# 1 Energetic electron precipitation characteristics observed from

## 2 Antarctica during a flux dropout event

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- 23 Abstract.

Data from two autonomous VLF radio receiver systems installed in a remote region of the 24 Antarctic in 2012 is used to take advantage of the juxtaposition of the L=4.6 contour, and the 25 Hawaii-Halley, Antarctica, great circle path as it passes over thick Antarctic ice shelf. The ice 26 sheet conductivity leads to high sensitivity to changing D-region conditions, and the quasi-27 constant L-shell highlights outer radiation belt processes. The ground-based instruments 28 observed several energetic electron precipitation events over a moderately active 24-hour period. 29 during which the outer radiation belt electron flux declined at most energies and subsequently 30 recovered. Combining the ground-based data with low- and geosynchronous-orbiting satellite 31 observations on 27 February 2012, different driving mechanisms were observed for three 32 precipitation events with clear signatures in phase space density and electron anisotropy. 33 Comparison between flux measurements made by Polar-orbiting Operational Environmental 34 35 Satellites (POES) in low Earth orbit and by the Antarctic instrumentation provides evidence of different cases of weak and strong diffusion into the bounce-loss-cone, helping to understand the 36 physical mechanisms controlling the precipitation of energetic electrons into the atmosphere. 37 Strong diffusion events occurred as the <600 keV fluxes began to recover as a result of adiabatic 38 transport of electrons. One event appeared to have a factor of about 10 to 100 times more flux 39 than was reported by POES, consistent with weak diffusion into the bounce-loss-cone. Two 40 events had a factor of about 3 to 10 times more >30 keV flux than was reported by POES, more 41 consistent with strong diffusion conditions. 42

#### 44 **1. Introduction**

The energetic electron fluxes that form the outer radiation belt can be highly dynamic [Thorne, 45 2010; Horne et al., 2005] with observed fluxes changing by >3 orders of magnitude on 46 timescales of hours to days [Morley et al., 2010]. There are significant uncertainties about the 47 source, loss, and transport of these energetic electrons. Due to their impact on spacecraft systems 48 [Baker, 2002] and astronauts [Maalouf, 2011] as well as polar atmospheric chemistry [Randall et 49 al., 2005] the primary research focus has been on energetic electrons with energies >10 keV as 50 well as relativistic electrons (>500 keV). Geostationary satellites, which orbit within the outer 51 radiation belt, can be "upset" or even "killed" by enhanced energetic electron fluxes [Lam et al., 52 2012; Clilverd et al., 2012b]. 53

The high dynamism in radiation belt electron fluxes has been associated with geomagnetic 54 storms, although in a complex and non-linear fashion. Large geomagnetic storms, perhaps 55 correlated with the impact of Coronal Mass Ejection on the magnetosphere, have been observed 56 to cause to very large flux changes, triggering significant acceleration and loss processes [e.g., 57 Clilverd et al., 2005, Horne et al., 2005]. Weak geomagnetic storms triggered by the arrival of a 58 high speed solar wind stream interface (SWSI) can also lead to rapid "dropouts" in energetic 59 electron fluxes [Denton and Borovsky, 2008; Miyoshi and Kataoka, 2008; Morley et al., 2010] 60 followed shortly afterwards by trapped enhancements with associated precipitation [Hendry et 61 al., 2013] probably reflecting the physics of the acceleration processes which rebuild the fluxes 62 after a dropout. The correlation of high solar-wind speed and elevated energetic-electron fluxes 63 in the outer radiation belt is one of the most striking aspects of radiation belt dynamics [e.g. 64 Paulikas and Blake, 1979]. 65

A major scientific goal is to understand the physical drivers causing radiation belt electron flux dynamics, such that accurate predictive models can be built [*Fok et al.*, 2008]. This requires physical understanding of the drivers leading to the enhancements in radiation belt fluxes, as

well as the losses, i.e., describing the source and sink terms for the predictive models. Satellites 69 can provide much information on the particle and wave environment. However, geostationary 70 satellites are less well placed to identify the particles losses into the atmosphere, because of the 71 difficulty in resolving the pitch angle bounce loss cone (BLC). Geostationary satellites are much 72 better placed to give context to, and describe, the dynamics of the trapped particle populations 73 [Borovsky and Denton, 2010; Hartley et al., 2013]. Low Earth Orbit (LEO) satellites are usually 74 better able to make observations of electron populations in the BLC, but are not geosynchronous 75 and only have short windows of observations in each orbit that are relevant for outer radiation 76 belt research [Rodger et al., 2010a]. In this paper we will use data sets from the geosynchronous 77 satellite GOES-13 [Hanser, 2011] in combination with the LEO satellites carrying the SEM-2 78 detector, i.e., the NOAA POES and the MetOp satellites [Rodger et al., 2010a,b]. The electron 79 80 detectors on POES give a good idea of varying precipitation levels, but suffer from uncertainties in their measurement of flux levels due to proton contamination and only partial measurement of 81 the BLC. The electron detectors on GOES are limited to a single point in space, but subsequent 82 calculations of phase space density and the anisotropy of the electron pitch-angle distribution can 83 provide further useful clues as to which acceleration and/or loss mechanisms might be operating 84 [Turner et al., 2012; Hartley et al., 2013]. Determining, on an event by event basis, how each 85 satellite characterises the event provides some insight into the physical processes that are 86 occurring. 87

Outer belt losses occur into the polar atmosphere due to the shape of the geomagnetic field; hence we have installed a network of radio receivers in the Arctic and Antarctic to monitor these inputs. The Antarctic-Arctic Radiation-belt (Dynamic) Deposition - VLF Atmospheric Research Konsortium (AARDDVARK) receivers use powerful very-low-frequency (VLF) transmitters [*Gamble et al.*, 2008; *Clilverd et al.*, 2008b] as radio sources, and provide measurements by placing radio receivers at high latitudes in order to sample radio propagation conditions that are

influenced by outer radiation belt dynamics [Clilverd et al., 2009; Rodger et al., 2012]. 94 AARDDVARK is able to significantly enhance the effort of satellite-based research into 95 radiation belt loss mechanisms. This is possible because it uses the fact that VLF radio waves are 96 trapped between the ground and lower ionosphere; energy inputs into the lower ionosphere from 97 the outer radiation belts alter the electrical properties and thus the propagation conditions of 98 received radio waves [Barr et al., 2000]. Measuring the perturbation of the radio wave allows a 99 direct calculation of the characteristics of the energetic particle precipitation to be made. The 100 ground-based instruments effectively use the ionosphere as a massive particle detector and thus 101 give a quantitative indication of precipitating electron flux levels, but are limited in their ability 102 to place their observations into global context. However, in combination with satellite 103 observations it is possible to identify the physical mechanisms underlying, and characteristics of, 104 105 energetic particle losses from the radiation belts. These are the key properties required for the loss terms in predictive models of the radiation belts [Fok et al., 2008]. 106

In this study we compare and contrast AARDVVARK ground-based observations of energetic 107 electron precipitation events in Antarctica, which occurred over a moderately active 24-hour 108 period, with POES and GOES satellite observations. In the first analysis of data from two 109 Autonomous AARDDVARK systems (solar and wind powered, very remote VLF receivers) 110 installed in the Antarctic in January 2012, we show that bringing together of all of the 111 instruments to study individual events is a powerful technique, yielding significant insight into 112 the radiation belt processes involved. The events studied here occurred during the onset and main 113 phase of a moderate geomagnetic storm in February 2012 where trapped energetic radiation belt 114 electron fluxes are observed to dropout and begin to recover. Different driving mechanisms were 115 observed for the precipitation events with clear signatures in phase space density and electron 116 anisotropy, evidence of periods of weak and strong diffusion into the bounce-loss-cone, and 117

energy-dependent variations in electron flux enhancements or losses as observed by the satellites.

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### 121 **2. Geomagnetic conditions**

The geomagnetic conditions for the period at the end of February 2012 are shown in Figure 1. 122 In this study we concentrate on three energetic electron precipitation events that occurred on 27 123 February 2012. In the figure the solar wind speed and density variations indicate a coronal mass 124 ejection occurred late on 26 February, with the solar wind increasing to  $\sim$ 500 km s<sup>-1</sup>, and the 125 density increasing by a factor of ~3. A solar wind shock was detected by SOHO at 2107 UT on 126 26 February, and both Kp and Dst variations indicate moderately disturbed geomagnetic 127 conditions beginning half way through 27 February, peaking a few hours before UT midnight 128 129 with values of Kp=5, and Dst=-55 nT. The solar wind speed remained elevated for more than a day before returning to its pre-event level. 130

The conditions described in Figure 1 broadly similar to those studied by *Hendry et al.* [2013] 131 where trapped energetic radiation belt electron fluxes are observed to dropout during small 132 geomagnetic disturbances, triggered by the arrival of an extended period of fast solar wind. 133 Hendry et al. [2013] used superposed epoch analysis of low-Earth orbiting POES spacecraft 134 observations to show that dropouts in the trapped flux triggered by a Solar Wind Stream 135 Interface (SWSI) are followed ~3 hours later by large increases of energetic electron 136 precipitation (EEP) which start as the trapped electron fluxes observed at geostationary orbits 137 begin to recover as acceleration processes become significant. The aim of this paper is to 138 combine ground-based and satellite observations to look in detail at the characteristics of the 139 EEP events that occur around the time of a small radiation belt electron flux dropout. 140

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## 142 **3. Experimental setup**

In January 2012 we deployed low-powered narrow band very low frequency (VLF) radio 143 receivers in two key locations in the Antarctic in order to monitor energetic particle precipitation 144 coming from the outer radiation belt, impacting the great circle path between a transmitter and a 145 receiver. The Autonomous AARDDVARK systems monitor VLF signals from the powerful 146 man-made transmitter located in Hawaii (NPM, 21.4 kHz, 500 kW) to monitor the changes in 147 subionospheric radio wave propagation conditions caused by processes occurring in the outer 148 radiation belt. Combined with an AARDDVARK receiver at Halley [Clilverd et al., 2009], 149 Antarctica, the locations selected for the low-powered autonomous receivers make use of a 150 unique geometry that monitors the same radio signal on the same great circle path and at the 151 same geomagnetic latitude at different sites, thus providing unprecedented spatial resolution of 152 the lower ionosphere in this region. Figure 2 shows a map of the Antarctic Peninsula region, and 153 154 the locations of the Autonomous AARDDVARK receivers (blue asterisks from left to right, Pine Island Glacier – AA3, Fletcher Ice Dome - AA2) and the Halley receiver (red diamond) with 155 respect to the great circle path of the NPM signal received at Halley (green line). The L-shell 156 contours for L=4.0, 4.6, and 7.0 are shown, indicating that the three VLF receivers are located 157 close to the L shell contour at L=4.6 in the region where the path crosses the Antarctic Ice shelf 158 at the southern end of the Antarctic Peninsula. For context we also plot the southern hemisphere 159 geomagnetic footprint of the GOES-13 satellite (square), indicating a region rich in 160 measurements despite the extreme remoteness of this part of the Antarctic. 161

Electron flux data are provided at geostationary orbit (L=6.6) by GOES-13 >800 keV and >2 MeV detectors [*Onsager et al., 1996*]. At the time of this study GOES-13 was located at 75°W. Thus the satellite was well positioned to observe the effects of substorm-injected energetic electrons, as well as variations in outer radiation belt electron fluxes, occurring in a similar longitude sector as the ground-based instrumentation. The GOES-13 D3 dome detector provides both the >800 keV and >2 MeV electron fluxes, primarily responding to trapped outerradiation belt particles. The relative variations of the electron fluxes observed at each energy
channel are useful for scientific studies. We use the 5 minute averaged GOES data which has
been corrected for proton contamination and backgrounds.

The Magnetospheric Electron Detector (MAGED) on GOES-13 also provides electron flux 171 measurements in the energy range 30-600 keV. Facing anti-Earthward, MAGED consists of nine 172 telescopes, a North-South fan as well as an East-West fan. The central telescope of each fan is 173 directed radially anti-Earthward while the two fans are oriented at  $\pm 35^{\circ}$  and  $\pm 70^{\circ}$  to the central 174 telescope [Hanser, 2011]. All telescopes measure flux in five energy channels given as 30-50, 175 50-100, 100-200, 200-350 and 350-600 keV. The pitch angles of all telescopes are calculated 176 from the relative orientation of the magnetic field measured by the GOES fluxgate magnetometer 177 and the particle velocity defined as the opposite direction to the central look direction of the 178 telescope in question. These pitch angles vary in time. In this study we calculate the pitch-angle 179 anisotropy as the ratio between fluxes from 0-30° (parallel), and between 75-105° 180 (perpendicular), i.e.,  $\log_{10}(j_{para}/j_{perp})$ . Calculation of partial moments for the distribution between 181 30-600 keV also allows estimates of the electron temperature, T (in the parallel and 182 perpendicular directions), and the electron number density, *n*, to be made: 183

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$$n = 2\pi \iint f_{\nu}(\alpha, v) v^2 \sin(\alpha) d\alpha \, dv \quad (\text{cm}^{-3})$$

$$T_{para} = \frac{2\pi m_o}{n} \int f_v(\alpha, v) v^4 \cos^2(\alpha) \sin(\alpha) d\alpha dv$$
(keV)

187 
$$T_{perp} = \frac{\pi m_o}{n} \int f_v(\alpha, v) v^4 \sin^3(\alpha) d\alpha dv \quad (\text{keV})$$
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189 where the velocity distribution,  $f_{y}$ , is calculated from the measured differential flux as:

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$$f_{\nu}(\alpha,\nu) = \frac{m_o}{\nu^2} j(\alpha,E) \quad (s^3 \text{ cm}^{-6})$$

191 Using the MAGED instrument we can investigate the behaviour of electrons at geostationary 192 orbit in terms of transport away from the satellite, and loss from the environment of the satellite 193 (including loss into the atmosphere).

We also make use of particle measurements by the Space Environment Monitor-2 instrument package onboard the POES spacecraft which are in Sun-synchronous orbits at ~800-850 km altitudes [*Evans and Greer, 2004*]. SEM-2 includes the Medium Energy Proton and Electron Detector (MEPED), in addition to the Total Energy Detector (TED). Together these instruments monitor electron fluxes from 50 eV up to 2700 keV. We make use of SEM-2 observations from all 6 POES spacecraft operational at that time. The SEM-2 detectors include integral electron telescopes with energies of >30 keV, >100 keV, and >300 keV, pointed in two directions.

All POES data is available from http://poes.ngdc.noaa.gov/data/ with the full-resolution data 201 202 having 2-s time resolution. Analysis by Rodger et al. [2010a] indicated that the levels of contamination by comparatively low energy protons can be significant in the MEPED 203 observations. As much as  $\sim 42\%$  of the 0° telescope >30 keV electron observations were typically 204 found to be contaminated, although the situation was less marked for the 90° telescope (3.5%). 205 However, NOAA has developed new techniques to remove the proton contamination from the 206 POES SEM-2 electron observations, as described in Appendix A of Lam et al. [2010]. This 207 algorithm is available for download through the Virtual Radiation Belt Observatory (ViRBO; 208 http://virbo.org), and has been applied to the SEM-2 observations examined in our study. The 0°-209 pointing detectors are mounted on the three-axis stabilized POES spacecraft so that the centre of 210 each detector field of view is outward along the local zenith, parallel to the Earth-centre-to-211 satellite radial vector. Another set of detectors, termed the 90°-detectors are mounted 212 approximately perpendicular to the 0° detector. In addition, there is also a set of omnidirectional 213 measurements made from a dome detector which is mounted parallel to the 0° detectors. The 214 detectors pointing in the 0° and 90° directions are  $\pm 15^{\circ}$  wide, while the omnidirectional dome 215

detectors (termed "omni") are  $\pm 60^{\circ}$  wide. For the 3<*L*<10 range we consider in this study the 90°-detector appears to primarily respond to trapped electrons but with pitch angles only a few degrees above the loss cone, and hence we will refer to it as the "quasi trapped detector", while the 0°-detector responds to the electrons in the bounce loss cone, and is thus referred to as the "BLC detector" [see the modeling in the Appendix of Rodger et al., 2010b].

In addition to the electron telescopes, the MEPED instrument also includes a number of proton 221 telescopes. The SEM-2 proton detectors also suffer from contamination, responding to electrons 222 with relativistic energies [Evans et al., 2008] which can be useful for radiation belt studies [e.g., 223 Sandanger et al., 2007; Millan et al., 2008; Rodger et al., 2010a] outside of solar proton events 224 when significant energetic proton fluxes are present. In particular the P6 telescope detectors, 225 which are designed to measure >6.9 MeV protons, also respond to electrons with energies in the 226 227 relativistic range [Yando et al., 2011]. In this paper we refer to the P6 telescope as a >800 keV detector, although this is only approximately correct as it implies both high detection efficiencies 228 and a sharp increase in electron detections at an energy of 800 keV. Monte Carlo simulations of 229 the proton telescopes indicate that the P6 telescope exhibits a sensitivity of  $G \sim 1.9 \times 10^{-3}$  cm<sup>2</sup>sr at 230 800 keV, and  $G \sim 9 \times 10^{-3}$  cm<sup>2</sup> sr<sup>-1</sup> near 2000 keV [Yando et al., 2011]. As shown in Figure 8 of 231 that study, the P6 channel plays a complementary role to the E1-E3 channels for detection of 232 relativistic electrons, and is sensitive to electrons of energy larger than roughly 800 keV. 233

In this study the ground-based Autonomous AARDDVARK data are combined with Halley riometer data. Riometers observe the integrated absorption of cosmic radio noise through the ionosphere [*Little and Leinbach*, 1959], with increased absorption due to additional ionization in the lower D-region, for example due to both proton and electron precipitation. The riometer absorption at Halley is provided by a widebeam, 30 MHz, vertically pointing antenna. The dominant altitude of the absorption is typically in the range 70-100 km, i.e., biased towards relatively soft particle energies (~30 keV electrons). Because of their sensitivity to D-region ionization, the combination of AARDDVARK and riometer data sets is a powerful tool in the analysis of the characteristics of energetic electron precipitation events [*Rodger et al.*, 2012]. In order to provide wider geographical context for the precipitation events studied in this paper we make use of riometer data from Fort McMurray, Canada (56.7°N, 111.2°W, L=5.5), and Sodankylä, Finland (67.4°N, 26.4°E, L=5.1). Both these riometer systems have a wide-beam, 30 MHz, vertically pointing antenna.

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### 248 **3. Results**

On 27 February 2012 at least three energetic electron precipitation events occurred and their 249 impacts on the ionosphere were captured by the Autonomous AARDDVARK systems in the 250 251 Antarctic. Figure 3 shows the amplitude and phase of the NPM transmitter received at (in order of increasing distance from Hawaii) AA3, AA2, and Halley. The upper panel shows the diurnal 252 amplitude variation on 27 February as a solid line, with a representative quiet day curve shown 253 as a dotted line. The amplitude levels from each receiver site have been offset in order to allow 254 some differentiation between the sites. Three vertical dashed lines indicate the start of the three 255 events under study, which can be seen as departures from the quiet day curve lasting about 1-2 256 hours (which we will call the 02, 18, 20 UT events after their approximate start times). The 257 lower panel is of a similar format, but with the diurnal phase variations shown. Again, a phase 258 offset has been applied in order to allow some differentiation between the sites. 259

From looking at the overall amplitude and phase variations around the times of the three events indicated (~02, 18, 20 UT) we can tell that the propagation conditions prior to the events were essentially ones of daytime along the whole great circle path. This can be determined by the amplitude variations at all three sites between 16-04 UT, and the characteristic daytime phase advance at 14-17 UT associated with sunrise conditions on the great circle path. Because of the event timing we are able to model the pre-event propagation conditions using the Long Wave
Propagation Code (LWPC) [*Ferguson and Snyder*, 1990], after applying the appropriate daytime
D-region electron density profile parameterization as set out in *McRae and Thomson* [2000] and *Thomson et al.* [2011a; 2011b]. The profile parameterization varies along the great circle path as
a function of solar zenith angle. The VLF analysis/modeling is less uncertain during the daytime
because the propagation conditions are more reproducible than during nighttime conditions.

The deployment of the Autonomous AARDDVARK systems was planned to take advantage of 271 the juxtaposition of the L=4.6 contour and the NPM-Halley great circle path as shown in Figure 272 2. From AA3 to Halley the propagation path is quasi-constant in L-shell (L~4.6) and passes over 273 thick Antarctic ice shelf. The low ice sheet conductivity will result in a high sensitivity to 274 changing D-region conditions [Westerlund et al., 1969], and the quasi-constant L-shell will focus 275 276 on electron precipitation that is driven by outer radiation belt processes. Prior to reaching AA3 the propagation path from NPM, Hawaii, crosses the sea and experiences few effects of 277 precipitating electrons from the outer radiation belt because the majority of the path is at very 278 low L-shell [Clilverd et al., 2005]. This part of the great circle propagation path is much less 279 sensitive to energetic electron precipitation. In this respect we would anticipate that most of the 280 observed perturbations are generated on the great circle path between AA3 and Halley, and this 281 is borne out by the observation of only small effects observed at AA3, while larger effects are 282 observed at Halley during the event periods shown in Figure 3. 283

In order to put the three precipitation events into some sort of context we show zonallyaveraged POES data for 27 February 2012 in Figure 4. The upper panel shows the variations observed at LEO in the quasi-trapped fluxes of >100 keV electrons from L=2-8. The enhanced fluxes associated with the outer radiation belts occur at L≈4-8, while the slot region can be seen at L≈3-4. During two of the events (18 UT and 20 UT) enhanced quasi-trapped fluxes are observed with fluxes increasing from ~10<sup>4</sup> el.cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> to ~10<sup>6</sup> el. cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>, and the L-shell

range of enhanced fluxes increasing to L $\approx$ 3.5 to L>8. The earliest event (02 UT) does not show 290 any increase in quasi-trapped fluxes, rather a relatively indistinct decrease in flux levels at higher 291 L-shells (L $\approx$ 6-8). Overall this figure suggests that the trapped >100 keV electron flux decreases 292 during the second half of the day, with noticeably reducing background outer radiation belt 293 fluxes. The 02 UT event seems to have little long-term effect on the trapped fluxes, while the 18 294 and 20 UT events coincide with a significant long-term increase in the trapped fluxes. As there is 295 a weak solar proton event ongoing during 27 February 2012 we checked the POES P5 data (2.5-296 6.9 MeV protons) to see if the enhancements seen in the >100 keV electrons could be due to 297 proton contamination. POES P5 indicates smoothly reducing fluxes of protons for L>5 from 00 298 UT to 24 UT on 27 February, with no suggestion of enhancements at 18 or 20 UT and thus no 299 sign of any significant proton contamination in the electron data shown. The L>5 distribution of 300 301 the low 2.5-6.9 MeV proton fluxes on 27 February 2012 is consistent with the influence of rigidity cutoff effects, and suggests that the >800 keV electron fluxes at L<5 shown in the lower 302 panel of Figure 4 are not generated by protons. 303

The middle panel of Figure 4 shows the variation of the >100 keV electron BLC fluxes. Enhanced electron precipitation fluxes are observed at 02, 18, and 20 UT, coincident with the radiowave data, but the 02 UT event is much weaker in the POES data than the 18 and 20 UT events where precipitating flux levels are an order of magnitude larger and extend over a wider range of L-shells. The 02 UT event is only noticeable because of the fact that the precipitation signature is stronger at L≈4-5.5 than the immediate background levels.

The lower panel shows the variation of the trapped relativistic electron fluxes (>800 keV) from the P6 telescope. The relativistic electron fluxes show a decrease of about a factor of 10 in the outer radiation belt starting at ~13 UT, initially at higher L-shells, this is concurrent with the onset of the main phase of the moderate disturbance described in Figure 1, and similar to the decreases seen in the >100 keV trapped fluxes. The decline of the outer radiation belt fluxes over the period 13-16 UT is consistent with the superposed epoch analysis reported by *Hendry et al.* [2013], suggesting that this behavior can be considered to be a small radiation belt dropout event. However, no recovery is seen in the relativistic fluxes after the 18 and 20 UT events, unlike that seen in the >100 keV trapped fluxes. There is also a suggestion that the relativistic fluxes decrease during the 02 UT event, particularly at L≈6.

In this study there are two L-shell ranges to consider. One is at geosynchronous orbit ( $L\sim 6.6$ ) 320 where GOES-13 can provide insight into the conditions in the radiation belt, and the other is the 321 latitude range from L=4.5-5.0 which covers the L-shells of the ground-based instrumentation. 322 Figure 5 shows the diurnal variation of the NPM phase perturbation observed at AA3 (dotted 323 line), AA2 (solid line), and Halley (dashed line) in the middle panel, and the Halley riometer 324 absorption in the lower panel. The times of the three events (02, 18, 20 UT) are indicated by 325 326 vertical dashed lines. In both data sets the perturbations are shown relative to a typical quiet day curve for the time of year. The upper panel shows the POES >30 keV (solid line) and >100 keV 327 (dotted line) electron fluxes observed in the BLC over the range L=4.75-5.0. The three panels 328 show good consistency in that elevated electron precipitation fluxes are observed by both energy 329 channels in POES at the same times as increased D-region ionization is detected by the 330 AARDDVARK and riometer experiments. 331

In the riometer panel there are four distinct peaks in absorption at Halley, all of which have 332 levels that are ~1 dB. Three are identified as events studied in this paper, and have relatively 333 sudden onsets (the 02, 18, 20 UT events). The fourth absorption peak exhibits a more gradual 334 onset before reaching a maximum at ~14-15 UT. Similar features can be seen in the NPM phase 335 data (middle panel) and the POES fluxes (upper panel). In this study we concentrate on the 336 events which are clearly identified by their sudden onsets as this allows us to identify the events 337 more readily in the different data sets. In the upper panel of Figure 5 it is clear that the 338 precipitation fluxes involved in the 02 UT event are smaller by a factor of ~40 than the fluxes 339

involved in the 18 and 20 UT events ( $8 \times 10^4$  at 2 UT c.f.  $3 \times 10^6$  el cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> at 18 UT). This is 340 inconsistent, not only with the Halley riometer peak absorption levels, but with the Halley phase 341 perturbations which are close to 100° in all four cases, suggesting similar precipitating fluxes 342 into the atmosphere in all of the cases. The phase perturbations at AA2 are also typically the 343 same value for all of the events, i.e.,  $\sim 50^\circ$ , while AA3 shows similar consistency at  $\sim 25^\circ$ . 344 Understanding this difference, between the ground-based observations and satellite 345 measurements is key to using these instruments to understand the physical mechanisms 346 controlling the precipitation of energetic electrons into the atmosphere. 347

In both the upper and middle panels of Figure 4 the >100 keV trapped electron and BLC flux 348 data show an enhancement at ~14-15 UT. In Figure 5 there are also increases in >30 keV fluxes, 349 AARDDVARK phase, and riometer absorption at ~14-15 UT. Although this event appears to be 350 351 the first significant enhancement of trapped fluxes in the outer radiation belt following the onset of the geomagnetic storm we do not analyse it in detail, as it occurs during the complex sunrise 352 period in the Autonomous AARDDVARK data, and is very difficult to model as a result. 353 However, the characteristics of the ~14-15 UT event are similar to those of the 18 and 20 UT 354 events, in that there appears to be a phase perturbation of ~100° at Halley, POES BLC fluxes 355 >30 keV of  $\sim 10^6$  el. cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>, and a riometer absorption level of  $\sim 1$  dB. Unlike the 18 and 20 356 UT events, Figure 4 shows that the >100 keV trapped fluxes do not remain enhanced, but return 357 towards pre-event levels, and therefore the processes that generated the enhancement in trapped, 358 and BLC fluxes does not appear to have any long lasting influence on the outer radiation belt. 359

In Figure 6 we compare the geosynchronous GOES-13 data, and zonally averaged POES electron data over the equivalent range, L=5-7, during 27 February 2012. As we stated before, the GOES-13 data is representative of trapped fluxes, while POES can provide information on precipitating (BLC) and quasi-trapped electron fluxes. The times of the three events are identified by vertical dashed lines.

The response of the trapped electron fluxes during the 02 UT event in this dataset is one of a 365 decrease by a factor of ~10. This is observed by GOES-13 in the 350-600 keV channel, as well 366 as the >800 keV channel. POES sees similar behavior in the >300 keV and the >800 keV 367 channels. Electron precipitation measured by POES is enhanced during the 02 UT event, 368 particularly at energies of >30 keV, but at >300 keV there is little variation to be seen, with 369 fluxes close to the instrument noise floor most of the day. Overall, the picture at 02 UT is one of 370 loss of trapped fluxes from the outer radiation belt over a wide range of energies, with enhanced 371 electron precipitation into the atmosphere as a loss mechanism, particularly for the lower energy 372 electrons. At higher energies it is not possible to use POES P6 to determine if electron 373 precipitation is occurring or not because it is close to its sensitivity level. 374

The responses of the trapped electron fluxes during the 18 and 20 UT events are quite different to the 02 UT event. GOES-13 and POES trapped fluxes show increases in the 350-600 keV and >300 keV channels, respectively. While the GOES-13 >800 keV channel also shows small increases after the onset of the two events, this does not happen for the equivalent POES energy range. However, the POES relativistic electron detector has nearly an order of magnitude more sensitivity at 1.5 MeV than at 0.5 MeV [*Yando et al.*, 2011], suggesting that the extended flux dropout is probably occurring for energies of >1 MeV rather than <1 MeV.

The L=5-7 precipitating electron fluxes at >30 keV are elevated during the 18 and 20 UT events, 382 although as with the 02 UT event, the >300 keV fluxes are unchanged and at the instrument 383 noise floor. Clearly these events differ from the 02 UT event in that the later two events appear 384 to be cases where the electron precipitation is occurring at the same time as the increase in 385 trapped fluxes, and therefore the precipitation appears to be a consequence of the enhanced 386 fluxes, which could have occurred either through acceleration processes which also causes losses 387 or losses from the transport and energization of electrons within the radiation belts. We discuss 388 the evidence for these two different ideas in the following section. 389

#### 391 **4. Discussion**

#### 392 **4.1 Ground-based observations**

Clilverd et al. [2008a; 2012a; 2012b] combined riometer absorption data and AARDDVARK 393 radio wave data to estimate the electron precipitation flux occurring during substorms. A more 394 detailed description of this technique can be found in *Clilverd et al.* [2008a], so we provide only 395 an outline of the process here. We undertake the calculation of electron precipitation flux using 396 the NPM daytime phase and amplitude perturbations from AA3, AA2, and Halley, and the 397 Halley riometer observations. By comparing the observed fluxes for the 02, 18 and 20 UT events 398 with the flux responses calculated for the NPM amplitudes, NPM phases, and riometer 399 absorption, we can identify the actual precipitating flux for each event. 400

401 Energetic electron precipitation produces mesospheric ionization, and its resulting effects on VLF wave propagation can be modeled using the Long Wave Propagation Code [LWPC]. 402 LWPC models VLF signal propagation from any point on Earth to any other point. Given 403 electron density profile parameters for the upper boundary conditions, LWPC calculates the 404 expected amplitude and phase of the VLF signal at the reception point. A more detailed 405 description of this technique can be found in Clilverd et al. [2008a]. In Clilverd et al. [2010] a fit 406 was made to DEMETER electron spectra from ~90-700 keV in terms of a power law where the 407 slope (scaling exponent, k) typically ranged from -1 to -3. A power law slope of k=-3 represents 408 the LANL-97A substorm spectra in Clilverd et al. [2008a], and the Galaxy 15 substorm spectra 409 in Clilverd et al, [2012b]. The ionospheric electron density profile is found by introducing an 410 additional ionization source from the electron precipitation in a simple ionospheric model to 411 describe the balance of electron number density,  $N_e$ , in the lower ionosphere. This simple 412 electron density model is based on that given by Rodger et al. [1998], which was further 413 developed by Rodger et al. [2007, 2012]. 414

In addition, we can calculate the Halley riometer absorption from the same electron number density as was applied to LWPC. By calculating height-integrated differential absorption using the method described in *Rodger et al.* [2012], we can estimate the Halley riometer absorption generated by the same energetic electron precipitation characteristics used in the VLF modeling runs.

Figure 7 shows the results of the calculations using a wide range of >30 keV electron flux 420 magnitudes. The upper panel shows the calculated NPM amplitude perturbation at AA3 (dotted 421 line), AA2 (solid line) and Halley (dashed line) for a power law spectrum with the gradient k=-3422 suggested by previous authors (see text above). The gradient was also consistent with that 423 determined from a fit to the three POES electron channels (>30, >100, >300 keV). The flux was 424 varied from  $10^{1}$ - $10^{9}$  >30 keV el cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>. The peak perturbation values for each of the 02, 18, 425 426 and 20 UT events plotted on the panel with AA3 (squares), AA2 (triangles), and Halley (diamonds) represented by separate symbols. The middle panel is the same format as the upper 427 panel, but represents the NPM phase changes. The lower panel is also a similar format, but only 428 shows the riometer absorption calculations for Halley, and not AA3 and AA2. In all three panels 429 of this figure the symbols representing the observations were placed in order to fit the 430 observations to the modeling calculations. For some observations (like the amplitude changes 431 observed at AA3) the dependence of the amplitude change is very weak, which would lead to a 432 large error in flux even if the measurement error was small. From this figure we can see that the 433 calculated VLF response to increasing flux levels (with a constant spectrum) is different at each 434 site, with amplitudes increasing at AA3 and AA2, but decreasing at Halley. However, at all three 435 sites the NPM phase perturbation increases as the precipitation flux increases. Similarly the 436 riometer absorption increases smoothly with increasing precipitation flux. For all three 437 parameters shown, significant responses are only seen once the >30 keV precipitating fluxes 438 exceed  $10^5$  el cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>. 439

The scatter of observations during the events ranges from flux levels of  $10^{5}$ - $10^{9}$  for >30 keV 440 electron precipitation, with the majority suggesting fluxes of 10<sup>6</sup>-10<sup>7</sup> el cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>. No clear 441 distinction can be made between the flux estimates of any of the three events, as the ground-442 based data suggest that these three events are of similar magnitude, as noted earlier. There are 443 two significant outliers in this analysis, namely the  $\sim 100-120^{\circ}$  phase changes observed at Halley 444 during the 02 and 18 UT events. These values give very large fluxes which are at odds with the 445 other data during the same events. At the time of writing it is apparent that the phase change 446 values have been accurately measured, but it is unclear why they are so large in comparison with 447 the modeling results expected for fluxes of  $10^6$ - $10^7$  el cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>. 448

These results confirm the earlier observation that suggested that the POES BLC flux 449 observations during the 02 UT event were surprisingly low. The modeling calculations for the 450 451 AARDDVARK and riometer instruments suggest that if the POES >30 keV BLC fluxes of  $8 \times 10^4$  el cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> were correct then neither ground-based instrument would have registered an 452 observable perturbation starting at 02 UT. Clearly, this was not the case. For the 18 and 20 UT 453 events the POES >30 keV BLC fluxes  $(3 \times 10^6 \text{ el cm}^2 \text{ s}^{-1} \text{ sr}^{-1})$  are similar to the modeling 454 calculations, and thus POES observations represent a reasonable description of the electron 455 precipitation during those events. *Rodger et al.* [2010a] described in detail some of the issues 456 surrounding the difficulties in using POES BLC measurements. One significant aspect that we 457 note here is that the detector is not usually measuring the whole of the BLC, but only a fraction 458 of it. This is particularly true for observations made at L>2. Thus in the case of the 02 UT event 459 we can assume that the POES BLC measurement is not representative of the whole electron 460 population within the BLC, and is in fact, missing a large proportion of it. This is consistent with 461 the effects of a weak diffusion process [Horne, 2002] which only pushes electrons into the BLC 462 close to the outer edge of the loss cone (in pitch angle space), and not all the way into the 463 detector viewing angle (i.e., the pitch angle range sampled by the BLC detector). This 464

mechanism was also suggested to explain the observations during a VLF chorus event described 465 in Clilverd et al. [2012b], however in the 02 UT event no chorus waves were observed by the 466 Halley VELOX instrument [Smith et al., 1995]. We also note here that the 02 UT event was not 467 associated with any Pc 1-2 waves at Halley using the Augsburg College search coil 468 magnetometer [Engebretson et al., 2008], and that neither of the 18 or 20 UT events show 469 coherent Pc 1-2 wave power. In Figure 8 we show the 0.5-10 kHz wave intensity received by the 470 VELOX instrument at Halley on 27 February 2012. Waves in the range 6-10 kHz, and 0.5-0.6 471 kHz are typically associated with distant lightning impulses, while waves in the range 0.6-6 kHz 472 are likely to be chorus or plasmaspheric hiss. Of the three events studied here, only the period 473 associated with the 20 UT event shows an enhancement in 1-2 kHz chorus wave power at 474 Halley. However, there is also an enhancement in 1-2 kHz wave intensity at ~14 UT, coincident 475 476 with the ~14-15 UT precipitation event discussed previously.

Another possibility that could explain the disparity between POES and the ground-based 477 instruments during the 02 UT event is that the region of precipitation is localized to the 478 longitudes of Halley, and thus the zonally averaged POES data is under-estimating the actual 479 flux involved. In order to investigate this we undertook two checks. The first was to look at the 480 location of the POES satellites when they detected an enhancement in BLC flux at ~02 UT, and 481 the second was to determine if riometers at different longitudes around the world also saw the 482 02 UT event. In the first check we found that POES detected enhanced BLC flux at ~02 UT with 483 a uniform scatter around the globe, and that the majority of observations consisted of peak values 484 of  $1 \times 10^4 - 4 \times 10^4$  el cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup>. None gave flux values of  $10^6$ , although the highest flux was 485 reported as  $6 \times 10^5$  el cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> at a southern longitude about 70° east of Halley. 486

For the second check, Figure 8 shows the riometer data from three geomagnetic longitudes for 27 February 2012. The three event times are indicated by vertical dashed lines, and details of the site name, L-shell, and geomagnetic longitude are given in each panel. The sites: Fort McMurray, Halley, and Sodankylä all show some indication of the three electron precipitation events, although with different absorption levels. Typically Halley shows the smallest absorption levels for the events. Sodankylä to the east of Halley shows the largest absorption during the 02 UT event, consistent with the POES longitudinal picture, but also with absorption levels suggestive of precipitation fluxes significantly higher than POES. Thus, the riometer signature at Halley does not provide an over-estimate of the actual flux involved, and POES is genuinely under-reporting the precipitation fluxes.

Overall, the ground-based data suggest that the three events studied have precipitation fluxes of  $10^{6}-10^{7}$  el cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> for >30 keV electrons. The 02 UT event appears to have a factor of ~10-100 times more flux than was reported by POES, consistent with weak diffusion into the BLC. The 18 UT and 20 UT events only have a factor of <10 times more >30 keV flux than was reported by POES, much more consistent with strong diffusion conditions.

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#### 505 4.2 GOES-13 observations

It has been shown that the three EEP events are observed over a range of L-shells including 506 those of the geostationary satellite GOES-13. As such, the detailed observations from the GOES-507 13 MAGED instrument, in addition to magnetometer data, can be used to investigate in detail 508 what mechanisms or process might be taking place. Figure 9 shows the electron flux, and 509 anisotropy (defined as  $\log_{10}(j_{\text{para}}/j_{\text{perp}})$ ) for two energy channels, 200-350 keV and 350-600 keV, 510 during 27 February 2012. In general the anisotropy would be expected to be more parallel 511 (positive) on the nightside and more perpendicular on the dayside (negative) due to drift shell-512 splitting. Superposed on this behavior may be more short-term changes caused by processes such 513 as those leading to the three EEP events under study here. The lower panel shows the parallel 514

and perpendicular temperature derived for the whole energy range (50-600 keV). The times of
 the three events are indicated by three vertical dashed lines.

For the 02 UT event (nightside: ~21 LT), both energy channels show a decrease in flux about 517 an hour in duration. At the event onset, the anisotropy, which had been steadily increasing over 518 the preceding hour indicating an increasingly parallel oriented distribution, suddenly drops back 519 towards zero indicating an isotropic distribution. At onset, the parallel electron temperature 520 decreases, whilst the perpendicular electron temperature increases slightly. These observations 521 suggest a loss of electrons over a wide energy range, with the reduction of parallel temperature 522 and sudden decrease of anisotropy supporting the idea of the precipitation of parallel-orientated 523 electrons into the atmosphere. 524

However, for the 18 and 20 UT EEP events (dayside: 13 and 15 LT), the observations in Figure 525 526 9 indicate quite different behavior when compared with the 02 UT event. The electron fluxes over the 200-600 keV energy range exhibit an increase rather than a decrease at the event onset, 527 while the anisotropy returns to near-zero (approximately isotropic distribution) from small 528 negative values (slightly perpendicularly oriented distribution) rather than large positive ones 529 (parallel oriented distribution). The parallel and perpendicular electron temperatures both 530 increase. These observations suggest an overall increase in flux over a wide energy range, which 531 includes parallel-propagating electrons. Rather than a loss mechanism, the 18 and 20 UT EEP 532 events appear to be part of a transport process as indicated by the L\* variation in the top left 533 panel of Figure 10. 534

We investigate these ideas further by calculating the phase space density (PSD) using techniques described by *Selesnick and Blake* [2000] and *Green and Kivelson* [2004], accounting for the physical behaviour of the electrons as a function of the three adiabatic invariants ( $\mu$ , K and L\*). Figure 10 shows the PSD plotted as a function of L\* and time during 27 February 2012, for constant  $\mu$  and K (chosen  $\mu$  value corresponds to the 350-600 keV electron channel from

GOES-13, chosen K value corresponds to more parallel oriented electrons), in addition to the full 540 pitch-angle distribution for 350-600 keV electrons from GOES-13 and a comparison of the 541 magnetic field measured by GOES-13 and the output of the T96 magnetic field model 542 [Tsyganenko and Stern, 1996] used in the PSD calculation. The vertical dashed lines indicate the 543 times of magnetic midnight and noon at the satellite. During the 02 UT EEP event the calculated 544 phase space density reduces by ~2 orders of magnitude from an initial high level whilst there is 545 little variation in L\*. The magnetometer data indicates large stretching of the magnetic field, 546 with a subsequent dipolarization occurring around 02 UT (suggestive of substorm activity). 547 Electron flux rapidly decreases and then recovers across all pitch angles. The PSD reduction at 548 this time indicates that any electron losses are unlikely to be driven by adiabatic transport and 549 may be due to loss to the atmosphere (although it is noted that PSD calculations are limited by 550 551 the accuracy of the implemented magnetic field model).

The 18 and 20 UT EEP events occur as the spacecraft moves from noon towards dusk and in a 552 regime of low PSD with large L\* variation, indicating the likelihood of adiabatic transport of 553 electrons is occurring. Onset times for these events are approximately coincident to step changes 554 in the magnetic field stretching angle. The 20 UT event seems to be associated with a large 555 discontinuity in the solar wind, intensification of the IMF, sign change in all 3 IMF components, 556 and a large drop in solar wind density. These characteristics could define one kind of event that 557 leads to strong pitch-angle diffusion. During these events, an initial loss of electrons at all pitch 558 angles is observed, with the pitch-angle distribution shifting from a distribution peaked around 559 90 degrees to a more isotropic distribution as electron flux increases. A concurrent increase in 560 the parallel flux is also observed. 561

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#### 563 **5. Summary**

During 27 February 2012 a moderate geomagnetic disturbance began to influence the outer radiation belt. At about 13 UT the outer radiation belt fluxes from 100 keV-1 MeV began to decline, with the earliest onset occurring at higher L-shells. Following EEP events at 18 and 20 UT the radiation belt trapped fluxes <600 keV were dramatically enhanced, in contrast to the >800 keV fluxes which continued to decline. Several strong EEP events were observed, i.e., at 02, ~15, 18 and 20 UT, but they seem to be super-imposed on, rather than the cause of, the decline in the outer radiation belt fluxes.

571 The findings of this study can be summarized as follows:

In the 02 UT event loss of trapped electrons was observed over a wide range of
energies, i.e., 30-600 keV, >800 keV and >2 MeV, particularly over the L=5-7 range.
Precipitation was observed from L=4-6, with a pre-event build up of parallel-orientated
electrons, suddenly lost during the event. The event does not appear to be a large, classical
substorm because of the narrow range of L-shells involved in the EEP. However, GOES
magnetometer data at the time indicates a large stretching of the magnetic field, with a
subsequent dipolarization, confirming the occurrence a substorm.

Large differences were found between the precipitation flux at ~02 UT observed by
 instruments on the ground and those observed by POES, suggesting a weak diffusion
 process only partially filling the BLC. No long-lasting effects on the trapped fluxes were
 observed.

The 18 and 20 UT events are super-imposed on a declining outer radiation belt, which started around 13 UT. The events themselves show increases in both trapped and precipitating flux over a wide range of energies, i.e., 30 keV-2 MeV, and a wide range of Lshells, i.e., L=3.5-10. The variations in anisotropy and PSD suggest a transport mechanism acting on the radiation belt electrons. The ground-based observations indicate EEP flux levels that are similar to those
 observed by POES, which is consistent with a strong diffusion mechanism filling the BLC.
 Following these events the radiation belt trapped fluxes <600 keV remain enhanced,</li>
 possibly because the EEP has stopped. However, the relativistic fluxes remain low.

5) The EEP events are clearly part of the process that triggers the recovery of the outer radiation belt to a flux dropout, and the GOES PSD analysis suggests that this is due to adiabatic transport of electrons.

Overall this study period shows similarities with the picture of electron precipitation and loss 595 during a flux dropout event as described by Hendry et al. [2013]. The reduction in the 596 background radiation belt fluxes that began at 13 UT on 27 February 2012 does not appear to be 597 related to any individual EEP events. However, several EEP events occurred between 15-20 UT, 598 599 with the final one causing electron energies of <600 keV to remain elevated and produce the well known picture of a flux dropout event at high electron energies (~1 MeV) with enhanced lower 600 energy fluxes. Enhanced VLF chorus waves were observed at Halley, Antarctica, at the time of 601 the 20 UT event whereas EMIC waves were absent, although it is unclear if the chorus was 602 instrumental in the radiation belt recovery as the waves were only observed for as long as the 603 EEP event itself. 604

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Acknowledgments. MAC and NCO would like to acknowledge the important contributions from Nick Alford and Tom Stroud, particularly for their skill and assistance in building and deploying the Autonomous AARDDVARK systems. The authors would like to thank the Space Physics Data Facility (SPDF) for providing the solar and geomagnetic data. The research leading to these results has received funding from the Natural Environmental Research Council under the Antarctic Funding Initiative (AFI/11/22). CJR was supported by the New Zealand

- 612 Marsden Fund. MHD was supported by STFC grant ST/I000801/1 and DH was supported by a
- 613 STFC PhD Studentship. JVR was supported by the GOES-R Risk Reduction Program.
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- 828 (Received N x, 2013; N x 27, 2013;
- 829 accepted N x, 2013.)
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#### 833 Figures

Figure 1. The geomagnetic conditions for the period 23-29 February 2012. Solar wind speed and density variations are shown in the top two panels, indicating that a high speed solar wind event driven by a CME occurred late on 26 February. Kp and Dst variations are shown in the lower two panels, and indicate moderately disturbed geomagnetic conditions beginning half way through 27 February, peaking a few hours before UT midnight with values of Kp=5, and Dst=-55 nT.

Figure 2. A map of the great circle path (green line) from the Hawaii NPM VLF transmitter to Halley, Antarctica (red diamond). The locations of the two autonomous VLF receivers, labeled AA Rx, are shown (blue asterisks). The southern hemisphere geomagnetic footprint of the GOES-13 satellite is also shown (black square), as well as the L-shell contours for L= 4, 4.6 and 7. The great circle path and the three VLF receivers are located close to the L shell contour at L= 4.6 in the region where the path crosses the Antarctic Ice shelf at the southern end of the Antarctic Peninsula.

Figure 3. The amplitude and phase variations observed at three sites in the Antarctic (AA3, AA2, and Halley) from the NPM transmitter in Hawaii on 27 February 2012. Typical quiet-day curves for each site are shown as dotted lines, and the times of energetic electron precipitation events identified by vertical dashed lines. The amplitude and phase values have been offset to allow comparison between data sets.

Figure 4. POES electron flux observations for 27 February 2012. Upper panel.
POES >100 keV trapped fluxes. Middle panel. POES >100 keV BLC fluxes. Bottom
panel. POES relativistic trapped electron fluxes (energies larger than about 800 keV).
Figure 5. Upper panel. POES BLC electron fluxes (>30 keV and >100 keV) over
the range L=4.75-5.0 on 27 February 2012. Middle panel. AARDDVARK phase
perturbations at Halley (dashed line). AA2 (solid line), and AA3 (dotted line). Lower

panel. Halley riometer absorption. The times of the three study events are indicatedby the vertical dashed line.

Figure 6: Top to bottom panels. The GOES-13 >800 keV electron fluxes, GOES-13 350-600 keV electron fluxes, POES >800 keV trapped electron flux over the L=5-7 range, POES trapped >300 keV electron flux in the range L=5-7, the POES >30 keV and >300 keV BLC electron fluxes over the range L=5-7. Times of the electron precipitation events under study on 27 February 2012 are indicated by vertical dashed lines. Some similarities between the GOES-13 and POES trapped fluxes can be seen. See text for more details.

Figure 7: Upper panel. The NPM amplitude perturbation as a function of electron 867 integral precipitation flux >30 keV, for a k=-3 power law spectra. The precipitation 868 869 covers the great circle path from L=3.5 to AA3 (dotted line), to AA2 (solid line), and to Halley (dashed line). Square symbols represent the 3 event perturbation levels as 870 measured at AA3, triangles represent perturbation levels at AA2, and diamonds at 871 Halley. Middle panel. The same format as the upper panel, but for the NPM phase 872 perturbation. Lower panel. The same format as the upper and middle panels but for 873 the Halley riometer absorption level. See text for more details. 874

Figure 8: Halley 0.5-10 kHz wave intensity on 27 February 2012. Of the three electron precipitation events studied (02, 18, and 20 UT) only the 20 UT event is associated with the occurrence of enhanced 1-2 kHz waves.

Figure 9: Riometer absorption levels during  $27^{th}$  February 2012, spanning ~180° of magnetic longitude at L~5. The stations in Canada, Antarctica, and Finland show similarities in the occurrence of periods of excess ionization at the three times of interest (indicated by the dashed vertical lines), although there are notable differences in absorption level, and structure at times.

Figure 10: Upper panel. The GOES-13 200-350 and 350-600 keV electron flux 883 channels (cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> keV<sup>-1</sup>) during 27 February 2012. At the times of the 884 perturbations under study (shown by vertical dashed lines) decreases and increases in 885 flux are observed in both energy channels. Middle panel. The electron anisotropy in 886 the two energy channels. The electron precipitation event at  $\sim 02$  UT shows a marked 887 change in anisotropy, whereas the two later events show less systematic variations. 888 Lower panel. The GOES-13 parallel and perpendicular temperature (keV) over the 889 same period. 890

Figure 11: Top left panel. Phase space density as a function of thee three adiabatic 891 invariants during 27th February 2012, calculated using GOES-13 observations and 892 T96 [Tsyganenko and Stern, 1996] magnetic field model. Top right panel. Pitch-893 angle distribution from GOES-13 for 350-600 keV electrons during 27<sup>th</sup> February 894 2012. Bottom left panel. A comparison of the measured magnetic field magnitude 895 and that produced by the T96 model. Bottom right panel. A comparison of the 896 measured magnetic field stretching angle, defined 897 as  $\vartheta_{stretch} = \arctan(B_Z/(B_X^2 + B_F^2)^{1/2})$ , and that produced by the T96 model in 898 geomagnetic coordinates. In all panels, the vertical dashed lines indicate local 899 magnetic midnight (5 UT) and noon (17 UT) for GOES-13. 900



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Time (UT)

















Halley 2012-02-27 (Day 58) Mean log amplitude















