

1 **Can we intercalibrate satellite measurements by means**  
2 **of data assimilation? An attempt on LEO satellites**

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10 **Key Points:**

- 11 • A new data-assimilative intercalibration method for electron fluxes in the radi-  
12 ation belts is presented and validated against conjunctions.
- 13 • The method is used to intercalibrate POES observations against Van Allen Probes,  
14 recalibration coefficients are within a factor of two.
- 15 • The proposed method strongly improves intercalibration statistics, such that less  
16 data is required than for traditional conjunction studies.

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## 17 Abstract

18 Low Earth Orbit (LEO) satellites offer extensive data of the radiation belt region,  
 19 but utilizing these observations is challenging due to potential contamination and dif-  
 20 ficulty of intercalibration with spacecraft measurements at Highly Elliptic Orbit (HEO)  
 21 that can observe all equatorial pitch-angles. This study introduces a new intercalibra-  
 22 tion method for satellite measurements of energetic electrons in the radiation belts us-  
 23 ing a data assimilation approach. We demonstrate our technique by intercalibrating the  
 24 electron flux measurements of the National Oceanic and Atmospheric Administration  
 25 (NOAA) Polar-orbiting Operational Environmental Satellites (POES) NOAA-15,-16,-  
 26 17,-18,-19 and MetOp-02 against Van Allen Probes observations from October 2012 to  
 27 September 2013. We use a reanalysis of the radiation belts obtained by assimilating Van  
 28 Allen Probes and Geostationary Operational Environmental Satellites (GOES) obser-  
 29 vations into 3-D Versatile Electron Radiation Belt (VERB-3D) code simulations via a  
 30 standard Kalman filter. We compare the reanalysis to the POES dataset and estimate  
 31 the flux ratios at each time, location and energy. From these ratios we derive energy and  
 32  $L^*$  dependent recalibration coefficients. To validate our results, we analyse on-orbit con-  
 33 junctions between POES and Van Allen Probes. The conjunction recalibration coeffi-  
 34 cients and the data-assimilative estimated coefficients show strong agreement, indicat-  
 35 ing that the differences between POES and Van Allen Probes observations remain within  
 36 a factor of two. Additionally, the use of data assimilation allows for improved statistics,  
 37 as the possible comparisons are considerably increased. Data-assimilative intercalibra-  
 38 tion of satellite observations is an efficient approach that enables intercalibration of large  
 39 datasets using short periods of data.

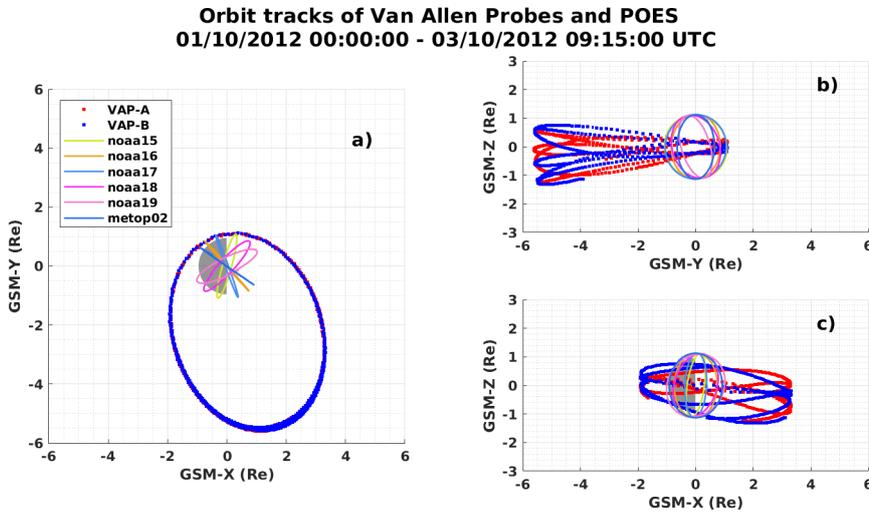
## 40 Plain Language Summary

41 This study presents a novel intercalibration method for satellite measurements of  
 42 energetic electrons in the radiation belt region using data assimilation. We demonstrate  
 43 the technique by comparing electron flux measurements from NOAA Polar-orbiting Op-  
 44 erational Environmental Satellites (POES) against Van Allen Probes observations. For  
 45 this, we use a data-assimilative reconstruction of the radiation belts, a so-called reanal-  
 46 ysis, obtained by assimilating Van Allen Probes and Geostationary Operational Envi-  
 47 ronmental Satellites (GOES) observations into code simulations. The results are vali-  
 48 dated by analyzing on-orbit conjunctions between the POES and Van Allen Probes. The  
 49 recalibration coefficients obtained through data assimilation show strong agreement with  
 50 the conjunction recalibration coefficients. While for energies  $< 700$  keV the observations  
 51 of both fleets display similar behaviour and need no intercalibration, at higher energies  
 52 recalibration coefficients remain within a factor of two. This data-assimilative intercal-  
 53 ibration approach allows for efficient recalibration of large datasets using short periods  
 54 of data, while also improving statistics through increased comparisons.

## 55 1 Introduction

56 Since the discovery of the Van Allen belts in the 1960s, a number of inner magne-  
 57 topheric satellite missions have been launched to observe the radiation in the near-Earth  
 58 environment. Most of these spacecraft operate at LEO, e.g. NOAA-POES; at Medium  
 59 Earth Orbit (MEO), s.a. Los Alamos National Laboratory (LANL) LANL-GPS constel-  
 60 lation; at HEO, e.g. Van Allen Probes mission (Mauk et al., 2012), Exploration of En-  
 61 ergization and Radiation in Geospace (ERG/Arase) (Miyoshi et al., 2018), Polar (NASA),  
 62 Time History of Events and Macroscale Interactions during Substorms (THEMIS) (Sibeck  
 63 & Angelopoulos, 2008), Cluster (ESA); or at Geostationary Orbit (GEO), e.g. Geosta-  
 64 tionary Operational Environmental Satellites (GOES) constellation (Data Book GOES,  
 65 2005), LANL-GEO (G. Reeves et al., 1997), among others.

66 In-situ multi-spacecraft measurements are a crucial for studying near-Earth radi-  
 67 ation. These measurements provide the foundation for validating existing physics-based  
 68 models of various particle populations, improving our understanding of the underlying  
 69 physics, and creating more accurate models. Statistical parametrization of the most en-  
 70 ergetic magnetospheric regions enables the planning of multi-year satellite missions, par-  
 71 ticularly at MEO and HEO orbits (Friedel et al., 2005). Furthermore, recent studies on  
 72 data assimilation (Cervantes, Shprits, Aseev, Drozdov, et al., 2020; Castillo et al., 2021)  
 73 and assimilative real-time radiation belt forecasting leverage large datasets from mul-  
 74 tiple spacecraft. However, the quality and reliability of multi-source observations can be  
 75 affected by several factors. Differences in instrumentation performance or design, lack  
 76 or degradation of detector shielding, non-standardized instrument calibration (e.g., Cay-  
 77 ton & Tuszewski, 2005), and differences in satellite location can all result in significant  
 78 deviations between measurements from multiple spacecraft. Thus, even observations from  
 79 similar orbits and magnetospheric regions can vary significantly and require proper in-  
 80 tercalibration between the different instruments.



**Figure 1. Datasets:** Example of the orbital tracks in GSM-coordinates for NOAA-15,-16,-17,-18,-19, MetOp-02 and Van Allen Probes (probes A and B) for October, 1st till 3rd, 2012.

81 Traditionally, satellite data intercalibrations are performed using satellite conjunc-  
 82 tions, which involve comparing real data in magnetic coordinates (e.g., Friedel et al., 2005;  
 83 C. Wang et al., 2013; Szabó-Roberts et al., 2021) or matching phase space density (PSD)  
 84 in adiabatic space (e.g., Chen et al., 2005, 2007; Ni et al., 2011; Zhu et al., 2022). Both  
 85 approaches require a benchmark instrument (a "gold standard" (**GS**) as by Friedel et  
 86 al. (2005)) that provides high-fidelity data and is used to intercalibrate measurements  
 87 from other instruments. A conjunction between different satellites is defined by impos-  
 88 ing strict spatial and temporal criteria on the observations to ensure that physical con-  
 89 straints are met. Then, statistical analysis of the residuals from data comparisons is per-  
 90 formed, and scaling factors can be estimated. Although satellite conjunctions have demon-  
 91 strated reliable results and are an established methodology for satellite data cross-calibration,  
 92 the strict constraints imposed on the data to make them comparable greatly reduce the  
 93 number of observations that qualify as a conjunction. This leads to poor statistics and  
 94 requires large amounts of data. These issues are particularly exacerbated when compar-  
 95 ing satellites at very different orbits that observe vastly different magnetospheric regions  
 96 and particle populations (s.a., LEO vs. HEO, see Figure (1)). In such cases, a spacecraft  
 97 with extensive  $L$ -coverage should be used as a reference for intercalibration (Friedel et  
 98 al., 2005).

99 To address some of the limitations of data cross-calibration via conjunctions, it would  
 100 be useful to have an approximation of the state of the entire radiation belts. Data as-  
 101 simulation (DA) techniques, s.a. the Kalman filter (**KF**) (Kalman, 1960), the Extended  
 102 Kalman filter (**EKF**) (Jazwinski, 1970), or the Ensemble Kalman filter (**EnKF**) (Evensen,  
 103 2003), have been utilized in the space weather community since the 2000s to estimate  
 104 the optimal state of this region using satellite observations and physics-based models (e.g.,  
 105 Naehr & Toffoletto, 2005; Koller et al., 2007; Y. Y. Shprits et al., 2007; Ni et al., 2009;  
 106 Kondrashov et al., 2011; Bourdarie & Maget, 2012; Godinez & Koller, 2012; G. D. Reeves  
 107 et al., 2012; Schiller et al., 2012; Y. Y. Shprits et al., 2012; A. Y. Drozdov et al., 2023).  
 108 The resulting reconstruction of the system (a time-dependent 3-D PSD volume) is re-  
 109 ferred to as a data-assimilative reanalysis and represents the state of the radiation belts  
 110 system that is statistically closest to the "true state". Reanalyses have been used in the  
 111 past to study the dynamic behavior of the system and to identify missing processes in  
 112 physics-based models (e.g., Kondrashov et al., 2007; Cervantes, Shprits, Aseev, & Al-  
 113 lison, 2020).

114 In this study, we elaborate on an idea proposed by Y. Shprits et al. (2007), and present  
 115 a new satellite intercalibration method based on the modeling of the outer radiation belt  
 116 by means of data assimilation. We test our novel intercalibration technique by cross-calibrating  
 117 six satellites of the NOAA-POES fleet against Van Allen Probes (used here as the refer-  
 118 ence dataset). To do so, a one year reanalysis of the radiation belts using Van Allen  
 119 Probes and GOES data is estimated. By flying the six NOAA-POES satellites through  
 120 the reanalysis, we can perform on-orbit data comparisons at each POES location, and  
 121 consequently conduct a statistical analysis of the residuals to estimate the recalibration  
 122 coefficients. In order to validate our approach, a traditional conjunction study between  
 123 Van Allen Probes and POES is also carried out. Comparison between the cross-calibration  
 124 coefficients estimated with both methodologies is presented.

125 In the next Section, we describe the proposed method. In Section 3, we present the  
 126 used Van Allen Probes and reanalysis datasets. Utilized POES observations and their  
 127 necessary processing is described in Section 4. Section 5 deals with the POES fly-through  
 128 the data assimilative reanalysis and the statistical analysis of the related on-orbit com-  
 129 parisons. In Section 6, we present the statistical analysis of the comparisons from the  
 130 conjunction study. General results, final cross-calibration factors and discussion are of-  
 131 fered in Section 7, followed by the conclusions and outlook in Section 8.

## 132 2 Rationale and Methodology

133 For lab-calibration procedures, the instrument is exposed to a radioactive source  
 134 with a well-known spectrum (or signal) and then the measurement is compared to the  
 135 expected signal. In the case of satellite observations such a procedure is not feasible, be-  
 136 cause lab recreation of the space conditions is not possible. The problem, however, would  
 137 be solved, if one could have an approximation of the space environment (the radiation  
 138 source), in which the non-calibrated spacecraft (NS) is immersed. In this case, having  
 139 the entire state of the radiation belt system or at least an approximation of it would al-  
 140 low us to easily compare observations, thus avoiding the limitations tied to conjunction  
 141 cross-calibrations.

142 Data assimilation techniques enable us to estimate such a state-approximation by  
 143 blending physics-based models and satellite observations in an optimal way. The infor-  
 144 mation contained in the satellite data will propagate to other areas of the modeling space,  
 145 giving us a time dependent global reconstruction of the system that is statistically clos-  
 146 est to the true state of the system, a so-called reanalysis (RA). Once this reconstruction  
 147 has been estimated, we can fly satellites/instruments at different orbits through it and  
 148 compare the real observations ( $j_{NS}$ ) with the state-estimate ( $j_{RA}$ ) at all locations, en-

149 energies and equatorial pitch-angles. The idea is to find factors  $\eta$ , such that for each time,  
 150 location and energy of the instrument it holds:

$$j_{RA} = \eta \cdot j_{NS}; \quad \implies \quad \eta = \frac{j_{RA}}{j_{NS}} = R_{DA}.$$

151 We rename  $\eta$  as  $R_{DA}$ , the flux ratio between reanalysis and observations. Note that,  $R_{DA}$   
 152 may be influenced by a variety of factors, such as geomagnetic activity (or  $K_p$ ), energy  
 153 ( $E$ ), and even location ( $L^*$ ) and equatorial pitch-angle ( $\alpha_{eq}$ ). However, the extent to which  
 154 these factors contribute to  $R_{DA}$  can only be assessed through a statistical analysis of all  
 155 the resulting ratios.

156 The step-by-step procedure can be summarized as follows:

- 157 1. Choose a reference dataset to be used as the GS. Ideally, the GS data is pitch-angle  
 158 resolved, has high energy resolution, provides large  $L^*$ -coverage and observes the  
 159 most dynamic regions of the radiation belts (i.e. satellites at HEO would be most  
 160 suitable here), as this will reflect in the quality of the RA.
- 161 2. Select time periods when geomagnetic activity is low to moderate, i.e.  $K_p \leq 4^-$   
 162 (More details in Section 4.1).
- 163 3. Convert GS observations to PSD to Phase Space coordinates (after (Chen et al.,  
 164 2005)) using a realistic magnetic field model.
- 165 4. Combine converted GS data and physics-based radiation belts model using a fil-  
 166 tering technique (e.g. KF, EnKF), and estimate the RA of the radiation belts for  
 167 the desired period of time.
- 168 5. Convert RA into electron fluxes in observational space.
- 169 6. Process and constrain NS observations if necessary (e.g. for LEO satellites the use  
 170 of trapped electron data is greatly important. More details in Section 4.1).
- 171 7. Fly NS satellite through the RA. This is equivalent to an interpolation of GS-data  
 172 into the grid of NS satellite.
- 173 8. Estimate the ratios  $R_{DA}$  at each NS-time and -location.
- 174 9. Perform statistical analysis of  $R_{DA}$  in dependence of  $L^*$ ,  $E$ ,  $\alpha_{eq}$  and  $K_p$  to deter-  
 175 mine the most important parameters influencing the ratios  $R_{DA}$ .
- 176 10. Estimate recalibration coefficients and their uncertainties in dependence of param-  
 177 eters found in the previous step. For this use suitable statistical measures depend-  
 178 ing on the shape of the obtained distributions, e.g., statistical mean ( $\overline{R_{DA}}$ ) or medi-  
 179 an ( $Q_2(R_{DA})$ ).

180 We validate our approach by presenting a comparison of the recalibration factors  
 181 obtained through a traditional geomagnetic conjunction study.

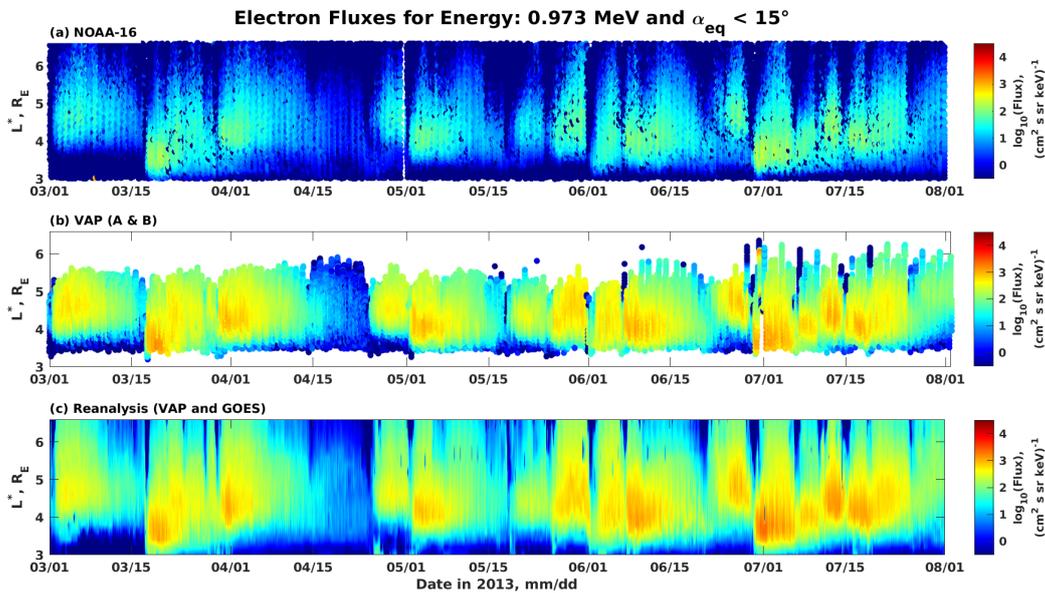
### 182 3 Reference Dataset and Reanalysis Data

183 For this study, we choose the instruments onboard Van Allen Probes as our refer-  
 184 ence GS dataset, and use these observations together with those from GOES 13 and 15  
 185 to estimate a data assimilative reanalysis of the radiation belt region for the period of  
 186 October, 2012 to September, 2013. A comparison between the POES and Van Allen Probes  
 187 datasets, and the Van Allen Probes+GOES reanalysis is displayed in Figure (2). Sim-  
 188 ple visual inspection of the figure clearly shows the need for these datasets to be inter-  
 189 calibrated. An overview of these datasets is given in this section.

#### 190 3.1 Van Allen Probes and GOES observations

191 NASA's Van Allen Probes mission (former Radiation Belt Storm Probes), launched  
 192 on 30 August 2012 from the Cape Cañaveral site, consisted of two spacecraft (probes A

193 and B) at nearly identical HEO orbits with perigee at about 618 km altitude, apogee at  
 194  $\sim 30400$  km ( $\sim 5.8 R_E$  geocentric) and  $10^\circ$  inclination (Mauk et al., 2012). The En-  
 195 energetic Particle, Composition and Thermal Plasma Suite (ECT) (Spence et al., 2013)  
 196 onboard both Van Allen Probes hosts four identical Magnetic Electron Ion Spectrom-  
 197 eters (MagEIS) (Blake et al., 2013) and three Relativistic Electron Proton Telescopes  
 198 (REPT) (Baker et al., 2012). These instruments provided pitch-angle resolved differ-  
 199 ential electron flux data since 01 September, 2012 covering large energy ranges: a) MagEIS:  
 200 electron seed population to relativistic electron population (20 – 240 keV, 80 – 1200  
 201 keV, 800–4800 keV) and b) REPT: very energetic electrons (1.8–10 MeV and above).  
 202 After more than 7 years on orbit, both spacecraft were deactivated in October, 2019 (JHU/APL,  
 203 2022). In this study, we used MagEIS measurements from probes A and B averaged over  
 204 30min. An example of the Van Allen Probes dataset used in this work is presented in  
 205 panel b) of Figure (2) for fixed energy ( $\sim 1$  MeV) and  $\alpha_{eq} < 15^\circ$ .



**Figure 2. Datasets:** Electron fluxes for the period of 01.03 to 01.08.2013 for  $E = 0.973$  MeV,  $\alpha_{eq} < 15^\circ$  for a) NOAA-16; b) Van Allen Probes (probes A and B); c) Reanalysis using Van Allen Probes + GOES.

206 The GOES fleet are a series of meteorological geostationary satellites operated by  
 207 the U.S. NOAA at nearly geosynchronous orbit (Data Book GOES, 2005). Each GOES  
 208 spacecraft hosts Magnetospheric Electron Detectors (MAGED) and two Energetic Pro-  
 209 ton, Electron, and Alpha Detectors (EPEAD). MAGED consists of nine solid-state-detector  
 210 telescopes, five in the east-west (equatorial) plane and the other four in the north-south  
 211 (meridional) plane, measuring differential electron fluxes at energies of: 30 – 50 keV,  
 212 50 – 100 keV, 100 – 200 keV, 200 – 350 keV and 350 – 600 keV (Hanser, 2011; Ro-  
 213 driguez, 2014a). In addition, the EPEADs measure MeV electron and proton flux data  
 214 in two energy ranges:  $> 0.8$  MeV and  $> 2$  MeV. To perform the data assimilative re-  
 215 analysis, we use MAGED and EPEAD pitch-angle resolved electron flux measurements  
 216 from GOES 13 and 15. The observations are averaged over 30min. EPEAD integral fluxes  
 217 and pitch-angles are obtained by averaging the measurements of the East and West tele-  
 218 scopes (Rodriguez, 2014b). Integral fluxes as a function of energy are fitted to a power  
 219 law in order to extend up to 1 MeV energies. We use the  $90^\circ$  pitch-angle differential flux  
 220 data from MAGED and fit the two integral channels of EPEAD to an exponential func-  
 221 tion to obtain differential flux at the interpolated energies.

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### 3.2 Reanalysis data using Van Allen Probes and GOES

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In this study, we estimate a data assimilative reanalysis of the outer radiation belt for the period of October, 2012 till September, 2013 following Cervantes, Shprits, Aseev, Drozdov, et al. (2020). We assimilate the observations of Van Allen Probes (probes A and B), as well as GOES-13 and GOES-15 into the VERB-3D code (Y. Y. Shprits et al., 2009; D. A. Subbotin & Shprits, 2009) using a 3D split-operator Kalman filter (Y. Y. Shprits et al., 2013) with a timestep of model and assimilation of 1 hour. In order to assimilate flux measurements, these need to be converted to PSD in coordinates of phase space ( $L^*$ ,  $\mu$ ,  $K$ ). To calculate  $\mu$ , in-situ magnetic field measurements from Van Allen Probes are used. For the calculation of  $K$  and  $L^*$ , we use the magnetic field model T89 (Tsyganenko, 1989) and IRBEM-ONERA library (Boscher et al., 2022). Differential fluxes ( $j$ ) are converted to PSD ( $f$ ) in units of  $(c/cm/MeV)^3$  following Rossi and Olbert (1970) by  $f = j/p^2$ .

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The VERB-3D code computes the numerical solution of the bounce-averaged Fokker-Planck-equation (Y. Y. Shprits et al., 2008; D. Subbotin et al., 2010) using a fully implicit finite differences method on a high resolution grid with  $(29 \times 101 \times 91)$  points for  $(L^* \times E \times \alpha_{eq})$ , respectively. VERB-simulations include radial, energy and pitch-angle diffusion, as well as losses to the magnetopause. The radial diffusion coefficient is calculated after Brautigam and Albert (2000) in terms of  $L^*$  and used by the VERB-code for all  $K_p$  values. The plasmapause position is calculated after Carpenter and Anderson (1992). The bounce-averaged diffusion coefficients for hiss and dayside and nightside chorus waves are computed using the Full Diffusion Code (FDC) (Y. Y. Shprits & Ni, 2009), and with the parameterizations provided by Orlova et al. (2014), and Orlova and Shprits (2014), respectively. The range of  $L^*$  reaches values from 1 to 6.6 and for equatorial pitch angles from  $0.7^\circ$  to  $89.3^\circ$ . The energy at the outer radial boundary ( $L^* = 6.6$ ) is defined in the range of 0.01 MeV to 10 MeV. At the low energy boundary, the energy varies in dependence of the  $L^*$  value, because electrons are energized during their transport to lower L-shells (e.g., D. Subbotin & Shprits, 2009), and correspond to  $\mu \approx 9$  MeV/G for electrons at  $\alpha_{eq} = 90^\circ$ . For further details about the reanalysis, the boundary and initial conditions, we refer the reader to the work by Cervantes, Shprits, Aseev, Drozdov, et al. (2020).

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The resulting assimilated state of the radiation belts is then a time-dependent three-dimensional PSD volume. In order to compare this state to POES measurements, we convert the assimilative reanalysis to differential flux in the coordinates of the observational space ( $L^*$ ,  $E$ ,  $\alpha_{eq}$ ) by  $f = j/p^2$ . A fragment of the electron fluxes from the reanalysis dataset used in this study is displayed in panel c) of Figure (2) for fixed energy and equatorial pitch-angles  $\alpha_{eq} < 15^\circ$ .

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## 4 POES Dataset

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Our goal is to test our new intercalibration approach to intercalibrate electron flux data from six satellites of the POES fleet, i.e. MetOp2, NOAA-15, 16, 17, 18, 19 (an overview is given in Table 1). In this study, we focus on the observations over the time period of 01 October 2012 till 30 September 2013.

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The particle flux dataset provided by the POES fleet has gained particular importance due to its large temporal coverage, extensive  $L^*$ -distribution, and short orbital period. These spacecraft are in Sun-synchronous LEO at about 850 km altitude and have an orbital period of  $\sim 100$  min. Since the launch of NOAA-15, the fleet carries the Space Environment Monitor (SEM-2) instrument package (Evans & Greer, 2000), which contains the Medium Energy Proton and Electron Detector (MEPED), and the Total Energy Detector (TED). The SEM-2 MEPED instrument consists of eight particle detector systems: two proton solid-state detector telescopes (each  $\pm 15^\circ$  wide), two electron

272 solid-state detector telescopes (each  $\pm 15^\circ$  wide) and four omni-directional (dome) pro-  
 273 ton detector systems. The electron/proton telescopes are mounted with different orien-  
 274 tation in order to observe different particle populations: 1) the  $0^\circ$ -telescope has the cen-  
 275 tral axis of its field of view rotated  $9^\circ$  in the XZ plane pointing away from the local zenith,  
 276 2) the  $90^\circ$ -telescope is oriented almost perpendicular to the  $0^\circ$ -telescope with the cen-  
 277 tral axis of its field of view rotated  $9^\circ$  in the YZ plane pointing away from the antiram  
 278 direction. Original SEM-2 MEPED electron data are reported in three integral electron  
 279 channels (E1, E2, E3) with a nominal energy range of 30 keV to 2.5 MeV, 100 keV to  
 280 2.5 MeV, and 300 keV to 2.5 MeV, respectively (Evans & Greer, 2000; Peck et al., 2015).  
 281 MEPED count rates (counts/s) are reported in 16 s intervals (Codrescu et al., 1997).

<i>Satellite</i>	<i>Altitude (km)</i>	<i>Inclination Angle (<math>^\circ</math>)</i>	<i>LTAN</i>	<i>Data Window</i>
MetOp-02(A)	817	98.7	2129	03/12/06–present
NOAA-15	807	98.5	1741	01/07/98–present
NOAA-16	849	99.0	2101	10/01/01–09/06/14
NOAA-17	810	98.7	1902	12/07/02–10/04/13
NOAA-18	854	98.7	1740	07/06/05–present
NOAA-19	870	98.7	1429	23/02/09–present

**Table 1.** NOAA POES satellites used in this study and their characteristics. Columns are satellite name, altitude, inclination angle, local time of the ascending node (LTAN), and the intervals of the data used in this study (Lam et al., 2010; Asikainen & Mursula, 2011).

282 POES observations have been reported to suffer from a number of issues that make  
 283 their use rather challenging. The rotation angles of the telescopes allow for a clear field  
 284 of view and for monitoring a mixture of particle populations. Thus, the  $0^\circ$ -telescopes ob-  
 285 serve mostly particles in the atmospheric loss cone (LC) and only at the geomagnetic  
 286 equator trapped populations are measured, while the  $90^\circ$ -telescopes monitor trapped par-  
 287 ticles at high latitudes and  $L^* > 1.4$  (Evans & Greer, 2000). Additionally, Rodger, Clil-  
 288 verd, et al. (2010) documented proton contamination of the SEM-2 MEPED electron data,  
 289 as the detectors respond to protons with energies of up to 2.7 MeV. The amount of con-  
 290 tamination varies for each electron energy channel (Yando et al., 2011), but electron data  
 291 from the  $90^\circ$ -telescopes are of good quality with only 3.5% (on average) to 7% (disturbed  
 292 times) contamination occurring beyond  $L = 7$ . Radiation damage, due to long-term  
 293 exposure, may also affect the electron detectors, but its impact on the measurements is  
 294 expected to be rather rather negligible (Galand & Evans, 2000; McFadden et al., 2007;  
 295 Asikainen & Mursula, 2011).

296 In order to address some of the issues mentioned in the previous paragraph, we use  
 297 the corrected differential electron fluxes estimated by Peck et al. (2015). The authors  
 298 reduced proton contamination of the MEPED E1 to E3 electron channels. Additionally,  
 299 using the information about relativistic electrons embedded in the observations of both  
 300 P6 proton detectors (integral proton channel (P6) with a nominal energy range of 30 keV  
 301 to  $> 6.9$  MeV), the authors produced a virtual fourth electron channel (E4) with en-  
 302 ergies between 300 keV – 2.5 MeV, centered at  $\sim 612$  keV (Green, 2013). The count rates  
 303 estimated for the E1 – E4 electron energy channels were then used to calculate contin-  
 304 uous spectra over the energy range from 25 keV to 10 MeV (total of 27 energy channels).  
 305 Peck-corrected MEPED dataset also contains error estimates accounting for measure-  
 306 ment errors and for errors in the fitting of the spectral distributions. An example of the  
 307 electron fluxes measured by MEPED onboard NOAA-16 used in this study are displayed  
 308 in panel a) of Figure (2) for  $\sim 1$  MeV energy and equatorial pitch-angles  $\alpha_{eq} < 15^\circ$ .

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#### 4.1 Processing of POES observations

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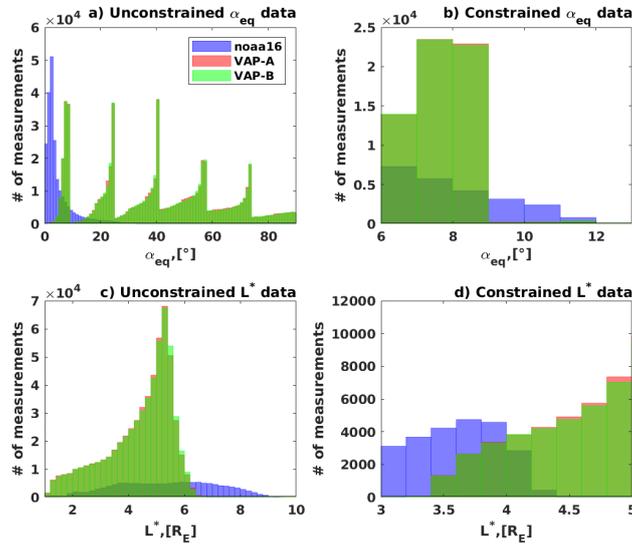
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For a proper comparison of the Van Allen Probes and POES datasets some considerations need to be taken into account, and consequently further processing and/or constraining of the observations has to be performed. All POES data are processed with the IRBEM-ONERA library using the magnetic field model (T89) (Tsyganenko, 1989). We first constrain the POES data to observations at equatorial pitch-angles  $\alpha_{eq} \geq 6^\circ$  because the smallest pitch-angle channel of MagEIS can detect  $\alpha_{eq} \sim 6^\circ$  based on the center point. Only time intervals of quiet to low geomagnetic activity are used (i.e. times when  $K_p \leq 4^-$ ) to reduce possible inaccuracies of the magnetic field model. Additionally, we restrict the  $L^*$ -range to values between 3–6.6  $R_E$ , as we want to focus on observations of the outer radiation belt. Figure (3) presents the  $L^*$  and  $\alpha_{eq}$ -distributions of the raw (panels a and c) and the constrained (histograms b and d) datasets. The final overlap of the distributions for the constrained data suggests that comparison of Van Allen Probes and POES observations for the studied time period is only feasible for  $L^* = 3 - 5 R_E$  and  $\alpha_{eq} = 6^\circ - 12^\circ$ .



**Figure 3. Data distributions:**  $L^*$  and equatorial pitch-angle ( $\alpha_{eq}$ ) observed by Van Allen Probes (a and b) and Peck-corrected data of NOAA-16 for 01. October, 2012 till 30. September, 2013. a) and c)  $L^*$  and  $\alpha_{eq}$ -distributions of raw data, respectively. b) and d)  $L^*$  and  $\alpha_{eq}$ -distributions of constrained datasets for intercalibration.

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As previously mentioned, the POES-fleet observes a mixture of electron populations, therefore we only use measurements from the  $90^\circ$ -telescopes. Since these observations are very close to the loss cone, we need to isolate the measured populations and remove drift- and bounce loss cone (DLC and BLC, respectively) measurements from our datasets. The purpose of this step is twofold: 1) DLC and BLC observations from POES cannot be compared to Van Allen Probes measurements because Van Allen Probes does not resolve the loss cone; 2) the use of only trapped particles allows us to rely on Liouville's theorem to map PSD at the geomagnetic equator.

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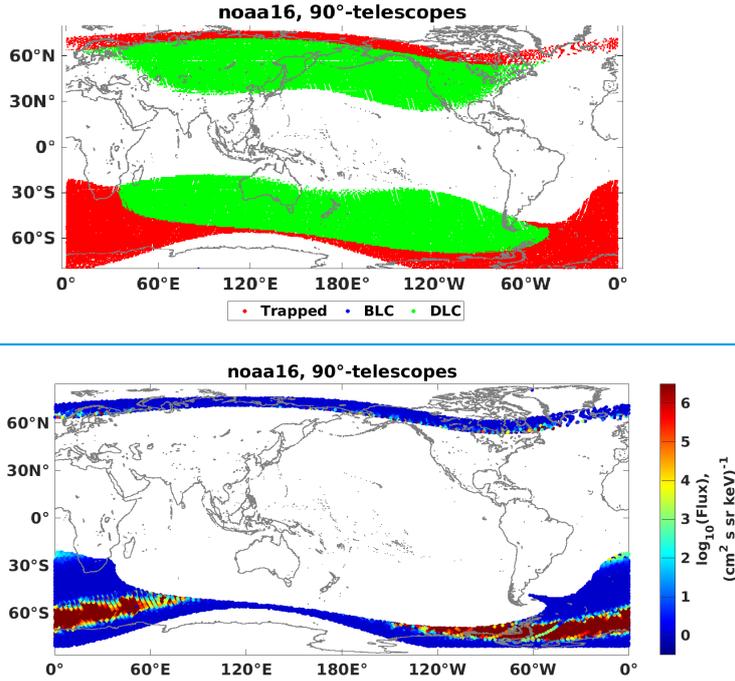
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The approach used to isolate POES populations used in this work is similar to the one presented by Y. Y. Shprits et al. (2023), and is described in the next paragraphs. Measurements of the MEPED detector for each energy channel are reported as the total counts per second estimated over 8 consecutive integration periods of 2s. Due to the wide angle of aperture of the detector and the integration time for the measurement, a large range of electrons with local pitch-angles between  $\alpha_{loc} \pm 15^\circ$  can enter the detector, so that the measurement of the central angle may be biased. For this reason, using

339 the local pitch-angle from the central-angle measurement  $\alpha_c = \alpha_{loc}$ , we estimate the  
 340 other two possible edge values for the local pitch-angle at satellite position (assuming  
 341 a symmetric detector opening), i.e.  $\alpha_{min} = \alpha_{loc} - 15^\circ$  and  $\alpha_{max} = \alpha_{loc} + 15^\circ$ . Using  
 342 the conservation of the first adiabatic invariant ( $\mu$ ), we can calculate the corresponding  
 343 magnetic field intensity at the mirror point for each of these pitch-angle values, (i.e.  $B_c$ ,  
 344  $B_{min}$ ,  $B_{max}$ , respectively) using IRBEM-ONERA library. For the characterization, we  
 345 only use the minimum of the three values (here notated as  $B_M = \min(B_c, B_{min}, B_{max})$ ),  
 346 thereby imposing the strongest assumption to ensure that measurements labeled as trapped  
 347 are accurate. However, an unambiguous characterization of the observed electron pop-  
 348 ulations is rather impossible. The intensity of the Earth's magnetic field at 100km alti-  
 349 tude ( $B_{foot}$ ) is estimated using the IGRF-12 model (Thébault et al., 2015).



**Figure 4.** Global distribution of electron populations in the radiation belts as observed by the averaged 90°-telescopes MEPED onboard NOAA-16, as of Peck-corrected SEM-2 data. DLC = Drift loss cone, BLC = Bounce loss cone.

350 We then determine if a particle precipitates into the atmosphere or not, as follows:

- 351 • The **BLC** is defined as the range of pitch-angles at satellite location with mirror  
 352 points below the atmosphere in either hemisphere. These particles will precipi-  
 353 tate into the atmosphere within one bounce period. For each measurement, we  
 354 find the minimum  $B_{foot}$  value between both hemispheres and compare this value  
 355 to  $B_M$ . It holds: if  $B_{foot} \leq B_M$ , the particle bounces below the atmosphere and  
 356 will be lost, therefore the measurement is labeled as **BLC**.
- 357 • The **DLC** is defined as the range of  $\alpha_{loc}$  at fixed drift-shell, that reach altitudes  
 358 lower than  $\sim 100$ km at the South Atlantic Anomaly (SAA) and will therefore pre-  
 359 cipitate into the atmosphere within one drift period. We estimate the L-shell (McIl-  
 360 wain value) for each POES measurement using IGRF. We then find the minimum  
 361  $B_{foot}$  for the given L-shell along constant longitude (longitude of satellite loca-  
 362 tion). This is the magnetic field intensity at the SAA ( $B_{SAA}$ ) and we compare it  
 363 to  $B_M$ . It holds: if  $B_{SAA} \leq B_M$ , the particle drifts below 100km at the SAA and  
 364 it will be lost, therefore the measurement is labeled as **DLC**.

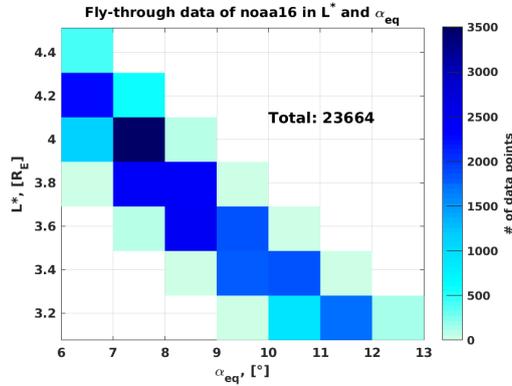
- If the measurement is not labeled as BLC nor as DLC, it will be labeled as **TRAPPED**. Only these data are used for the present work.

The obtained geographical distributions of the electron populations agree well with those obtained by Rodger, Carson, et al. (2010) (see Figure 4). Only trapped data are used for the comparison with Van Allen Probes+GOES-reanalysis, Van Allen Probes observations, and for the respective estimation of recalibration coefficients.

## 5 POES fly-through across the Reanalysis

In this and the following sections, we present the formal tests and results of our intercalibration approach on the NOAA-16 satellite dataset. The results obtained for the other satellite missions mentioned in Table (1) are summarized in the Supporting Information.

Since the reanalysis represents the “optimal state” of the outer radiation belt (i.e. the closest to the true state) at all times and locations, we can fly each POES satellite through this global reconstruction. A spacecraft fly-through across the data assimilative reanalysis is equivalent to an interpolation of the assimilated electron fluxes onto the spatial/temporal-grid of the POES fluxes. For the fly-through, POES data are binned into 1h time bins (i.e. the time step of the reanalysis) and the  $(L^*, E, \alpha_{eq})$ -nodes in the VERB-grid closest to the satellite measurement are labeled. To obtain the flux value of the reanalysis at the satellite location, we perform three 1D interpolations using piecewise cubic splines. We interpolate electron fluxes over 1D intervals enclosing the measured POES-data point and at least five RA grid nodes around it. Since the VERB-code only models diffusion of energetic particles trapped in the radiation belts without convection, we focus on radiation belt energies from  $\sim 200$  keV to 1 MeV (i.e. energy channels 10 to 17 of the Peck-corrected data).



**Figure 5. Fly-through data:** 2D-histogram of  $L^*$  vs.  $\alpha_{eq}$  covered by the fly-through of NOAA-16 for the period of October 2012 till September 2013. A total of 23664 data points are available, color-coded is the number of data points per bin.

We then extract the corresponding flux values of the reanalysis ( $j_{RA}$ ) at POES location ( $L^*$ ), energy ( $E$ ) and pitch-angle ( $\alpha_{eq}$ ), and compare them with the actual flux values measured by the LEO satellites ( $j_{POES}$ ) at same location, energy and pitch-angle. Figure (5) shows the 2D-histogram of  $L^*$  and  $\alpha_{eq}$  values, at which fly-through data are available. We find a total of 23664 data points available for comparison in the ranges of  $L^* = 3.2 - 4.4$  and  $\alpha_{eq} = 6^\circ - 12^\circ$ . Bins with the largest number of data points are located around  $L^* = 3.2 - 4.2$  and  $\alpha_{eq} = 6^\circ - 12^\circ$ .

Since we now have two flux values at same location, we can estimate the flux ratios ( $R_{DA}$ ) between the reanalysis fluxes ( $j_{RA}$ ) and the measured fluxes ( $j_{POES}$ ) for each

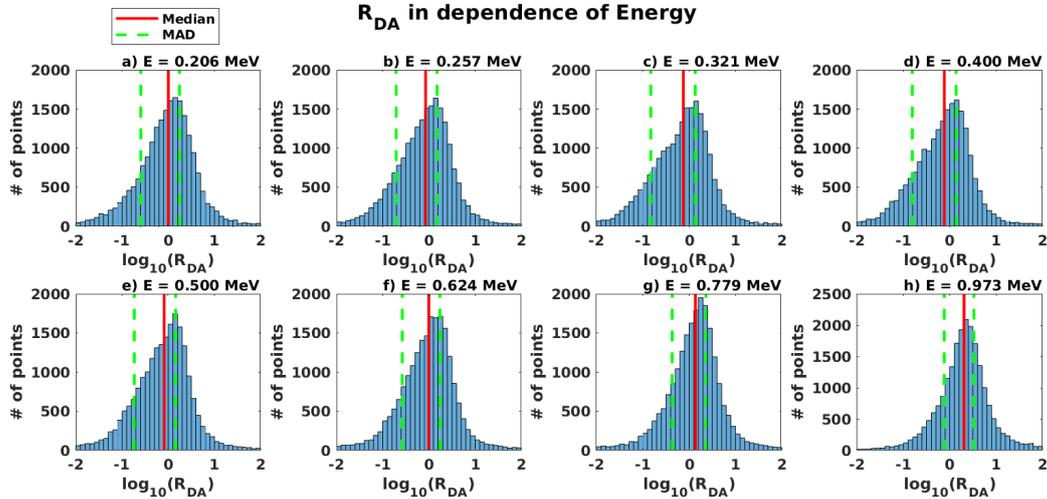
398 time-bin (reanalysis time ( $t_{RA}$ )), satellite location ( $L^*$ ), energy channel ( $E$ ) and equa-  
 399 torial pitch-angle ( $\alpha_{eq}$ ), as follows:

$$R_{DA}(t_{RA}, L^*, E, \alpha_{eq}) = \frac{j_{RA}(t_{RA}, L^*, E, \alpha_{eq})}{j_{POES}(t_{RA}, L^*, E, \alpha_{eq})} \quad (1)$$

400 We analyse the distributions of  $R_{DA}$  in dependence of  $E$ ,  $\alpha_{eq}$ ,  $L^*$  and  $K_p$ , in order  
 401 to determine the influence of each of these parameters on the flux ratios. The his-  
 402 tograms of  $R_{DA}$  in dependence of the energy channel are presented in Figure (6). The  
 403 distributions show slightly skewed bell shapes with clear peaks. The spread and skew-  
 404 ness of the distributions appears to be larger for  $E \leq 500$  keV. We estimate the median  
 405 of  $R_{DA}$  over time for each energy channel  $E_i$  (red line), i.e.  $Q_2(R_{DA}(E_i)) = \text{median}(R_{DA}(E_i))$ ,  
 406 and use the Median Absolute Deviation (**MAD**) (green lines) to estimate the median  
 407 variation of the residuals around the median of the distribution. For skewed distribu-  
 408 tions the MAD is more robust than the standard deviation, because it is more resilient  
 409 to outliers, and it is defined as the median of the absolute deviations from the median  
 410 of the data, as follows (Rousseeuw & Croux, 1993):

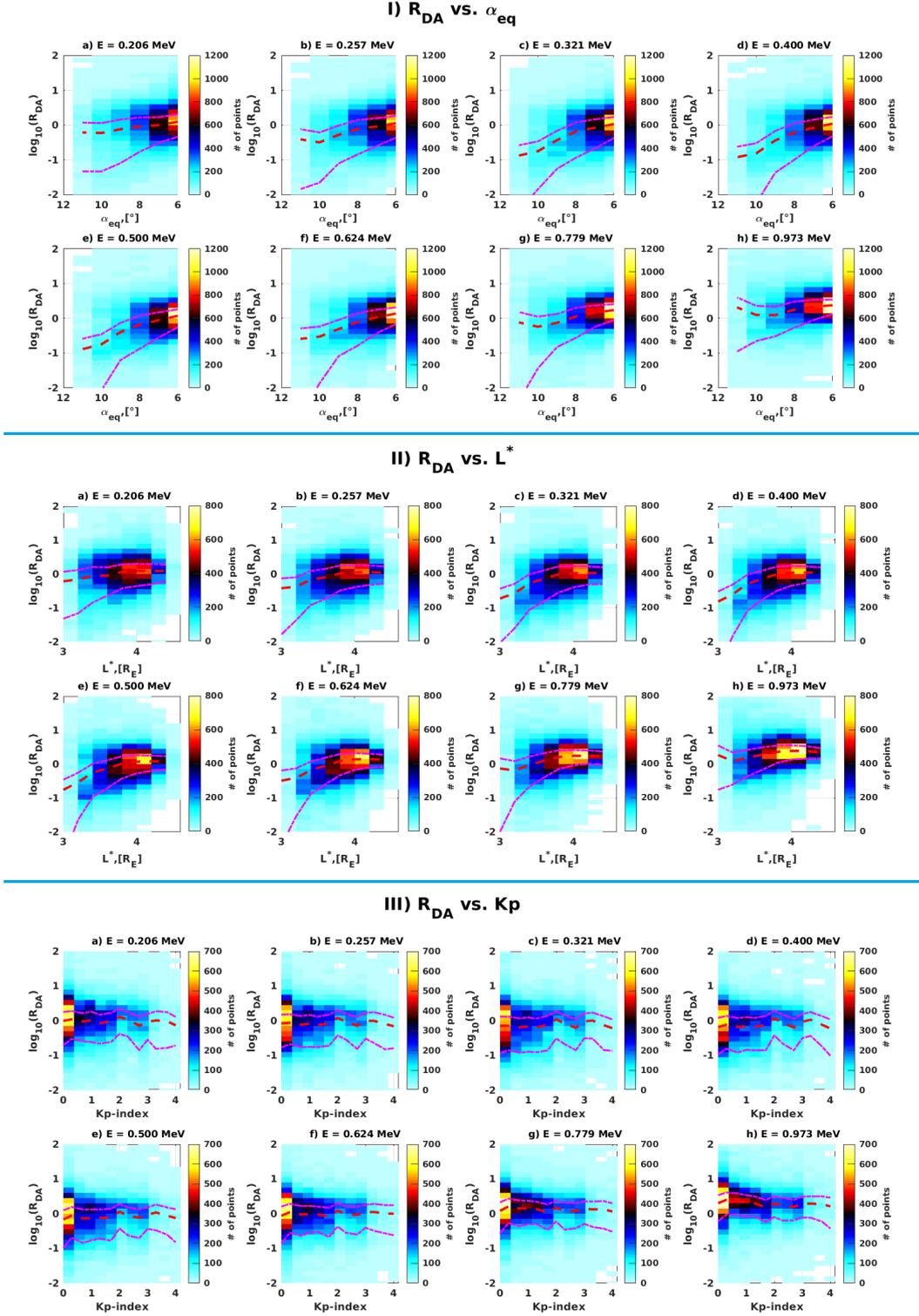
$$\text{MAD} = \text{median}(|R_{DA}(t_{DA}, E_i) - Q_2(R_{DA}(E_i))|). \quad (2)$$

411 The median of  $R_{DA}$  for energies  $< 700$  keV remains close to 1 (note that the  $x$ -  
 412 axis is  $\log_{10}(R_{DA})$ ), but at higher energies it shows a clear increase up to values of  $\sim$   
 413 2 for  $E = 973$  keV. The lower MAD values constantly fall around 0.8 – 0.9, but notice-  
 414 ably increase above 1 for  $E = 779$  keV and  $E = 973$  keV. For most energy chan-  
 415 nels, the upper bounds of the MAD oscillate around 2–3, reaching highest values ( $>$   
 416 4) at  $E = 779$  keV and  $E = 973$  keV. These features suggest a strong dependence of  
 417 the  $R_{DA}$  on the energy channel.



**Figure 6.** Distribution of  $R_{DA}$  in energy for NOAA-16: Histograms of  $R_{DA}$  (in  $\log_{10}$  scale) vs number of samples for each energy channel (each  $R_{DA}$  unit is divided into 10 bins). The median is indicated by the red lines, while the MAD is given by the magenta lines.

418 We further study the dependence of  $R_{DA}$  on  $\alpha_{eq}$  for each energy channel, as shown  
 419 in the 2D-histograms in Figure (7.I). The red dashed line represents the median and the  
 420 magenta dashed lines are the MAD of the distributions (note that the  $y$ -axis is  $\log_{10}(R_{DA})$ ).



**Figure 7.** 2D-Distributions of  $R_{DA}$  for NOAA-16: I) 2D-Histograms of  $R_{DA}$  (in  $\log_{10}$  scale) vs.  $\alpha_{eq}$  for each energy channel (plotted in  $1^\circ$ -bins and  $R_{DA}$ -bins of 1.4 width). II) 2D-Histograms of  $R_{DA}$  (in  $\log_{10}$  scale) vs.  $L^*$  for each energy channel (plotted in  $L^*$ -bins with  $0.25R_E$  width). III) 2D-Histograms of  $R_{DA}$  (in  $\log_{10}$  scale) vs.  $K_p$  for each energy channel (plotted in  $K_p$ -bins of 0.33 width). Color-coded are the number of samples. The median is indicated by the red dashed lines, and the MAD is given by the magenta dashed lines.

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Here, the skewness and spread of the distributions also appear to decrease with increasing energy. Clusters in the data can be well seen for all energy channels at least up

423 to  $\alpha_{eq} = 9^\circ$ , with highest sample density around  $\alpha_{eq} = 6^\circ - 7^\circ$ . The median of the  
 424 distributions seems to decrease with increasing value of  $\alpha_{eq}$  in a non-linear way at all  
 425 energies. For  $E < 300$  keV, the median of  $R_{DA}$  moves from values close to  $\sim 1$  at  $\alpha_{eq} =$   
 426  $6^\circ$  down to  $\sim 0.6$  at  $\alpha_{eq} = 11^\circ$ . Furthermore, for  $E > 300$  and  $E < 700$  keV, the me-  
 427 dian of  $R_{DA}$  also peaks around 1 at  $\alpha_{eq} = 6^\circ$ , but it reaches down to  $\sim 0.2$  at  $\alpha_{eq} =$   
 428  $11^\circ$ . Higher energy channels show larger values for the median of  $R_{DA}$  with the max-  
 429 imum being  $> 2$  at  $\alpha_{eq} = 6^\circ$  and the minimum falling close to 1 at  $\alpha_{eq} = 11^\circ$ . For  
 430 all the energy channels, the upper limit of the MAD remains around 0.3 above the me-  
 431 dian, while the lower bound decreases rapidly with increasing value of  $\alpha_{eq}$ , so that it can-  
 432 not be estimated for  $\alpha_{eq} = 11^\circ$  in most of the cases.

433 Similar trends in the skewness and spread are observed in Figure (7.II), which dis-  
 434 plays the 2D-histograms  $R_{DA}$  vs.  $L^*$  for each energy channel. These distributions also  
 435 show clear bulks between  $L^* = 3.2-4.2$  with peaks at  $L^* = 3.6-4.0$  for all ener-  
 436 gies. The median curves of  $R_{DA}$  present inverse parabolic behaviour that seems to flat-  
 437 ten at  $E = 973$  keV. The median reaches its minimum at  $L^* = 3$  and increases within  
 438 one order of magnitude until it finds its maximum at  $L^* = 4$  and then begins to de-  
 439 crease at  $L^* = 4.2$ . The median at  $L^* = 4$  oscillates close to 1 for  $E < 600$  keV, but  
 440 increases its value above 2 at higher energies. The trends in the MAD are similar to those  
 441 seen in Figure (7.I), which is expected due to the inverse proportionality of  $L^*$  and  $\alpha_{eq}$ .

442 Finally, we analyse the variation of  $R_{DA}$  with respect to the geomagnetic activity  
 443 index  $K_p$  (see Figure (7.III)). The same trends in the skewness and spread with regard  
 444 to the energies observed before, are also seen here. However, in this case the spread of  
 445 the distributions appears to be less than one order of magnitude. The histograms show  
 446 clear bulks of samples between  $K_p = 0 - 3$ . Unlike the previous cases, the median of  
 447  $R_{DA}$  does not show much variation and oscillates around 1 for all  $K_p$  values and  $E <$   
 448  $700$  keV. At higher energies, the median curve also increases its values slightly showing  
 449 a small peak at  $K_p \sim 0.3$ , but remaining rather constant otherwise. The MAD shows  
 450 larger uncertainties in the upper limits around the median, but remains within 0.4 of the  
 451 median values. The spread of the MAD also decreases noticeably with increasing energy.

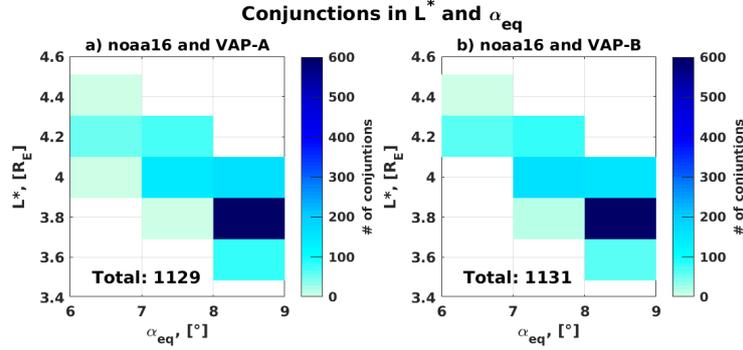
452 The analysis of  $R_{DA}$  presented in this section suggests a strong dependence on the  
 453 energy channel,  $L^*$ -location and  $\alpha_{eq}$ . In contrast, the value of  $K_p$  shows a rather small,  
 454 if not negligible, influence on the flux-ratios. Before we look deeper into these param-  
 455 eters and their influence on  $R_{DA}$ , we check in the next section if a traditional conjunc-  
 456 tion approach delivers similar insights into the behaviour of the flux-ratios.

## 457 6 Conjunction Study between Van Allen Probes and NOAA-16

458 In this section, we analyse the behaviour of flux-ratios obtained from a geomag-  
 459 netic conjunction study performed between the NOAA-16 and Van Allen Probes (A and  
 460 B) satellites. In this case, we choose Van Allen Probes observations to be the "gold stan-  
 461 dard", which we use as a reference to carry out on-orbit comparisons with NOAA-16 mea-  
 462 surements in geomagnetic space (Friedel et al., 2005). For a pair of (Van Allen Probes,  
 463 NOAA-16) observations to be considered a conjunction, the following conditions should  
 464 be met: 1) The location of both satellites must be within  $\pm 0.1L^*$ , 2) ideally the observed  
 465 electrons have the same equatorial pitch-angles:  $\pm 0.5^\circ \alpha_{eq}$ , 3) the energy of the measure-  
 466 ments has a maximum deviation of  $\pm 10\%$ :  $E_{VAP} = E_{POES} \pm 10\%$ , 4) the conjunction  
 467 must occur within a time frame of  $\Delta t = \pm 1$  hour, and 5) the conjunction occurs dur-  
 468 ing low to moderate levels of geomagnetic activity:  $K_p \leq 4^-$ .

469 Figure (8) presents the 2D-histogram of  $L^*$  and  $\alpha_{eq}$  values, at which the geomag-  
 470 netic conjunctions are found. We have a total of 1129 conjunctions between Van Allen  
 471 Probe-A and NOAA-16 (Figure 8.a) and, 1131 conjunctions between Van Allen Probe-

472 B and NOAA-16 (Figure 8.b), in the ranges of  $L^* = 3.6 - 4.4$  and  $\alpha_{eq} = 6^\circ - 8^\circ$ . Bins  
 473 with the largest number of data points are centered around  $L^* = 3.8$  and  $\alpha_{eq} = 8.5^\circ$ .



**Figure 8. Conjunction data:** 2D-histogram of  $L^*$  vs.  $\alpha_{eq}$ , at which geomagnetic conjunctions between NOAA-16 and a) Van Allen Probe-A; and b) Van Allen Probe-B are available for the period of October 2012 till September 2013. The total number of conjunctions is displayed in the lower left part of each plot, color-coded is the number of data points per bin.

474 Since we now have comparable pairs of (Van Allen Probes, NOAA-16) observations,  
 475 we can perform flux-comparisons at same satellite location and estimate the flux ratios  
 476 (here notated as  $R_{Conj}$ ) between Van Allen Probes measured fluxes ( $j_{VAP}$ ) and POES  
 477 measured fluxes ( $j_{POES}$ ) for each time-bin (Van Allen Probes time ( $t_{VAP}$ )), satellite location  
 478 ( $L^*$ ), energy channel ( $E$ ) and equatorial pitch-angle ( $\alpha_{eq}$ ), as follows:

$$R_{Conj}(t_{VAP}, L^*, E, \alpha_{eq}) = \frac{j_{VAP}(t_{VAP}, L^*, E, \alpha_{eq})}{j_{POES}(t_{VAP}, L^*, E, \alpha_{eq})} \quad (3)$$

479 Similar to the previous section, we analyse the statistical dependence of  $R_{Conj}$  on  
 480  $E$ ,  $L^*$ ,  $\alpha_{eq}$  and  $K_p$ . Figure (9) shows the histograms of  $R_{Conj}$  per energy channel. Since  
 481 the distributions are rather irregular and show large spread, we estimate their peak as  
 482 the median of  $R_{Conj}$  over time for each energy (i.e.  $Q_2(R_{Conj}(E_i)) = \text{median}(R_{Conj}(E_i))$ )  
 483 (indicated by the red bar); and their deviation through the MAD (green lines) is esti-  
 484 mated by:

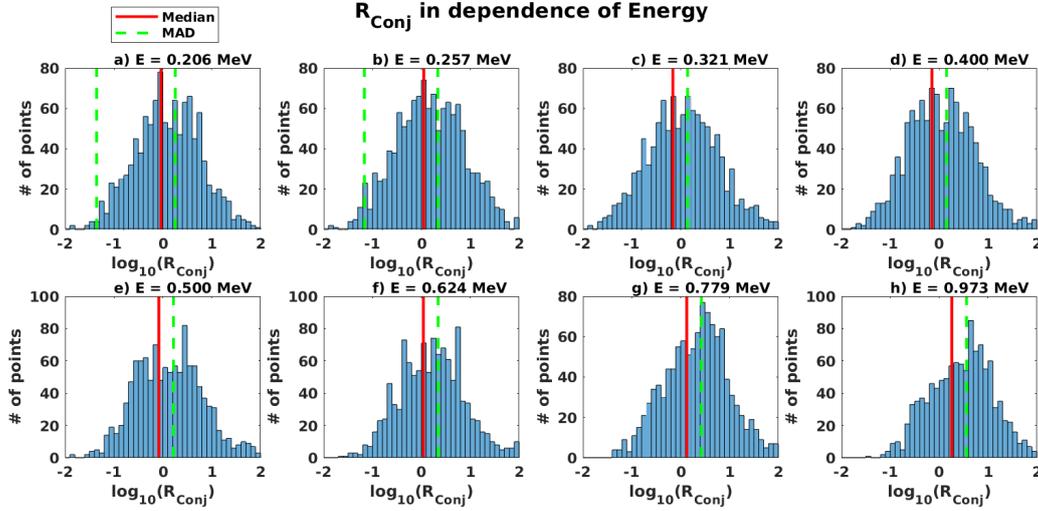
$$\text{MAD} = \text{median}(|R_{Conj}(t_{VAP}, E_i) - Q_2(R_{Conj}(E_i))|). \quad (4)$$

485 For energies  $< 700$  keV, the value of the median remains close to 1, but it increases  
 486 for higher energies reaching a maximum at  $E = 973$  keV. While the upper bound of  
 487 the MAD seems to stick constantly close to the median for all energies, the lower bound  
 488 becomes too small for several energies and cannot, therefore, be displayed in  $\log_{10}$  scale.

489 Figure (10.I) presents the 2D-histograms of  $R_{Conj}$  in dependence of  $\alpha_{eq}$ . Although  
 490 the distributions show high spread and nonuniform behaviour, a clear peak can be seen  
 491 between  $\alpha_{eq} = 8^\circ - 9^\circ$ . The median of  $R_{Conj}$  (red dashed line) appears to remain con-  
 492 stant around a value of 1 for energies below 700 keV, showing a decrease in value at the  
 493  $6^\circ$  bin. At higher energies the value of the median increases, as also observed in the pre-  
 494 vious figure. The MAD bounds (magenta dashed lines) indicate higher deviation to the  
 495 upper values of  $R_{Conj}$ . Figure (10.II) displays the 2D-histograms of  $R_{Conj}$  in dependence  
 496 of  $L^*$ . The distributions are again rather irregular and show large spread.

497 However, a clear peak in sample density is observed at  $L^* = 3.6 - 4$ . For  $E <$   
 498  $700$  keV, the value of the median of  $R_{Conj}$  seems to remain constantly around 1 or in-  
 499 creases with increasing  $L^*$  value, showing a peak at the  $L^* = 4.0$  bin and then decreas-  
 500 ing again. MAD values for the upper bound remain around 2 units above the median,

501 but the lower limit becomes too small for  $L^* < 3.8$  in most energy channels. Addition-  
 502 ally, Figure (10.III) shows the 2D-histograms of  $R_{Conj}$  in dependence of the geomagnetic  
 503 index  $K_p$ .



**Figure 9.** Distribution of  $R_{Conj}$  in energy for NOAA-16: Histograms of  $R_{Conj}$  (in  $\log_{10}$  scale) vs number of samples for each energy channel (each  $R_{Conj}$  unit is divided into 10 bins). The median is indicated by the red lines, while the MAD is given by the magenta lines.

504 While a clear peak in sample density can be observed at  $K_p = 0$ , the distributions  
 505 show large spread and for  $K_p > 1$  no clear peak can be seen. The median value at the  
 506 bulk of the samples is very close to 1 for all energy channels. However, the curve of the  
 507 median oscillates in rather random way at higher  $K_p$  values, so no clear trend can be ob-  
 508 served. While the upper bound of the MAD closely follows the median value, the lower  
 509 MAD limit becomes too small for the log-scale.

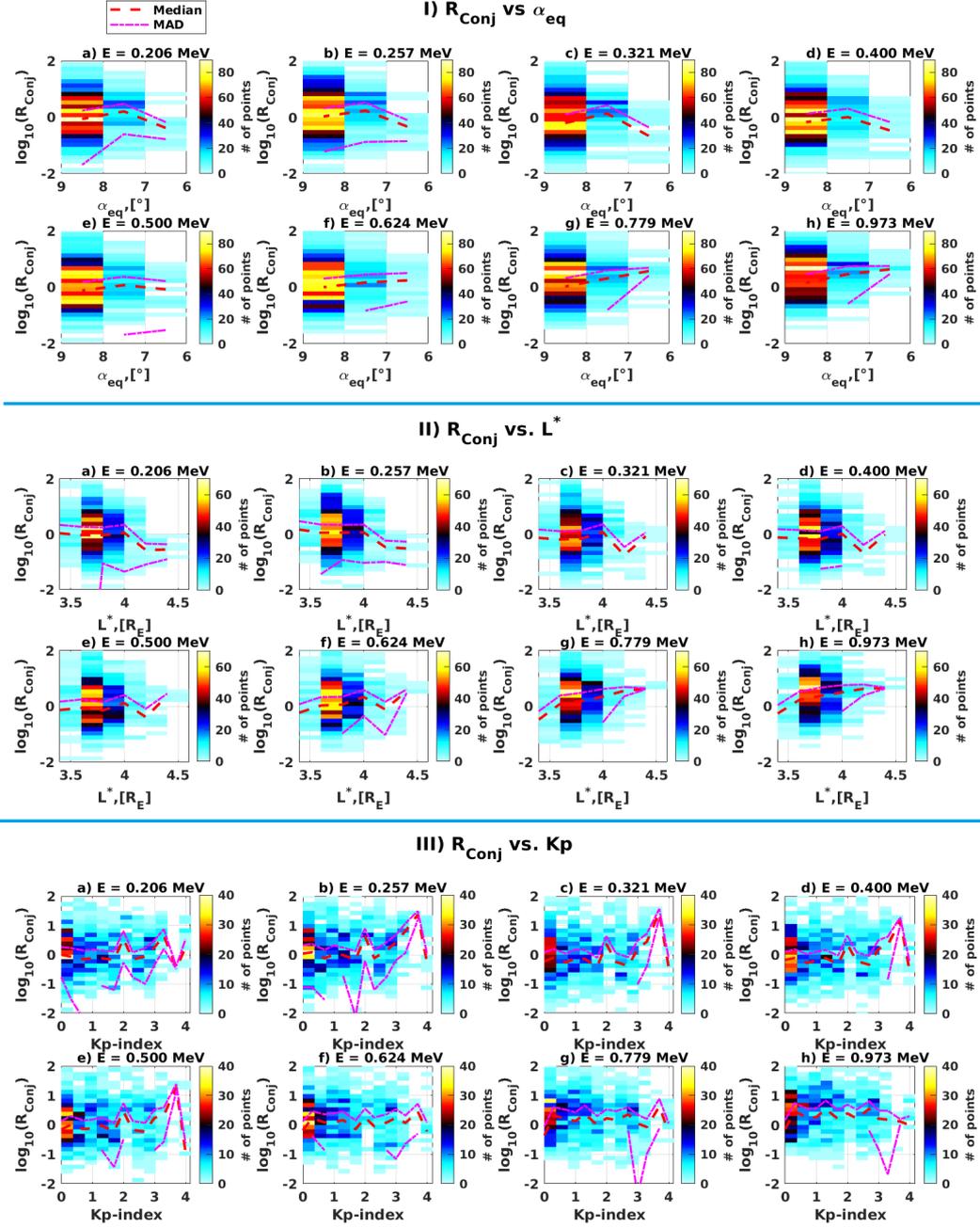
## 510 7 Results and Discussion

511 Taking into account the statistical analyses presented in sections 5 and 6, here we  
 512 compare the median values of  $R_{DA}$  and  $R_{Conj}$  (denoted by  $Q_2(R_{DA})$  and  $Q_2(R_{Conj})$ ,  
 513 respectively), in dependence of  $E$ ,  $L^*$ ,  $\alpha_{eq}$  and  $K_p$  (i.e. the red lines in the previous his-  
 514 tograms). We discuss our findings and estimate final intercalibration coefficients for NOAA-  
 515 16.

### 516 7.1 Comparison of Intercalibration Coefficients

517 We begin by analysing how the median values of  $R_{DA}$  and  $R_{Conj}$  behave in terms  
 518 of the energy channel (shown in Figure (11)). The error bars show the spread given by  
 519 the MAD (red bars for  $Q_2(R_{DA})$  and blue bars for  $Q_2(R_{Conj})$ , respectively). Both curves  
 520 clearly display the similar trends and values for all energy channels. Largest differences  
 521 between  $Q_2(R_{DA})$  and  $Q_2(R_{Conj})$  are seen at  $E = 257$  keV and  $E = 973$  keV, but  
 522 these remain within a factor of  $\sim 0.5$ . The values of both  $R$ -medians decrease from low  
 523 to middle energies, and then increase again from middle to high energies. Most values  
 524 remain below the value of 2, but a clear increase is seen for  $E > 600$  keV, where  $Q_2(R_{Conj})$ -  
 525 values get close to 2.

526 The uncertainties of both datasets are quite large to the upper limits of the me-  
 527 dian. Lower bound uncertainties never reach a factor of 1, but they do increase for  $Q_2(R_{DA})$   
 528 at  $E > 600$  keV.

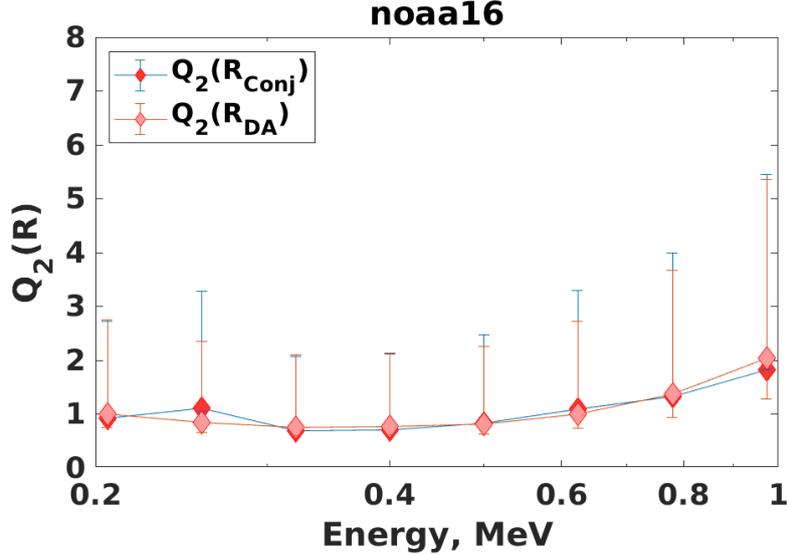


**Figure 10.** 2D-Distributions of  $r_{Conj}$  for NOAA-16: I) 2D-Histograms of  $R_{Conj}$  (in  $\log_{10}$  scale) vs.  $\alpha_{eq}$  for each energy channel (plotted in  $1^\circ$ -bins and  $R_{Conj}$ -bins of 1,4 width). II) 2D-Histograms of  $R_{Conj}$  (in  $\log_{10}$  scale) vs.  $L^*$  for each energy channel (plotted in  $L^*$ -bins with  $0.25R_E$  width). III) 2D-Histograms of  $R_{Conj}$  (in  $\log_{10}$  scale) vs.  $K_p$  for each energy channel (plotted in  $K_p$ -bins of 0.33 width). Color-coded are the number of samples. The median is indicated by the red dashed lines, and the MAD is given by the magenta dashed lines.

529 The upper limit uncertainty for  $Q_2(R_{DA})$  remains around a factor of  $\sim 2$  for  $E <$   
 530  $700$  keV, but increases up to a factor of  $\sim 3.5$  for higher energy channels. The upper  
 531 bound uncertainties of  $Q_2(R_{Conj})$  are generally larger than those of  $Q_2(R_{DA})$ , but re-  
 532 main within a factor of  $\sim 2 - 2.5$ .

533 We further study the behaviour of the median values of  $R_{DA}$  and  $R_{Conj}$  with re-  
 534 spect to  $L^*$ ,  $\alpha_{eq}$  and  $K_p$  for each energy channel. Panels a) and b) of Figure (12) show  
 535 the median of  $R_{DA}$  and  $R_{Conj}$  (respectively) in terms of  $L^*$  and energy.  $Q_2(R_{DA})$  curves

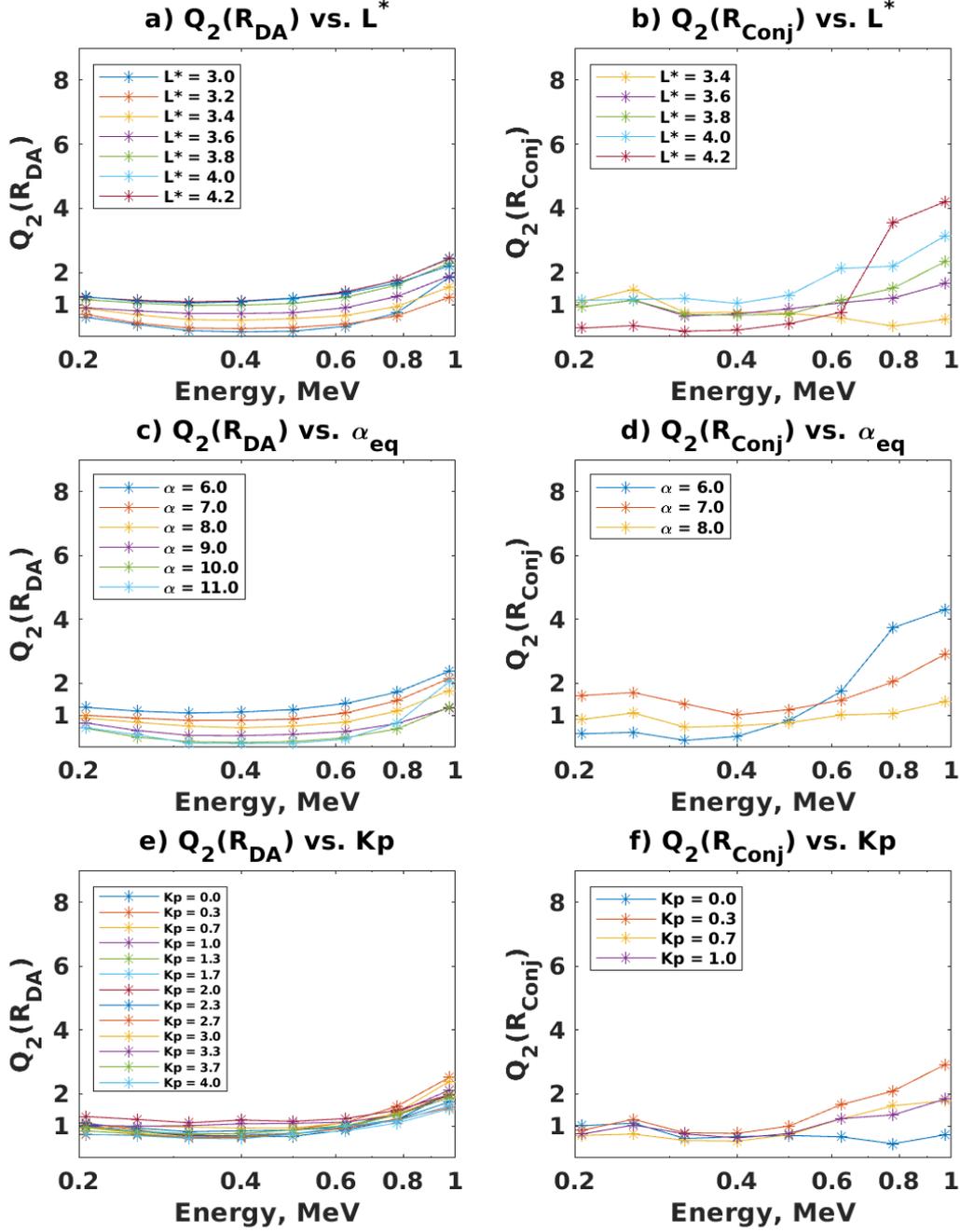
536 are smooth and present similar trends as those seen in Figure (11) for all  $L^*$ -bins. The  
 537 values of  $Q_2(R_{DA})$  increase with increasing  $L^*$ -value for fixed energy, but remain between  
 538  $\sim 0.5$  and  $\sim 1.5$  at 200 keV, and reach  $\sim 1.2 - 2.5$  at 973 keV. At  $L^* \leq 3.8$  and for  
 539  $E < 0.6$  MeV, MEPED slightly underestimates the reanalysis fluxes. For  $E \geq 0.8$  MeV,  
 540 this underestimation is seen in all  $L^*$ -bins and also maximum values of  $Q_2(R_{DA})$  are ob-  
 541 served here. Below  $L^* = 3.6$  and for  $E < 0.6$  MeV MEPED consistently overestimates  
 542 the reanalysis fluxes. The curves of  $R_{Conj}$ -median values (Figure 12.b) are less smooth  
 543 than those of  $Q_2(R_{DA})$ , and no clear trends are observed. For most  $L^*$  and energy val-  
 544 ues, MEPED underestimates Van Allen Probes fluxes, only at  $L^* = 4$  below 0.5 MeV  
 545 mild overestimation or agreement are observed. Highest  $Q_2(R_{Conj})$  values are at  $E >$   
 546 600 keV for most  $L^*$ -values.



**Figure 11.** Values of  $Q_2(R_{DA})$  and  $Q_2(R_{Conj})$  vs. Energy. Plotted in linear scale are the median values of  $R_{DA}$  (pink diamonds) and  $R_{Conj}$  (red diamonds) estimated for NOAA-16 in dependence of the energy channel. Error bars are estimated from the corresponding MAD values and displayed for  $Q_2(R_{DA})$  in pink color and for  $Q_2(R_{Conj})$  in blue.

547 The median values of  $R_{DA}$  and  $R_{Conj}$  in dependence of  $\alpha_{eq}$  and energy channel  
 548 are presented in Figure (12, panels c and d), respectively.  $R_{DA}$ -median curves clearly  
 549 resemble the trends observed in Figure (12.a). In general,  $Q_2(R_{DA})$  increases with de-  
 550 creasing value of  $\alpha_{eq}$  for fixed energy. For  $E < 600$  keV, most  $Q_2(R_{DA})$  values are be-  
 551 low 1, indicating that POES measurements tend to be larger than the reanalysis. MEPED  
 552 fluxes at  $\alpha_{eq} = 6^\circ - 7^\circ$  appear to be very close to the reanalysis fluxes below 700 keV.  
 553 The largest difference between the data assimilative output and the POES measurements  
 554 is observed above  $E = 700$  keV. Trends of  $Q_2(R_{Conj})$  in Figure (12 panel d) coincide  
 555 well with those in Figure (12, panel b). For  $E < 400$  keV, Van Allen Probes measure-  
 556 ments at  $\alpha_{eq} = 7^\circ$  are higher than MEPED fluxes, but at  $\alpha_{eq} = 6^\circ$ , the opposite is  
 557 the case. For  $E > 600$  keV and at  $\alpha_{eq} = 6^\circ - 7^\circ$ , MEPED fluxes underestimate Van  
 558 Allen Probes observations.

559 The curves of  $Q_2(R_{DA})$  and  $Q_2(R_{Conj})$  in dependence of  $K_p$  and energy channel  
 560 are displayed in Figure (12, panels e and f, respectively). For most energy channels,  $Q_2(R_{DA})$ -  
 561 curves are equal or close to 1. At  $E > 600$  keV, we observe an increase in the median  
 562 value, suggesting that POES underestimates Van Allen Probes fluxes at these energies.  
 563  $Q_2(R_{Conj})$ -values move close to 1 only for  $E < 600$  keV. At  $E > 600$  keV, an increase  
 564 in  $Q_2(R_{Conj})$ -values up to a factor of 2 is well observed.



**Figure 12.** Values of  $Q_2(R_{DA})$  and  $Q_2(R_{Conj})$  vs.  $L^*$ -bin,  $\alpha_{eq}$  and  $K_p$ . Curves of  $Q_2(R_{DA})$  in dependence of the energy channel for NOAA-16, color-coded are the curves a) for each  $L^*$ -bin, c) for each  $\alpha_{eq}$ -bin, e) for each  $K_p$ -bin. Curves of  $Q_2(R_{Conj})$  in dependence of the energy channel for NOAA-16, color-coded are the curves b) for each  $L^*$ -bin, d) for each  $\alpha_{eq}$ -bin, e) for each  $K_p$ -bin. The Y-axes in all plots is in linear scale.

565 With increasing  $K_p$ -value the statistical significance of the  $K_p$ -bins is strongly re-  
 566 duced (i.e. points per bin  $\leq 10$ ), which resembles in the irregular behaviour of the curves.  
 567 Therefore, we only plot the results for  $K_p \leq 1$ .

## 568 7.2 Discussion

569 The comparisons presented in the previous sections clearly show how the data-assimilative  
 570 method is able to compare more data points (Figure (5)) than the conjunction study (Fig-  
 571 ure (8)), thereby consistently improving the statistics for the intercalibration. This is be-

572 cause the reanalysis provides a global reconstruction of the entire space of the radiation  
 573 belts, allowing us to compare much of the real observations at all satellite locations. In  
 574 Figures (6) and (7), an increase in spread and skewness of the  $R_{DA}$  distributions below  
 575  $E < 500$  keV is well observed. This is not the case for  $R_{Conj}$  (Figures (9) and (10)).  
 576 The reason for this may be lay in the physics used by the VERB-3D code, which as a  
 577 diffusion model is more suitable to model energetic particles. Comparison of Figures (11)  
 578 clearly shows the potential of our data-assimilative intercalibration approach.

579 Differences between  $Q_2(R_{DA})$  and  $Q_2(R_{Conj})$  may be related to the very differ-  
 580 ent statistics of both datasets. All conjunction statistics contain most less data points  
 581 than the statistics of the data-assimilative method. Another possibility is a bias com-  
 582 ing from the way the on-orbit comparisons are estimated. By just comparing the obser-  
 583 vations in space and time, we neglect the dependence of the instrument's response on  
 584 the hardness of the real energy spectrum. For instance, if due to a loss process, low en-  
 585 ergy particles are removed from the environment, the net energy of the spectrum will  
 586 increase. The observed dependence of  $Q_2(R_{DA})$  and  $Q_2(R_{Conj})$  on  $L^*$  and  $\alpha_{eq}$  (Figure  
 587 12 panels a, b, c and d, respectively) further supports this hypothesis. Such a dependence  
 588 was also reported by Peck et al. (2015), in comparison with the dataset from the Detec-  
 589 tion of Electro-Magnetic Emissions Transmitted from Earthquake Regions (DEMETER)  
 590 satellite Instrument for Detecting Particles (IDP) (Sauvaud et al., 2006). Since the orig-  
 591 inal energy channels of the POES measurements were derived as integral fluxes over broad  
 592 ranges of energy, the effect of spectrum hardening could be particularly high on the ef-  
 593 fective energy of the POES dataset. Restriction of the  $K_p$  values to  $\leq 4^-$  may help re-  
 594 duce the effect of hardening, however, the large width of the real energy channels, the  
 595 large field of view of the detector and possible remaining contamination can cause the  
 596 observations to be dominated by higher energy particles.

$L^* \backslash E$ [MeV]	0.206	0.257	0.321	0.400	0.500	0.624	0.779	0.973
3	0.61	0.38	0.19	0.15	0.17	0.32	0.74	1.85
3.2	0.69	0.42	0.27	0.25	0.29	0.39	0.65	1.22
3.4	0.88	0.68	0.53	0.51	0.56	0.66	0.94	1.54
3.6	0.90	0.80	0.72	0.72	0.75	0.90	1.25	1.89
3.8	1.15	1.05	0.98	0.98	1.04	1.22	1.61	2.29
4	1.23	1.12	1.07	1.09	1.18	1.38	1.76	2.45
4.2	1.23	1.13	1.09	1.11	1.20	1.40	1.76	2.42
4.4	1.24	1.10	1.04	1.09	1.20	1.36	1.67	2.21

**Table 2. Recalibration coefficients for NOAA-16:** Final intercalibration coefficients ( $Q_2(R_{DA})$ ) for estimated for NOAA-16 using our new data assimilation approach. The coefficients are given in terms of energy and  $L^*$ .

597 Values of  $Q_2(R_{DA})$  are similar for all  $L^*$  and  $\alpha_{eq}$ . This is not the case for  $Q_2(R_{Conj})$ ,  
 598 where values in dependence of  $L^*$  show higher maxima than those in dependence of  $\alpha_{eq}$ .  
 599 The proximity of POES pitch-angle measurements to the loss cone may be the reason  
 600 for this result. On the VERB-code the loss cone is modelled for a dipole field using an  
 601 exponential decay. Additionally, classification of observations as trapped contains un-  
 602 avoidable inaccuracies. On the other hand, Van Allen Probes observations in the small-  
 603 est pitch-angle channel are also very close to the loss cone, such that measurements from  
 604 these channels contain loss cone particles, even though the central angle of the instru-  
 605 ment may be outside of the loss cone. The use of a data-assimilative intercalibration ap-  
 606 proach also enables us to learn about possible improvements in the physics of our model.  
 607 In general,  $Q_2(R_{DA})$  values in  $L^*$  and  $\alpha_{eq}$  are lower than those of  $Q_2(R_{Conj})$ . This is  
 608 potentially an indication of inaccuracies in the latitudinal dependencies of the used dif-  
 609 fusion coefficient of the VERB-3D code, which determine the shape of the pitch-angle  
 610 distribution. In the future, more advanced diffusion coefficients such as A. Drozdov et  
 611 al. (2017); D. Wang et al. (2019); Saikin et al. (2022) may deliver better agreement.

612 The analysis on the  $K_p$  dependence of  $Q_2(R_{DA})$  and  $Q_2(R_{Conj})$  presents large in-  
 613 creases in both curves for  $E > 600$  keV. Since the last integral channel (E4) of the origi-  
 614 nal SEM-2 data is centered at about 612 keV, we find that this is an indication of a pos-  
 615 sible bias in the Peck-corrected differential fluxes, perhaps related to the spectral fit. While  
 616 this data product delivers large amounts of observations and the possibility to work with  
 617 higher energies, the broad width of the energy channels of the original POES dataset may  
 618 impose some limitations to extensions of the observations to higher energies.

619 For this reason, our results show that the highest dependence of  $Q_2(R)$  is on en-  
 620 ergy,  $L^*$  and  $\alpha_{eq}$ . Since in Figure (12) the inverse relation between  $L^*$  and  $\alpha_{eq}$  is eas-  
 621 ily observed, for the purpose of this study, we present final recalibration coefficients (val-  
 622 ues of  $Q_2(R_{DA})$ ) only in dependence of energy and  $L^*$  in tabular form (see Table (2)).

## 623 8 Conclusions

624 In the present study, we have shown the potential of a data-assimilative satellite  
 625 intercalibration approach. The proposed method was tested and validated using mea-  
 626 surements of energetic electrons in the radiation belt region from POES satellites (NOAA-  
 627 15,-16,-17,-18,-19) and MetOp-02, and Van Allen Probes. Using our intercalibration ap-  
 628 proach, we are able to considerably improve the statistics of on-orbit data comparisons.  
 629 Satellite intercalibration via data assimilative fly-through requires therefore shorter pe-  
 630 riods of data than comparisons through conjunctions. Our comparative analysis clearly  
 631 show that due to very few conjunctions, flux-ratios may be influenced and falsely esti-  
 632 mated, while using data-assimilative intercalibration shows that Peck-corrected POES  
 633 data are already in good agreement with Van Allen Probes observations below  $E \approx 600$   
 634 keV (i.e.  $R_{DA} \approx 1$ ), and can be used to reconstruct the global state of the radiation  
 635 belts. For higher energy channels the datasets are within a factor of 2, so that intercal-  
 636 ibration is required, as shown by both methods in this study. The recalibration factors  
 637 estimated with our data-assimilative method are consistent with the results from the con-  
 638 junction study.

639 The results of this study are encouraging as large satellite datasets can be efficiently  
 640 and automatically intercalibrated with this technique. In future, we plan to extend the  
 641 pitch-angle distribution of the Peck-corrected POES datasets using Smirnov et al. (2022)  
 642 approach and perform global reconstruction of the radiation belts using our recalibrated  
 643 dataset. We also want to perform a similar analysis using original uncorrected SEM-2  
 644 integral fluxes, including lower ring current energies. In this study, we have excluded such  
 645 a comparison since it would only concern one energy channel for radiation belt energies.  
 646 Additionally, we look forward to using this intercalibration method with other satellite  
 647 fleets providing large datasets, such as GPS.

## 648 Open Research Section

### 649 Data Availability Statement

650 The data used for this study is publicly available. The  $K_p$  index was provided by  
 651 GFZ Potsdam (<https://www.gfz-potsdam.de/kp-index/>). All RBSP-ECT data are  
 652 publicly available on the website: <http://www.RBSP-ect.lanl.gov/>. GOES electron  
 653 data can also be accessed online at [https://satdat.ngdc.noaa.gov/sem/goes/data/](https://satdat.ngdc.noaa.gov/sem/goes/data/full/)  
 654 [full/](https://satdat.ngdc.noaa.gov/sem/goes/data/full/). POES electron fluxes can be accessed online at [https://www.ngdc.noaa.gov/](https://www.ngdc.noaa.gov/stp/satellite/poes/dataaccess.html)  
 655 [stp/satellite/poes/dataaccess.html](https://www.ngdc.noaa.gov/stp/satellite/poes/dataaccess.html). The IRBEM library can be found under: [http://](http://github.com/PRBEM/IRBEM/)  
 656 [github.com/PRBEM/IRBEM/](http://github.com/PRBEM/IRBEM/).

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