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Key Points:

- Difference in SEM-1/SEM-2 telescope directions leads to large differences in fluxes
- Novel statistical methodology used to transform daily SEM-1 flux distributions to SEM-2 level is presented
- Spatially and temporally homogeneous record of daily energetic electron latitude distributions from 1979 to present is formed

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New Homogeneous Composite Of Energetic Electron Fluxes From POES: 2. Intercalibration of SEM-1 and SEM-2

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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 NOAA/POES (Polar Orbiting Environmental Satellites) data set, which extends nearly continuously from 1979 to present. The present study aims to construct a new homogeneous long-term composite record of daily latitude distributions of energetic electrons based on the MEPED (Medium Energy Proton and Electron Detector) data. Part 1 of this study corrected the data for temporally varying background noise related to cosmic rays and for the drift in the orientation of satellite orbital planes. The present paper addresses the final and most severe problem for the data homogeneity, caused by the difference of telescope pointing directions in older SEM-1 and newer SEM-2 versions of the MEPED instrument. Because the telescope pitch angles and the electron pitch angle distribution change with latitude, the difference in SEM-1 and SEM-2 fluxes depends on latitude and varies from time to time. The systematic flux differences between SEM-1 and SEM-2 can range between a factor of 1.5 to more than an order of magnitude. Novel statistical methodology based on principal components and canonical correlation mapping is presented here to robustly transform the daily SEM-1 electron latitude distributions into SEM-2 level. The data from different POES satellites are then combined into a spatially and temporally homogeneous composite series, which is well suited, for example, for long-term studies of radiation belts and precipitation related atmospheric ionization and its chemical and dynamical effects in the atmosphere/climate system.

1. Introduction

Measurements by the MEPED (Medium Energy Proton and Electron Detector) instrument onboard the POES (Polar Orbiting Environmental Satellites) form the longest record (from 1979 to present) of energetic particles measured at low-altitude orbit. Accordingly, the data set is of great interest in radiation belt and atmospheric studies. The MEPED data suffer from many instrumental problems related, for example, to radiation damage, contamination, and detector sensitivity. Fortunately, these instrumental problems have been studied and corrected in several past studies. The degradation of proton detectors due to radiation damage was corrected by Asikainen and Mursula (2011) and Asikainen et al. (2012). Asikainen and Mursula (2013) modeled the detector sensitivities of the SEM-1 (older) and SEM-2 (newer) versions of the MEPED instrument and developed methods to correct the electron measurements of both instruments for proton contamination and nonideal detector sensitivity.

However, when considering the entire POES data set formed by 12 satellites, it turns out that there are also other remaining factors, which jeopardize its homogeneity. The first part of this study (Paper 1, Asikainen & Ruopsa, 2019) considered the energetic electron measurements from the POES and showed that they display a temporally varying noise background, which is due to cosmic rays penetrating the instrument. It was also shown that the orientations of the POES orbital planes slowly drift in magnetic local time (MLT), thus changing the sampling location of the satellites over time. This causes a slow temporal change of the measured electron fluxes, which needs to be compensated to have a correct view of the true temporal evolution of the fluxes. In Paper 1 these two problems were discussed and corrected.

However, a third and the most severe problem was also pointed out, which is related to differences in telescope orientations between the older SEM-1 (flown until NOAA-14) and newer SEM-2 (starting with NOAA-15) versions of the MEPED instrument. Since the pitch angle distributions of electrons are typically anisotropic a systematic difference in telescope orientation means that the SEM-1 and SEM-2 telescopes

systematically measure different pitch angles and thus a different part of the electron distribution. Here it is shown that this leads to a large systematic difference between SEM-1 and SEM-2 measurements. 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 satellites. The difference in fluxes also varies somewhat with time because the electron pitch angle distribution at different latitudes changes from time to time. This paper presents novel statistical methodology for scaling the SEM-1 measurements to the level of SEM-2 in order to obtain a homogeneous record of energetic electrons. The scaling will be based on a careful intercalibration of simultaneous measurements from NOAA-12 (SEM-1 satellite) and NOAA-15 (SEM-2 satellite), which have already been corrected for the background noise and orbital plane drift in Paper 1.

The paper starts by first reviewing in section 2 the basic aspects of MEPED instruments and the data used in this work. Statistical methods necessary for understanding the SEM-1/SEM-2 scaling will be discussed in section 3. Section 4 then discusses the application of the statistical methodology to develop a scaling between SEM-1 and SEM-2 data, which will then be applied to data from all SEM-1 satellites. The resulting homogeneous composite record of electrons will then be discussed and the effects of the applied scaling will be assessed in section 5. Conclusions are given in section 6.

2. Data

The POES include a SEM (Space Environment Monitor) instrument package for measuring energetic protons and electrons. The satellites up to NOAA-14 had the SEM-1 version of the instrument package while from NOAA-15 (launched in mid-1998) onward the satellites carry an improved version called SEM-2. This work concentrates 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 telescope (0°) and the local horizontal telescope (90°). 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, 16-s averaged measurements (i.e., average of eight consecutive data points) have been used here. The data have been obtained from NOAA-6, NOAA-7, NOAA-8, NOAA-10, NOAA-12, NOAA-15, NOAA-16, NOAA-17, NOAA-18, METOP-2, NOAA-19, and METOP-1 satellites. (NOAA-14 is not used because its MEPED data are corrupted from launch).

SEM-1 and SEM-2 versions of the MEPED electron detector 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 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 POES proton measurements 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 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 and their use by Evans and Greer (2000), Rodger et al. (2010), and Green (2013). Note, however, that the data processing used here 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), and Asikainen and Mursula (2013).

Figure 1a shows a schematic of a POES satellite orbit along with the directions of SEM-1 and SEM-2 telescopes superposed on the same satellite. In SEM-2 the satellite coordinate system is defined so that X axis points radially toward Earth, Y axis is antiparallel to satellite velocity, and Z axis completes the right-handed system, being perpendicular to the satellite orbital plane. The 0° telescope points almost radially outward from Earth being rotated by 9° from $-X$ axis toward the $-Z$ axis. The 90° telescope is almost antiparallel to satellite velocity but has been rotated 9° from $+Y$ axis toward $-Z$ axis. These rotations were made to ensure a clear field of view.

Figure 1. (a) Schematic of telescope viewing directions in SEM-1 and SEM-2 relative to the satellite orbit and magnetic field. (b) A typical example of pitch angles of the 0° and 90° telescopes in SEM-1 and SEM-2 as a function of corrected geomagnetic latitude (CGMlat) during one day.

In SEM-1 the X axis points toward the Earth as in SEM-2 but there exists some confusion about the direction of the SEM-1 Y and Z axes. Seale and Bushnell (1987) state that the $+Y$ axis of the satellite coordinate system points along the satellite velocity, that is, opposite to that in the SEM-2 satellites. Consequently, the Z axis, which completes the right-handed set, would point opposite to SEM-2 Z axis. However, Raben et al. (1995) state that the $+Y$ axis would point opposite to the satellite velocity like in SEM-2. In the process of recalculating all auxiliary data (e.g., telescope pitch angles) dependent on satellite location (Asikainen, 2017) both satellite coordinate system definitions were tested. It was found that the original pitch angles stored in the SEM-1 data records are consistent with the Raben et al. (1995) definition, which will thus be used here. For the SEM-1 telescope directions both Seale and Bushnell (1987) and Raben et al. (1995) state that the 0° telescope points precisely along the $-X$ axis (no 9° tilt as in SEM-2). Seale and Bushnell (1987) state that the 90° telescope is pointed toward the $-Z$ axis from where it has been rotated by 9° toward $-X$ axis. Accordingly, the angle between the orientations of the 0° and 90° telescopes is 81° for SEM-1 and 88.6° for SEM-2.

Figure 1b shows the central pitch angles of SEM-1 and SEM-2 telescopes as a function of corrected geomagnetic latitude (CGMlat) during one day as a representative example. It is clear from this plot (and from the schematic in Figure 1a) that as the satellite orbits the Earth the angles between the telescopes and the local magnetic field vector, that is, the central pitch angle sampled by the telescopes, change, too. It should be noted, however, that since the field of view of the telescopes is 30°, the actual range of pitch angles that the telescopes sample can be quite large. At high latitudes the magnetic field is roughly radial and the pitch angles of the 0° telescopes in SEM-1 and SEM-2 are small so that they measure particles moving approximately parallel or antiparallel to field lines (depending on the hemisphere). At low latitudes the 0° telescopes point roughly perpendicular to the magnetic field lines. From Figure 1 one can see that the SEM-1 90° telescope samples nearly perpendicular direction relative to magnetic field at all latitudes, while the SEM-2 90° telescope samples roughly perpendicular direction only at high latitudes. At low latitudes the SEM-2 90° telescope actually measures field-aligned particles. Because of these differences it is clear that SEM-1 and SEM-2 satellites sample the particle pitch angle distributions with their telescopes in a very different way and this is expected to lead to a systematic difference in their measurements. Furthermore, this effect is latitude dependent, since the difference in telescope pitch angles depends on the latitude.

2.1. Daily Latitude Distributions of Electrons Corrected for Background Noise and Orbital Drift

In Paper 1 the POES electron measurements from all satellites were organized into daily averaged latitude distributions in 2° wide bins of CGMlat. These distributions were computed for each satellite separately in the two opposite local time sectors of the polar satellite orbit in both hemispheres and separately for the two telescopes (0° and 90°) and the three energy channels. More detailed information about the construction of these daily average distributions is given in Paper 1.

In Paper 1 the daily averaged distributions were corrected for temporally varying background noise and for the changes caused by slow drifts of the satellite orbital planes in MLT. The orbital drift correction effectively transforms the electron flux observed at the momentary MLT into the MLT sector, which the satellite

Figure 2. 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 (SSN) as a reference and the E1, E2, and E3 energy channels, respectively.

initially had in the beginning of its operational period. Figures 2 and 3 display a broad overview of the temporal evolution of the latitude distribution of electrons obtained as the result of the corrections in Paper 1. These data form the basis of the present study. The figures show a composite 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. Thus, the corrected fluxes from these satellites correspond to the same MLT sector at all times and are in this respect spatially homogeneous. The overall characteristics of the electron latitude distributions and their solar cycle variations were discussed in Paper 1.

Figures 2 and 3 clearly reveal the remaining problem related to the composite MEPED data set. In July 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 telescopes at all energy channels. The changes are larger at low latitudes and more clearly visible in the 90° telescope. In the SEM-1 era before July 1998 the fluxes especially below 60° CGMlat are systematically larger than after July 1998. There are similar differences even at higher latitudes, but their magnitude is smaller and are thus less clearly visible in the color plots. The cause for this systematic drop in the overall flux level is the difference in the telescope pointing directions between SEM-1 and SEM-2. Note that there are also other clear changes of

Figure 3. Same as Figure 2 but for the 90° telescope.

electron distribution, for example, in late 2005, but these are related to variations of geomagnetic activity and solar wind driving and not to instrumental changes. At low latitudes the SEM-2 90° telescope measures very small pitch angles, while the corresponding SEM-1 telescope measures pitch angles close to 90° (see Figure 1b). Because the pitch angle distributions typically peak at 90° pitch angle, the SEM-1 telescope systematically sees larger fluxes. At higher latitudes the difference in SEM-1 and SEM-2 90° telescope pitch angles decreases and so does the systematic difference between the fluxes. Although the differences in the pitch angles of the 0° telescopes are rather small, one can clearly see a systematic difference between the SEM-1 and SEM-2 fluxes, especially at latitudes below 60°. It is puzzling to see that the SEM-1 0° fluxes seem to be systematically somewhat higher than SEM-2 0° fluxes even though the corresponding pitch angles in SEM-1 should be slightly smaller. Possible reasons for this will be discussed later on.

3. Statistical Methods

Let us next discuss the statistical methods used here to correct the data for the differences caused by the differing SEM-1 and SEM-2 telescope orientations.

3.1. Principal Component and DINEOF Analysis

Principal component analysis (PCA) can be used to transform a multivariate set of m correlated data series into a new set of m variables, called principal components (PC), which are uncorrelated with each other and

have as large a variance as possible. The PCs are obtained by projecting the data onto the principal axes, or empirical orthogonal functions (EOFs), which are m -dimensional vectors. Before PCA the data series are first centered by subtracting the mean and then organized into a $n \times m$ data matrix $\mathbf{X}$, where each of the m columns represents one data series having n number of data points. The PCA is then computed by singular value decomposition (SVD) of the centered data matrix:

$$\mathbf{X} = \mathbf{U}\mathbf{S}\mathbf{V}^T, \quad (1)$$

where $\mathbf{U}$ is a $n \times m$ matrix, $\mathbf{S}$ is a $m \times m$ diagonal matrix, and $\mathbf{V}$ is an $m \times m$ orthonormal matrix so that $\mathbf{V}\mathbf{V}^T = \mathbf{V}^T\mathbf{V} = \mathbf{I}$. In PCA this decomposition is often written as

$$\mathbf{X} = \mathbf{P}\mathbf{V}^T, \quad (2)$$

where $\mathbf{P} = \mathbf{U}\mathbf{S}$. It can be shown that columns of the matrix $\mathbf{V}$ represent the EOFs and the columns of $\mathbf{P}$ represent the PCs, that is, projections of the data onto the EOFs. It can be shown that the standard deviations of the PCs are obtained as the diagonal values of $\mathbf{S}/\sqrt{n-1}$, where n is the number of data points. By using the full $\mathbf{P}$ and $\mathbf{V}$ matrices, one can always fully reconstruct the original data matrix. However, by using only the k first PCs (i.e., columns of $\mathbf{P}$ and $\mathbf{V}$), one can obtain an approximate reconstruction of the data matrix by

$$\mathbf{X}_{(k)} = \mathbf{P}_{(k)}\mathbf{V}_{(k)}^T. \quad (3)$$

Such approximate reconstructions are useful, because often only a few first PCs explain the majority of the variance in the data set.

PCA is a convenient method of distilling the dominant features from a large correlated set of data. However, difficulties often arise, when the data contain gaps. If the data gaps are small, one can merely discard the observations (rows of $\mathbf{X}$) where any of the m data values are missing. However, when a significant amount of the data are randomly missing, other methods are preferable. One of these methods is the DINEOF analysis (Data INterpolating Empirical Orthogonal Function) originally presented by Beckers and Rixen (2003). DINEOF is an iterative method, which can simultaneously fill the gaps in the data set, compute the PCA, and determine the optimum number of PCs, which contain the relevant information for efficiently reconstructing the entire data set. The DINEOF algorithm has been shown to be surprisingly powerful in realistically filling randomly occurring data gaps even in extreme cases of over 50% missing data (Beckers & Rixen, 2003).

A full description of the DINEOF algorithm is given by Beckers and Rixen (2003), but a short account of the method is given here. The DINEOF algorithm begins by taking a copy of a suitable fraction (in this work 10%) of the data aside to be used as a cross-validation set. This set will initially not be used to calculate the PCs but will be used to find an optimal solution. Next all the missing values and the original data chosen into the cross-validation set (not the copy) are filled by zeros, that is, mean value of centered data. Then PCA is calculated and the data set including the missing and cross-validation values is reconstructed using only the first PC (equation (3) with $k = 1$). The mean squared error (MSE) is then computed as a sum of the squared differences between the reconstructed validation data and the original validation data taken aside in the beginning. The PCA is then iteratively recomputed, and the missing and cross-validation values are continually being replaced by the reconstructed estimates based on the first PC from the previous iteration. The iteration is continued until the MSE converges.

Now, with the converged MSE value the above iteration loop is rerun, but by reconstructing the data now with the first 2 PCs until convergence. This procedure is then continued by successively increasing the number of PCs to be used for reconstruction until an optimal number for PCs is found and the MSE value converges. A final iteration loop is then run by inserting back the cross-validation data taken out in the beginning and using the optimal number of PCs to reconstruct the missing values.

The optimal PCs and EOFs obtained from DINEOF depend to some degree on which points get randomly chosen into the cross-validation data set in the beginning. Accordingly, successive applications of the DINEOF to the same data set will produce slightly different results each time. To reduce this randomness, the original DINEOF algorithm was extended here by forming an ensemble of N DINEOF runs. As the final ensemble result the ensemble average of the EOFs and the final PCs as a projection of the original data matrix on these ensemble averaged EOFs were computed. The final optimal number of PCs was chosen to be the

median of the optimal PC numbers from the ensemble runs. In PCA the sign of the PCs and corresponding EOFs is inherently ambiguous; that is, one can make the same sign change to both without changing the sign of the data matrix (see equation (2)). Because the numerical algorithm (SVD) performing the PCA does not constrict the PC/EOF sign the signs of PCs and corresponding EOFs can change (but not independently from each other) from one DINEOF run to the next. To prevent this, all the signs of the EOFs and PCs of all ensemble members were automatically changed to match the signs of the corresponding PCs/EOFs of the first ensemble run.

The performance of the ensemble DINEOF algorithm was tested and it was found that an ensemble size of $N = 51$ is sufficiently large to produce practically identical results each time. For the electron latitude distributions used in this work the average relative root-mean-square error of the DINEOF data gap filling was of the order of 3%, 5%, and 15% for E1, E2, and E3 energy channels, respectively (note that the fraction of missing data increases with energy channel as the fluxes approach the noise level, which has been removed).

3.2. Canonical Correlation Analysis

Canonical correlation analysis (CCA) is an extension of PCA to two centered multivariate data sets $\mathbf{X}$ and $\mathbf{Y}$. The purpose of CCA is to find projections $\mathbf{C}_X$ and $\mathbf{C}_Y$ (so called canonical variables) of $\mathbf{X}$ and $\mathbf{Y}$, which have a maximal cross correlation between the two data sets and at the same time are uncorrelated with each other. The canonical variables can thus be written as

$$\mathbf{C}_X = \mathbf{X}\mathbf{A} \quad (4)$$

$$\mathbf{C}_Y = \mathbf{Y}\mathbf{B} \quad (5)$$

where the so far unknown matrices $\mathbf{A}$ and $\mathbf{B}$ describe the projections from the original data matrices to the canonical variables. The CCA analysis can be computed by first obtaining the SVDs of $\mathbf{X}$ and $\mathbf{Y}$ as

$$\mathbf{X} = \mathbf{U}_X \mathbf{S}_X \mathbf{V}_X^T \quad (6)$$

$$\mathbf{Y} = \mathbf{U}_Y \mathbf{S}_Y \mathbf{V}_Y^T \quad (7)$$

and then performing SVD for the matrix $\mathbf{U}_X^T \mathbf{U}_Y$ as

$$\mathbf{U}_X^T \mathbf{U}_Y = \mathbf{U} \mathbf{S} \mathbf{V}^T. \quad (8)$$

Only the corresponding canonical variables (columns) in $\mathbf{C}_X$ and $\mathbf{C}_Y$ are set to be maximally correlated, while other canonical variable pairs are uncorrelated. This means that the cross-correlation matrix $\mathbf{C}_X^T \mathbf{C}_Y$ must be diagonal. It can be shown that this requirement is fulfilled by defining the projection matrices $\mathbf{A}$ and $\mathbf{B}$ as

$$\mathbf{A} = \mathbf{V}_X \mathbf{S}_X^{-1} \mathbf{U} \quad (9)$$

$$\mathbf{B} = \mathbf{V}_Y \mathbf{S}_Y^{-1} \mathbf{V}. \quad (10)$$

With this solution it can be shown that the standard deviation of all canonical variables in $\mathbf{C}_X$ and $\mathbf{C}_Y$ is then merely $1/\sqrt{n-1}$, where n is the number of data points. The results of the canonical correlation analysis can be used to obtain a general linear mapping between two multivariate data sets via the canonical variables. Since the projection matrices in equations (9) and (10) maximize the correlation between the canonical variables and these variables all have the same standard deviation, we can write

$$\mathbf{Y}\mathbf{B} = \mathbf{X}\mathbf{A} + \boldsymbol{\varepsilon}, \quad (11)$$

where $\boldsymbol{\varepsilon}$ is the matrix of residual noise with zero mean. Taking the expectation of equation (11) gives us a mapping:

$$\mathbb{E}(\mathbf{Y}|\mathbf{X}) = \mathbf{X}\mathbf{M}, \quad (12)$$

where the mapping matrix is

$$\mathbf{M} = \mathbf{A}\mathbf{B}^{-1}. \quad (13)$$

In case of nonsquare $\mathbf{B}$ the inverse is taken as the pseudoinverse.

Because the data series in both data sets are often highly correlated, it is often preferable to first reduce the effective dimensions of the data sets by obtaining an optimal set of PCs and EOFs for both data sets (e.g., using the DINEOF analysis outlined above) and then use the above CCA method to derive a mapping between these sets of chosen PCs. This methodology will be used here.

4. Correcting for the Telescope Viewing Angle Difference Between SEM-1 and SEM-2

4.1. Mapping From SEM-1 to SEM-2

In order to homogenize the entire SEM-1/SEM-2 data series, a transformation must be obtained, which maps the latitude distributions of SEM-1 to SEM-2 level. Fortunately, such a transformation can be determined by comparing simultaneous observations between NOAA-12 (SEM-1 satellite) and NOAA-15 (SEM-2 satellite) soon after the launch of NOAA-15 in mid-1998. Two periods from 1 July 1998 to 1 October 1999 and from 1 September 2000 to 1 March 2001, when the NOAA-12 data quality and coverage was still sufficiently good, were chosen for this comparison. These combined periods of time are referred to as the calibration time period. In between these time periods and after 1 March 2001 the temporal coverage of NOAA-12 measurements was too poor to perform a reliable comparison.

The simplest way to obtain the sought mapping between SEM-1 and SEM-2 would be to perform linear regression between SEM-1 and SEM-2 fluxes separately for each latitude bin and to use this relationship to scale SEM-1 to SEM-2 level in the corresponding bin. However, this method has a number of pitfalls. First, many latitude bins especially at high and low latitudes and at higher-energy channels are often dominated by noise. Using such a noise-dominated fit to scale the data can lead to large errors especially when applied to data outside the calibration time period. Second, the relationship between SEM-1 and SEM-2 fluxes depends not only on latitude (due to telescope pitch angle difference) but also on the pitch angle distribution of the electron population at that latitude. Because the pitch angle distribution at any latitude can change from day to day, the SEM-1/SEM-2 scaling relation may in principle change too.

However, these issues can be largely avoided by not considering the SEM-1/SEM-2 mapping separately for each latitude bin but instead a more general mapping between the full latitude distributions based on the CCA analysis discussed above in section 3.2. This mapping is derived separately for the latitude distributions of each telescope, energy channel, and quarter of the satellite orbit (corresponding to two opposite MLT sectors at the two hemispheres). Let us denote by $\mathbf{X}$ the NOAA-12 (SEM-1) and by $\mathbf{Y}$ the NOAA-15 (SEM-2) data matrices, which have already been cleaned for background noise and normalized for the changes in satellite orbital plane in Paper 1. Matrix $\mathbf{X}$ includes NOAA-12 data from three time periods with sufficient data coverage: 2 June 1991 to 14 December 1998, 28 December 1998 to 1 October 1999 and 1 September 2000 to 1 March 2001. Matrix $\mathbf{Y}$ includes NOAA-15 data from 1 July 1998 to 8 November 2016.

Figure 4 shows an example of NOAA-12 (top) and NOAA-15 (bottom) 90° E1 fluxes at Northern Hemisphere in the dawn sector during the selected calibration time period. The NOAA-12 data coverage was too poor for comparison with NOAA-15 between 1 October 1999 and 1 September 2000, which is why the data during this period are not included in Figure 4 or in the calibration data. At latitudes >75° the differences between NOAA-12 and NOAA-15 are small and difficult to see. Between 50° and 70° the NOAA-12 fluxes are slightly higher than NOAA-15 fluxes because the NOAA-15 90° telescope pitch angles are smaller than those of NOAA-12 (see Figure 1). The difference in telescope pitch angles is rather large at latitudes <50° (Figure 1), which leads to a large difference of over an order of magnitude in the fluxes at these latitudes.

The full NOAA-12 and NOAA-15 data matrices are first reduced into their PCs using the DINEOF algorithm (see section 3.1). The DINEOF procedure yields the optimal number of PCs that contain the physically relevant signal. The rest of the variation is uncorrelated noise. At the same time DINEOF optimally interpolates any data gaps in the latitude distributions. Before DINEOF analysis each column of $\mathbf{X}$ and $\mathbf{Y}$ is first standardized by subtracting the mean and dividing with the standard deviation of the corresponding column. Also, only the 25 lowest latitude bins (i.e., latitudes from 40° to 88° in either hemisphere) are included, because the highest latitude bin is mostly empty (the satellites rarely sample those high latitudes because of the orbital inclination). The standardization can be conveniently computed by the following matrix operations:

$$\mathbf{X}_{\text{std}} = (\mathbf{X} - \bar{\mathbf{X}}) \Sigma_{\mathbf{X}}^{-1} \quad (14)$$

Figure 4. Example of NOAA-12 (top row) and NOAA-15 (bottom row) 90° E1 fluxes at Northern Hemisphere in the dawn sector during the calibration time period as a function of time and corrected geomagnetic latitude (CGMlat).

$$\mathbf{Y}_{\text{std}} = (\mathbf{Y} - \bar{\mathbf{Y}}) \Sigma_{\mathbf{Y}}^{-1} \quad (15)$$

Here the $\bar{\mathbf{X}}$ denotes a matrix with same size as $\mathbf{X}$ with all rows equal to the vector of mean values of the columns of $\mathbf{X}$. This same notation is used for $\mathbf{Y}$ and for other matrices from here on. Matrices $\Sigma_{\mathbf{X}}$ and $\Sigma_{\mathbf{Y}}$ are 25×25 diagonal matrices with the diagonal values containing the standard deviations of the columns of $\mathbf{X}$ and $\mathbf{Y}$, respectively. Corresponding notation for the standard deviation matrices will be used from here on.

Figure 5 shows an example of the DINEOF analysis for 90° E1 fluxes in the Northern Hemisphere at dawn sector. In this case the DINEOF analysis indicates that NOAA-12 has eight and NOAA-15 nine optimal PCs. Figure 5a shows that these PCs explain about 92% (94%) of variation in the latitude distribution of the fluxes for NOAA-12 (NOAA-15). Figure 5b shows the EOFs corresponding to the first four PCs of both satellites. One can see that the EOFs are very similar but have some subtle differences. However, in some other cases (e.g., E3 channel) the NOAA-12 and NOAA-15 EOFs display larger differences and their ordering in the DINEOF analysis may even be different in NOAA-12 and NOAA-15 if the relative variance related to the corresponding PCs is ordered differently. As an example for 90° E3 fluxes in north/dawn the second NOAA-15 PC/EOF actually corresponds to the third NOAA-12 PC/EOF (not shown). While the latitudinal structure of the EOFs contains interesting information about the modes governing the variation of the fluxes, their detailed analysis is not the purpose of the present study.

After the DINEOF analysis the mapping matrix $\mathbf{M}$ between the optimal number of NOAA-12 and NOAA-15 PCs is calculated using CCA analysis (see section 3.2 and equation (13)). The mapping matrix is not calculated for the standardized data matrices themselves, but for matrices $\mathbf{P}_{\mathbf{X},\text{cal}}$ and $\mathbf{P}_{\mathbf{Y},\text{cal}}$ which contain the $m_{\mathbf{X}}$ and $m_{\mathbf{Y}}$ optimal number of PCs from the calibration time period (see above). Note that because only a subset of data points from the full PC time series are included in the calibration time period the mean values of the columns of $\mathbf{P}_{\mathbf{X},\text{cal}}$ and $\mathbf{P}_{\mathbf{Y},\text{cal}}$ are generally nonzero. Thus, they need to be centered before computing the CCA. Taking this into account, the relation between these two matrices can be expressed with the $m_{\mathbf{X}} \times m_{\mathbf{Y}}$ mapping matrix $\mathbf{M}$ as

$$\mathbf{P}_{\mathbf{Y},\text{cal}} = (\mathbf{P}_{\mathbf{X},\text{cal}} - \bar{\mathbf{P}}_{\mathbf{X},\text{cal}}) \mathbf{M} + \bar{\mathbf{P}}_{\mathbf{Y},\text{cal}} = \mathbf{P}_{\mathbf{X},\text{cal}} \mathbf{M} + \bar{\mathbf{P}}_{\mathbf{Y},\text{cal}} - \bar{\mathbf{P}}_{\mathbf{X},\text{cal}} \mathbf{M}. \quad (16)$$

Figure 5. Example of NOAA-12 and NOAA-15 DINEOF analysis for 90° E1 fluxes at Northern Hemisphere in the dawn sector. (a) The cumulative fraction of data variance explained as a function of the number of PCs (Principal Components) included. The blue curve corresponds to NOAA-15 and red curve to NOAA-12. The black points indicate the optimal PCs for reconstructing the data according to the DINEOF (Data INterpolating Empirical Orthogonal Function) method. (b) The first four EOFs (Empirical Orthogonal Function) of NOAA-15 (thin curves) and NOAA-12 (thick curves) as a function of corrected geomagnetic latitude.

The mapping matrix $\mathbf{M}$ is computed by the theory outlined in section 3.2 so that matrices $\mathbf{P}_{\mathbf{X},\text{cal}} - \bar{\mathbf{P}}_{\mathbf{X},\text{cal}}$ and $\mathbf{P}_{\mathbf{Y},\text{cal}} - \bar{\mathbf{P}}_{\mathbf{Y},\text{cal}}$ correspond to matrices $\mathbf{X}$ and $\mathbf{Y}$ of section 3.2, respectively.

Figure 6a shows a graphical example of the mapping matrix computed for 90° E1 fluxes in the Northern Hemisphere dawn sector. The mapping matrix corresponds to the optimal number of PCs and associated EOFs, the first four of which were displayed in Figure 5. One can see that the largest values in the mapping matrix appear on the diagonal except at the highest rows 7–8. This means that majority of the NOAA-15 PCs correlate mostly only with the corresponding NOAA-12 PC. However, row 8 indicates that NOAA-15 PC8 has a significant linear relation between NOAA-12 PC7 and PC8. This is one example where one can see that the mapping matrix formulation automatically includes linear relationships between all possible pairs of NOAA-12/NOAA-15 PCs and thus accounts, for example, for situations, where the corresponding PCs are ordered differently in NOAA-12 and NOAA-15 (as discussed above). Figure 6b shows the offset part of equation (16) for 90° E1 fluxes in north/dawn. Note that each row in the offset matrix $\bar{\mathbf{P}}_{\mathbf{Y},\text{cal}} - \bar{\mathbf{P}}_{\mathbf{X},\text{cal}}\mathbf{M}$ in equation (16) is identical and is thus displayed as a line plot. Mostly, the offsets are rather small, but for PC1 and PC2 the offsets are significantly different from zero.

Figure 6. Example of (a) the canonical correlation mapping matrix between NOAA-12 and NOAA-15 PCs and (b) the offset between NOAA-15 and NOAA-12 PCs (Principal Components) for the 90° E1 fluxes in the Northern Hemisphere dawn sector. Note that each row in the offset matrix $\bar{\mathbf{P}}_{\mathbf{Y},\text{cal}} - \bar{\mathbf{P}}_{\mathbf{X},\text{cal}}\mathbf{M}$ is identical and is displayed as a line plot.

Equation (16) can be used to convert the optimal number of PCs from SEM-1 to SEM-2 level, but it does not consider the remaining data variance, which is not included in these PCs. This remaining variance in both data sets is largely uncorrelated residual noise, and its amplitude and mean values can be latitudinally dependent and different for SEM-1 and SEM-2. For a full intercalibration between SEM-1 and SEM-2 the residual noise should also be scaled from SEM-1 to SEM-2 level. To achieve this, the matrices of the residuals in the calibration time period are first computed as

$$\epsilon_{X,cal} = \left(\mathbf{X}_{std,cal} - \mathbf{P}_{X,cal,(m_X)} \mathbf{V}_{X,(m_X)}^T \right) \Sigma_X \quad (17)$$

$$\epsilon_{Y,cal} = \left(\mathbf{Y}_{std,cal} - \mathbf{P}_{Y,cal,(m_Y)} \mathbf{V}_{Y,(m_Y)}^T \right) \Sigma_Y, \quad (18)$$

where $\mathbf{P}_{X,cal,(m_X)}$ and $\mathbf{P}_{Y,cal,(m_Y)}$ are the matrices containing the time series of optimal number (m_X and m_Y) of PCs from the calibration time period and $\mathbf{V}_{X,(m_X)}$, $\mathbf{V}_{Y,(m_Y)}$ are the matrices containing the corresponding EOFs. The SEM-1 and SEM-2 residuals are roughly normally distributed but with different means and standard deviations. The scaling of SEM-1 residuals is based on transforming their probability distribution to roughly match that of the SEM-2 residuals. This can be done by setting the standardized SEM-1 and SEM-2 residuals equal. It turns out that the scaling for the residuals can then be written in matrix form as

$$\epsilon_{Y,cal} = \epsilon_{X,cal} \alpha + \beta, \quad (19)$$

where α is a 25×25 diagonal matrix given by

$$\alpha = \Sigma_{\epsilon_{Y,cal}} \Sigma_{\epsilon_{X,cal}}^{-1} \quad (20)$$

and

$$\beta = \bar{\epsilon}_{Y,cal} - \bar{\epsilon}_{X,cal} \alpha. \quad (21)$$

Equations (20) and 21 use the same notation for mean and standard deviation matrices as above.

4.2. Applying the Mapping to SEM-1 Satellites

The transformation of daily latitude distributions from SEM-1 level to SEM-2 level is based on separately transforming the part described by the optimal number of PCs (equation (16)) and the remaining residual variation (equations (17)–(21)). It is important to note that the above mapping of PCs was developed between NOAA-12 PCs and NOAA-15 PCs. The EOFs of other SEM-1 satellites can differ from the NOAA-12 EOFs, which means that the mapping developed above cannot be applied to the PCs of other SEM-1 satellites computed as projections of the data to the EOFs of the corresponding satellite. However, when the data of a SEM-1 satellite are projected to the NOAA-12 EOFs used above, the obtained projections can then be treated as PCs and be transformed to SEM-2 level using the mapping developed above.

As the first step in transforming the data of a SEM-1 satellite the data gaps in the data set are optimally interpolated with the DINEOF method. The data matrix is here denoted as $\mathbf{Z}$ to distinguish from $\mathbf{X}$ used for NOAA-12 above. The matrix $\mathbf{Z}$ can refer to any SEM-1 satellite including NOAA-12 (in this special case $\mathbf{Z} = \mathbf{X}$). First, the data matrix is standardized by

$$\mathbf{Z}_{std} = (\mathbf{Z} - \bar{\mathbf{X}}) \Sigma_X^{-1}. \quad (22)$$

It is important to note here that the standardization of $\mathbf{Z}$ is performed using the mean and standard deviation matrices of NOAA-12 obtained from the matrix $\mathbf{X}$ and used in equation (14). This ensures that $\mathbf{Z}$ is standardized in the same way as NOAA-12 above and is consistent with the mapping based on the PCs developed for NOAA-12. The standardized data set is then projected to the subset of the optimal number (m_X) of NOAA-12 EOFs used above ($\mathbf{V}_{X,(m_X)}$ matrix) by equation

$$\mathbf{P}_Z = \mathbf{Z}_{std} \mathbf{V}_{X,(m_X)}. \quad (23)$$

These PCs are then transformed to SEM-2 scale by applying equation (16). This gives

$$\mathbf{P}_{Z,scaled} = \mathbf{P}_Z \mathbf{M} + \bar{\mathbf{P}}_{Y,cal} - \bar{\mathbf{P}}_{X,cal} \mathbf{M}. \quad (24)$$

Figure 7. Example of the relationship between original (blue) NOAA-15 and NOAA-12 PCs (Principal Components) as well as NOAA-15 and scaled NOAA-12 PCs (red). The black line depicts the perfect one-to-one relationship. The depicted PCs have been computed by the DINEOF (Data INterpolating Empirical Orthogonal Function) method for the 90° E1 fluxes in the Northern Hemisphere dawn sector. The four panels correspond to first four PCs with corresponding empirical orthogonal functions shown in Figure 5b.

The residuals are then calculated by using the optimal number of PCs (m_X determined for NOAA-12 above) from equation (23) and NOAA-12 EOFs as

$$\epsilon_Z = \left(\mathbf{Z}_{\text{std}} - \mathbf{P}_Z \mathbf{V}_{X(m_X)}^T \right) \Sigma_X. \quad (25)$$

These residuals are then scaled to the SEM-2 level by applying equations (19)–(21), which give

$$\epsilon_{Z,\text{scaled}} = \epsilon_Z \alpha + \beta, \quad (26)$$

with α and β defined in equations (20) and (21). The data matrix scaled to the SEM-2 level is then finally computed by the equation

$$\mathbf{Z}_{\text{scaled}} = \bar{\mathbf{Y}} + \left(\mathbf{P}_{Z,\text{scaled}} \mathbf{V}_{X(m_X)}^T \right) \Sigma_Y + \epsilon_{Z,\text{scaled}}. \quad (27)$$

5. Evaluation of the Homogenized Data

Let us next consider some representative examples of the effects of the scaling procedures discussed above applied to the SEM-1 satellites. Figure 7 shows as an example the relationship between original NOAA-15 and NOAA-12 PCs (blue) as well as original NOAA-15 and scaled (with equation (16)) NOAA-12 PCs (red) for the 90° E1 fluxes in the Northern Hemisphere dawn sector. Only the first four PCs are shown, and these correspond to the EOFs shown in Figure 5b. One can see a good correlation between the first three PCs and a fair correlation between the fourth PCs. However, the relationships between the original NOAA-12 and NOAA-15 PCs are significantly different from the ideal one-to-one relationship (shown with black lines)

Figure 8. Examples of scatter plots between logarithmic ($\log_{10}$) NOAA-12 and NOAA-15 90° fluxes at Northern Hemisphere in the dawn sector. The blue points correspond to unscaled NOAA-12 fluxes and red points to the scaled NOAA-12 fluxes. The black line in each panel shows the one-to-one relationship. The green and cyan dashed lines show the best fit lines to the red (NOAA-12 scaled) and blue (unscaled) data points, respectively, estimated with the total least squares method. The three columns correspond to three latitude bands 44–46°N (low latitudes below the precipitation zone), 62–64°N (at the heart of the precipitation zone), and 74–76°N (at the outer edge of the precipitation zone). The three rows correspond to E1, E2, and E3 energy channels.

especially for the first three PCs. After the scaling of NOAA-12 PCs by equation (16) all the NOAA-12 PCs correspond much better to the respective NOAA-15 PCs and are aligned around the one-to-one relationship.

In order to assess the effect of the SEM-1 scaling procedures discussed above, Figure 8 shows the relationship between NOAA-15 and unscaled NOAA-12 fluxes (blue) as well as NOAA-15 and scaled NOAA-12 fluxes (red). This comparison is shown for E1, E2, and E3 90° fluxes (different rows), in Northern Hemisphere dawn sector for three selected latitude bands, which correspond to low latitudes below the radiation belt precipitation zone (44–46°N), the heart of the precipitation zone (62–64°N), and the outer edge of the precipitation zone (74–76°N). As the standard reference each plot indicates the perfect one-to-one relationship with a black line. The plots also indicate the best fit lines to the red (NOAA-12 scaled) and blue (unscaled) data points estimated with the total least squares method. In all energy channels and latitudes one can see that

Figure 9. Same as Figure 8 but for 0° telescope.

the scaling decreases the NOAA-12 fluxes and aligns them rather well around the one-to-one line. Note that in all cases the best fit line is also rather close to the ideal one-to-one relationship. The differences between the original and scaled fluxes are largest, an order of magnitude, at the lowest latitudes (first column). This is understandable because the differences between 90° telescope pitch angles between NOAA-12 (SEM-1) and NOAA-15 (SEM-2) are largest there (see Figure 1b). With increasing latitude the effect of the scaling decreases as the difference between the 90° telescope pitch angles decreases with latitude. Figure 9 shows the same flux comparison for 0° telescope fluxes. One can see similar, rather large, differences between the unscaled and scaled fluxes as in the 90° telescope. However, it is surprising to see such large differences, especially in the lower latitudes, where the SEM-1 and SEM-2 0° pitch angles should be very close to each other (see Figure 1b). On the other hand, it is interesting that the scaling has a very small effect on the 0° fluxes at the outer edge of the precipitation zone, where the pitch angle difference of SEM-1 and SEM-2 0° telescopes is the largest. This implies that the fluxes at these high latitudes, which are mostly associated to substorm injections, are also rather isotropic.

Figure 10. A composite of electron fluxes as a function of time and corrected geomagnetic latitude (CGMlat) cleaned from background noise and normalized for MLT drift of the satellite orbital planes and homogenized for the difference in the telescope viewing directions between SEM-1 and SEM-2 satellites. The composite has been computed using the data from the 90° 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 MLT (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, respectively.

Figures 10 and 11 show the composite data sets for all three energy channels of the 90° telescope and 0° telescope, respectively. The composites are based on homogenized NOAA-6, NOAA-8, NOAA-10, NOAA-12, and NOAA-15 measurements and were computed in the same way as those discussed in Paper 1 and in section 2.1 (Figures 2 and 3). Overall, one can see that the composites appear homogeneous throughout the entire time interval and the obvious discontinuity in mid-1998, which was seen in Figures 2 and 3, has now been removed. To aid the comparison of the final homogenized composites with the composites produced in Paper 1 (and shown in Figures 2 and 3), Figures 12 and 13 show the logarithmic ratio of the unscaled (but corrected for background noise and satellite orbital drift) and fully homogenized flux composites. That is, the positive values indicate how much larger the unscaled fluxes are compared to the scaled fluxes.

By comparing Figures 3 and 10, one can see that the scaling noticeably decreases the 90° fluxes in the SEM-1 era before mid-1998 in most latitudes, especially below 60° in both hemispheres. The 90° flux decrease due to scaling increases with decreasing latitude. At low latitudes the flux decrease is on average around a factor of 5, while at higher latitudes it is a factor of about 1.5–3. However, one can also see that the magnitude of the

Figure 11. Same as Figure 10 but for 0° fluxes.

flux decrease due to scaling changes temporally. This is caused by the temporal changes of the electron pitch angle distribution. The latitudinal tendency of the flux decrease due to scaling is easy to understand, since the difference in SEM-1 and SEM-2 90° pitch angles (Figure 1b) is largest at lower latitudes and decreases with latitude. However, one can also see that in the E3 channel in south the scaling increases the 90° fluxes in the outer part of the precipitation zone (60–70°S), although only by a rather small factor (roughly 1 to 1.3). Comparing the SEM-1 and SEM-2 90° telescope pitch angles in Figure 1b, one can see in the south (but not in the north) the SEM-2 pitch angles are actually slightly closer to 90° (where the fluxes are typically largest) than the SEM-1 pitch angles at these latitudes. This explains why the SEM-1 scaling increases the fluxes at these latitudes. A very small increase is also visible in the E2 channel in the south roughly in the same latitudes and also weakly even in the E1 channel. It is unclear why the magnitude of this increase in the flux seems to grow with energy, but apparently, it indicates that the pitch angle distributions close to the local transverse direction of the field lines at these latitudes are steeper (i.e., flux increases more with pitch angle) in the higher energies than in the lower energies possibly due to differences in the pitch angle diffusion at different energies.

By comparing Figures 2 and 11, one can see that the scaling noticeably decreases also the 0° fluxes in the SEM-1 era especially in the latitudes below 60° in both hemispheres. This effect is particularly visible in the ratio of these composites in Figure 13 in the E1 and E2 channels. In the Northern Hemisphere the scaling decreases the E1 fluxes below 60°N latitude on average by about a factor of 3 in linear scale (about 0.5 in $\log_{10}$

Figure 12. Logarithmic ratio between unhomogenized and homogenized 90° telescope flux composites shown in Figures 2 and 10 respectively. Panels from top to bottom depict the monthly sunspot number (SSN) as a reference and the E1, E2, and E3 energy channels, respectively.

scale). At higher latitudes the fluxes are decreased somewhat less, by a factor between 2 and 3. In the south the flux decrease due to the scaling is much larger than in the north. At latitudes below 60°S the E1 fluxes are decreased by an order of magnitude. At higher latitudes the decrease is of the same order of magnitude as in the north. In the E2 and E3 channels the latitudinal tendency of the flux decrease due to scaling is similar as in E1, with some small differences in the magnitude of the effect.

When comparing the effects of SEM-1 flux scaling in 0° and 90° telescopes, it seems that the effects are larger for the 0° in most latitudes. This is very surprising because the difference in SEM-1 and SEM-2 90° telescope pitch angles, especially at latitudes below 60°, is much larger than for the 0° telescopes. Even more surprising is the fact that the unscaled 0° telescope fluxes in SEM-1 are noticeably larger than in SEM-2 although according to Figure 1b the SEM-2 0° telescope pitch angle is somewhat larger at high latitudes and nearly the same as SEM-1 pitch angle at lower latitudes, where the flux difference is highest. In order to observe such differences, the electron pitch angle distribution would have to have a local maximum in the field-aligned direction. This seems an extremely unlikely explanation since the typical pitch angle distributions observed in the inner magnetosphere peak in the transverse direction (e.g., Shi et al., 2016). Another reason to the SEM-1 fluxes being higher than SEM-2 could be errors in the detector efficiencies estimated by Asikainen and Mursula (2013). However, to explain, for example, the SEM-2 E1 flux being lower by more than a factor

Figure 13. Logarithmic ratio between unhomogenized and homogenized 0° telescope flux composites shown in Figures 3 and 11, respectively. Panels from top to bottom depict the monthly sunspot number (SSN) as a reference and the E1, E2, and E3 energy channels, respectively.

of 5 would require a dramatic decrease of SEM-2 detector efficiency shifting the effective energy threshold of the E1 channel from 30 keV to almost 100 keV (this possibility was roughly estimated with the E1 and E2 channel fluxes, but not shown here). Note also that in E2 and E3 channels, where the flux scaling also has a similarly large effect, the differences in SEM-1 and SEM-2 detector efficiencies are much smaller than in E1 channel (Asikainen & Mursula, 2013; Yando et al., 2011). Accordingly, the 0° flux differences in SEM-1 and SEM-2 cannot be explained by possibly miscalculated detector efficiencies. Perhaps, the only remaining explanation is that the SEM-1 0° (and possibly 90°) telescope orientation stated in the instrument documentation is incorrect, for example, due to instrument being aligned slightly differently than documented in Seale and Bushnell (1987) and Raben et al. (1995). In order to explain the observed SEM-1/SEM-2 flux difference, the SEM-1 0° telescope would have to be oriented to have a larger pitch angle than the SEM-2 0° telescope, for example, by rotating the telescope around the Z axis. However, a detailed analysis of possible errors in reported telescope alignment is out of the scope of the present study, which is only aiming at homogenizing the SEM-1 and SEM-2 fluxes to the same level.

Many previous studies have used energetic electron fluxes averaged over the entire hemisphere to study their overall long-term behavior. Thus, it is of interest to see how the new composite data set appears, when taking hemispheric averages of fluxes. The effect of the different corrections applied in Paper 1 and in this paper

Figure 14. Hemispheric averages of the 0° telescope composites of (top row) E1, (middle row) E2, and (bottom row) E3 channels in (left column) Northern and (right column) Southern Hemispheres. Yellow curves show the original uncorrected fluxes, blue curves show the fluxes corrected only for background noise and orbital plane MLT (Magnetic Local Time) drift (in Paper 1), and red curves show the fully homogenized fluxes corrected for background noise, orbital plane drift and differences in telescope viewing direction between SEM-1 and SEM-2 satellites.

is examined in Figures 14 and 15. Figure 14 shows the monthly averaged logarithmic 0° telescope fluxes of the three different energy channels averaged separately over the Northern and Southern Hemispheres. To highlight the overall effect of all applied corrections, the yellow curves show the uncorrected fluxes as a reference, the blue curves show the fluxes corrected only for background noise and satellite orbital drift in Paper 1, and the red curves show the fluxes corrected for background noise, orbital drift, and differences in SEM-1/SEM-2 telescope viewing directions. In Figure 14 one can see that the corrections for background noise and orbital drift do not significantly change the hemispheric average fluxes of the E1 channel. However, the SEM-1 scaling has a significant effect on the average fluxes. In linear scale the average SEM-1 E1 fluxes in north (south) are decreased by roughly a factor of 2 (a factor of 3). In the E2 channel the decrease is somewhat larger, on average about a factor of 2.5 in north and about a factor of 5 in south when compared to the fluxes corrected only for noise and orbital drift. Compared to the uncorrected fluxes, the differences are even larger in E2 channel and affect also the SEM-2 fluxes where the baseline is decreased by roughly a factor of 3 in linear scale due to the background noise removal. In 0° E3 channel the differences between noise/orbital drift corrected fluxes and fluxes corrected also for telescope viewing direction are about the same order of magnitude as in E2. However, the difference between the uncorrected fluxes and the fully corrected ones is quite large and mainly caused by the decrease of the overall flux level by roughly an order of magnitude due to the background noise removal already discussed in Paper 1.

Figure 15. Same as Figure 14 but for 90° fluxes.

In Figure 15 shows the effect of different corrections in the 90° telescope fluxes. Here one can see that the corrections for background noise and satellite orbital plane drift do not significantly change the overall average 90° fluxes of any channel on either hemisphere; that is, the yellow and red curves are practically indistinguishable. Note, however, that the effects of these corrections are important in different latitudes separately as discussed in Paper 1. The scaling of SEM-1 fluxes has a large effect in all energy channels in the Northern Hemisphere. On average the decreases caused by the scaling are about a factor of 1.9, 1.7, and 1.6 for the E1, E2, and E3 channels in the north, respectively. In the Southern Hemisphere the differences are somewhat smaller. In the E1 (E2) channel the corrections decrease the average fluxes by about a factor of 1.8 (1.5). Curiously, the effect of all corrections on the monthly averages of the 90° E3 fluxes in the Southern Hemisphere is very small. Note, however, that this is true only for the hemispheric averages. As shown in Figure 13 the 90° E3 fluxes at latitudes below 60°S are generally decreased by the telescope viewing direction correction, while at latitudes above 60°S they are increased. When averaging over the entire hemisphere these two opposite effects tend to cancel each other.

Although the net effect of the corrections for the hemispheric averages was merely summarized by the average decrease or increase of the SEM-1 fluxes, it is very important to note that even the hemispheric averages cannot be homogenized for the telescope viewing direction difference by multiplying with any constant factor. Closer inspection of the monthly fluxes shown in Figures 14 and 15 shows that even the ratios of the corrected and uncorrected monthly fluxes vary significantly with time and depict long-term variations related, for example, to drifts of the satellite orbits and to solar cycle variations (presumably due to long-term solar cycle changes in pitch angle distribution of electrons). Only a rough correction for the inhomogeneities in the POES data set could be achieved by multiplication with a constant factor.

6. Summary and Conclusions

Paper 1 began to construct a homogeneous composite record of energetic electron fluxes measured by the NOAA/POES with their MEPED instrument. The data were first reduced into daily latitude distributions from two opposite MLT sectors, two hemispheres and for the 0° and 90° telescopes separately. In Paper 1 these data were corrected for temporally varying background noise mostly caused by cosmic rays and for the slow changes in the orientation of the satellite orbit. The most significant issue related to the different telescope orientations of the SEM-1 and SEM-2 satellites was discussed in the present paper. Because the telescope viewing directions relative to the local magnetic field change with latitude and the electron pitch angle distributions are typically very anisotropic, the different viewing directions in SEM-1 and SEM-2 cause these two instrument versions to sample the electron distributions systematically in a very different way. As a result there is a large discontinuity in the composite data set built by using NOAA-6, NOAA-8, NOAA-10, NOAA-12, and NOAA-15 satellites, which all have the same dawn-dusk orbit.

To correct the discrepancy between the SEM-1 and SEM-2 data, roughly two years of overlapping NOAA-12 (SEM-1) and NOAA-15 (SEM-2) data were compared. It was found that because both the difference of telescope pitch angles between SEM-1 and SEM-2 and the electron pitch angle distribution change with latitude the relationship between SEM-1 and SEM-2 fluxes depends on latitude and may also change temporally. A novel statistical method based on PCs and canonical correlation analysis was presented here to find a transformation that maps the latitude distributions of electron fluxes from SEM-1 to SEM-2 level. Thus, the method provides a robust estimate of the electron latitude distributions that a SEM-2 satellite on a dawn-dusk orbit would see in the SEM-1 time period had it been measuring then.

It was found that in almost all cases 90° telescopes of the SEM-1 satellites measure larger pitch angles than the corresponding telescopes in the SEM-2. Because of this the scaling of the SEM-1 fluxes to SEM-2 level decreases the fluxes. The magnitude of the decrease is different at different latitudes, times, and energy channels. However, in general this decrease is largest at the lower latitudes (over an order of magnitude) and decreases toward higher latitudes where it can be a factor of 1.5 to 5 depending on hemisphere and energy channel.

Interestingly, it was found that the magnitude of the flux decrease due to the correction is of the same order of magnitude and sometimes even larger for the 0° telescopes than for the 90° telescopes. This is very surprising, because the documented 0° telescope orientations suggest that SEM-1 0° telescope should have a smaller pitch angle than the corresponding SEM-2 telescope. Although the exact reason for this puzzling observation could not be found here, it is possible that it is caused by the SEM-1 telescopes being oriented in a slightly different directions than documented.

As a result of the past work on correcting the instrumental problems in POES data (Asikainen & Mursula, 2011, 2013; Asikainen et al., 2012) and the work presented in Paper 1 and in this paper we have now constructed a new spatially and temporally homogeneous composite of energetic electron fluxes observed at low-altitude polar orbit. This composite provides information of the latitude distribution of energetic electron fluxes in both hemispheres in three energy channels and two telescopes in daily time resolution nearly continuously from 1979 to present. The main advantage of the new composite data set is that it addresses rigorously the various spatial and temporal inhomogeneities, which distort the apparent temporal evolution of the electron flux distributions. The new composite is ideally suited, for example, to studying the long-term evolution of the electron radiation belts and to estimating the long-term effects of electron precipitation on atmospheric ionization, chemistry, and resulting radiative and dynamical changes in the atmosphere and climate system.

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