altitudes and seeing approximately the same flux distribution. Over 50 SPEs in the period 1997–2005 were observed by the GOES-8 or GOES-11 satellites. Measurements in SEM integral flux channels were log-log interpolated to the dosimeter channel threshold energy values. After integrating the dosimeter data to match the 5 min GOES measurement interval the ratios between the dosimeter channel count rates and SEM fluxes were obtained for all intervals over all SPEs. The average of this set provides the effective geometric factor for the dosimeter channel. Recomputing the dosimeter data as integral fluxes over the set of SPE measurements using this factor and then computing the ratio to the SEM values allows for statistical computation of the residual error in the natural log of the integral flux values predicted by the dosimeters at the channel threshold energies. Standard errors of \( \ln(j) \) for the HEO and ICO integral channels are typically of order 0.2–0.4 though the lowest energy HEO-F3 channel (＞5 MeV) has a value of 0.9.

To convert the integral flux intensities at a relatively small number of energies into differential flux intensities over a range of energies, a spectral inversion technique must be employed. The task is simplified by noting that in the energy range relevant to the HEO and ICO dosimeters the trapped proton spectrum can be reasonably approximated as a power law. Fig. 1 illustrates the power-law nature in the \( \sim 10–100 \text{ MeV} \) range by showing spectra from the empirical CRRESPRO Quiet, CRRESPRO Active and AP-8 models near the heart of the inner zone proton belt. Also shown is the spectrum derived from the numerical diffusion model of Selesnick, et al. [25]. For spectral inversion a power-law function is assumed for the range 10–100 MeV, with the amplitude and spectral index being free parameters. Above 100 MeV, the power law attaches to an exponential function with a fixed e-folding energy of 345 MeV, a value determined from the Selesnick model to be a reasonable approximation over much of the inner belt. At each measurement interval the inversion process begins with an estimate of the count rates in each dosimeter channel obtained by assuming nominal values for the power-law parameters and integrating the spectrum over the channel energy range. Multiplying by the channel geometric factor yields an estimate of the count rate. A lognormal penalty function combining all channels is evaluated and numerical optimization processes are employed to find the optimal power-law parameters that minimize the penalty. If a channel has a zero count rate, the process assigns a zero value to the power-law amplitude. Variances of the natural log of the differential flux are estimated using the empirically determined error of the integral fluxes and standard error propagation analysis.

To validate the process, differential fluxes obtained from the inversion process were compared to the GOES fluxes during six SPEs for several different energy channels. Fig. 2(a) shows differential flux as a function of time at 51 MeV obtained from inverting the ICO, HEO-F1, and HEO-F3 data compared to the values directly measured by the GOES-8 P5 channel at 51.2 MeV for the 28 Oct 2003 SPE. The average flux spectrum over the interval indicated in Fig. 2(a) is shown in Fig. 2(b). Agreement is good, especially given that the SPE spectrum is
not a pure power law between 10–100 MeV as demonstrated by the baseline GOES curve in Fig. 2(b). Results in Fig. 2 are typical of all the SPEs investigated, with agreement always the best in the range 40–70 MeV.

As a final step, the angle-averaged fluxes (but now differential in energy) measured by the approximately $2\pi$ solid angle field-of-view dosimeters must be transformed into an estimate of the unidirectional flux at a specific pitch angle. To do this a model of the proton pitch-angle distribution developed from the CRRESPRO quiet model is used to derive an energy and $L_m$ dependent conversion factor between the omnidirectional flux and the locally mirroring unidirectional flux, i.e., $j(E, K, \Phi)$, where $(K, \Phi)$ are the invariant coordinates of a locally mirroring particle at the spacecraft location and time of the measurement. An additional averaging over all look directions must be included since the attitude of the spacecraft is unknown. Estimates of error due to the pitch angle modeling and look-angle averaging are then added to the error budget of the final $j(E, K, \Phi)$ reported as a function of time along the satellite orbits.

III. PROTON FLUX MAPS

The time history databases of all the satellites processed to provide $j(E, K, \Phi)$ values with variances can then be used to construct maps of the proton flux distribution. Flux intensity values will be reported on a standard energy grid of 1, 2, 4, 8, 10, 15, 20, 30, 50, 60, 80, and 100 MeV.

Fig. 3 shows the spatial coverage of the inner belt and slot region by the CRRES, HEO, and ICO satellites. A $(K, \Phi)$ grid is used with a uniform spacing of 0.05 (RE$^2$/Gauss$^{1/2}$)$^{3/2}$ in $K^{3/2}$ and 0.025 RE$^2$/Gauss in $\Phi$ with ranges as indicated in the figure. All references to $(K, \Phi)$ hereafter will be made in these units. Also illustrated is the $(K, \Phi)$ curves approximating the loss-cone (solid black curve) and the values of $\Phi$, where $L^* = 2$ ($\Phi = 1.05$) and $L^* = 3$ ($\Phi = 0.625$). For each satellite sequential flux and variance values in the same $(K, \Phi)$ bin are averaged to produce a reduced time history database at the grid resolution. Fig. 3 shows the total number of observations as a function of $(K, \Phi)$ for each satellite. The spatial coverage of the HEO and ICO satellites is far from uniform. Striations in the CRRES coverage are artifacts of the initial flux time series which were binned at 5º pitch-angle resolution.

Temporal coverage is also intermittent. Fig. 4 shows a typical time profile including all the data assigned to a particular bin, in this case the bin illustrated by the black square in Fig. 4(a) $(K = 0.05, \Phi = 0.725)$. Each measurement is shown by three points at a given time, the median of $\ln(j)$ and the median ± the standard deviation as calculated from the logarithmic errors reported with each measurement.

Examining Figs. 3 and 4, several features become apparent. CRRES provides comprehensive spatial coverage but is limited in time, covering only 18 months in 1990–1991. This period includes the great geomagnetic storm of March 1991 which created new radiation belts in the slot region. HEO-F3 provides a much longer time series (> 10 years) but has limited spatial coverage including a large wedge-like gap in K for $\Phi < 0.9$ [Fig. 3(b)]. ICO also has a relatively long time series (> 5 years) but its spatial coverage is restricted to an even smaller region at low $K$ near $\Phi = 0.75$, i.e., near the magnetic equator towards the outer part of the slot region. HEO-F1 has reasonable spatial coverage spanning a wide swath of $\Phi$ at low $K$ [Fig. 3(d)] but has only a few short periods of coverage intermittently spread over the time interval.

Merging the individual flux maps derived from each satellite into a single map representative of the complete proton belt climatology presents challenges. Without coverage of all the possible states of the radiation belt in all locations over a statistically meaningful period of time, i.e., at least several solar cycles, a statistically accurate empirical map is simply not possible. Conceivably, gaps could be filled with quasi-empirical and physics-based techniques (Section V) but such analysis is beyond the scope of this paper. Rather, two composite empirical models will be presented to illustrate the range of variation possible by combining the individual satellite data sets in ways that emphasize different features of the limited coverage.

To combine a set of measurements in a given $(K, \Phi)$ to determine a statistical quantity such as the mean, median or 95th percentile, a bootstrapping method has been employed [26]. Boot-
strapping involves computing a statistical quantity by repeatedly reanalyzing a data set created by resampling the baseline distribution with replacement. After a large number of repeats, an average value and standard deviation of the statistical quantity is obtained which has been shown to be characteristic of the underlying distribution. For the satellite data considered here a further feature will be added in that each resample of a data point will choose a random variation of the amplitude of the point. The variation will be weighted by a Gaussian centered on the nominal $\ln(j)$ value with a standard deviation equal to the standard logarithmic error. In this way, measurement error is introduced into the map. All models presented in this paper have used 100 bootstrap iterations.

Composite Model 1 is computed by a bootstrap of the entire data set in each bin, irrespective of satellite. The resultant median and 95th percentile values are shown in Fig. 5(a) and (b), re-
spective, for 60 MeV. A weighted nearest-neighbor smoothing routine has been implemented and, for intuitive purposes, the \((K, \Phi)\) coordinates have been plotted in a dipole-like manner but with the same definition of bins as was used in Fig. 3. \(\Phi\) decreases monotonically outward and the center bin axis is the equivalent to the magnetic equator with \(\Phi(L^*)\) decreasing (increasing) from 1.75 (1.0) at the inner boundary to 0.5 (3.8) at the outer boundary. Starting at a \(\Phi\) point on the equator, where \(K = 0\), \(K\) increases along a line resembling a dipole field line until high latitudes where the loss cone is reached. The dark horizontal line represents the equator, and the median map is shown above this line, while the 95th percentile map is shown below the line. Dark lines in the middle represent the \(L^* = 2\) (inner) and \(L^* = 3\) (outer) points (cf. Fig. 3.)

Composite Model 2 is derived by first computing the bootstrapped mean, median, and 95th percentile for each satellite data set independently. The composite value is then simply the average of the available satellite bootstrapped values in a given bin, i.e., four at the most. Fig. 6 presents the median and 95th percentile values of Composite Model 2 for 60 MeV.

Profiles of the 60 MeV composite models compared to AP8 as functions of \(K\) for a fixed \(\Phi = 0.9\) \((L^* = 2.15)\) in the slot region (square marker in Fig. 5) are shown for the median and 95th percentile flux in Fig. 7. Similar profile comparisons with respect to \(L^*\) for \(K = 0\) are shown in Fig. 8. It was assumed that \(L_{\text{min}} = L^*\) in plotting the AP8 model results. Typical spectra from both composite models are illustrated in Fig. 9 for points within the inner zone [Fig. 9(a)] and the slot region [Fig. 9(b)]. The locations of the points are denoted by circle (inner) and square (slot) markers in Fig. 5(a). Spectra computed from both the median and 95th percentile maps are shown together with the AP8\(\text{max/min}\) models (dotted line) are shown.

**IV. DISCUSSION**

At first reflection it might seem that Composite Model 1, the bootstrap of the complete set, should give the best answer. It more accurately represents the probability of occurrence of different flux values since each time measurement is weighted equally, assuming the systematic errors between data sets are much smaller than the residual errors. However, when there is incomplete spatial coverage some unphysical features can appear. An example of this can be seen in the \(K\) profiles of Fig. 7(a) and (b), where the Composite Model 1 flux increases with increasing \(K\) in the range \(K^{3/4} = 0.1\). Pitch-angle diffusion theory dictates that trapped protons should have monotonically decreasing profiles in \(K\) on the time scales investigated here. The model behavior is due to the relatively large number of HEO-F3 measurements compared to CRRES measurements below \(K^{3/4} \sim 0.1\) [Fig. 3(b)]. Since HEO-F3 did not sample the March 1991 storm and its aftermath the sampled values of the flux in this region are on average of lesser magnitude than CRRES, and the bootstrap process will emphasize the more numerous low amplitude HEO-F3 values. Above \(K^{3/4} \sim 0.1\) the number of CRRES measurements exceed those of HEO-F3 and consequently the higher amplitude CRRES values dominate. If HEO-F3 had visited the higher \(K\) region more frequently, it can be assumed that the profile would become monotonically. This effect is also seen in the 95th percentile \((K, \Phi)\) maps [Fig. 5(b)] as the bulges of high intensity off the equator.
Composite Model 2, the average of the individual bootstrapped satellite sets, is limited in that it does not appropriately weight the fraction of time measured by a particular satellite if the satellite’s measurement period is significantly shorter than the characteristic time scale for the system, i.e., the solar cycle. This is especially relevant to the proton maps given the very high intensity environment measured by the CRRES satellite after the March 1991 storm, though only for a relatively short time (≈ 6 months.) The behavior is apparent in Fig. 8(b), where the Composite Model 2 values dominate in the slot region where a second proton radiation belt was formed after the March 1991 storm. The opposite effect is illustrated by the discontinuity in the Composite Model 2 flux at $L^*=1.5$. Below this value there are no HEO-F3 measurements and the CRRES values determine the model value. Above this value the HEO-F3 and HEO-F1 measurements begin to appear and even though smaller in number and much lower in amplitude they have a significant effect since the three satellite values are being combined with equal weight.

Despite the unusual characteristics, the composite model results can be compared meaningfully to AP8 as is done with the profiles in Figs. 7 and 8 and the spectra in Fig. 9. In general, median values of the composite models are higher than AP8 in the inner zone and of the same order or somewhat lower in the slot region. The 95th percentile values are always higher than AP8, sometimes by more than an order of magnitude. More relevant to satellite design applications is a comparison of the predicted dose versus depth of shielding for characteristic satellite orbits. Table II shows the dose due to 30–80 MeV protons behind several thicknesses of Aluminum for medium-Earth orbits at 9000 km ($L^*=1.41$) circular and 0 and 90 degrees inclination using flux map of the means. Not surprisingly, Composite
Model 2, which weights the CRRES results more heavily, predicts a dose approximately a factor of 8 higher than the NASA models while the Composite Model 1 is only about 1.1–3 times higher.

V. SUMMARY

A set of empirical energetic proton flux maps has been developed for the inner belt and slot region using data from the CRRES, HEO-F3, HEO-F1, and ICO satellites – all with orbits directly measuring the high-altitudes relevant to MEO. A relatively large volume of data was used compared to previous models, and comprehensive processing was performed to ensure all satellite databases estimate the differential, unidirectional flux on a common energy and spatial grid with estimates of the variance. These improvements provide more information and insight into the radiation environment with a definite reduction. The level where a “standard solar cycle” model of the complete space weather phenomena could be produced has been developed for the inner belt and slot region using data from the CRRES satellite, IEEE Trans. Nucl. Sci., vol. 43, no. 2, p. 353, Apr. 1996.


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