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Key Points:

- We build a 39-year composite of POES energetic electron fluxes as daily latitude distributions
- We remove temporally varying background noise due to cosmic rays from the electron fluxes
- We remove the significant long-term variation in the electron fluxes due to changing orientation of satellite orbital planes

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New Homogeneous Composite of Energetic Electron Fluxes From POES Satellites: 1. Correction for Background Noise and Orbital Drift

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Abstract One of the most popular long-term data sets of energetic particles used in, for example, long-term radiation belt studies and in atmospheric/climate studies is perhaps the National Oceanic and Atmospheric Administration/Polar Orbiting Environmental Satellites (POES) data set, which extends nearly continuously from 1979 to present. The energetic particle measurements by the Medium Energy Proton and Electron Detector instrument onboard the POES satellites have had many instrumental problems, which have made quantitative estimates of energetic particle fluxes somewhat difficult. However, in the recent years, these instrumental deficiencies have been studied and corrected. Here we aim to construct a new long-term composite record of energetic electrons based on the Medium Energy Proton and Electron Detector data. In this study we point out that there are also other remaining factors, not related to instrument construction, which still severely impact the overall homogeneity of the 39-year POES data set. We concentrate here on studying and correcting two issues: (1) temporally varying background noise related to cosmic rays and (2) drift in the orientation of satellite orbital planes, which changes the sampling location of the satellites over time. In particular, we show that the drift of satellite orbital planes leads to rather large changes in the electron fluxes over time, which could be misinterpreted as true temporal changes without the corrections. These changes can be rather large, a factor of 3 or more in the poleward edge of the precipitation zone, and are likely to have a large impact, for example, on atmospheric ionization estimates based on POES data.

Plain Language Summary One of the longest satellite records of energetic electrons has been measured by the Polar Orbiting Environmental Satellites (POES) since 1979. These data are actively being used to study, for example, radiation belts and atmospheric and climate effects of energetic particle precipitation. Here we point out two problems jeopardizing the homogeneity of the long-term POES record of energetic electrons: (1) varying level of background noise related to high-energy cosmic rays that contaminate the measurements and (2) slow change of the orientation of satellite orbital planes, which changes the location where electrons are being measured. In particular, we show that the orbital change can lead to large long-term drifts in the measurements, which could be misinterpreted as being true temporal changes without the corrections presented here. These changes can be rather large, a factor of 3 or more, and are likely to have a large impact, for example, on atmospheric ionization estimates based on POES data, which are used to study climate effects of energetic electron precipitation.

1. Introduction

Currently, one of the most widely used data set on precipitating energetic particles in atmospheric studies is the National Oceanic and Atmospheric Administration (NOAA)/Polar Orbiting Environmental Satellites (POES) data set, which spans nearly continuously from 1979 to present. During the 39 years of operation, the POES program has consisted of 14 satellites altogether, with five still operational. However, it has been long recognized that the energetic particle measurements by the Medium Energy Proton and Electron Detector (MEPED) instrument onboard the POES satellites have numerous instrumental problems, which have made quantitative estimates of energetic particle fluxes somewhat problematic. In the recent years, significant effort has been put into understanding and correcting these instrumental deficiencies. Asikainen and Mursula (2011) and Asikainen et al. (2012) studied the radiation damage induced degradation and effects of electronic noise of MEPED proton detectors and presented correction factors and associated methods to

correct the proton measurements of all POES satellites. Recently, also Sandanger et al. (2015) and Ødegaard et al. (2016) studied the effects of radiation damage with slightly different methodology and also essentially verified the earlier results.

From an atmospheric viewpoint, precipitation of energetic electrons is perhaps even more interesting than proton precipitation, since electrons penetrate deeper in the atmosphere than protons of similar energies. However, the MEPED electron measurements are well known to be contaminated by energetic protons, which can also penetrate the electron instrument through the shielding foil that covers the instrument aperture. Asikainen and Mursula (2013) studied the response of MEPED detectors to electrons and protons and showed that the difference in the thickness of the shielding foil of Space Environment Monitor (SEM)-1 MEPED instruments (flown on satellites up to NOAA-14) versus SEM-2 instruments (flown starting with NOAA-15, launched in mid-1998) leads to a significant systematic difference in the electron measurements by these two instrument versions. Asikainen and Mursula (2013) presented modeled instrument efficiency curves and associated methodology to correct the electron measurements for contamination due to energetic protons and to calibrate them for nonideal instrument efficiencies. These corrections were shown to greatly reduce the differences due to instrument design and to improve the homogeneity of the entire POES data series.

However, as we will show in this study, there are also other remaining problems which cause long-term biases and inhomogeneities in the 39-year long POES electron data set. The first problem is a background noise level in the electron measurements, which is not related to electrons but rather to cosmic rays penetrating the instrument. Since cosmic rays vary with time (roughly in antiphase with the sunspot cycle), this background noise level also slowly varies with time. In order to obtain a clean data set for electron precipitation, this varying background level needs to be removed.

The second problem is related to the drift in the orientation of satellite orbital planes over long periods of time. For some of the longest running satellites, for example, NOAA-15, this drift is rather large, over six magnetic local time (MLT) hours. Because particle populations in space are highly dependent on magnetic local time, such large orbital drifts are expected to lead to potentially large changes in the observed fluxes. Accordingly, some parts of the long-term changes in the measured fluxes, especially in decadal scale, result from orbital plane changes misinterpreted as true temporal change in the fluxes. It should be noted that while the cosmic ray noise is a general problem of electron data quality, the flux change related to orbital plane drift is not a problem per se if one is specifically considering the MLT distribution of the fluxes. The orbital plane drift only becomes a problem if one wishes to obtain a spatially and temporally homogeneous record of the fluxes.

The third and most severe problem is related to the orientation of the two nearly orthogonal telescopes in the SEM-1 and SEM-2 carrying satellites. The orientations of both the local vertical telescope (0° telescope) and the local horizontal telescope (90° telescope) differ between SEM-1 and SEM-2. Since the pitch angle distributions of electrons are typically anisotropic, the systematic difference in telescope orientations means that the SEM-1 and SEM-2 telescopes systematically measure different pitch angles and thus a different part of the electron pitch angle distribution. This is expected to lead to a systematic difference between SEM-1 and SEM-2 electron fluxes. Furthermore, this difference is dependent on latitude, since the pitch angles of the telescopes depend predominantly on the latitude on the polar orbits of the POES satellites.

In this paper we will discuss and correct the varying background noise floor and variations related to orbital plane drift. The inhomogeneity caused by differing telescope orientations in SEM-1 and SEM-2 will be discussed and corrected in a follow-up paper (part 2 of this work). For the purpose of creating a long-term homogeneous data set with sufficient spatial and temporal resolution to be used, for example, in atmospheric and radiation belt studies, we construct a spatial distribution of energetic electrons as a function of corrected geomagnetic latitude (CGMlat) and MLT in daily time resolution for both hemispheres. In section 2, we will shortly review the MEPED data and construction of the daily flux distributions. In section 3, we discuss the identification and removal of the varying background noise floor from the measurements before other corrections. Section 4 discusses the MLT distribution of electrons and presents a method of removing the long-term variation in the fluxes caused by changing orientation of the satellite orbits. In section 5, we evaluate the effect of these two corrections on the data. Section 6 presents a summary and conclusions.

2. Data

2.1. MEPED Instrument: SEM-1 and SEM-2 Differences

The POES satellites include a Space Environment Monitor (SEM) instrument package for measuring energetic protons and electrons. Satellites up to NOAA-14 had the SEM-1 version of the instrument package, while from NOAA-15 onward (launched in mid-1998), the satellites carry an improved version called SEM-2. In this work we concentrate on energetic electrons, which are measured in three integral energy channels: E1 (>30 keV), E2 (>100 keV) and E3 (>300 keV) by the MEPED instrument. The measurements are made by two nearly orthogonal telescopes, the local vertical (0°) telescope and the local horizontal (90°) telescope. The sampling time of both telescopes is 2 s, but in regions of very low particle fluxes, the 2-s sampling time can be too short to obtain meaningful counts. To overcome this, we have used 16-s averaged measurements (i.e., average of 8 consecutive data points). In this work we use satellites NOAA-6, NOAA-7, NOAA-8, NOAA-10, NOAA-12, NOAA-15, NOAA-16, NOAA-17, NOAA-18, Medium Energy Proton and Electron Detector (METOP)-2, NOAA-19, and METOP-1. (NOAA-14 is not used because its MEPED data are corrupted since its launch.)

The orientations of the SEM-1 and SEM-2 telescopes differ significantly. In both instrument versions, the 0° telescopes point roughly in the radial direction (outward from Earth) with only a small but significant difference in telescope orientation. In SEM-1, the 90° telescope points roughly perpendicular to the satellite orbital plane, while in SEM-2, it points antiparallel to satellite velocity being thus almost perpendicular to the orientation of the corresponding SEM-1 telescope. SEM-1 and SEM-2 versions of the MEPED electron detector also have some important differences in instrument construction. The most important difference in the detector is the thickness of the nickel foil shielding the instrument aperture from low energy protons, which also affects the instrument sensitivity. The MEPED electron telescope sensitivities to electrons and protons were recently modeled by Asikainen and Mursula (2013), and they presented efficiency functions and algorithms to calibrate the electron measurements. The electron calibration was performed by removing the contamination due to energetic protons by using the NOAA/POES proton measurements recently corrected for effects of radiation damage and electronic back detector noise (Asikainen & Mursula, 2011; Asikainen et al., 2012) and correcting the fluxes by the modeled electron efficiencies. It was noted that in the higher E2 and E3 energy channels, the proton contamination can seriously affect the measurements and sometimes even dominate the real electron fluxes. It was also noted that the sensitivity differences between the two MEPED versions cause a significant overall difference between the measured fluxes (on average a factor of about 2 in the E1 channel, where the effect is the largest), which is eliminated by the calibrations. More detailed information about the SEM-1 instruments are given by Hill et al. (1985), Seale and Bushnell (1987), and Raben et al. (1995) and about the SEM-2 instruments by Evans and Greer (2000) and Green (2013). Note, however, that our data processing is based on the raw MEPED data and not on the processing methodology described by Green (2013). The corrections and calibrations introduced to the MEPED measurements have been documented by Asikainen and Mursula (2011), Asikainen et al. (2012), Asikainen and Mursula (2013), and Asikainen (2017).

2.2. Daily Latitude Distributions of Electrons

The purpose of this work is to produce a spatially and temporally homogeneous long-term energetic electron data set with sufficient spatial and temporal resolution to be used, for example, in studying and modeling the atmospheric response of electron precipitation and long-term evolution of the radiation belts. To this end, we first computed for each day the average electron fluxes in 2° wide bins of CGMlat (Gustafsson et al., 1992) of the foot of the field line (FOFL; set at 120-km altitude) threading the satellite location poleward from 40° latitude (i.e., $L \approx 1.75$) in both hemispheres. The fluxes below this latitude were omitted, since they are usually very small except in the region dominated by the South Atlantic Anomaly. The measurements in this region may also have some problems related to calibration caused by the very large fluxes of relativistic electrons, which may contaminate the proton measurements (Yando et al., 2011) that are needed to remove proton contamination from the electron measurements.

The CGMlat is essentially computed by tracing the magnetic field line determined from the International Geomagnetic Reference Field magnetic field model from the FOFL point to the magnetic equator and then tracing back from that point to the same FOFL altitude along a dipolar magnetic field line. It should be noted that the CGMlat at the FOFL point, λ_{fofl} , is approximately related to the L-value of the field line by the equation $L = \cos^{-2} \lambda_{\text{fofl}}$. Unlike geographic or even dipolar geomagnetic coordinates, the corrected geomagnetic coordinates organize the particle fluxes on roughly constant CGM latitudes much like using the L-value as the organizing parameter. However, the advantage of using CGMlat instead of L-value is that the

Figure 1. A composite of unnormalized electron fluxes from the 0° telescope of NOAA-6, NOAA-8, NOAA-10, NOAA-12, and NOAA-15 satellites as a function of time and Corrected Geomagnetic Latitude (CGMlat). The fluxes in both hemispheres have been averaged over the two opposite magnetic local time sectors sampled by the satellites. Panels from top to bottom depict the monthly sunspot number (SSN) as a reference and the E1, E2, and E3 energy channels. Note that the region between latitudes -40° and 40° is not considered here and has been excluded from the plots.

Figure 2. Same as Figure 1 but for the 90° telescope.

satellites sample all CGM latitudes with the same rate, that is, the number of data points in each CGMlat bin is roughly constant along the orbit. Due to the relation between L-value and invariant latitude, the number of data points per unit L-value change decreases strongly as a function of L and causes the low L-values to be sampled at much higher rate than the higher L-values, where actually most of the particle precipitation occurs. The daily CGMlat distributions of the electron fluxes were computed separately for the three energy channels in each satellite, each telescope and each quarter of the satellite orbit (i.e., two opposite MLT sectors from north and south).

To give a broad overview of the temporal evolution of the latitude distribution of electrons, Figures 1 and 2 show composites of data from NOAA-6, NOAA-8, NOAA-10, NOAA-12, and NOAA-15 satellites, which are all initially at the time of their launch on a similar dawn-dusk orbit. As a general feature, one can see that the precipitation is mostly concentrated on two belts, the outer belt between about 60° and 75° and another one most clearly visible in 90° telescope (Figure 2) between 45° and 60° with a clear slot region with weaker fluxes in between around 60° . One can also see the systematic solar cycle variation in the fluxes peaking in the declining phase of the cycles in 1984–1985, 1994, and 2003, which was recently discussed in more detail by Asikainen and Ruopsa (2016). In many cases, one can see large enhancements of the fluxes (esp. in 90° telescope), which cover the entire range of latitudes penetrating from the outer belt into the inner belt and filling the slot region between. These enhancements typically occur during magnetic storms driven by coronal mass ejections and high speed streams. Another clear feature are the intermittent spikes of flux filling the entire polar regions poleward from the outer belt (75° – 90°). These spikes are solar particle events, where large amounts of energetic solar protons and electrons penetrate the polar caps, which are magnetically connected to the solar wind. Note that many studies do not consider MEPED electron data during solar particle events because of severe proton contamination, but the corrections discussed above applied to the MEPED data remove the proton contamination also during these times.

The last subtle but significant feature relevant for the present study is the very low intensity background flux level, which is especially visible in the E2 and E3 channels of the 0° telescope. One can clearly see, especially in the polar regions, how this background level changes with the solar cycle and is the strongest during solar minima around 1987, 1995, and 2010 and the weakest around solar maxima, for example, in 1990 and 2001–2002 and 2014. This varying background level in the polar regions is due to cosmic rays, which penetrate the electron instrument, but cannot be fully removed by the correction algorithm presented in Asikainen and Mursula (2013). At some latitudes, the proton decontamination algorithm can remove part of the background relatively successfully (e.g., between 65° N and 75° N in 0° telescope E3 channel), but mostly, it is visible in the fluxes. A similar cosmic ray background is also present in the 0° E1 channel and all 90° telescope channels, but because of the color scaling, it is not clearly visible in Figures 1 and 2. It should be noted that the noise background is present to some degree in all latitudes and generally results partly from cosmic rays, partly from low level fluctuations of the magnetospheric electron fluxes and partly from the inherent statistical error in the measurement process, when the count rates are low.

Figures 1 and 2 also reveal our motivation to homogenize the MEPED data set. In mid-1998, when NOAA-15 carrying the first SEM-2 version of MEPED was launched, one can see a sudden and clear change in the latitude distribution of electrons in both hemispheres and both telescopes in all energy channels. This discontinuity is caused by the difference of telescope viewing directions between SEM-1 and SEM-2 instruments. We will discuss these differences and their correction in a follow-up paper. While the difference between the SEM-1 and SEM-2 telescope orientations causes the most visible inhomogeneity in the data set, there are other issues as well, which need to be addressed before the telescope orientation difference can be normalized. One of these is the removal of the cosmic ray noise background, and the other is the normalization of the fluxes due to the drift in satellite orbits. In the next two sections, we will discuss these two problems.

3. Removing the Temporally Varying Noise Floor

The top panel of Figure 3 shows as an example the E1, E2, and E3 fluxes of 90° telescope at 86° N– 88° N latitude bin from NOAA-15. In this plot one can clearly see the varying background flux level superimposed with solar particle events seen as intermittent spikes. Note that the fluxes related to solar particle events are partly due to energetic protons and partly due to energetic electrons. The proton contribution has been removed as a part of the proton decontamination (Asikainen & Mursula, 2013). The remaining part, which is due to electrons, is an important source of electron precipitation in the polar latitudes and has to be retained in the data. By experimenting with different methods, we found that the noise level for a time series from a single latitude bin could be determined as follows. For each 181-day window, we found the points where (1) the absolute difference in the linear flux between two consecutive days is less than $10 \text{ cts/cm}^2 \text{ sr s}$ and (2) the flux is below $150 \text{ cts/cm}^2 \text{ sr s}$ (i.e., $\log_{10}(\text{flux}) = 2.1761$). After this, we computed the average flux Y and average time T of these data points in each window. We then smoothed the windowed values with a 5 point running mean, and finally, to obtain the daily noise flux level, we interpolated the smoothed values for

Figure 3. (top) E1, E2, and E3 fluxes of the 90° telescope at 86–88° N latitude from NOAA-15 demonstrating the slowly varying background flux levels. (bottom) Logarithmic ratio of the E1 and E3 flux levels (blue) and E2 and E3 flux levels (red).

each day with a smooth Piecewise Cubic Hermite Interpolating Polynomial. The results of this computation for the 90° E1, E2, and E3 channels are also shown in the top panel of Figure 3. One can see that this method can fairly well identify the varying noise floor. However, at some latitudes, mostly between 46° and 74° the ring current and radiation belt related fluxes are typically so high that the noise floor is difficult to identify. In those latitudes, where the noise floor could not be identified with the method described above, we interpolated the noise levels with a Piecewise Cubic Hermite Interpolating Polynomial from those adjacent latitudes where identification could be made.

In the E1 and E2 energy channels, the fluxes are typically so high at all latitudes except at the pole that reliable direct identification of the noise background cannot be done. One can also see from Figure 3 that the noise levels at different energy channels are different with the noise decreasing with energy. This is also generally true for other latitudes and satellites as well. However, the bottom panel of Figure 3, which shows the logarithmic ratios of E1/E3 and E2/E3 fluxes clearly indicates that the ratio of the varying noise levels at the different energy channels is relatively constant. By examining the different latitudes, we found that the floors of the E1/E3 and E1/E2 flux ratios in these latitudes do not depend on the latitude. Assuming that the same holds true also for those latitudes where E1 and E2 noise floor cannot be directly observed but E3 can, we can use the E3 noise floor to estimate the noise floor of the other energy channels. When examining the E1/E3 and E2/E3 flux ratios at different hemispheres and different satellites, we found that the ratios are also very similar in north and south and in all satellites, although with SEM-1 satellites having slightly larger ratios. We calculated for all satellites in both hemispheres the fifth percentile of the E1/E3 and E2/E3 flux

Figure 4. Example of background noise level removal for 90° telescope E3 channel in NOAA-15 in the dusk sector in three different corrected geomagnetic latitude (CGMlat) bins. (top) 86–88° corresponding to polar regions. (middle) 62–64° corresponding to center of the outer radiation belt. (bottom) 42–44° corresponding to region inside the inner radiation belt.

ratios at each latitude bin poleward of 80° and then took the median of these percentile values as estimates of the noise floor ratios. Roughly, it was found that the E1/E3 logarithmic flux ratio was about 0.2 and for E2/E3 about 0.1, with small differences between hemispheres and satellites. Finally, the noise backgrounds of E1 and E2 channels were estimated by adding the offset implied by these logarithmic noise floor ratios to the logarithmic E3 noise floor.

After the noise levels for each latitude bin, telescope and energy channel were determined; the noise level was subtracted from the data in linear scale. This was done separately for all satellites in the two opposite MLT sectors and hemispheres. Those flux values, which became negative after the subtraction, were set to zero. As a typical result of the noise removal procedure, Figure 4 displays the original data (blue), noise-corrected data (red), and the determined noise level (black) for NOAA-15 in the dusk sector for three different latitude bins in the polar region (top), heart of the radiation belts (middle), and in the innermost magnetosphere inside the inner radiation belt (bottom). One can see that the procedures outlined above effectively remove the varying noise level and set the remaining fluxes at a constant baseline level at all latitudes. The noise removal has the largest effect on those fluxes which are close to the flux level of 100 cts/cm² sr s but has a negligible effect on larger fluxes observed during active times.

Figure 5. Monthly averaged Magnetic Local Time of the ascending part of satellite orbits on the Northern Hemisphere at 40° N corrected geomagnetic latitude (CGMlat). Different colors depict different satellites as indicated on the figure. The descending part (not shown) of the orbits is roughly on the opposite side of the Earth and thus separated by 12 MLT hours from those shown in the figure.

4. Correcting for the MLT Drift of Orbital Planes

It is known that the intensity of energetic electron populations in space and the various processes that scatter them into the loss cone are highly dependent on the MLT sector (e.g., Lam et al., 2010). This is a concern for the homogeneity of the MEPED data series if the orientations of the satellite orbital planes change considerably with time. Figure 5 shows the monthly averaged MLT of the ascending part of the orbit in the Northern hemisphere at 40° N CGMlat for all the satellites used in this work. One can see that all the satellites up to NOAA-15 (apart from NOAA-7) were placed on a dawn-dusk orbit with the ascending phase around 19 MLT. Starting from NOAA-16, the satellites were also positioned on differently oriented orbits thus increasing the local time coverage of the measurements considerably. The most striking feature visible in Figure 5 is the rather large periodic drift in the orientation of the satellite orbits. For example, for NOAA-15, the orbit drifts back and forth with an amplitude of about three MLT hours with a period which can be estimated to be about 25 years. Such drifts are observed for all other satellites with the largest amplitude of about eight MLT hours observed in NOAA-16. With such a large change, it is probable that some of the long-term variation in the electron fluxes observed by the satellite is actually caused by the change in the orientation of the orbit, which brings the satellite into a different part of the electron population in space.

In order to normalize the observations for the changes in MLT, we first need to estimate the MLT distribution of electrons. This can be done by considering simultaneous observations from as many satellites as possible in different MLT sectors. We used NOAA-15, NOAA-16, NOAA-17, NOAA-18, METOP-2, NOAA-19, and METOP-1 for the time period 3 December 2006 (determined by start of METOP-2 observations, see Figure 5) until 2 October 2016 (end of the data set at the time of writing) to construct an MLT distribution of the fluxes relative to a reference MLT. That is, for each hemisphere and latitude band of each satellite separately, we computed the difference of the monthly averaged logarithmic fluxes and the reference flux at a roughly constant MLT, which was conveniently obtained from METOP-2 satellite, whose orbital plane does not drift in time. The reference MLT from METOP-2 could be chosen either from the premidnight or prenoon MLT sector. It turned out that the absolute flux as a function of MLT depicts quite a large variation, because the overall flux level can vary considerably between quiet and disturbed times. However, the logarithmic flux difference relative to a reference MLT has a much smaller scatter and better reveals how the fluxes are relatively distributed over MLT. Moreover, we found that the fluxes at all latitude bins in the in the Southern Hemisphere are better organized by using the MLT of the most equatorward part (-40° latitude) of the orbital segment in question instead of using the MLT of the corresponding latitude bin, which may be significantly different especially at high latitudes. However, in the Northern Hemisphere, the fluxes are

Figure 6. An example of MLT (magnetic local time) distributions of relative E1 fluxes from 90° telescope from the latitude band 74–76° at north (left) and south (right). The large colored dots depict monthly averaged data, and the color indicates the time of the data point from earliest (blue) to latest (red) according to the color scale. The fluxes have been computed as a difference of the logarithmic flux at a given MLT and the flux observed by METOP-2 at a roughly constant MLT in premidnight (upper cluster of points) or prenoon (lower cluster of points). The black curves display nonparametric fits to the monthly averaged points, and the magenta curves are averages of these fits.

slightly better organized by using the MLT of the corresponding latitude bin (the result is not significantly different even if we use the MLT of the equatorward part also in the north).

Figure 6 shows two examples of MLT distributions at a particular latitude band of 74–76° in north (left) and south (right). The large colored dots depict the difference of the monthly averaged logarithmic fluxes of individual satellites (other than METOP-02) and the logarithmic fluxes of METOP-02 at the reference MLT. The colors of the points indicate the time of the data point from earliest (blue) to latest (red) according to the color scale. The upper (lower) cluster of points depicts log-flux differences relative to METOP-2 premidnight (prenoon). The plots clearly show that the relative MLT distribution at monthly time scale does not significantly depend on time and that the form of the MLT distribution is very similar regardless of which of the two METOP-2 MLT sectors is chosen as the reference. To obtain an overall average MLT distribution for the relative flux difference, we smoothed the two clusters of points separately with the robust LOcally reWEighted Scatterplot Smoothing method and computed their average. The two individual nonparametric fits are shown in Figure 6 by the black curves and their average as the magenta curve. When considering the MLT distributions, we found that for latitudes poleward of 82° there was no evidence of a systematic MLT dependence of the fluxes, indicating that the solar particles cover the polar caps relatively uniformly in MLT. Note also that because of the uniform MLT distribution of electron fluxes related to solar particle events, these fluxes do not affect the relative MLT distributions.

The MLT distributions can now be used to normalize the change in the flux caused by drift of the satellite MLT in time. In this procedure we first calculated for each satellite the average MLT (at -40° latitude of the corresponding orbital segment in south or at the corresponding latitude bin in the north) during the first 365 days of operation. Let us denote this MLT as MLT_0 . The idea of the MLT normalization is to estimate how much the fluxes have changed as the MLT of the satellite changes from the initial value of MLT_0 to $MLT(t)$ as a function of time. The MLT normalized flux is then an estimate of what the satellite should have measured at MLT_0 had it not drifted. Denoting the relative MLT distribution of the flux at latitude bin i as $Y_i(MLT)$, the observed flux $F_i(t)$ at time t (corrected for noise background) can be normalized for MLT changes with the equation

$$\log_{10} F_{MLTnorm,i}(t) = \log_{10} F_i(t) + \log_{10} Y_i(MLT_0) - \log_{10} Y_i(MLT(t)), \quad (1)$$

where $F_{MLTnorm,i}(t)$ is the MLT normalized flux at latitude bin i . We used this same equation and the MLT distributions estimated for SEM-2 satellites to normalize also the fluxes of SEM-1 satellites, because SEM-1 satellites do not have a sufficient MLT coverage to directly estimate the MLT distribution for them. Even

Figure 7. Relative MLT (magnetic local time) distributions of 0° telescope. The (a)–(c) depict E1, E2, and E3 energy channels, respectively. Panels on the left-hand side depict Northern Hemisphere and those on the right-hand side Southern Hemisphere. The color indicates the difference in $\log_{10}(\text{flux})$ relative to midnight (0 MLT).

though there is a systematic difference in the fluxes between SEM-1 and SEM-2 due to the telescopes pointing in different directions, this difference is mainly seen as an offset in the logarithmic fluxes. This means that the form of the MLT distribution in each latitude bin is very similar in SEM-2 and SEM-1 satellites and only differ by roughly a constant offset in logarithmic scale. In fact, we checked the differences of logarithmic fluxes between two opposing MLT sectors in the SEM-1 satellites and found that they closely agree with the MLT distributions derived from the SEM-2 data.

We also considered the daily MLT distribution of the fluxes and found that they depict considerable scatter with a range of several orders of magnitude (not shown). Thus, the MLT distributions of any given day can deviate significantly from those determined by the fits based on monthly averages. Furthermore, the

Figure 8. Same as Figure 7 but for the 90° telescope.

deviations of the distribution from the fit depend on the MLT indicating that also the form of the daily MLT distribution can vary significantly. This means that the MLT distributions found above cannot be taken as an accurate measure of daily MLT distribution but can only be used to make a rough statistical estimate of how the flux changes due to relatively small changes of MLT.

To obtain an overall view of the relative MLT distributions over all latitudes, Figures 7 and 8 show the MLT-CGMLat distributions of E1, E2, and E3 fluxes at North and South for 0° and 90° telescopes. These distributions have been calculated relative to midnight by subtracting at each latitude the value of the distribution of that latitude at 0 MLT. To display estimates of the full MLT distributions, also in those MLTs

Figure 9. Example of the effect of MLT (magnetic local time) normalization of 90° E1 fluxes of NOAA-15 at two different latitude bins of the Northern Hemisphere. The blue curves depict the monthly averaged original fluxes not normalized for MLT and the red curves the MLT normalized fluxes. Top panel corresponds to 74–76° N at the poleward edge of the precipitation region and the bottom panel to 64–66° N at the heart of the ring current/radiation belt. For comparison, the panels also show the corresponding flux, not normalized for MLT, from NOAA-16 (yellow curves). Note that NOAA-16 occupies the same MLT with NOAA-15 around 2008 and the same MLT as NOAA-15 is normalized to in 2011.

where there is no data (see, e.g., Figure 6), we linearly interpolated the values of the MLT distributions for all MLTs separately for each latitude bin (note that the MLT distributions are periodic so that, e.g., values between 20 and 4 MLT can be interpolated with values from premidnight and post-midnight MLTs). Note also that this interpolation was not needed when the fluxes were normalized for the MLT change. As a general feature, one can see that the 0° and 90° fluxes tend to maximize relative to midnight at the dawn to noon sector, which is consistent with the distribution of whistler mode chorus waves mainly thought to be responsible for the pitch angle scattering of electrons at these energies (e.g., Lam et al., 2010; Meredith et al., 2011). An exception to this general pattern is the 0° E3 fluxes, which are slightly smaller at the dayside than at nightside (Figure 7c). The MLT distributions depicted in these figures contain many interesting features, but they are not the main interest in the present paper, which only uses the distributions to homogenize the MEPED electron data set.

To demonstrate the effect that the MLT normalization has on the fluxes, Figure 9 displays an example of 90° E1 fluxes of NOAA-15 at two different latitude bins of the Northern Hemisphere. Top panel corresponds to 74–76° N at the poleward edge of the precipitation region and the bottom panel to 64–66° N at the heart of the ring current/radiation belt. The blue curves depict the fluxes not normalized for MLT and the red curves the MLT normalized fluxes. For comparison, the panels also show the corresponding flux, not normalized for MLT, from NOAA-16 (yellow curves). Note that NOAA-16 occupies the same MLT as NOAA-15 around 2008 and the same MLT as NOAA-15 is normalized to (i.e., about 19 MLT) in 2011 (see Figure 5). From the top plot, one can see that the MLT normalization has quite a large effect at the poleward edge of the precipitation region. In the beginning, the normalized and unnormalized fluxes are practically identical

Figure 10. A composite of electron fluxes cleaned from background noise and normalized for magnetic local time drift of the satellite orbital planes. The composite has been computed using the data from the 0° telescope of NOAA-6, NOAA-8, NOAA-10, NOAA-12, and NOAA-15 satellites. The fluxes in both hemispheres have been averaged over the two opposite magnetic local time sectors sampled by the satellites. Panels from top to bottom depict the monthly sunspot number as a reference and the E1, E2, and E3 energy channels.

Figure 11. Same as Figure 10 but for the 90° telescope. CGMlat = Corrected Geomagnetic Latitude.

(the small differences result from the variations of satellite MLT at timescales shorter than 1 year), but the MLT normalization increasingly enhances the flux up to about a factor of 2 from 2003 to 2016. One can see that the monthly averaged unnormalized fluxes of NOAA-15 and NOAA-16 closely agree in 2008, when the two satellites were in the same MLT. The MLT normalized NOAA-15 flux in 2011 is about a factor of 2 larger than the unnormalized flux, but one can see that it closely agrees with the unnormalized flux of NOAA-16 in 2011, when NOAA-16 is at the same MLT as NOAA-15 is normalized to. This confirms that the MLT normalization of the flux truthfully compensates the effect of the satellite orbital plane drift. From the

Figure 12. Ratio between corrected and original 0° telescope flux composites shown in Figures 10 and 1, respectively. Panels from top to bottom depict the monthly sunspot number as a reference and the E1, E2, and E3 energy channels. CGMlat = Corrected Geomagnetic Latitude.

bottom plot of Figure 9, one can see that in the heart of the radiation belts, where the fluxes are the largest, the MLT normalization for NOAA-15 has a relatively small effect. This is because the fluxes at this particular latitude depend only weakly on MLT in the MLT range in which NOAA-15 drifts during its operational period. Also generally, the net effect of the MLT normalization depends strongly on the latitude because the MLT distribution is highly dependent on latitude (see Figures 7 and 8).

Figure 13. Ratio between corrected and original 90° telescope flux composites shown in Figures 11 and 2, respectively. Panels from top to bottom depict the monthly sunspot number as a reference and the E1, E2, and E3 energy channels. CGMlat = Corrected Geomagnetic Latitude.

5. Evaluation of Corrected Data

Figures 10 and 11 show a composite of electron fluxes from 0° and 90° telescopes, respectively, which have been cleaned for background noise and normalized for the MLT drift of the satellite orbital planes. As in Figures 1 and 2, this composite has been built from NOAA-6, NOAA-8, NOAA-10, NOAA-12, and NOAA-15 satellites. One can see that the noise removal effectively eliminates the varying background flux level, which

was apparent especially at the polar latitudes. This greatly improves the visibility of electron flux variations on top of the background. However, one can also see that in the E3 channel of the 0° telescope, the electron fluxes recorded by the SEM-2 satellites are mostly very small and close to the limit of detectability. One can clearly distinguish these fluxes from the background only during strong activity times, for example, in 2003 and 2004, while, for example, in 2008–2011, the fluxes are mostly lost into the suppressed noise background. The SEM-1 satellites have a better visibility of 0° E3 fluxes due to the fact that the telescope samples slightly larger pitch angles than the corresponding SEM-2 telescope. These differences will be discussed in the follow-up paper in more detail.

The effect of the MLT normalization is less visible in Figures 10 and 11. Thus, for better evaluation of the net effect introduced by the noise removal and the MLT normalization, Figure 12 displays the ratio between corrected and original flux composites from the 0° telescope shown in Figures 10 and 1, respectively. Figure 13 shows the corresponding ratios for the 90° telescope composites (Figures 11 and 2). The effect of the noise removal is also seen here as the decrease in the fluxes roughly by an order of magnitude in those regions which are dominated by background noise. One can also see, especially in the E1 channels, that the MLT normalization tends to affect the fluxes especially in 1986, 1996–1998, and 2003–2006, when NOAA-6, NOAA-12, and NOAA-15 drifted significantly over MLT (see Figure 5). Comparing with the statistical MLT distributions in Figures 7 and 8, one can see that the drift in the orbital planes brings the satellites further away from the intense precipitation in the dawn sector. Thus, compensating for this drift increases the fluxes. This effect is particularly evident at the poleward edge of the outer belt (70–75° in both hemispheres) in NOAA-15, where the MLT normalization compensates the decrease in the flux caused by NOAA-15 orbit drifting further away from the intense precipitation region at the dawn-noon sector (see Figure 5). This correction can increase the fluxes up to a factor of more than 3 at these latitudes. This was also seen before in Figure 9. Thus, the MLT normalization is important, and without it, the flux decrease at these latitudes would be misinterpreted as a temporal change, when in fact, it is due to a spatial change of the satellite location.

6. Summary and Conclusions

The energetic particle measurements from the MEPED instrument onboard the NOAA/POES satellites currently form the most important long-term data set providing information about precipitation of energetic electrons and protons into Earth's atmosphere. Previous work on this data set has solved many problems related to instrument degradation and calibration and has greatly improved the quality of the data (Asikainen, 2017; Asikainen & Mursula, 2011, 2013; Asikainen et al., 2012). Based on these previously corrected energetic electron measurements, we here first composed from each satellite the daily averaged latitude distribution of electrons in three integral energy channels, two nearly orthogonal telescopes, two opposite MLT sectors, and two hemispheres. This data set can provide information about the latitudinal distribution of electron precipitation in daily time resolution.

By studying this data set, we found that even after the correction of instrumental issues, there remained mainly three problems that still cause significant spatial and temporal inhomogeneities in the data series from 1979 to present. In this paper we addressed the first two problems, which are related to temporally varying background noise and to the slow drift of the satellite orbital planes, which changes the sampling location of the satellite.

We showed here that the energetic electron measurements suffer from background noise, which is mostly caused by cosmic rays varying in antiphase with the solar cycle. This background noise is not related to variation of electrons in the ring current and radiation belts or to solar energetic particles and thus needs to be removed. We showed that especially in the highest energy E3 channel measuring electrons above 300 keV, the background noise significantly distorts the perceived long-term evolution of these fluxes. We developed methods, which allow us to identify and remove the temporally varying background noise level separately in each latitude. This greatly improved the overall visibility of the electron fluxes in all energy channels. However, in 0° telescope of SEM-2 satellites, the highest energy electron fluxes are often so small that they remain below the limit of detectability and cannot be distinguished from the noise background.

We showed that the orientations of the satellite orbital planes slowly drift in MLT over long time periods (of the order of 10–30 years). It was shown that because the energetic electron populations around Earth are strongly organized by MLT, the drift of the satellite orbital plane led to slow temporal drift in the electron

fluxes, which could easily be misinterpreted as real temporal change of the flux level related, for example, to simultaneous solar cycle variations. Fortunately, with the rather large number of operational POES satellites from 2006 to present in differently oriented orbits, the MLT coverage of measurements was sufficient to estimate the average MLT-latitude distribution of fluxes in both hemispheres. Using these distributions, we were able to normalize the measurements to compensate the effects of satellite orbital drift. It was shown that these orbital drift-related changes depend on the latitude and were the strongest at the poleward edge of the outer radiation belt, where the magnitude of MLT drift-related change could be more than a factor of 3. Since the most significant atmospheric effects of electron precipitation are confined to the high latitudes, the large effects introduced at the poleward edge of the precipitation zone may have significant implications for the atmospheric effects of electron precipitation estimated from these data.

After the correction of these two problems, the temporal homogeneity of the data set was greatly improved, but there still exists a large difference between the measurements of SEM-1 and SEM-2 satellites. This is caused by the difference in telescope viewing directions between SEM-1 and SEM-2 satellites and will be discussed in a follow-up paper.

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References

- Asikainen, T. (2017). Calibrated and corrected POES/MEPED energetic particle observations, *The ESPAS e-infrastructure: Access to data in near-Earth space* (pp. 57–69). London, UK: EDP Sciences. <https://doi.org/10.1051/978-2-7598-1949-2>
- Asikainen, T., & Mursula, K. (2011). Recalibration of NOAA/MEPED energetic proton measurements. *Journal of Atmospheric and Solar-Terrestrial Physics*, 73, 335–347. <https://doi.org/10.1016/j.jastp.2009.12.011>
- Asikainen, T., & Mursula, K. (2013). Correcting the NOAA/MEPED energetic electron fluxes for detector efficiency and proton contamination. *Journal of Geophysical Research: Space Physics*, 118, 6500–6510. <https://doi.org/10.1002/jgra.50584>
- Asikainen, T., Mursula, K., & Maliniemi, V. (2012). Correction of detector noise and recalibration of NOAA/MEPED energetic proton fluxes. *Journal of Geophysical Research*, 117, A09204. <https://doi.org/10.1029/2012JA017593>
- Asikainen, T., & Ruopsa, M. (2016). Solar wind drivers of energetic electron precipitation. *Journal of Geophysical Research: Space Physics*, 121, 2209–2225. <https://doi.org/10.1002/2015JA022215>
- Evans, D. S., & Greer, M. S. (2000). *Polar Orbiting Environmental Satellite Space Environment Monitor—2: Instrument descriptions and archive data documentation*, (NOAA Technical Memorandum OAR SEC-93). Boulder, CO: U.S. Dept. of Commerce.
- Green, J. (2013). MEPED telescope data processing algorithm theoretical basis document version 1.0. NOAA NESDIS-NGDC.
- Gustafsson, G., Papitashvili, N. E., & Papitashvili, V. O. (1992). A revised corrected geomagnetic coordinate system for epochs 1985 and 1990. *Journal of Atmospheric and Terrestrial Physics*, 54(11–12), 1609–1631. [https://doi.org/10.1016/0021-9169\(92\)90167-J](https://doi.org/10.1016/0021-9169(92)90167-J)
- Hill, V. J., Evans, D. S., & Sauer, H. H. (1985). *TIROS-N/NOAA satellites Space Environment Monitor archive tape documentation*, (NOAA Technical Memorandum ERL SEL-71). Boulder, CO: NOAA Environmental Research Laboratories.
- Lam, M. M., Horne, R. B., Meredith, N. P., Glauert, S. A., Moffat-Griffin, T., & Green, J. C. (2010). Origin of energetic electron precipitation >30 keV into the atmosphere. *Journal of Geophysical Research*, 115, A00F08. <https://doi.org/10.1029/2009JA014619>
- Meredith, N. P., Horne, R. B., Lam, M. M., Denton, M. H., Borovsky, J. E., & Green, J. C. (2011). Energetic electron precipitation during high-speed solar wind stream driven storms. *Journal of Geophysical Research*, 116, A05223. <https://doi.org/10.1029/2010JA016293>
- Ødegaard, L.-K. G., Tysøy, H. N., Sandanger, M. I. J., Stadsnes, J., & Sørås, F. (2016). “Space weather impact on the degradation of NOAA POES MEPED proton detectors”. *Journal of Space Weather and Space Climate*, 6(A26), 15. <https://doi.org/10.1051/swsc/2016020>
- Raben, V. J., Evans, D. S., Sauer, H. H., Sahm, S. R., & Huynh, M. (1995). *TIROS/NOAA satellite Space Environment Monitor data archive documentation: 1995 update*, (NOAA Technical Memorandum ERL SEL-86). U.S. Dept. of Commerce.
- Sandanger, M. I., Ødegaard, L.-K. G., Nesse Tysøy, H., Stadsnes, J., Sørås, F., Oksavik, K., & Aarsnes, K. (2015). In-flight calibration of NOAA POES proton detectors—Derivation of the MEPED correction factors. *Journal of Geophysical Research: Space Physics*, 120, 9578–9593. <https://doi.org/10.1002/2015JA021388>
- Seale, R. A., & Bushnell, R. H. (1987). *The TIROS-N/NOAA A-J Space Environment Monitor subsystem*, (NOAA Technical Memorandum ERL SEL-75). Boulder, CO: U.S. Dept. of Commerce.
- Yando, K., Millan, R., Green, J., & Evans, D. (2011). A Monte Carlo simulation of the NOAA POES Medium Energy Proton and Electron Detector instrument. *Journal of Geophysical Research*, 116, A10231. <https://doi.org/10.1029/2011JA016671>