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1 Relativistic microburst storm characteristics: combined satellite and ground-based  
2 observations

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13 **Abstract.** We report a comparison of SAMPEX detected relativistic electron microbursts and  
14 short-lived subionospheric VLF perturbations termed FAST events, observed at Sodankylä  
15 Geophysical Observatory, Finland, during 2005. We show that only strong geomagnetic  
16 disturbances can produce FAST events, which is consistent with the strong link between storms  
17 and relativistic microbursts. Further, the observed FAST event perturbation decay times were  
18 consistent with ionospheric recovery from bursts of relativistic electron precipitation. However,  
19 the one-to-one correlation in time between microbursts and FAST events was found to be very  
20 low (~1%). We interpret this as confirmation that microbursts have small ionospheric  
21 footprints, and estimate the individual precipitation events to be <4 km radius. In contrast, our  
22 study strongly suggests that the region over which microbursts occur during storm event

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23 periods can be at least  $\sim 90^\circ$  in longitude ( $\sim 6$  hours in MLT). This confirms earlier estimates of  
24 microburst storm size, suggesting that microbursts could be a significant loss mechanism for  
25 radiation belt relativistic electrons during geomagnetic storms. Although microbursts are  
26 observed at a much higher rate than FAST events, the ground-based FAST event data can  
27 provide additional insight into the conditions required for microburst generation and the time  
28 variation of relativistic precipitation.

29 **1. Introduction**

30 The dynamics of Earth's Van Allen radiation belts are governed by a number of competing  
31 acceleration and loss mechanisms. Particle fluctuation often coincides with a period of  
32 disturbance caused by a geomagnetic storm, with the outer belt flux frequently decreasing during  
33 storm onset, followed by a gradual repopulation during the recovery period [*Baker et al.*, 1986;  
34 *Li et al.*, 1997]. However, this is not always the case; *Reeves et al.* [2003] found that the post-  
35 storm outer belt relativistic electron flux levels can increase (seen to occur for 53% of events  
36 studied), decrease (19%) or have no significant change (28%), relative to pre-storm levels. The  
37 flux of the outer belt relativistic electron population at geostationary orbits, defined as having  
38 energies  $>1$  MeV, is seen to drop over a period of hours during geomagnetic storms [*Onsager et.*  
39 *al.*, 2002]. Multiple mechanisms may contribute to these decreases and it has been shown that  
40 losses to the atmosphere are likely to be a contributing factor [*Green et al.*, 2004; *Clilverd et al.*,  
41 2006].

42 Numerical modeling predicts Relativistic Electron Precipitation (REP) to penetrate into the  
43 atmosphere to altitudes of 40-60 km, lower altitudes than most other magnetospheric particles  
44 are able to reach [*Baker et al.*, 1987; *Callis et al.*, 1991], depositing large enough amounts of  
45 energy so as to dominate all other ionisation sources at this altitude range. REP events can occur  
46 across a wide range of timescales, lasting from minutes to hours, or taking the form of a brief  
47 microburst ( $<1$  s) of precipitating electrons. The occurrence of relativistic microbursts has been  
48 studied since they were first reported by *Brown and Stone* [1972], but there are still significant  
49 unknowns. The first reports of relativistic microbursts (as distinct from those in the tens of keV  
50 range) appear to have been made by the S81-1 satellite [*Imhoff et al.*, 1992]. Observations from  
51 the Solar Anomalous Magnetospheric Particle Explorer (SAMPEX) have helped to determine  
52 some characteristics of REP microbursts, showing that they are spatially small [*Blake et al.*,

53 1996]. *Nakamura et. al.* [2000] found that microbursts tend to occur during storm time in the  
54 local dawn sector and are likely to be produced through interactions with electron whistler-mode  
55 waves. Microburst production has also been linked to interaction with chorus waves [*Lorentzen*  
56 *et. al.*, 2001a; *O'Brien et. al.*, 2004; *Bortnik and Thorne*, 2007], which occur predominantly in  
57 the dawn sector. The majority of geomagnetic storms show a sharp increase in microburst  
58 activity, tending to occur at lower  $L$  during the storm onset, then slowly moving outward during  
59 the recovery period [*Johnston and Anderson*, 2010; *Nakamura et. al.*, 2000]. At this stage it is  
60 unclear from spacecraft data how large a spatial region is affected when relativistic microbursts  
61 take place. However, estimates have shown that relativistic microbursts could totally deplete the  
62 relativistic electron population of the outer belt during a geomagnetic storm [*Lorentzen et al.*,  
63 2001b; *O'Brien et. al.*, 2004]. Further information is required to understand the nature of  
64 magnetospheric relativistic electron losses [*Thorne et al.*, 2005], requiring additional (and  
65 preferably) simultaneous measurements of microburst characteristics.

66 As there are many suggestions but little certainty about the behavior of microbursts, methods  
67 of sensing REP at its lowest penetration altitude would be advantageous. Ionisation levels at the  
68 40-60 km altitude range can be difficult to probe, with one of the few effective monitoring  
69 techniques being the use of long-range Very Low Frequency (VLF) signals. VLF waves  
70 propagate by reflecting between the Earth's surface and the lower edge of the ionosphere,  
71 travelling in what is effectively an Earth-ionosphere waveguide. The altitude of the lower  
72 boundary of the ionosphere varies with solar zenith angle and local geomagnetic conditions,  
73 having an approximate value of 70-85 km. Hence, REP tends to penetrate to below the lower  
74 ionospheric boundary, causing a pronounced increase in ionospheric ionization in the region of  
75 the precipitation event. Any VLF signal whose propagation path passes through the ionization  
76 change region will be perturbed in amplitude and phase, and as a result imprinted with an

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77 indication of REP activity. Recent studies of subionospheric VLF signals have found  
78 perturbation signatures of  $\sim 1$  s to occur during periods of geomagnetic disturbance [*Clilverd et.*  
79 *al.*, 2006; *Rodger et. al.*, 2007]. These perturbations have been termed FAST events and are  
80 thought to be the first documented ground-based detection of REP microbursts. It is  
81 hypothesized that each FAST event is the signature of one microburst, with a "rainstorm" of  
82 multiple microburst "raindrops" occurring in the area local to the receiver.

83 In this paper we make a comparison between the characteristics of FAST events detected by  
84 subionospheric VLF and microbursts detected on a satellite, to determine the validity of the  
85 hypothesis that FAST events are the subionospheric signature of relativistic electron microburst  
86 precipitation events. Correlations in space and time will be examined to determine as much as  
87 possible about the nature of FAST events and to expand upon what is currently known about  
88 microbursts. In particular, the potential size of a single REP microburst, or "raindrop" size, is  
89 investigated, as is the size of the region across which microbursts can occur simultaneously, the  
90 "rainstorm" size.

## 91 **2. Instrumentation**

92 This study combines subionospheric VLF signals and satellite data recorded from December  
93 2004 – June 2005. We examine subionospheric VLF data detected at a VLF receiver located at  
94 the Sodankylä Geophysical Observatory (SGO), in Finland ( $67.4^\circ\text{N}$ ,  $26.4^\circ\text{E}$ ,  $L=5.3$ ). We use  
95 signals from transmitters located in Europe and North America, i.e., NDK ( $46.4^\circ\text{N}$ ,  $98.3^\circ\text{E}$ ,  
96  $L=3.3$ ; North Dakota, USA; 25.2 kHz), NAA ( $44.6^\circ\text{N}$ ,  $67.3^\circ\text{E}$ ,  $L=2.9$ ; Maine, USA; 24.0 kHz),  
97 NRK ( $64.2^\circ\text{N}$ ,  $21.9^\circ\text{W}$ ,  $L=5.6$ ; Keflavik, Iceland; 37.5 kHz), DHO ( $53.1^\circ\text{N}$ ,  $7.6^\circ\text{W}$ ,  $L=2.4$ ;  
98 Ramsloh, Germany; 23.4 kHz) and ICV ( $40.9^\circ\text{N}$ ,  $9.8^\circ\text{W}$ ,  $L=1.5$ ; Tavolara Island, Italy;  
99 20.27 kHz). The transmitter locations and their signal transmission paths to SGO are shown in  
100 Figure 1. The SGO VLF receiver is part of the Antarctic-Arctic Radiation-belt Dynamic

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101 Deposition VLF Atmospheric Research Consortia (AARDDVARK) network. Further  
102 information about the AARDDVARK network can be found in *Clilverd et. al.* [2009a], and the  
103 AARDDVARK website at  
104 [http://www.physics.otago.ac.nz/space/AARDDVARK\\_homepage.htm](http://www.physics.otago.ac.nz/space/AARDDVARK_homepage.htm).

105 The Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) satellite carries the  
106 Heavy Ion Large Telescope (HILT), which gives high sensitivity and 30 ms time resolution  
107 measurements of the flux of >1.05 MeV electrons [*Klecker et. al.*, 1993]. While the Si-Li  
108 detectors are dominated by relativistic electrons during passes through the outer radiation belt,  
109 they may also be contaminated by protons during solar proton events. Monte Carlo calculations  
110 predict that 1 MeV electrons see the HILT as having an effective geometric factor of  $\sim 100 \text{ cm}^2 \text{sr}$   
111 [*Blake et al.*, 1996; *Nakamura et al.*, 1998], a substantial viewing window that is ideal for  
112 studying energetic electron precipitation. HILT data with a high-rate sampling period of 20 ms  
113 was used in our investigation. The detectors on HILT saturate at a particle flux of  $10^4$  electrons  
114  $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ .

115 The SAMPEX orbital period is  $\sim 96$  minutes and the magnetic local time of the satellite repeats  
116 approximately every 80 days [*Blake et al.*, 1996]. The SAMPEX satellite's low altitude, polar  
117 orbit means that it passes through Earth's radiation belts four times with each orbit, totaling  
118 approximately 60 passes a day, at  $\sim 24$  minutes a pass. SAMPEX has an orbital inclination of  
119  $81.7^\circ$  [*Nakamura et al.*, 1998].

120 HILT mainly views the Bounce and Drift Loss Cones (BLC and DLC respectively), thus  
121 detecting electrons that will precipitate within at least one drift period (i.e.,  $\sim 15$  min at  $L=4$  for a  
122 1.5 MeV electron).

### 123 **3. FAST Events**

124 *Clilverd et al.* [2006] presented what is thought to be the first ever ground based detection of  
125 relativistic electron microbursts. This study undertook an analysis of subionospheric VLF  
126 AARDDVARK data during a magnetospheric electron flux decrease that took place at 17:10 UT  
127 on the 21st of January, 2005. Short lived VLF amplitude and phase perturbations observed  
128 during the flux decrease were termed FAST events. It has been reported that FAST events are  
129 consistent with the expected effects of microbursts of relativistic electrons impacting on the  
130 atmosphere and scattering VLF transmissions, as shown by the modelling in *Rodger et al.*  
131 [2007]. Approximately 99% of individual FAST events occurring during the 21 January 2005  
132 storm were not coincident across different received signals [*Clilverd et al.*, 2006]. The lack of  
133 event coincidence suggests that FAST events are the result of a precipitation “rainstorm”  
134 producing spatially small (tens of km or less) “raindrop”-like ionisation density changes, caused  
135 by a physical process spanning a much larger region, i.e., many hundreds of kilometres in  
136 diameter [*Clilverd et al.*, 2006], centred on or near Sodankylä.

137 A search for FAST events across the time period December 2004-June 2005 identified four  
138 additional periods in SGO AARDDVARK data. As with 21 January 2005, all four additional  
139 periods occurred during geomagnetic storms, with two occurring during the local day time. This  
140 is expected as the relativistic electron precipitation that is thought to cause FAST event  
141 signatures should penetrate so deeply into the ionosphere that they would be observable both  
142 during the local day and night. The characteristics of all five documented FAST periods are  
143 listed in Table 1 and an example of a single FAST event is shown in Figure 2. Included in Table  
144 1 is the peak  $>10$  MeV proton flux reported by the GOES for each period. No FAST event  
145 signatures were observed for  $K_p < 6$ , suggesting that only strong geomagnetic disturbances can  
146 produce FAST events. This is consistent with the strong  $D_{st}$  link previously reported between  
147 storms and microbursts [*O'Brien et al.*, 2003].

148 The 21 January 2005 FAST events decayed over an average time period of 0.8 s each, while  
149 those for 4-5 April 2005 were observed to decay in an average of 1.2 s each. *Rodger et al.* [2007]  
150 showed the latter result is consistent with the modelled ionosphere recovery of ionization  
151 increases produced at altitudes as low as 40-60 km due to REP with energies  $>2$  MeV. The  
152 shorter 21 January 2005 decay time was explained by the upper parts of the REP-produced  
153 ionisation changes being “masked” by excess ionization because of proton precipitation during a  
154 solar proton event. The time decays of the new FAST perturbations were examined, and  
155 contrasted with the geophysical conditions at the time.

156 In Table 1 the shortest decay times are found for daytime ionospheric conditions when a solar  
157 proton event was occurring (15 May 2005), while the longest were for nighttime ionospheric  
158 conditions with essentially no precipitating proton flux (4-5 April 2005). A simple “cartoon  
159 model” would suggest that daytime REP produced ionization would have shorter decay times  
160 than that for nighttime REP. Similarly, REP produced ionization occurring during solar proton  
161 events would also have shorter decay times than non-SPE periods, due to increased high-altitude  
162 ionization levels perturbing the ionosphere. The FAST event decay times in Table 1 are  
163 consistent with the cartoon model of a rainstorm of REP microbursts.

#### 164 **4. SAMPEX microbursts**

165 To investigate whether FAST events are caused by relativistic electron microbursts, a survey  
166 was undertaken of microbursts detected by the SAMPEX’s HILT instrument during the FAST  
167 periods identified. The survey was confined to REP detected while HILT was viewing the  
168 bounce-loss cone exclusively, as these microbursts represent local precipitation. This was  
169 defined by periods for which the mirror altitude of the SAMPEX-reported electron fluxes were  
170 less than 120 km, indicating that the SAMPEX was only viewing the bounce loss cone.

171 In the current study we use the 100 km altitude projection of SAMPEX's geomagnetic field  
 172 line, as this provides the coordinates where any SAMPEX observed REP would precipitate into  
 173 the atmosphere. As relativistic electron microbursts occur during large geomagnetic storms,  
 174 some uncertainties might be expected in the field line mapping. We used the  
 175 Definite/International Geomagnetic Reference Field (DGRF/IGRF), employing the GEOPACK  
 176 software routines calculated for April 2005, to trace from the geomagnetic latitude and longitude  
 177 of SAMPEX's location, down the magnetic field line to the top of the atmosphere. The effective  
 178 top of the atmosphere was taken to be  $\sim 100$  km, as in the SAMPEX data. To test the effect of a  
 179 geomagnetic storm upon the 100 km altitude field line position, the  $K_p$ -dependent Tsyganenko  
 180 magnetospheric field model was used [Tsyganenko, 1989]. The model was supplied with the  
 181 maximum  $K_p$  during the 4-5 April 2005 FAST period ( $K_p=7$ ). This showed that the maximum  
 182 displacement was  $<1$  km, thus the field line mapping to the atmosphere is sufficiently accurate  
 183 for the purpose of this investigation.

184 To determine whether a SAMPEX reported flux increase can be identified as a microburst, two  
 185 criteria were employed as suggested by O'Brien *et. al.* [2004]. It was required that HILT  
 186 recorded a flux increase lasting  $<1$  s before decaying back to the level of the background flux, as  
 187 well as measuring above a specified threshold flux during the increase. We follow O'Brien *et. al.*  
 188 [2004] and set the threshold flux increase,  $J$ , is  $\sqrt{10}$  times the background population,  $J_0$ , that  
 189 SAMPEX records, i.e.,

$$J \geq \sqrt{10} \times J_0 = 3.16 J_0$$

191 We also use O'Brien's method of establishing the baseline flux as the 10<sup>th</sup> percentile of the  
 192 fluxes, while also placing a floor at a flux level of  $10^1 \text{ cm}^{-2} \text{ str}^{-1} \text{ s}^{-1}$  [O'Brien *et. al.*, 2004]. Any  
 193 deviations from the  $J(\text{DLC})$  level may represent bounce loss cone precipitation.

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194 We follow the approach outlined in *Rodger et al.* [2010] to examine the radiation belt electron  
195 populations observed by SAMPEX's HILT instrument. SAMPEX orbital datafiles include the  
196 IGRF-determined pitch angle at the spacecraft of a particle heading down the instrument  
197 boresight, which have been processed to produce a world map of median pitch angles with a  $1^\circ$   
198 latitude/longitude resolution. Using the IGRF model for an average SAMPEX altitude of  
199 494 km, we have created a similar world map for the angular width of the bounce and drift loss  
200 cones at the satellite. When these are combined with the HILT boresight pitch angle width of  
201  $68^\circ$  we can describe the geographical variation of the particle populations detected, taking into  
202 account the HILT viewing width.

203 Figure 3 presents a world map of the changing radiation belt population observed by HILT. In  
204 this figure "T" indicates trapped flux, "DLC" is drift-loss cone, and "FL BLC" is field line  
205 bounce loss cone. Note that the FL BLC angle is defined as the largest of the two loss cone  
206 angles defined for the two hemispheres. Near the geomagnetic equator the instrument only  
207 measures fluxes inside the bounce-loss cone (FL BLC), i.e., precipitating beneath the  
208 spacecraft, but for most of the globe it observes a mix of DLC and BLC populations [*Klecker*  
209 *et. al.*, 1993; *Nakamura et. al.*, 2000]. Note that above the SAMA the instrument detects part of  
210 the BLC, all of the DLC and a fraction of the trapped population. In contrast, in the Northern  
211 Hemisphere from about  $85^\circ\text{W}$  to  $55^\circ\text{E}$  the HILT detects only BLC fluxes, consistent with  
212 statements by *Li et al.* [1997]. While Figure 3 was made for the satellite mean altitude of  
213 494 km, very similar plots are produced for the full range of altitudes over which SAMPEX  
214 orbits ( $\sim 450\text{-}530$  km).

215 A survey of SAMPEX's HILT data found relativistic electron microbursts to occur during each  
216 of the FAST periods identified in the subionospheric data. These microbursts were sorted by  
217 their northern hemisphere mirror altitude to determine whether they were in the local drift or

218 bounce loss cones, with the total number of microbursts detected and the number of those that  
219 were detected while viewing the BLC shown in Table 2. There is no simple relationship between  
220 the number of SGO FAST events and SAMPEX microbursts occurring on any given day. This is  
221 also true when considering  $K_p$  and the number of microbursts, as is also seen with  $K_p$  and the  
222 number of FAST events.

223 The  $L$ -variation in the occurrence number and average flux of SAMPEX detected BLC  
224 microbursts in our data catalogue is shown in Figure 4. The left-hand panel shows the recorded  
225 number of microbursts in each  $L$ -value range, which is in agreement with previously published  
226 results [Millan and Thorne, Fig. 5(b), 2007]. The right-hand panel shows the  $L$ -variation in the  
227 HILT reported BLC microburst intensities, in terms of the median increase in flux relative to the  
228 background. The dotted line shows the absolute flux increase with units of  $\log_{10}(\text{electrons cm}^{-2}\text{s}^{-1}\text{str}^{-1})$ , while the solid line shows the relative flux increase. A typical BLC microburst event  
229 observed in this study had a median  $>1.05$  MeV flux of  $\sim 400$  el.  $\text{cm}^{-2}\text{s}^{-1}\text{str}^{-1}$ , and was ten times  
230 larger than the background flux. Note that the mean flux increases are considerably larger, due to  
231 the very wide distribution of intensities. For example, the relative mean flux increase is 45 times  
232 above background for our BLC microburst events.

## 234 5. Microburst Characteristics

235 To investigate the link between FAST events and REP microbursts, the BLC microbursts  
236 catalogued in this study were compared with the occurrence times of all SGO FAST events in  
237 our study period. For two events to be considered as coincident in time, the peak perturbations of  
238 the events must be separated by less than the average microburst duration, which we found to be  
239  $<0.29$  s. The percentage of temporal overlap of the two perturbations is not used as a criterion for  
240 determining coincident occurrence because the rise and fall of a FAST event appears to be  
241 determined by ionospheric conditions and can be partially masked by multiple FAST events

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242 occurring in a short time period. From a total of 219 BLC microbursts and 829 SGO FAST  
243 events, only two microbursts were found to be coincident with a FAST event, leading to a  
244 coincidence rate of ~1%.

245 Periods of SAMPEX microbursts and SGO FAST events were also compared to look for event  
246 “patterns”; to test if there was a time offset in the SAMPEX data set and to see if any groups of  
247 events appeared to be coincident in time if the time-axis was moved linearly. This effect was not  
248 seen. The drift loss cone microbursts catalogued were also tested to search for any one-to-one  
249 time correlations with FAST events, but none were found.

## 250 **5.1 Microburst size**

251 To determine the spatial extent of an individual microburst, two point measurements of the  
252 same microburst are needed. These two point measurements must be coincident in time and  
253 would ideally be separated by  $\leq 10$  km, the previous SAMPEX-derived estimate for the  
254 horizontal extent of a single REP microburst [Blake *et. al.*, 1996]. If the SAMPEX size estimate  
255 is correct, two measurements that are coincident in time but separated by a greater distance will  
256 not detect the same microburst, but could give some insight into the maximum possible  
257 microburst size. Hence, points coincident in time but separated by a distance of up to 20 km will  
258 be considered in this study.

259 In order to obtain two spatially close, temporally coincident point measurements for our study,  
260 SAMPEX must be reporting microbursts while passing over a monitored VLF transmission path,  
261 during a period in which FAST events are observed. Of the five FAST periods identified in our  
262 study, only one SAMPEX pass was found to meet these conditions. At ~3 UT on 5 April 2005,  
263 microbursts were detected while SAMPEX was viewing only the BLC on fieldlines which map  
264 to the atmosphere over the VLF transmitter-receiver path from ICV to SGO, as shown in Figure  
265 5. The green crosses in Figure 5 are the field line traced positions of the 24 BLC microbursts that

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266 SAMPEX detected while it travelled north-east, crossing over the VLF transmission path  
267 (marked in black) and passing near the SGO receiver (marked by a red diamond). Thirteen of  
268 these 24 BLC microbursts were detected when SAMPEX was  $\leq 20$  km from the ICV path, hence  
269 these 13 fall within our criteria for "closeness". The two closest BLC microbursts occur at  
270 distances of 4.2 km and 4.3 km away from the path from ICV to SGO. However, no FAST  
271 events are observed at SGO coincident with these two microbursts, or for any of the other 11 of  
272 this set. The SGO observations of transmissions from ICV for this time period are shown in the  
273 upper panel of Figure 6. Vertical thin lines mark the times of the first ten SAMPEX observed  
274 BLC microbursts for this time period. Clearly, no coincident FAST events are seen at these  
275 times. To provide context, the lower panel of this Figure presents examples of FAST events on  
276 this transmitter signal, which occurred approximately one hour earlier. The ten microbursts  
277 shown in the upper panel of Figure 6 have a median flux of  $\sim 3900$  el.  $\text{cm}^{-2} \text{s}^{-1} \text{str}^{-1}$ , a value  $\sim 10$   
278 times greater than that found in Section 4. Even though the fluxes of these microbursts greatly  
279 exceed the typical flux we have identified, no coincident FAST events were seen. One  
280 interpretation of the lack of coincidence between BLC microbursts and FAST events in this case  
281 is that individual microbursts have radii  $< 4$  km; this estimate assumes that microbursts are  
282 roughly circular and each one is approximately the same spatial size. Our estimate is consistent  
283 with the *Blake et al.* [1996] suggestion of a diameter of  $< 10$  km, but at this point we have not  
284 been able to "catch a raindrop".

285 During our analysis we also identified SAMPEX BLC microbursts that occurred on 19 January  
286 2005, as SAMPEX was passing above western Iceland. The eastern part of Iceland hosts the US  
287 Navy VLF transmitter NRK, which is monitored at SGO and at the AARDDVARK receiver in  
288 Ny Ålesund, Svalbard ( $79^\circ$  N,  $11^\circ$  E,  $L=18.3$ ). While the NRK observations at SGO showed  
289 FAST events, those from Ny Ålesund did not, with no coincident BLC microbursts and SGO

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290 FAST events. This strongly suggests that the precipitation needs to occur close to the receiver to  
291 produce a detectable FAST event, as otherwise FAST events should have been seen in the data  
292 from both AARDDVARK stations. In this case SAMPEX reported BLC microbursts over  
293 Iceland and FAST events were reported by SGO. Given that these two points are roughly  $50^\circ$  in  
294 longitude apart, it appears that the size of the rainstorm which produces microbursts may be very  
295 large. We consider this in more detail in the next section.

## 296 **5.2 Storm size**

297 If the storm size, the spatial extent of the magnetospheric process that is causing microbursts,  
298 is to be determined, a minimum of two point measurements are again needed. Detection of  
299 microbursts occurring at similar times while being spatially separated by  $>10$  km, would help to  
300 determine the minimum size of a “microburst storm”. Here we assume that FAST events are  
301 indeed relativistic electron microbursts, while we acknowledge that so far, we have been unable  
302 to “catch a raindrop”. In this way we can attempt to measure the size of the storm driving  
303 microburst production.

304 At about 14:20 UT on 8 May 2005 SAMPEX moved into the North Atlantic region in which it  
305 views only the BLC. During this period, SGO had been reporting FAST events and, as expected,  
306 SAMPEX detected a series of relativistic BLC microbursts as it passed from about  $L=4$  to  $L=6$ .  
307 The SAMPEX events occurred while the satellite was passing over the mouth of the Gulf of  
308 Saint Lawrence in eastern Canada. The simultaneous observation of REP precipitation at  
309 SAMPEX's location and SGO suggests either two widely separated storms or one single large  
310 storm spanning  $94^\circ$  in longitude from the easternmost microburst position to SGO, stretching  
311 across 5,061 km and spanning  $\sim 6$ -12 MLT. Further support for the existence of a single storm  
312 region comes from precipitation observed on 19 January 2005. During  $\sim 1$ -6 UT SAMPEX  
313 detected BLC microbursts over the North East coast of North America and also in the North

314 Atlantic. Across this time period SGO also observed FAST event activity. The fieldline traced  
315 locations of these microbursts are shown in Figure 7 as green circles, superimposed upon the  
316 orbital track for which SAMPEX is observing only the BLC (smaller blue circles). The position  
317 of SGO is shown by a red diamond. Here a single storm system of a minimum of  $\sim 90^\circ$  in  
318 longitude again spanning a minimum of  $\sim 6$  MLT seems most likely. Note that this is consistent  
319 with earlier SAMPEX studies which established that relativistic microbursts are most common  
320 from  $\sim 6$ -12 MLT [Millan and Thorne, Fig. 5(b), 2007], and suggests that such large storm sizes  
321 may well be typical. The MLT range and extent in which SAMPEX detects microbursts is quite  
322 similar to that reported for chorus whistler-mode waves [Meredith *et al.*, 2003], particularly for  
323 off-equatorial locations where wave-particle interactions with relativistic electrons are possible  
324 [Bortnik *et al.*, 2007].

325 We are currently unable to test if a storm can be any wider, due to the fixed receiver placement  
326 at SGO and due to the restricted longitude range in which SAMPEX detects only BLC  
327 microbursts (as shown in Figure 3). In addition, we do not currently have another receiver in the  
328 AARDDVARK network in the correct longitude and  $L$ -range, although a new deployment is  
329 expected in western Canada in October 2010 which should allow expanded microburst storm  
330 viewing.

## 331 **6. Discussion**

332 Earlier work reported that FAST events detected by AARDDVARK subionospheric VLF have  
333 a one-to-one correlation of  $\sim 1$ -2% when observed across multiple VLF signals [Rodger *et al.*,  
334 2007]. This very low one-to-one correlation appears to support a small scale size of  $\leq 4$  km for an  
335 individual relativistic electron microburst and also suggests that the precipitation is occurring in  
336 a “rainstorm”. There are some uncertainties concerning this interpretation, however. Previous  
337 studies have demonstrated how spatially small, highly conductive regions (produced by many

338 order of magnitude increases in D-region ionization levels) can produce high-levels of scattering  
339 of subionospheric VLF transmissions [e.g., *Rodger et al.*, 1999, 2003]. One example of this  
340 situation is the VLF perturbations produced by red sprites. In these cases, the ionization change  
341 can be located well off the transmitter-receiver great circle path and still lead to a significant  
342 VLF perturbation [*Hardman et al.*, 1998]. Extreme cases of VLF perturbations caused by  
343 ionization changes occurring “behind” the receiver have been reported [*Dowden et al.*, 1996]. As  
344 such, one might expect that the spatially small ionization changes produced by relativistic  
345 electron microbursts would lead to FAST events irrespective of whether they are very close to  
346 the transmitter-receiver great circle path or somewhere close to the receiver. In these cases, wide-  
347 angle scattering would cause a single ionization change located within a few 100 km of the  
348 receiver to produce coincident VLF perturbations on multiple transmitter paths. Clearly,  
349 however, this is not observed in our current study. One possible reason for this is that the  
350 expected maximum D-region electron density change calculated for a reasonable representation  
351 of a typical relativistic electron microburst of  $100 \text{ el. cm}^{-2} \text{ s}^{-1} \text{ str}^{-1}$  [*Rodger et al.*, Fig. 5, 2007] is  
352 an increase of  $\sim 20\text{-}40$  times, while red sprites produce 4-6 order of magnitude electron density  
353 increases [e.g., *Rodger and Nunn*, 1999; *Nunn and Rodger*, 1999; *Armstrong et al.*, 2000], in  
354 comparison with the ambient night-time ionosphere. This suggests that a typical relativistic  
355 electron microburst is likely to be too small to lead to significant wide-angle VLF scattering.

356 During each 24 minute pass through the outer radiation belt, SAMPEX travels from  $L=4$  to  
357  $L=6$ , the region where the majority of microbursts occur, in just 1 minute 45 s. In contrast, the  
358 SGO receiver has a fixed position it can potentially detect FAST events at any time. This shows  
359 up the challenge in directly comparing ground-based and satellite observations of short lived  
360 events occurring only during major geomagnetic storms. However, we can use the results shown  
361 in Table 2 to estimate an occurrence rate for FAST events and BLC microbursts, and thus

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362 compare the two data sets more closely. During the 5 event periods FAST events are typically  
363 observed at a rate of  $\sim 0.6 \text{ min}^{-1}$ , while the BLC microbursts are observed at a typical rate of  
364  $\sim 8 \text{ min}^{-1}$ . These estimates suggest that only  $\sim 8\%$  of BLC microbursts are observable as FAST  
365 events in the subionospheric data. This might suggest that FAST event signatures are generated  
366 by the  $\sim 10\%$  of microbursts which have the largest precipitation flux, although the lack of any  
367 clear one-to-one linkage makes this suggestion quite speculative. In addition, based on the  
368 occurrence rates and event duration, one would expect FAST and BLC microbursts to agree in  
369 time by chance  $\sim 4\%$  of the time. Given that the observed rate of co-incidence between FAST  
370 events and BLC microbursts determined earlier in this study was  $\sim 1\%$ , it is likely that this  
371 coincidence rate is due to chance, rather than direct agreement. Thus it is not clear that we have  
372 the simultaneous observation of the same relativistic precipitation bursts from SAMPEX and  
373 SGO, even though both datasets indicate relativistic precipitation bursts are occurring during a  
374 given time window.

375 Although the rate of occurrence of FAST events is low in comparison with BLC microbursts,  
376 the SGO data does provide some additional information regarding the time variation of  
377 relativistic precipitation, which is difficult to determine from low-Earth orbit satellite data alone.  
378 Figure 8 is an example of the type of information that ground-based observations of relativistic  
379 precipitation detected through FAST events can provide. The plot shows FAST events on the  
380 transmitter NDK received at SGO from 17-22 UT on 21 January 2005. Vertical dashed lines  
381 indicate the times of large solar wind pressure pulses [e.g., *Cilverd et al.*, 2007]. Two periods  
382 labeled "S" represent the times of SAMPEX observations in the BLC over the  $L=3-8$  range. As  
383 can be seen from the plot, FAST events occur following the times of the pressure pulses, with  
384 only low levels of occurrence between the two shock events. During this storm period  
385 SAMPEX's orbit was such that it was unable to observe most of the time variation in the

386 relativistic microburst activity that was occurring. Clearly, continuous ground-based  
387 observations can provide additional insight into the conditions required for microburst  
388 generation.

389 There is currently a satellite mission in its planning stages, which aims to determine the spatial  
390 extent and energy dependence of relativistic and non-relativistic electron microbursts. This  
391 project is the Focused Investigations of Relativistic Electron Burst Intensity, Range, and  
392 Dynamics (FIREBIRD) [Moretto, 2009] mission, to be launched in early 2012. A pair of  
393 satellites will be launched together, each carrying a solid-state detector with a large geometric  
394 factor measuring 30 keV-3 MeV electrons. The two FIREBIRD satellites will gradually drift  
395 apart over the course of the mission, reaching a separation of  $\sim 300$  km [Moretto, 2009]. The  
396 FIREBIRD mission will provide a two-point microburst detection system, and as such will be a  
397 further opportunity for two-point measurements of relativistic microbursts, following on from the  
398 recent ground based work. Combining the FIREBIRD observations with additional ground-based  
399 measurements may provide additional clarity to the storm size measurements.

## 400 **7. Conclusions and Summary**

401 We have attempted to show that FAST events detected in subionospheric VLF observations  
402 are caused by relativistic electron microbursts, through a comparison with SAMPEX detected  
403 relativistic electron precipitation occurring during FAST event periods. We have also attempted  
404 to demonstrate the spatial extent of a single microburst raindrop and the size of an entire  
405 microburst storm.

406 By building upon previous research into the nature of FAST events, it appears that FAST  
407 events are indeed caused by relativistic electron microburst precipitation. In this study we have  
408 shown that only strong geomagnetic disturbances can produce FAST events, consistent with the

409 strong  $D_{st}$  link between storms and relativistic microbursts and we have shown that SAMPEX  
410 detects relativistic microbursts during the identified FAST event periods. In addition, the  
411 dependence of observed FAST event perturbation decay times on ionospheric conditions is also  
412 consistent with the subionospheric perturbations being caused by short lived bursts of relativistic  
413 electron precipitation.

414 However, this study suggests that only the strongest (i.e., highest flux) microbursts might  
415 produce an observable FAST event, such that there is little direct agreement between individual  
416 microbursts and FAST events. The one-to-one correlation in time between microbursts and  
417 AARDDVARK FAST events is very low ( $\sim 1\%$ ), and occurs most likely by chance rather than a  
418 direct detection. In the one case where SAMPEX flew along a transmitter-receiver path, none of  
419 the BLC microbursts reported by SAMPEX corresponded in time to FAST events. One  
420 interpretation of this is that the individual microbursts have radii  $< 4$  km, which is consistent with  
421 earlier satellite-based findings. Our study strongly suggests that the magnetospheric process  
422 which generates relativistic microbursts is vastly larger than the individual bursts. Two examples  
423 are provided where the storm stretches  $\sim 90^\circ$  in longitude and  $\sim 6$  hours in MLT. This is  
424 particularly important given that *Lorentzen et al.* [2001b] used a  $\sim 6$  MLT estimate of microburst  
425 storm size when showing that relativistic electron microbursts could flush out the entire radiation  
426 belt relativistic electron population in less than a day. Our findings support this previous work,  
427 which concluded that REP microbursts could be a highly significant loss mechanism for  
428 relativistic electrons during geomagnetic storms.

429

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#### 434 **References**

435 Armstrong, R.A., D. M. Suszcynsky, W. A. Lyons, T. Nelson, (2000). Multi-Color Photometric  
436 Measurements of Ionization and Energies in Sprites, *Geophys. Res. Lett.*, 27, 653-656.

437  
438 Baker, D. N., R. W. Klebesadel, P. R. Higbie, and J. B. Blake (1986), Highly relativistic  
439 electrons in the Earth's outer magnetosphere, 1. Lifetimes and temporal history 1979-1984, *J.*  
440 *Geophys. Res.*, 91, 4265-4276.

441  
442 Baker, D. N., J. B. Blake, J. D. Gorney, and P. R. Higbie (1987), Highly relativistic  
443 magnetospheric electrons: a role in coupling to the middle atmosphere?, *Geophys. Res. Lett.*,  
444 14, 1027.

445  
446 Blake, J. B., M. D. Looper, D. N. Baker, R. Nakamura, B. Klecker, and D. Hovestadt (1996),  
447 New high temporal and spatial resolution measurements by SAMPEX of the precipitation of  
448 relativistic electrons, *Adv. Space Res.*, 18(8), 171-186.

449  
450 Bortnik, J., and R. M. Thorne (2007), The dual role of ELF/VLF chorus waves in the  
451 acceleration and precipitation of radiation belt electrons, *J. Atmos. Sol. Terr. Phys.*, 69, 378-  
452 368.

453  
454 Bortnik, J., R. M. Thorne, and N. P. Meredith (2007), Modeling the propagation characteristics  
455 of chorus using CRRES suprathermal electron fluxes, *J. Geophys. Res.*, 112, A08204,  
456 doi:10.1029/2006JA012237.

457  
458 Callis, L. B., D. N. Baker, J. B. Blake, J. D. Lambeth, R. E. Bouhner, M. Natarajan, R. W.  
459 Klebesadel, and D. J. Gorney (1991), Precipitating relativistic electrons: their long term effect  
460 on stratospheric odd nitrogen levels. *J. Geophys. Res.*, 96, 2939.

461  
462 Clilverd, M. A., C. J. Rodger, and T. Ulich (2006), The importance of atmospheric precipitation  
463 in storm-time relativistic electron flux drop outs, *Geophys. Res. Lett.*, 33, L01102,  
464 doi:10.1029/2005GL024661.

465  
466 Clilverd M. A., C. J. Rodger, R. M. Millan, J. G. Sample, M. Kokorowski, M. P. McCarthy, T.  
467 Ulich, T. Raita, A. J. Kavanagh, E. Spanswick (2007), Energetic particle precipitation into the  
468 middle atmosphere triggered by a coronal mass ejection, *J. Geophys. Res.*, 112, A12206,  
469 doi:10.1029/2007JA012395.

470  
471 Clilverd, M. A., C. J. Rodger, N. R. Thomson, J. B. Brundell, Th. Ulich, J. Lichtenberger, N.  
472 Cobbett, A. B. Collier, F. W. Menk, A. Seppälä, P. T. Verronen, and E. Turunen (2009),  
473 Remote sensing space weather events: the AARDDVARK network, *Space Weather*, 7,  
474 S04001, doi: doi:10.1029/2008SW000412.

- 475  
476 Clilverd, M. A., A. Seppälä, C. J. Rodger, M. G. Mlynczak, and J. U. Kozyra (2009b),  
477 Additional stratospheric NO<sub>x</sub> production by relativistic electron precipitation during the 2004  
478 spring NO<sub>x</sub> descent event, *J. Geophys. Res.*, 114, A04305, doi:10.1029/2008JA013472.  
479
- 480 Hardman, S. F., R. L. Dowden, J. B. Brundell, J. L. Bähr, Z. I. Kawasaki, and C. J. Rodger  
481 (2000), Sprite observations in the Northern Territory of Australia, *J. Geophys. Res.*, 105(D4),  
482 4689-4697.  
483
- 484 Imhof, W. L., H. D. Voss, J. Mabilia, D. W. Datlowe, E. E. Gaines, J. P. McGlennon, and U. S.  
485 Inan (1992), Relativistic Electron Microbursts, *J. Geophys. Res.*, 97(A9), 13, 829–13, 837.  
486
- 487 Klecker, B., D. Hovestadt, M. Scholer, H. Arbing, M. Ertl, H. Kästle, E. Küneth, P.  
488 Laeverenz, E. Seidenschwang, J. B. Blake, N. Katz, and D. Marby, (1993), HILT: a Heavy Ion  
489 Large area proportional counter Telescope for solar and anomalous cosmic rays, *IEEE Trans.*  
490 *Geosci. Remote Sens.*, 31(3), 542–548, doi:10.1109/36.225520.  
491
- 492 Li, X., D. N. Baker, M. Temerin, T. E. Cayton, E. G. D. Reeves, R. A. Christensen, J. B. Blake,  
493 M. D. Looper, R. Nakamura, and S. G. Kanekal (1997), Multisatellite observations of the outer  
494 zone electron variation during the November 3-4, 1993, magnetic storm, *J. Geophys. Res.*,  
495 102, 14,123-14,140.  
496
- 497 Lorentzen, K. R., J. B. Blake, U. S. Inan, and J. Bortnik (2001a), Observations of relativistic  
498 electron microbursts in association with VLF chorus, *J. Geophys. Res.*, 106, 6017-6027,  
499 doi:10.1029/2000JA003018.  
500
- 501 Lorentzen, K. R., M. D. Looper, and J. B. Blake (2001b), Relativistic electron microbursts  
502 during the GEM storms, *Geophys. Res. Lett.*, 28(13) 2573–2576.  
503
- 504 Meredith, N. P., R. B. Horne, R. M. Thorne, and R. R. Anderson, Favored regions for chorus-  
505 driven electron acceleration to relativistic energies in the Earth's outer radiation belt, *Geophys.*  
506 *Res. Lett.*, 30(16), 1871, doi:10.1029/2003GL017698, 2003.  
507
- 508 Millan, R. M. and R. M. Thorne (2007), Review of radiation belt relativistic electron losses, *J.*  
509 *Atmos. Sol. Terr. Phys.*, 69, 362-377.  
510
- 511 Moretto, T. (2009). Update on the NSF Cubesat Program. *The CEDAR Post*, 56:3-4.  
512
- 513 Nakamura, R., K. Kamei, and Y. Kamide (1998), SAMPEX observations of storm-associated  
514 electron flux variations in the outer radiation belt. *J. Geophys. Res.*, 103(A11) 26,261–26,269.  
515
- 516 Nakamura, R., M. Isowa, Y. Kamide, D. N. Baker, J. B. Blake, and M. Looper (2000), SAMPEX  
517 observations of precipitation bursts in the outer radiation belt, *J. Geophys. Res.*, 103(A7),  
518 15,875-15,885.  
519
- 520 Nunn, D., and C. J. Rodger, 1999, Modeling the relaxation of red sprite plasma, *Geophysical*  
521 *Research Letters*, 26, 3293-3296.  
522

- 523 O'Brien, T. P., M. D. Looper, and J. B. Blake (2004), Quantification of relativistic electron  
524 microburst losses during the GEM storms, *Geophys. Res. Lett.*, 31, L04802,  
525 doi:10.1029/2003GL018621.  
526
- 527 O'Brien, T. P., K. R. Lorentzen, I. R. Mann, N. P. Meredith, J. B. Blake, J. F. Fennell, M. D.  
528 Looper, D. K. Milling, and R. R. Anderson (2003), Energization of relativistic electrons in the  
529 presence of ULF power and MeV microbursts: Evidence for dual ULF and VLF acceleration,  
530 *J. Geophys. Res.*, 108(A8), 1329, doi:10.1029/2002JA009784.  
531
- 532 Onsager, T. G., G. Rostoker, H.-J. Kim, G. D. Reeves, T. Obara, H. J. Singer, and C. Smithtro,  
533 Radiation belt electron flux dropouts: Local time, radial, and particle-energy dependence, *J.*  
534 *Geophys. Res.*, 107(A11), 1382, doi:10.1029/2001JA000187, 2002.  
535
- 536 Reeves, G. D., K. L. McAdams, R. H. W. Friedel, and T. P. O'Brien (2003), Acceleration and  
537 loss of relativistic electrons during geomagnetic storms, *Geophys. Res. Lett.*, 30(10), 1529,  
538 doi:10.1029/2002GL016513.  
539
- 540 Rodger, C.J., and D. Nunn (1999), VLF scattering from red sprites: Application of numerical  
541 modelling. *Radio Sci.*, 34, 923-932.  
542
- 543 Rodger, C. J. (1999), Red Sprites, Upward Lightning, and VLF Perturbations, *Rev. Geophys.*,  
544 37(3), 317-336.  
545
- 546 Rodger, C. J. (2003), Subionospheric VLF perturbations associated with lightning discharges, *J.*  
547 *Atmos. Sol. Terr. Phys.*, 65(5), 591-606.  
548
- 549 Rodger, C. J., M. A. Clilverd, D. Nunn, P. Verronen, J. Bortnik, and E. Turunen (2007), Storm  
550 time, short-lived bursts of relativistic electron precipitation detected by subionospheric radio  
551 wave propagation, *J. Geophys. Res.*, 112, A07301, doi:10.1029/2007JA012347.  
552
- 553 Rodger, C. J., M. A. Clilverd, J. Green, and M.-M. Lam (2010), Use of POES SEM-2  
554 observations to examine radiation belt dynamics and energetic electron precipitation in to the  
555 atmosphere, *J. Geophys. Res.*, 115, A04202, doi: 10.1029/2008JA014023.  
556
- 557 Thorne, R. M., T. P. O'Brien, Y. Y. Shprits, D. Summers, and R. B. Horne (2005), Timescale for  
558 MeV electron microburst loss during geomagnetic storms, *J. Geophys. Res.*, 110, A09202,  
559 doi:10.1029/2004JA010882.  
560
- 561 Tsyganenko, N. A. (1989), Determination of magnetospheric current system parameters and  
562 development of experimental geomagnetic models based on data from IMP and HEOS  
563 satellites, *Planet. Space Sci.*, 37:5-20.  
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575 Tables

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<b>Date</b>	<b>Day/Night</b>	<b>Occurrence (UT)</b>	<b>SPE Flux (pfu)</b>	<b>Decay time (s)</b>	<b><math>K_P</math></b>	<b><math>D_{st}</math> (nT)</b>
19 Jan 2005	Night	01:16-06:14	190	1.04	6.7	-75
21 Jan 2005	Night	17:12-19:50	374	0.8	8.0	-99
4-5 April 2005	Night	20:50-02:30	0.5	1.2	7.0	-79
8 May 2005	Day	12:55-15:16	0.1	0.84	8.3	-109
15 May 2005	Day	02:36-09:08	3790	0.63	8.3	-262

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577 **Table 1.** Properties of the five FAST periods found from a survey of SGO AARDDVARK  
 578 observations across December 2004-June 2005. A GOES pfu = proton flux unit = >10 MeV  
 579 protons  $\text{cm}^{-2} \text{str}^{-1} \text{s}^{-1}$ .

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<b>2005</b>	<b><i>Kp</i></b>	<b>FAST events</b>	<b>Microbursts</b>	<b>BLC microbursts</b>
19 <sup>th</sup> January	6.7	103	84	55
21 <sup>st</sup> January	8.0	271	29	2
4 <sup>th</sup> -5 <sup>th</sup> April	7.0	349	412	102
8 <sup>th</sup> May	8.3	17	287	60
15 <sup>th</sup> May	8.3	89	43	0

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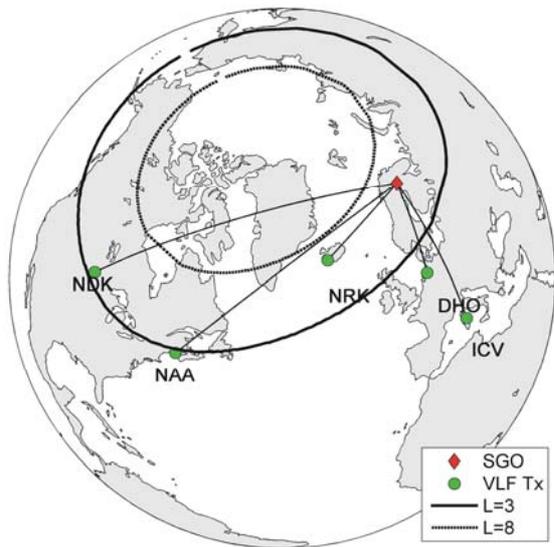
589 **Table 2.** SAMPEX microburst occurrence numbers for the five FAST periods occurring from  
 590 December 2004-June 2005, as identified in this study.

591

592 **Figures**

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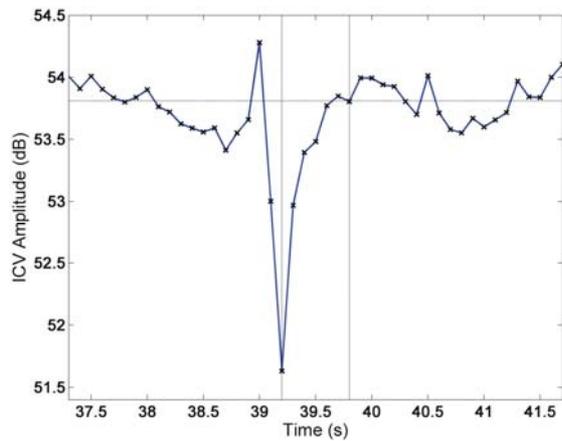


595

596 **Figure 1.** Map of the transmission paths of the five VLF signals that were used in this study.  
597 During the December 2004 – July 2005 period the AARDDVARK SGO receiver, indicated by  
598 a red diamond, was recording signals from the five transmitters that are marked by green  
599 circles. The  $L=3-8$  range across which SAMPEX typically detects REP activity is enclosed  
600 between the two ellipses.

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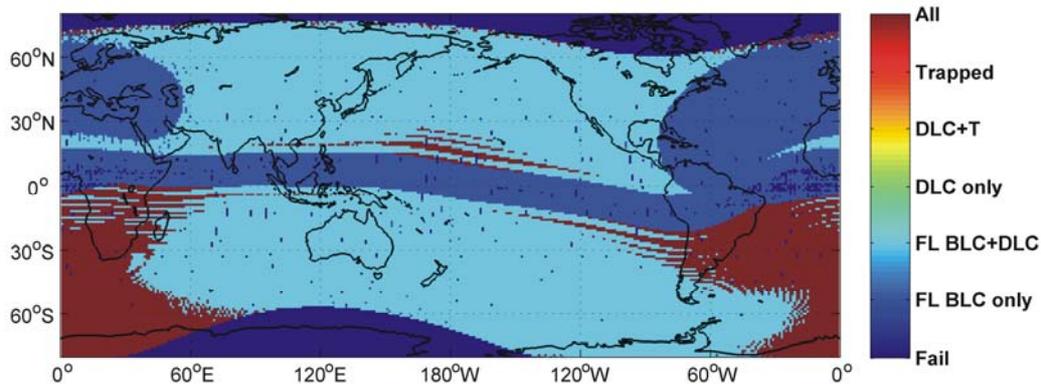


603

604 **Figure 2.** An example of a typical FAST event detected in SGO observations of ICV on 15  
605 May, 2005. Here the time is given in seconds from 05:58:00 UT. The first dashed vertical line  
606 at 39.2 s indicates the start of the ionisation decay, while the second vertical line at 39.8 s  
607 marks the perturbations end, where the amplitude has returned to the background level.

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609



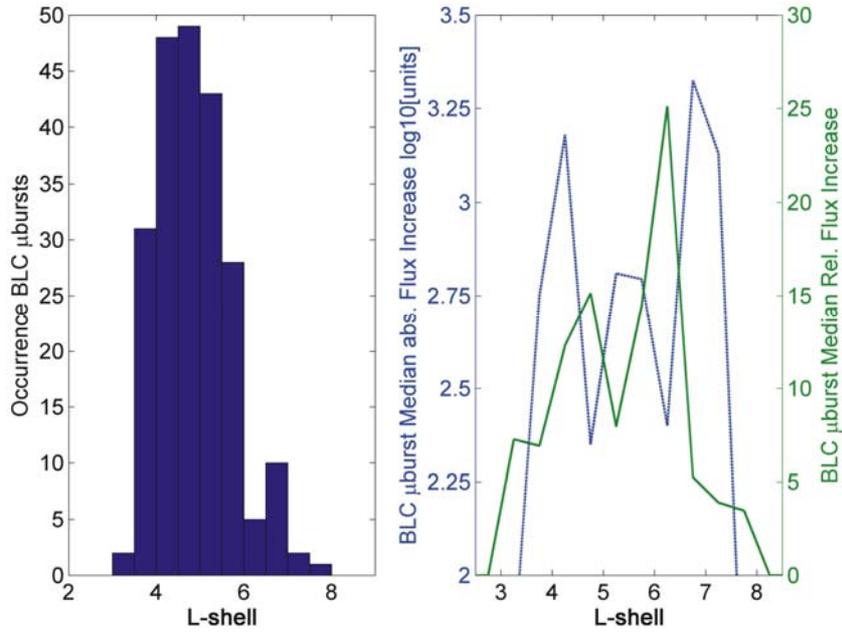
610

611 **Figure 3.** World map showing the changing radiation belt population observed by SAMPEX's  
612 HILT instrument. Here T indicates trapped flux, DLC is drift-loss cone, and FL BLC is field  
613 line bounce loss cone. For most locations where there is a significant radiation belt flux, it  
614 observes a mix of DLC and FL BLC populations.

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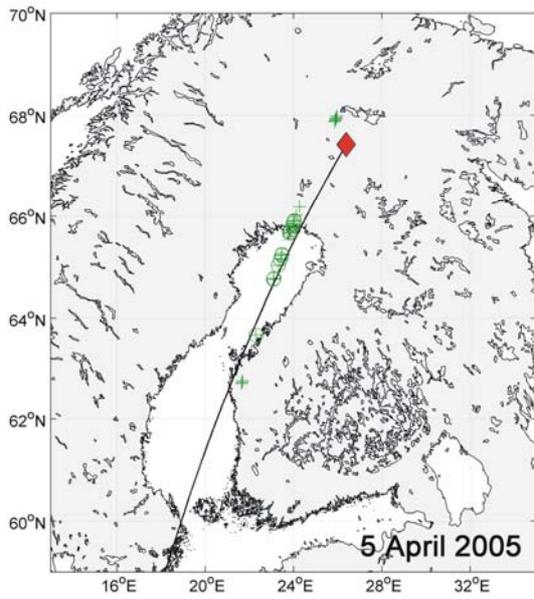
619 **Figure 4.** Occurrence of SAMPEX observed BLC microbursts examined in this study. The  
 620 variation in  $L$  is shown in the left-hand panel, while the right-hand panel presents the median  
 621 intensity of the microbursts observed. The dotted line shows the absolute flux increase with  
 622 units of  $\log_{10}(\text{electrons cm}^{-2}\text{s}^{-1}\text{str}^{-1})$ , while the solid line shows the relative flux increase.

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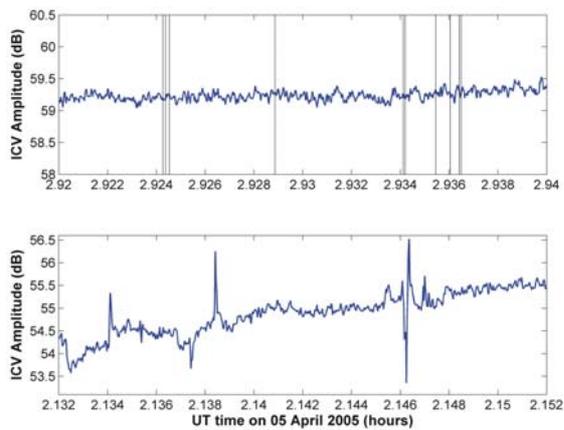
626

627 **Figure 5.** Map of the region around SGO in Finland (red diamond), showing a section of the  
628 ICV transmission path in black. The green crosses mark the positions of the SAMPEX satellite  
629 when it was detecting microbursts during 5 April 2005. The circled crosses are those within  
630 20 km of the transmitter-receiver path.

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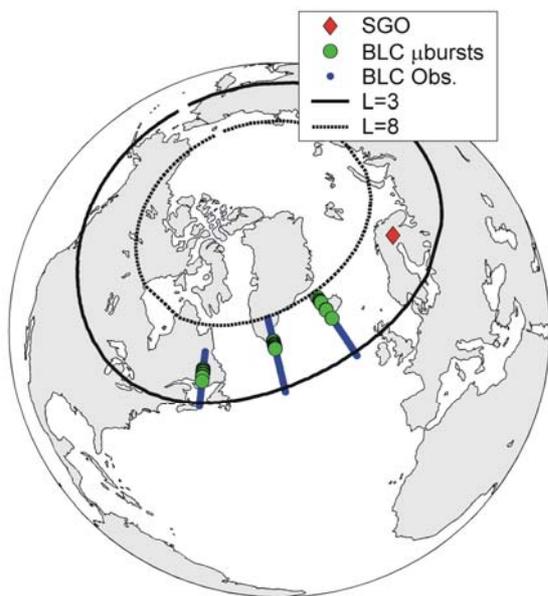
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635 **Figure 6.** The upper panel presents the amplitude of the VLF signal from ICV received at  
636 SGO during the SAMPEX observations shown in Figure 5. Vertical lines in the upper panel  
637 indicate the occurrence of the ten BLC microbursts that were shown as the southern-most green  
638 crosses in Figure 5. Examples of FAST events from the ICV channel are shown in the lower  
639 panel.

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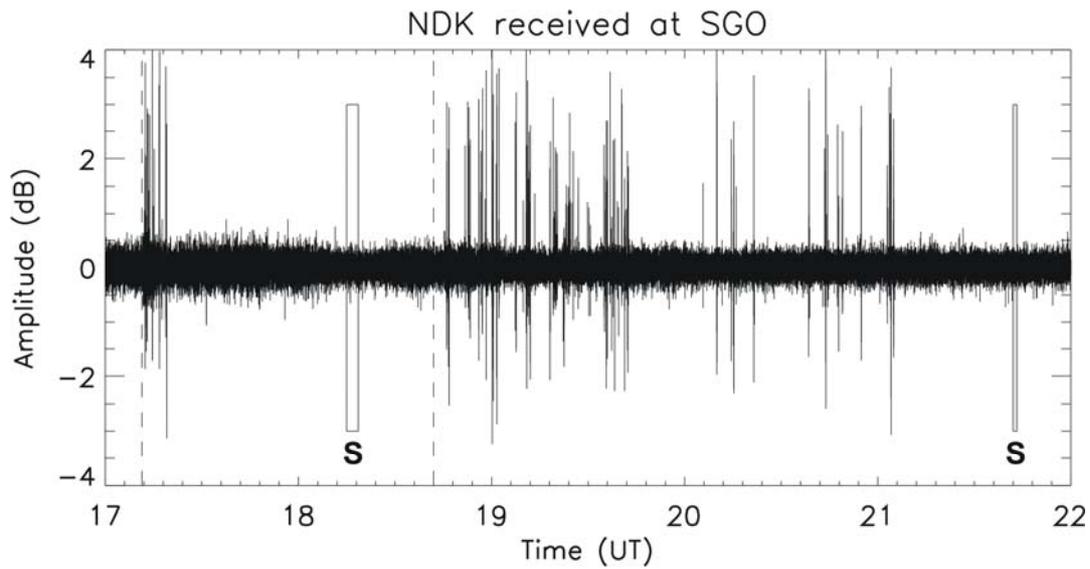
642 **Figure 7.** Locations of SAMPEX detected bounce loss cone microbursts (green circles) on 19  
643 January 2005 which occurred in the time period FAST events were detected at SGO (red  
644 diamond).

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650 **Figure 8.** Observations of FAST events observed on transmissions from N. Dakota (NDK) at  
651 Sodankylä (SGO) on 21 January 2005. The two vertical dashed lines at 17.2 UT and 18.7 UT  
652 indicate the times of two solar wind pressure pulses. The two periods labeled "S" represent the  
653 times of SAMPEX observations in the BLC over the  $L=3-8$  range.

654