# Outer Radiation Belt Flux and Phase Space Density Response to Sheath Regions: Van Allen Probes and GPS Observations

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#### Abstract

Turbulent and compressed sheath regions preceding interplanetary coronal mass ejections (ICMEs) strongly impact electron dynamics in the outer radiation belt. Changes in electron flux can occur on timescales of tens of minutes, which is difficult to capture by a two-satellite mission such as the Van Allen Probes (RBSP). The recently released Global Positioning System (GPS) data set has higher data density owing to the large number of satellites in the constellation equipped with energetic particle detectors. Investigating electron fluxes in a wide range of energies and sheaths observed from 2012 to 2018, we show that the flux response to sheaths on a timescale of 6 hours, previously reported from RBSP data, is reproduced by GPS measurements. Furthermore, GPS data enables derivation of the response on a shorter timescale of 30 minutes, which further confirms that the energy and L-shell dependent changes in electron flux are due to the impact of the sheath. Sheath-driven loss is underestimated over longer timescales as the electrons recover during the ejecta. We additionally show the response of electron phase space density (PSD), which is a key quantity in identifying true loss from the system and electron energization through wave-particle interactions. The PSD response is calculated from both RBSP and GPS data for the 6-hour timescale, as well as from GPS data for the 30-minute timescale. The response is divided based on the geoeffectiveness of the sheaths revealing that electrons are effectively accelerated only during geoeffective sheaths, while loss is commonly caused by all sheaths.

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#### Key Points:

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14	•	High data density GPS measurements confirm RBSP outer belt electron flux re-
15		sponse to ICME-driven sheaths at 6-hour and 30-minute timescales
16	•	PSD response shows that only geoeffective sheaths energize electrons but loss oc-
17		curs in response to all sheaths
18	•	Impacts in electron flux and PSD presented here are caused by sheaths, and the
19		early ejecta acts to replenish the lost electrons

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#### 20 Abstract

Turbulent and compressed sheath regions preceding interplanetary coronal mass ejec-21 tions (ICMEs) strongly impact electron dynamics in the outer radiation belt. Changes 22 in electron flux can occur on timescales of tens of minutes, which is difficult to capture 23 by a two-satellite mission such as the Van Allen Probes (RBSP). The recently released 24 Global Positioning System (GPS) data set has higher data density owing to the large 25 number of satellites in the constellation equipped with energetic particle detectors. In-26 vestigating electron fluxes in a wide range of energies and sheaths observed from 2012 27 to 2018, we show that the flux response to sheaths on a timescale of 6 hours, previously 28 reported from RBSP data, is reproduced by GPS measurements. Furthermore, GPS data 29 enables derivation of the response on a shorter timescale of 30 minutes, which further 30 confirms that the energy and L-shell dependent changes in electron flux are due to the 31 impact of the sheath. Sheath-driven loss is underestimated over longer timescales as the 32 electrons recover during the ejecta. We additionally show the response of electron phase 33 space density (PSD), which is a key quantity in identifying true loss from the system and 34 electron energization through wave-particle interactions. The PSD response is calculated 35 from both RBSP and GPS data for the 6-hour timescale, as well as from GPS data for 36 the 30-minute timescale. The response is divided based on the geoeffectiveness of the sheaths 37 revealing that electrons are effectively accelerated only during geoeffective sheaths, while 38 39 loss is commonly caused by all sheaths.

#### 40 **1 Introduction**

Electron content in the outer Van Allen radiation belt can undergo dramatic changes 41 on various timescales in response to magnetospheric disturbances (e.g., Reeves et al., 2003; 42 Baker et al., 2014; Turner et al., 2014). One of the key drivers of such disturbances are 43 interplanetary coronal mass ejections (ICMEs) that are large-scale heliospheric struc-44 tures originating from gigantic eruptions from the Sun (e.g., Kilpua, Balogh, et al., 2017; 45 Kilpua, Koskinen, & Pulkkinen, 2017). ICMEs typically consist of a leading shock and 46 a sheath region followed by the ejecta. The sheath and ejecta have different solar wind 47 properties, which lead to different responses of the radiation belt system (e.g., Kilpua 48 et al., 2015; Turner et al., 2019; Kalliokoski et al., 2020; Kalliokoski et al., 2022). Sheaths 49 are characterized by large amplitude magnetic field fluctuations and high dynamic pres-50 sure, and tend to cause intense wave activity in the inner magnetosphere and strong com-51 pression of the magnetopause. Thus, sheaths effectively accelerate electrons and scat-52 ter them away from the belts (e.g., Kilpua, Turner, et al., 2019; Da Silva et al., 2020; Kalliokoski 53 et al., 2022). 54

Typically, radiation belt studies consider the overall response of the outer radia-55 tion belt to geomagnetic storms. This overall response is estimated by comparing the 56 fluxes before and after the peak of the storm over relatively long time periods (at least 57 half a day or even several days; e.g., O'Brien et al., 2001; Reeves et al., 2003; Turner et 58 al., 2015; Moya et al., 2017; Turner et al., 2019). However, this approach cannot yield 59 information on isolated solar wind structures when they arrive in succession, which is 60 often the case (i.e., a sheath followed by an ejecta, or an ejecta followed by a fast stream), 61 or on localised spatial and temporal responses of the Earth's radiation belts. Kalliokoski 62 et al. (2020) used otherwise similar approach to study the outer belt electron response 63 to ICME sheath regions using the Van Allen Probes data, but compared the fluxes be-64 fore and after the sheath (instead of around the peak of a storm) and averaged the fluxes 65 over a shorter timescale of 6 hours. This enabled examination of the more immediate 66 electron flux response to the sheath regions and this study revealed a clear energy and 67 L-shell dependency of the response. Sheaths typically enhance electron fluxes at lower 68 energies (10s to 100s keV) and deplete them at higher energies (several 100s keV to sev-69 eral MeV), with both responses being more common at L > 4, while the innermost parts 70 of the outer belt remain mostly unchanged. This study, in addition to considering events 71

driving geomagnetic storms, included nongeoeffective sheaths and showed that such events
can cause a dramatic radiation belt response as well. A geoeffective sheath was defined
as having the SYM-H geomagnetic activity index drop below -30 nT during the sheath
or 2 hours after it, while during a nongeoeffective sheath SYM-H remains above -30 nT.
This definition is also employed in the current paper.

Case studies of outer belt electron variation have resolved changes on similar or shorter 77 timescales than the 6-hour period studied in Kalliokoski et al. (2020) in response to so-78 lar wind transients. Reeves et al. (2013) reported an outer belt electron flux enhance-79 80 ment occurring over 11 hours during a geomagnetic storm but the initial couple of orders of magnitude enhancement was resolved at about 6 hours. Morley, Friedel, Span-81 swick, et al. (2010) analysed a set of solar wind stream interfaces and found that the me-82 dian timescale for electron dropouts was about 7 hours. However, even faster changes 83 in the outer belt electron fluxes on timescales of 2 hours or less have been reported. Morley, 84 Friedel, Cayton, and Noveroske (2010) showed about 2 hours for a dropout and Olifer 85 et al. (2018) showed dropouts with timescales from 30 minutes to 2 hours during geo-86 magnetic storms, while enhancements at about 30 minute timescale were presented by 87 Kim et al. (2021). This indicates that, while much shorter than in previous response stud-88 ies, investigating the radiation belt response over 6 hours might still miss important changes. 89 The Van Allen Probes mission consists of two spacecraft and the data density they sup-90 ply cannot thus provide more accurate estimations with sufficient L-shell coverage. 91

An increased temporal resolution and broader spatial coverage given by higher data 92 density has recently been provided by the Global Positioning System (GPS) constella-93 tion (Morley et al., 2017). It consists of over 20 satellites currently in orbit. These satel-94 lites are equipped with Combined X-ray Dosimeters (CXD), Los Alamos National Lab-95 oratory developed and built energetic particle instruments, that measure electrons in the 96 outer radiation belt. A combination of the data from multiple individual GPS satellites 97 provides nearly continuous monitoring of any given L (McIlwain, 1961) or  $L^*$  (Roederer, 98 1970), down to a few tens of minutes temporal resolution (Morley et al., 2016). The downqq side of GPS satellites in comparison to RBSP is that the sensors can be considered roughly 100 hemispheric measuring particle populations with various pitch angles at once and the 101 satellites are not equipped with magnetometers. Therefore, models for the pitch angle 102 distribution (PAD) and geomagnetic field are needed in order to calculate phase space 103 density. Despite the operational nature of the CXD instruments, the reported omnidi-104 rectional fluxes from these instruments have been shown to compare well with observa-105 tions of the more sophisticated instrumentation on RBSP (Morley et al., 2016). 106

In this paper, we will first revisit the analysis of outer radiation belt electron flux 107 response to sheaths derived from RBSP observations by Kalliokoski et al. (2020). We 108 then reproduce this analysis using data from the GPS constellation. We will investigate 109 both differences and similarities in the response using the same 6-hour averaging for RBSP 110 and GPS data, and then repeat the analysis with GPS for temporal resolution of only 111 30 minutes. Then, we will perform a similar response analysis with electron phase space 112 density (PSD), which allows us to reveal the dependencies of non-adiabatic acceleration 113 and loss on the first adiabatic invariant and  $L^*$ . Again 6-hour averaging is used for RBSP 114 data and both 6-hour and 30-minute averaging are used for the GPS data. This part of 115 the study also differentiates between geoeffective and nongeoeffective events, as defined 116 above. More broadly, this approach will demonstrate the applicability of the GPS data 117 in scientific analysis, highlight the advantages and shortcomings of these two data sets, 118 and emphasize their combined potential for many future studies. The RBSP and GPS 119 data and the methodology to calculate fluxes and PSD from them are described in Sec-120 tion 2. Sections 3 and 4 present the response analysis results calculated for fluxes and 121 PSD, respectively. We discuss the results in Section 5 and summarise in Section 6. 122

#### <sup>123</sup> 2 Comparison of Van Allen Probes and GPS Data and Methods

#### 2.1 Van Allen Probes and GPS

The Van Allen Probes (RBSP) were a scientific mission that was designed to mea-125 sure the radiation belt system, and thus provide high quality data (Mauk et al., 2013). 126 For example, RBSP have excellent energy resolution to study the highly variable outer 127 belt electron dynamics and instrumentation to monitor the local plasma waves that are 128 critical for accelerating, precipitating and transporting the electrons. The two spacecraft 129 had highly elliptical orbits spanning  $L \sim 2-6$  with a low orbital inclination of 10° and 130 an orbital period of about 9 hours. The spacecraft thus frequently sampled nearly equa-131 torially mirroring particles ( $\sim 90^{\circ}$  pitch angles). Pitch angle resolved electron fluxes were 132 measured by the Magnetic Electron Ion Spectrometer (MagEIS; Blake et al., 2013) at 133 energies from 30 keV to 1.5 MeV and the Relativistic Electron Proton Telescope (REPT; 134 Baker et al., 2013) at energies from 1.8 to 10 MeV of the Energetic Particle, Composi-135 tion, and Thermal Plasma instrument suite (ECT; Spence et al., 2013). The local mag-136 netic field was measured by the Electric and Magnetic Field Instrument Suite and In-137 tegrated Science (EMFISIS; Kletzing et al., 2013). Information about the magnetic field 138 magnitude and particle pitch angles are required for calculating phase space density (see, 139 e.g., Morley et al., 2013; Hartley & Denton, 2014). However, having only two spacecraft 140 limits the temporal resolution in terms of spatial coverage, especially since the orbits were 141 designed so that one probe trailed the other. Therefore, the Van Allen Probes cannot 142 provide global data on the short timescales required to fully evaluate the radiation belt 143 response to solar wind transients. 144

While the primary purpose of GPS satellites is to provide information for naviga-145 tion, they can also provide useful data for space science (Morley et al., 2016, 2017). The 146 main advantage is the large number of satellites that are able to provide broader spa-147 tial coverage and thus finer temporal resolution in terms of L-shell and magnetic local 148 time. For example, Morley et al. (2016) showed that the data from 17 GPS satellites al-149 low nearly continuous coverage of the outer belt at a timescale of only 20 minutes. The 150 GPS satellites are on near-circular medium-Earth orbits, distributed on six orbital planes. 151 They cover the outer radiation belt slightly further out than RBSP with  $L \sim 4-8$  and 152 have an orbital period of 12 hours. The nominal orbital inclination is  $55^{\circ}$ , which limits 153 the range of equatorial pitch angles of the observed populations. Electron counts are mea-154 sured above about 120 keV by the Combined X-ray and Dosimeter (CXD; Tuszewski et 155 al., 2004) and the counts can be converted to fluxes using a flux forward model (Morley 156 et al., 2016). Morley et al. (2016) performed a cross-calibration of RBSP and GPS data, 157 and showed that the flux measurements are generally within a factor of 2 from each other. 158 The GPS instrumentation is also well inter-calibrated between GPS satellites. The pri-159 mary drawbacks of utilising GPS data for radiation belt studies are that the particle mea-160 surements are not pitch angle resolved and the satellites do not have magnetometers. There-161 fore, a PAD model and a geomagnetic field model are required in order to calculate PSD 162 and all three adiabatic invariants for GPS, whereas RBSP observed the directional fluxes 163 and had measurements available to compute the first adiabatic invariant. A global ge-164 omagnetic field model is required for the second and third adiabatic invariants in any 165 case since they depend on the global geometry of the field. 166

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#### 2.2 Flux Data and PSD Calculation

Electron fluxes are typically considered as a function of spatial location, energy and pitch angle (unless monitored by an omnidirectional instrument, such as onboard GPS satellites). Investigating changes in the flux shows how electrons in the outer belt respond to solar wind driving at different *L*-shells and energies (e.g., Turner et al., 2019; Kalliokoski et al., 2020). However, fluxes can be misleading as adiabatic processes (such as the Dst effect) can appear to cause losses or enhancements in the electron fluxes but do not per-

manently change the electron dynamics (Kim & Chan, 1997). Non-adiabatic changes ev-174 idencing true losses – precipitation to the atmosphere (e.g., Kennel & Petschek, 1966) 175 or loss through the magnetopause (e.g., Turner et al., 2012) – or energisation – via wave-176 particle interactions (e.g., Chen et al., 2007) – are revealed by studying PSD, which is 177 a quantity that remains constant under adiabatic processes. Calculating PSD includes 178 conversion from location, energy and pitch angle to presenting the data in terms of the 179 adiabatic invariants,  $\mu$ , K and L<sup>\*</sup> (see, e.g., Green & Kivelson, 2004), which requires the 180 use of a global geomagnetic field model. If PSD is calculated from GPS measurements, 181 a PAD model is also required to convert the omnidirectional measurements into pitch-182 angle resolved data. PSD is a more powerful tool for analysing electron acceleration, trans-183 port and loss mechanisms in the outer radiation belt in response to magnetospheric dis-184 turbances (e.g., Chen et al., 2007; Turner et al., 2012; Shprits et al., 2017; Kalliokoski 185 et al., 2022). Below, we have described how the flux and PSD were acquired and calcu-186 lated from RBSP and GPS data. 187

Van Allen Probes electron data is available on the ECT website (https://rbsp 188 -ect.newmexicoconsortium.org/science/DataDirectories.php, last access: 30 May 189 2022). The level-2 spin-averaged differential electron fluxes were used when comparing 190 with the omnidirectional GPS fluxes. For calculating PSD, we used the level-3 pitch an-191 gle resolved fluxes, as well as the magnetic field magnitude measurements from EMFI-192 SIS which are available on the EMFISIS website (https://emfisis.physics.uiowa.edu/ 193 data/index, last access: 30 May 2022). The magnetic ephemeris data, which are also 194 available on the ECT website, were used to acquire the second and third adiabatic in-195 variants K and  $L^*$  calculated from the Tsyganenko and Sitnov (2005) TS04D geomag-196 netic field model. PSD was calculated from MagEIS data at lower energies (10s keV to 197 1 MeV) and REPT data at higher energies (> 1 MeV) as described in Kalliokoski et 198 al. (2022), where flux was converted to PSD following the formulation in Chen et al. (2005). 199 No fits to pitch angle or energy distributions were employed in this method, and inter-200 polations were performed to get the K and  $L^*$  corresponding to the equatorial pitch an-201 gles mapped from observations and to increase the energy resolution by adding two ar-202 tificial energy channels in between the instrumental channels. We note that when inves-203 tigating RBSP PSD,  $\mu$  and K were calculated over ranges of the first and second invari-204 ants, instead of being fixed to a single value, which allows for a better resolution in PSD 205 (see Kalliokoski et al., 2022). We consider near-equatorially mirroring electrons with  $K \leq 1$ 206  $0.05 R_E G^{1/2}$  and for  $\mu$ , the range is 6.7% of the central value (e.g.,  $\mu = (3000 \pm 100) \text{ MeV/G}$ ). 207

CXD electron data from the GPS constellation are publicly available and archived 208 by the National Oceanic and Atmospheric Administration's National Centers for Envi-209 ronmental Information (https://www.ngdc.noaa.gov/stp/space-weather/satellite 210 -data/satellite-systems/gps/, last access: 30 May 2022). The GPS satellites are iden-211 tified by their satellite vehicle number (SVN) and in this study, we used GPS satellites 212 from ns53 to ns73. Data from these satellites are available from between 2001–2016 (start 213 date varies between satellites) until the present. GPS measured electron counts were con-214 verted to omnidirectional fluxes by a flux forward model which is a combination of three 215 relativistic Maxwellian functions and one Gaussian function (for details, see Morley et 216 al., 2014; Morley et al., 2016). The fit parameters are included in the GPS data prod-217 uct. The fitting can be used to calculate the omnidirectional flux at any given energy 218 from 140 keV to 4 MeV where the quality of measurements is good (Morley et al., 2016). 219 Due to intermittent noise, the fits from ns60 can be unreliable, so we have excluded it 220 from our study. Data from other satellites were filtered based on the goodness of fit fol-221 lowing Smirnov et al. (2020): the measured counts were compared to the modeled counts 222 from the fit in the five lowest energy channels, and the data was discarded if the discrep-223 ancy was too high. This approach is conservative and tends to exclude particularly low 224 flux data. This manifests as a removal of data at high L in addition to the removal of 225 bad fits. We note that suspect data indicated by the "dropped\_data" flag was also dis-226 carded. 227

PSD was calculated from the GPS data following the steps outlined in, e.g., Hartley 228 and Denton (2014). Briefly, this involves determining the energy and pitch angle from 229 given  $\mu$  and K values, obtaining the measured flux at that energy and pitch angle, cal-230 culating the corresponding  $L^*$ , and dividing the flux by momentum squared to obtain 231 the PSD as a function of the adiabatic invariants. PSD calculation from GPS data re-232 quires fitting with models, which means we can choose a constant value for  $\mu$  and K, in 233 contrast to RBSP. First, using the LANLGeoMag library (Henderson et al., 2018) with 234 the satellite position as input, we computed the equatorial pitch angles and  $L^*$  values 235 corresponding to the chosen K as well as the local and equatorial magnetic field mag-236 nitude. The TS04D global geomagnetic field model was used. Second, the electron en-237 ergy corresponding to the chosen  $\mu$  was determined using the modeled variables, and the 238 omnidirectional flux at this energy was derived from the flux forward model. Third, a 239 PAD model, describing the angular distribution of electron flux, was employed to acquire 240 the directional flux, which was converted to PSD as given in Chen et al. (2005). 241

We used the empirical relativistic electron pitch angle distribution (REPAD) model 242 (Chen et al., 2014), constructed from fitting Legendre polynomials to observed PADs, 243 which can describe a wide variety of observed PAD shapes (e.g., pancake, butterfly). Along 244 with parameters from the magnetic field model, it takes the AE index as input, which 245 we obtained from the OMNI database through the NASA Goddard Space Flight Cen-246 ter Coordinated Data Analysis Web at 1-minute cadence (https://cdaweb.gsfc.nasa 247 .gov/index.html/, last access: 30 May 2022). The equatorial PAD from the model was 248 normalized by the omnidirectional flux measurement by GPS. The model then gave the 249 directional flux at any equatorial pitch angle corresponding to the chosen K. Since the 250 GPS can be at high latitudes away from the equator, the range of equatorial pitch an-251 gles the satellite can measure may become small. This approach uses REPAD to define 252 the equatorial PAD and thus the directional fluxes at equatorial pitch angles not mea-253 surable at GPS can be considered an extrapolation from data. The uncertainty of the 254 directional differential fluxes at near-equatorially mirroring pitch angles is therefore larger 255 when CXD measures only a small fraction of the equatorial pitch angle space. To mit-256 igate this uncertainty, we computed the ratio of the portion of the PAD that GPS mea-257 sures and the full distribution, and discarded data where this ratio was less than 10%. 258 Again, data is most notably removed at high  $L^*$ , limiting the coverage of GPS PSD. The 259 calculation of the normalization and the aforementioned ratio is presented in more de-260 tail in Appendix A. 261

To illustrate how the two data sets compare, we show a sheath event that impacted 262 the magnetosphere on 15 February 2014 in Figure 1. This event resulted in overall loss 263 that was seen in both fluxes and PSD, and there was also a brief enhancement during 264 the leading part of the sheath. The top row shows RBSP data and GPS data is shown 265 on the bottom row, with fluxes shown on the left and PSD on the right. The data is binned 266 30 minutes in time and 0.1 in L-shell for fluxes or  $L^*$  for PSD. For fluxes, the dark grey 267 areas indicate bins with at least one satellite present but where the data is either below 268 the instrument level or low quality. For RBSP PSD, the dark grey areas similarly indi-269 cate that a satellite was present but PSD could not be computed in the given  $\mu$  and K 270 ranges. For GPS PSD, the dark grey color was chosen to show the regions where the PAD 271 model was uncertain (i.e., PAD ratio below 10%). 272

Figure 1 contrasts the spatial and temporal coverage of the two constellations, and 273 we can immediately see the differences in the data density of RBSP and GPS. GPS pro-274 vide nearly continuous coverage at a 30-minute timescale while RBSP data have gaps 275 of multiple hours at a given L-shell or  $L^*$ . This highlights how GPS data can provide 276 information further out in the belt than RBSP and how GPS provide data at higher time 277 resolution, though high quality GPS PSD can be restricted to about  $L^* \sim 4-5$ . The 278 GPS data can therefore be used to analyse the localised spatial and temporal dynam-279 ics of the outer belt electrons in a capacity not possible with the RBSP. This capacity 280



Figure 1. Comparison of data from two RBSP (top) and 12 GPS (bottom) satellites during a sheath event on 15 February 2014. Electron fluxes at 3.4 MeV are shown on the left and PSD at  $\mu = 3000 \text{ MeV/G}$  with a K value/range corresponding to near-equatorial electrons are shown on the right. The data are binned 30 minutes in time and 0.1 in L-shell or  $L^*$ . For fluxes and RBSP PSD, the dark grey areas show when the satellites were present but the data are deemed poor quality or PSD cannot be computed. For GPS PSD, the dark grey areas indicate poor quality PAD fitting. The black vertical lines indicate the shock, ejecta leading edge and ejecta trailing edge with the sheath region between the two first lines.

provided by GPS satellites is particularly important when evaluating the rapid changes
 caused by ICME-driven sheaths or other solar wind transients.

We analyse the outer radiation belt electron response with the higher data density GPS data in comparison with the results from RBSP in the next two sections considering both the electron fluxes and PSD.

<sup>286</sup> **3** Flux Response

This section presents the reproduction of the study by Kalliokoski et al. (2020) with the GPS data and discusses the differences in the results obtained using the RBSP and GPS data sets. The comparison is first done with similar 6-hour averaging for both data sets and then repeated for the GPS data with 30 minute averaging to explore the effect of capturing the more immediate sheath response.

In Kalliokoski et al. (2020), the authors studied the overall response of the outer radiation belt electron fluxes to the impact of ICME-driven sheath regions using RBSP measurements over a broad energy range (10s keV to several MeV). The study included 37 sheaths in 2012–2018. The change in electron fluxes was parameterized with the response parameter (R) based on the methodology of earlier response studies (e.g., Reeves et al., 2003; Turner et al., 2015, 2019). The flux was averaged before and after the sheath region and the response parameter was defined as the ratio of the post-sheath to presheath flux averages for each considered energy and *L*-shell. A 6-hour averaging period was selected as it was the shortest time period that still ensured sufficient *L*-shell coverage by RBSP. The response parameter was used to divide the outer belt response into three categories: enhancement (R > 2), depletion (R < 0.5) and no significant change  $(0.5 \le R \le 2)$ .

304 The energy and L-shell dependencies of the outer belt response as calculated from the RBSP data are shown in the top panels of Figure 2 (reproduced from Figure 6 in Kalliokoski 305 et al., 2020). The data are binned 0.1 in L-shell and according to the MagEIS and REPT 306 energy channels (note that the channels have variable widths and the energies covered 307 are not continuous). Each column shows a different type of response, with the color scale 308 showing the percentage of sheath events causing each response in each of the energy-L309 bins. The percentage value was calculated by dividing the number of events causing, for 310 example, enhancement in a given energy-L bin by the number of events where there were 311 data to compute the response parameter in that bin. This number of events where data 312 was available is shown in the right-hand column. We see that the response parameter 313 can be calculated from RBSP data throughout the outer belt from almost all events. At 314  $L \sim 3$  and at about 1 MeV energies, the lower RBSP data availability is due to low qual-315 ity MagEIS data. 316

The 6-hour averaged results reproduced using the GPS data are shown in the mid-317 dle panels of Figure 2 in the same format as the response from RBSP data. For each event, 318 fluxes at the same energies as the RBSP energy channels (in the range from 140 keV to 319 4 MeV) were derived from all GPS satellites with the measurements available. The re-320 sponse parameter could be computed from more than half of the events at about L =321 4–6 (GPS data availability is the same for all energies due to the flux forward model). 322 The data are more sparse further out since GPS spend less time there and the fitting 323 procedures do not perform as well at high L-shells leading to the goodness of fit filter-324 ing further reducing the data. 325

Visual comparison of the 6-hour averaged responses computed from the RBSP and 326 GPS data in Figure 2 (top and middle panels) indicates that GPS reproduces the over-327 all features of the results in all three categories at L = 4-6. The GPS response shows 328 very similar energy and L-shell dependencies: (1) enhancement is common at 100s keV 329 and its likelihood increases for higher energies (> 400 keV) with decreasing L-shell; (2) 330 depletion is common at > 1 MeV and its likelihood increases at lower energies (100s keV) 331 with increasing L-shell; (3) between enhancement at low energies and depletion at high 332 energies, there is a band at L = 4-6 where no significant changes (no flux increase or 333 decrease by over a factor of 2) are typical. There are only subtle differences. Slightly more 334 sheaths lead to enhancement at higher L-shells and to depletion at higher energies for 335 the RBSP than for the GPS. The no change response from the GPS is slightly more com-336 mon at higher energies as compared to the RBSP no change response. 337

The GPS data allows for calculating the response also at L-shells above the max-338 imum sampled L of RBSP, but our current data filtering to ensure reliable results is very 330 conservative and leads to low data availability at high L, with fewer than 10 events in-340 cluded. Therefore, the response shown from GPS at L > 6 should be carefully consid-341 ered with the number of available events in mind. The percentage value of response shown 342 in the panels can have very low or high values (appearing as, e.g., bright yellow spots) 343 344 due to the limited number of events at L > 6. The overall trend at L > 6 continues similarly as in lower L-shells with enhancement at low energies and depletion at high en-345 ergies. 346



Figure 2. Comparison of outer belt electron flux response calculated from 6-hour averaged RBSP data (top) and 6-hour and 30-minute averaged GPS data (middle and bottom). Panels on the first three columns show the percentage of sheath events causing enhancement, depletion, or no change at each energy and L-shell. Note that the sum of percentages from all three categories in any given energy-L bin is 100%. RBSP response below the minimum sampled L of GPS and GPS response above the maximum sampled L of RBSP are shown faded out to highlight the area in the heart of the outer belt where there are data from both missions. Similarly, response at energies which GPS do not measure are shown faded out for RBSP. The data availability panels on the right show the number of sheath events where the response parameter could be computed at each energy and L-shell. The dashed contours indicate the area where data are available from more than half of the events.



**Figure 3.** Pearson correlation coefficients calculated from data at each energy (top row) and *L*-shell bin (bottom row) for each response category, quantifying the agreement of RBSP and GPS flux response shown in Fig. 2. Purple lines show correlation between 6-hour averaged responses and blue lines between 6-hour RBSP and 30-minute GPS responses.

We give a more quantitative confirmation of the correspondence in responses from 347 RBSP and GPS by calculating the correlation between the response data in each cat-348 egory. The correlation was calculated both at each energy bin and each L-shell bin in 349 the range where the data is available from both missions (from 140 keV to 4 MeV and 350 L = 4-6.4). The correlation coefficients are shown in Figure 3 for each energy bin (top) 351 and for each L-shell bin (bottom) with the purple lines for the 6-hour responses. The 352 correlation computed at each L-shell is excellent and shows that the energy dependence 353 of the responses from both missions is virtually identical. The correlation drops at the 354 lowest and highest L, most notably for no change response with increasing L. The drop 355 is due to the GPS data availability decreasing at these L-shells which produces more abrupt 356 features in the response percentage values in contrast to RBSP, as well as the difference 357 in the energy extent of the no change responses noted above. The L-shell dependency, 358 shown by the correlation coefficients computed at each energy, is also mostly well cor-359 related, but the correlation is low at some energies. For example, both depletion and no 360 change display a drop to no correlation at about 300–500 keV, which indicate the largest 361 discrepancies in the L-shell extent of the responses mentioned above. Correlation between 362 enhancement responses is low at high energies as the likelihood of enhancement is close 363 to zero from both RBSP and GPS at these energies. When the response was computed 364 including only the subset of sheath events that had both RBSP and GPS data available 365 (determined per bin), we again found a low correlation at similar energies and L-shells 366 (though the correlation is overall higher; not shown). This indicates that the missions 367 resolve slightly different dependencies of the response. 368

We repeated the response analysis described above for the GPS data but averaging the fluxes over 30 minutes instead of 6 hours. RBSP cannot provide data at such a short timescale, so this study was enabled by employing data from multiple GPS satellites that provide better temporal resolution in the heart of the outer belt. The results are presented in the bottom row of Figure 2. The data are now largely limited to L =4–5, as this is the L range where the GPS data was available both 30 minutes before and after the sheath for the majority of the investigated events. Nevertheless, visual com-

parison to the RBSP response (Figure 2 top and bottom panels) and the correlation (blue 376 lines in Figure 3) show that similar energy and L-shell dependencies are reproduced at 377 the shorter timescale. This confirms that the observed changes in electron fluxes reported 378 in Kalliokoski et al. (2020) (and reproduced by the 6-hour averaged GPS data) were caused 379 specifically by the sheath with no significant contribution from processes during the ejecta. 380 However, the short timescale response reveals some differences to the 6-hour response. 381 We see that the 30-minute averaged GPS response shows enhancement being less com-382 mon and depletion being more common than for the 6-hour averaged responses (espe-383 cially evident when comparing responses for the same subset of sheath events; not shown). 384 This implies that some of the initial recovery of electron fluxes during the ejecta have 385 been included in the 6-hour response. 386

We also calculated the response from the GPS data when the sheath events were 387 divided to geoeffective and nongeoeffective events (Figure S1), similar to what was done 388 in Kalliokoski et al. (2020). A geoeffective event was identified by a drop in the SYM-389 H geomagnetic activity index below -30 nT during the sheath or 2 hours after it (as 390 the ring current takes time to build up). This analysis similarly reproduced the energy 391 and L-shell dependencies of the response from RBSP as presented in Kalliokoski et al. 392 (2020). Briefly, both enhancement and depletion are more common during geoeffective 393 events. While less common, significant changes occur also during nongeoeffective sheaths 394 where enhancement extends only up to  $\sim 300$  keV and depletion is likely above L  $\sim$ 395 5 except for only the highest energies which deplete also at lower L. For geoeffective sheaths, 396 enhancement extends up to  $\sim 700$  keV at low L and depletion is observed throughout 397 L = 4 - 6.398

#### <sup>399</sup> 4 Phase Space Density Response

The flux response shows how the electron content in the outer belt changes due to 400 sheaths and how variations depend on energy and L-shell. However, only PSD can re-401 veal the irreversible acceleration and loss of electrons. The methods to calculate PSD 402 from RBSP and GPS data were presented in Section 2.2. Since PSD is expressed in terms 403 of the adiabatic invariants, we consider next the  $\mu$  and  $L^*$  dependency of the response 404 instead of energy and L-shell. Furthermore, while we considered omnidirectional fluxes, 405 we now focus on the near-equatorially mirroring electrons and have chosen the K value 406 (or range) accordingly. GPS PSD was computed for  $K = 0.02 R_E G^{1/2}$  and RBSP PSD 407 for  $K \leq 0.05 R_E G^{1/2}$ . PSD was computed for  $\mu$  values from 100 to 5000 MeV/G at 408 100 MeV/G increments, and the response was binned 0.1 in  $L^*$ . 409

Our key focus here is to investigate the PSD response to geoeffective and nongeo-410 effective sheath events, which show interesting differences in their electron dynamics. To 411 briefly discuss the results for all events, they are shown combined for 6-hour averaged 412 RBSP PSD response and 6-hour and 30-minute averaged GPS PSD responses in Figure S2 413 in Supplementary materials. The results between the RBSP and GPS data are very sim-414 ilar. Correlation is lower than for the flux response, but is still quite high (Figure S3). 415 PSD changes are particularly small at lower  $\mu$  and  $L^*$ . In more than 30% of the cases, 416 a broad range of electron populations are depleted at  $L^* > 4.5$ . Electrons tend to be 417 accelerated only at very low  $\mu$  (< 500 MeV/G). 418

The PSD response for 17 geoeffective sheaths (top) and 20 nongeoffective sheaths 419 (bottom) are shown in Figure 4. We see that the data availability from RBSP is sim-420 ilar between the two event types with data from slightly more than half of the events at 421  $L^* < 5$ . GPS data is available from almost all nongeoeffective sheaths at  $L^* = 4-5$ 422 while good data coverage is more limited in  $L^*$  during geoeffective sheaths. We note that 423 the band of lower RBSP data availability at  $\mu < 2000 \text{ MeV/G}$  is related to PSD be-424 ing calculated predominantly from REPT and MagEIS data above and below this band, 425 respectively. Again, RBSP and GPS responses show overall very similar characteristics. 426

<sup>427</sup> The correlation coefficients shown in Figure 5 reveal also again quite large variability from <sup>428</sup> negligible correlation to strong correlation, but in general correlation with both  $\mu$  and <sup>429</sup>  $L^*$  is moderate or strong. There are no obvious trends in correlation found as a func-<sup>430</sup> tion of  $\mu$  or  $L^*$ , but the majority of strong correlation are found for mid-range  $\mu$  between <sup>431</sup> 1500–3500 MeV/G.

The distinct difference between geoeffective and nongeoeffective sheaths is that only 432 geoeffective sheaths accelerate electrons efficiently, causing an enhancing response in >433 30% of the events throughout the heart of the outer belt ( $L^* = 4-5$ ) at all  $\mu$  values. 434 Acceleration is more frequent (> 50% of the events) at low  $\mu$  (< 500 MeV/G). The 6-435 hour GPS response indicates local acceleration at  $L^* \sim 4$  at higher  $\mu$  values during a 436 larger number of sheaths than the 30-minute averaged response. This is only partly ex-437 plained by the higher data availability between 6-hour and 30-minute GPS responses, 438 suggesting that the extra acceleration in the 6-hour response is related to the ejecta. In 439 addition, due to better data availability, the GPS captures more sheaths, and hence its 440 statistics are expected to be more reliable than for RBSP. However, it should be noted 441 that good data coverage is limited to a very narrow  $L^*$  range for geoeffective events,  $L^* =$ 442 4–4.5. In this  $L^*$  range, in 6-hour GPS data about 30–60% of the events lead to accel-443 eration at a wide range of  $\mu$  values, while for RBSP the fraction of enhancing events in 444 the same  $L^*$  range is only about 20–30%. The GPS response also indicates more accel-445 eration even when the analysis is repeated using only the same subset of the sheath events 446 for GPS and RBSP (not shown). For nongeoeffective sheaths, acceleration is observed 447 only during very few events at  $L^* = 4-5.5$  for the lowest  $\mu$ . 448

Losses are observed frequently during both geoffective and nongeoeffective sheaths, 449 and in particular at the largest  $L^*$  captured where typically over half of the events cause 450 depletion for all  $\mu$  except the few lower bins. The two types of sheaths have some dif-451 ferences in the extent and  $\mu$  dependence of depletion. During geoeffective sheaths, losses 452 typically extend (for > 30% of the events) to lower  $L^*$  than for nongeoeffective events, 453  $L^* \sim 4$  and  $L^* \sim 4.5$ , respectively. However, the 30-minute GPS response shows losses 454 extending down to  $L^* \sim 4$  at the highest  $\mu$  values even during nongeoeffective events. 455 For nongeoeffective sheaths, loss is also more likely (in > 50% of the events) at high  $\mu$ 456 (> 2000 MeV/G) where the likelihood does not change much with  $L^*$  (above  $L^* = 4.5$ ). 457 At lower  $\mu$  values, loss is restricted to above  $L^* \sim 5$ . For the 30-minute averaged re-458 sponse, losses are also more frequent, which is clearly present also when the response is 459 computed only from the same subset of the nongeoeffective sheath events (not shown). 460 On the other hand, losses are observed about as frequently for 6-hour and 30-minute re-461 sponses at all  $\mu$  values during geoeffective sheaths. Losses seem to become more com-462 mon with increasing  $L^*$  but the data availability also decreases with increasing  $L^*$  for 463 both satellite missions, so no strong conclusions can be made regarding the  $L^*$  depen-464 dency or if depletion is more common during geoeffective than nongeoeffective sheaths. 465 We note that the RBSP response for geoeffective sheaths has only a few depleting events 466 for the lower  $\mu$  values (< 1500 MeV/G). Though, the difference in RBSP and GPS re-467 sponses in this  $\mu$  range is smaller when the analysis is repeated using only the same sub-468 set of the sheath events (not shown). Finally, the no-change response is much more com-469 mon during nongeoeffective sheaths. There is a trend of increased likelihood of no changes 470 in PSD at low  $\mu$  and low  $L^*$  which is visible in both cases but is more distinct in the GPS 471 response and during nongeoeffective sheaths. 472

#### 473 5 Discussion

This paper has investigated the usage of the recently released GPS constellation energetic particle data set for investigating the response and dynamics of radiation belt high-energy electrons. We first reproduced the analysis from Kalliokoski et al. (2020), who used RBSP data, with the energetic charged particle data from GPS. We then removed adiabatic effects, including those likely to arise from storm-time ring current build-



Figure 4. Comparison of outer belt electron PSD response for geoeffective (top) and nongeoeffective (bottom) sheath events in the same format as in Fig. 2. Response calculated from (a–c) 6-hour averaged RBSP data, (e–g) 6-hour averaged GPS data and (i–k) 30-minute averaged GPS data is shown for both set of events. Panels on the first three columns show the percentage of sheath events causing enhancement, depletion, or no change at each first and third adiabatic invariant,  $\mu$  and  $L^*$ . The second adiabatic invariant is  $K \leq 0.05 R_E G^{1/2}$  for RBSP PSD and  $K = 0.02 R_E G^{1/2}$  for GPS PSD. Note that for RBSP PSD,  $\mu$  values include a 6.7% range from the shown central value. RBSP response below the minimum sampled  $L^*$  of GPS is shown faded out to highlight the  $L^*$  range where there are data from both missions. The data availability panels on the right show the number of sheath events where the response parameter could be computed at each  $\mu$  and  $L^*$ . The dashed contours indicate the area where data are available from more than half of the events.



Geoeffective (17 events)

**Figure 5.** Pearson correlation coefficients for responses during geoeffective (top) and nongeoeffective (bottom) sheath events. Correlation is shown for each (a–c)  $\mu$  value and (d–f)  $L^*$  bin for each response category, quantifying the agreement of RBSP and GPS PSD response shown in Fig. 4.

up, by performing a similar analysis using PSD in adiabatic coordinates with both data 479 sets. The study investigated the response of the outer belt to 37 ICME-driven sheath 480 regions. The determination of the response parameter (i.e., parameter comparing the fluxes/PSD 481 before and after the sheath, in other words, the overall response to the sheath) is lim-482 ited to 6 hours for RBSP data as it consist of two spacecraft only. With GPS, the re-483 sponse parameter can be calculated with much higher temporal resolution of 30 minutes. 484 We compared the results using the response parameter calculated with 6-hour averag-485 ing for both RBSP and GPS, and for GPS also using 30-minute averaging. 486

The 6-hour averaged flux response calculated from GPS data was very similar to 487 the response calculated from the 6-hour averaged RBSP data. The 30-minute averaged 488 GPS response confirmed that the overall changes in fluxes as reported in Kalliokoski et 489 al. (2020) are due to the sheath region and not the early ejecta. In addition, they revealed 490 some subtle yet important differences. Enhancement is slightly less frequent and deple-491 tion more likely on fast time scales of 30 minutes after the sheath rather than 6 hours 492 after it, indicating that a portion of the depletion is quickly recovered after the sheath. 493 The higher likelihood for loss is also shown by Turner et al. (2019) who reported the response for isolated sheaths (i.e., no following ejecta to drive the recovery). Since deple-495 tion becomes less frequent during the ejecta at high energies (> 500 keV) and the num-496 ber of enhancing events increases at lower energies (< 500 keV), such flux recovery af-497 fects the overall outer belt electron populations. This can likely be explained by the longer 498 time period allowing for more substorm injections and subsequent acceleration to higher 499 energies, as well as by the lack of conditions leading to effective losses during the ejecta. 500 As shown by the statistical analysis of Kalliokoski et al. (2020), the geomagnetic distur-501 bances are stronger during the ejecta, which causes elevated substorm activity, while in 502 the sheath the combination of relatively high dynamic pressure compressing the mag-503 netopause and enhanced wave activity provide favorable conditions for electron losses 504 through the magnetopause (i.e., magnetopause shadowing; Turner et al., 2012) and scat-505 tering the electrons away from the belts. During the ejecta, in turn, the magnetopause 506 starts to move further out and wave activity is relatively less intense (e.g., Hietala et al., 507 2014; Kilpua, Fontaine, et al., 2019; Kalliokoski et al., 2020), diminishing magnetopause 508 shadowing losses and precipitation. 509

To remove adiabatic effects, we investigated the PSD response. This extends the analysis of Kalliokoski et al. (2020) who used RBSP data to examine the response to sheaths in radiation belt flux. The shape of PSD radial profiles can be used to identify the acceleration, transport and loss processes governing the electron dynamics (e.g., Chen et al., 2007; Turner et al., 2012; Shprits et al., 2017) but the response parameter studied in this paper hides such details during the sheath. Nevertheless, the  $\mu$  and  $L^*$  dependencies of the PSD response can shed light on the energisation and loss mechanisms.

During geoeffective sheaths, enhancements are seen near  $L^* \sim 4$  indicating local 517 acceleration. Geoeffective sheaths are typically associated with strong substorm activ-518 ity (e.g., Pulkkinen et al., 2007; Kalliokoski et al., 2020), which in turn excites chorus 519 waves that can efficiently accelerate electrons to > 1 MeV energies (Miyoshi et al., 2013; 520 Jaynes et al., 2015). Comparing the GPS response over the two timescales, acceleration 521 is more common over 6 hours than 30 minutes. Since geoeffective sheaths are also as-522 sociated with geoeffective ejecta (Kalliokoski et al., 2020), the geomagnetic activity started 523 during the sheath is expected to continue, and therefore also the excitation of chorus waves 524 and progressive acceleration of electrons to higher energies persist during the early ejecta. 525 Losses are observed to be common at high  $L^*$  at a variety of  $\mu$  values during geoeffec-526 tive sheaths, indicating loss at the magnetopause. Outward radial diffusion driven by ultra-527 low frequency waves, whose activity is elevated during sheaths and especially during geo-528 effective ones as shown by Kalliokoski et al. (2020), can further transport electrons to 529 the magnetopause. This tandem process of inward magnetopause incursion and outward 530

transport is also associated with enhancements at lower  $L^*$  due to concurrent inward radial diffusion (Turner & Ukhorskiy, 2020).

Losses in PSD are common at high  $L^*$  indicating magnetopause shadowing losses 533 also during nongeoeffective sheaths. The 30-minute response shows losses to be even more 534 frequent which points, as also discussed above, to electrons being energised during the 535 ejecta to about pre-event levels especially at  $L^* = 4-4.5$ . For nongeoeffective sheaths, 536 the losses penetrate as deep into the outer belt as during geoeffective events only at high 537  $\mu$  values with the 30-minute response. The magnetopause erosion is however not as ef-538 ficient for nongeoeffective sheaths as for geoeffective sheaths (Kalliokoski et al., 2020), 539 which could imply that in the inner parts of the outer belt scattering by wave-particle 540 interactions has a key role in causing losses. Electromagnetic ion cyclotron (EMIC) waves 541 can scatter multi-MeV electrons rapidly (Aseev et al., 2017; Shprits et al., 2017; Kurita 542 et al., 2018). This scattering loss can also contribute to losses during geoeffective sheaths 543 during which EMIC wave activity is more elevated (Kalliokoski et al., 2020). Conversely, 544 our results clearly demonstrate that nongeoeffective sheaths do not produce favorable 545 conditions for electron acceleration. Enhancements in fluxes (seen in Figure S1) are there-546 fore due to adiabatic processes. During nongeoeffective sheaths, the ring current is not 547 enhanced like during the main phase of a geomagnetic storm. Instead, the SYM-H in-548 dex tends to increase (Kalliokoski et al., 2020), indicating a weakened ring current which, 549 in turn, causes the equatorial geomagnetic field to strengthen. Electrons move inward 550 to conserve the third adiabatic invariant and the fluxes increase. This can be described 551 as the "opposite Dst effect". We note however that the flux response presented here was 552 computed from the omnidirectional fluxes, whereas the PSD response focused on the near-553 equatorially mirroring electrons. Using the pitch angle resolved RBSP flux data, we com-554 puted the response of  $90^{\circ}$  pitch angle electrons (not shown) which is very similar to the 555 omnidirectional flux response shown for nongeoeffective sheaths in Figure S1. Therefore. 556 the adiabatic flux enhancements occur also for the near-equatorially mirroring electrons 557 sampled by our PSD. 558

#### 559 6 Conclusions

To summarize, ICME-driven sheath regions cause significant changes in outer belt 560 electron populations with distinct differences between geoeffective and nongeoeffective 561 sheaths. The irreversible energisation and loss are revealed by phase space density anal-562 ysis in contrast to electron fluxes which include changes due to adiabatic processes. Over-563 all, sheaths are important drivers of outer belt electron loss, while geoeffective sheaths 564 can also cause efficient acceleration. Enhancements in electron flux during nongeoeffec-565 tive sheaths are adiabatic, caused by the "opposite Dst effect". By considering the im-566 mediate changes in outer belt electrons after the impact of the sheath, it is confirmed 567 that the observed variation is caused specifically by the sheath. The response over longer 568 time periods of a few hours underestimates the sheath-driven loss as electrons recover 569 during the early ejecta. 570

We showed that GPS data reproduces the results from analysis performed with RBSP 571 data, confirming the good inter-calibration between these missions. In addition, this study 572 highlights that synergy of GPS with RBSP establishes compelling possibilities for stud-573 ies combining the data sets, with the denser GPS data being able to fill in the gaps in 574 RBSP observations with its spatially better temporal resolution as well as reaching higher 575 L-shells. The time the GPS satellites spend at higher L-shells (L > 6) is however clearly 576 less than in the heart of the outer belt, but for case and statistical studies of solar wind 577 structures that are more frequent than sheaths (e.g., slow-fast stream interaction regions), 578 combined RBSP and GPS data can provide information of the outer belt covering L from 579 2.5 to 8. This could better reveal, for example, the peaks and dips in electron fluxes and 580 PSD, and the associated acceleration and loss mechanisms that could be missed or mis-581 interpreted with only the RBSP data (Boyd et al., 2018; Olifer et al., 2021; Turner et 582

al., 2021). GPS measurements also provide a continuation of radiation belt monitoring in the post-RBSP era.

Future work is needed to expose the local spatial effects and timescales of changes in PSD in individual sheath events in more detail, as the response parameter approach does not take into account the details of the changes during the sheath. Such studies will allow comparisons of the timescales of changes to the timescales of known acceleration and loss processes (e.g., driven by wave-particle interactions with specific wave modes). High density GPS data are reliable tools that can be used to perform such studies.

#### <sup>591</sup> Appendix A PAD Model Normalization

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We present the equations for the normalization of the PAD model and calculating the parameter to determine goodness of fit. We follow Hess (1968, p. 65) and the GPS convention of defining the omnidirectional flux as per steradian (i.e., adding a  $1/4\pi$  factor). The omnidirectional flux measured locally by a GPS satellite can be expressed by the integral of directional flux over the full solid angle

$$J(E) = \frac{1}{4\pi} \int \int j(E,\alpha) d\Omega = \int_0^{\pi/2} j(E,\alpha) \sin(\alpha) d\alpha$$
(A1)

where we have assumed that the directional fluxes are gyrotropic and that the distribution is symmetric in pitch angle. According to Liouville's theorem, the local and equatorial directional fluxes should match. Thus,

$$j(E,\alpha) = j(E,\alpha_{eq}) \tag{A2}$$

where  $\alpha_{eq}$  is the equatorial pitch angle corresponding to the local pitch angle  $\alpha$  based on the conservation of the first adiabatic invariant.

Since GPS satellites do not measure the pitch angle resolved fluxes, a PAD model is used in order to compute the directional fluxes and the model is normalized by the measured omnidirectional flux. Denoting the PAD model as  $\hat{j}(E, \alpha_{eq})$ , the modeled directional flux is thus

$$j(E, \alpha_{eq}) = N(E)j(E, \alpha_{eq}) \tag{A3}$$

where the energy-dependent normalization N(E) can be solved using the equations presented above. Additionally, a change of variables is needed to integrate over the equatorial PAD since Eq. A1 is expressed in terms of the local pitch angle. We thus have

$$_{612} J(E) = N(E) \frac{B}{2B_{eq}} \int_0^{\alpha_{90}} \hat{j}(E, \alpha_{eq}) \frac{\sin(2\alpha_{eq})}{\sqrt{1 - \frac{B}{B_{eq}}\sin^2(\alpha_{eq})}} d\alpha_{eq} (A4)$$

where B and  $B_{eq}$  are the local and equatorial magnetic field magnitudes, respectively, and the integration limit is the equatorial pitch angle corresponding to local 90° pitch angle solved from the conservation of the first adiabatic invariant as

$$\alpha_{90} = \arcsin\left(\sqrt{\frac{B_{eq}}{B}}\right). \tag{A5}$$

<sup>617</sup> By computing the integral in Eq. A4, we can solve the normalization at each en-<sup>618</sup> ergy and time step, as J(E) is known from observations, and thus solve the directional <sup>619</sup> flux from Eq. A3.

As discussed in the main text, if the equatorial pitch angle range observable by the GPS satellite is limited, there is more uncertainty in the directional fluxes especially near the equator. Depending on the shape of the PAD and how small the highest observable equatorial pitch angle  $\alpha_{90}$  is, the above described normalization can be based on only a small part of the full PAD which might lead to poor PAD fitting and fluctuations in the derived PSD. Thus, we calculate the ratio of the PAD integral over the part GPS can measure to the integral over the full PAD:

$$\frac{I_{GPS}}{I_{tot}} = \frac{\int_0^{\alpha_{90}} \hat{j}(E, \alpha_{eq}) \sin(\alpha_{eq}) d\alpha_{eq}}{\int_0^{\pi/2} \hat{j}(E, \alpha_{eq}) \sin(\alpha_{eq}) d\alpha_{eq}}.$$
(A6)

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In this paper, data are discarded if the ratio is below 10%.

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# **@AGU**PUBLICATIONS

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Supporting Information for

## Outer Radiation Belt Flux and Phase Space Density Response to Sheath Regions: Van Allen Probes and GPS Observations

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### Contents of this file

Figures S1 to S3

### Introduction

The figures presented here show additional response data and corresponding Pearson correlation coefficients that complement the main article.



**Figure S1.** Same as Figure 2 but electron flux response is shown separately for (top) geoeffective and (bottom) non-geoeffective sheaths.



Figure S2. Same as Figure 4 but the response is for all sheath events.



Figure S3. Pearson correlation coefficient corresponding to Figure S2.