

# Pitch Angle Isotropy of Relativistic Electron Microbursts as Observed by SAMPEX/HILT: Statistical and Storm-time Properties

Conrad Meyer-Reed<sup>1,2</sup>, Lauren Blum<sup>1,2</sup>, Mykhaylo Shumko<sup>3</sup>

<sup>1</sup>University of Colorado Boulder

<sup>2</sup>Laboratory for Atmospheric and Space Physics

<sup>3</sup>NASA Goddard Space Flight Center

AGU will probably make you add the state  
and country to the affiliations.

## Key Points:

- Low flux magnitude microbursts have varying isotropy and high flux magnitude microbursts have consistently high isotropy.
- Microburst isotropy relative to background events is highest in the evening magnetic local time region and lowest in the noon region.
- During intense geomagnetic storms, microburst isotropy relative to background events is highest in the initial phase and lowest in the recovery phase.



## Abstract

Observations of relativistic electron precipitation events from Earth's inner magnetosphere to the upper atmosphere have provided essential information about the source/loss processes and dynamics of Earth's radiation belts. Equatorial electron pitch angle isotropy is a known indicator of electron precipitation into the atmosphere, with isotropic populations resulting in a full bounce loss cone (BLC) and anisotropic populations resulting in an empty BLC. ~~This study discusses~~ electron microbursts, which are ~100 millisecond duration streams of relativistic electrons that are thought to be scattered into the BLC ~~by means of a resonant interaction between electrons and plasma waves in the magnetosphere.~~ By measuring ~~electron flux differentials across~~ the four detector rows composing the Heavy Ion Large Telescope (HILT) instrument onboard the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) satellite, we ~~have developed a qualitative measurement of~~ electron pitch angle isotropy. ~~Applying this calculation to microburst events, we have determined the dependence of~~ microburst pitch angle isotropy ~~on~~ flux magnitude, MLT, and L-Shell. Additionally, we conduct a storm-time analysis of microburst pitch angle isotropy using ground-based measurements of geomagnetic storm activity. ~~Results from this study have shown~~ that high flux magnitude microbursts typically scatter electron pitch angles into the BLC more than low flux magnitude microbursts. ~~This study has also found that~~ microbursts are more isotropic than the background population in the morning, evening, and midnight local times and more similar in anisotropy to the background population in the noon local times. Furthermore, the results of this study show that microbursts are most effective at scattering electron pitch angles during the initial and main phases of intense geomagnetic storms.

## Plain Language Summary

Understanding the fundamental mechanisms that drive electron loss from Earth's radiation belts is essential for the success of various human operations. During geomagnetically active periods, increased electron fluxes can damage orbiting satellites, cause GPS signal errors, and black out ground-based power grids. When electrons resonate with plasma waves in the magnetosphere, sub-second bursts of electrons are generated. These loss mechanisms, called microbursts, often cause electrons previously trapped in the radiation belts to stream into the atmosphere. Although past studies have quantified total microburst-induced electron loss for given time periods, assumptions were made regarding how directly electrons were scattered into the atmosphere. This study uses differential electron count rates across the detector rows of the HILT instrument onboard the SAMPEX satellite to develop a qualitative measurement of the degree to which individual microbursts scatter electrons parallel to the local magnetic field lines. By applying this measurement, called the isotropy index, to past calculations of electron loss, a more accurate electron loss rate associated with microbursts can be determined. Furthermore, the spatial and storm-time dependence of the microburst isotropy index is detailed in the results section.

## 1 Introduction

Electron precipitation  is widely known as an essential loss process from the Earth's radiation belts into the upper atmosphere. While there have been many recent studies on the space weather phenomena that cause electron precipitation, characteristics of electron microbursts are still relatively unknown. ~~First observed in 1964 (Anderson & Milton, 1964),~~  microbursts have been found to occur primarily in the 2-10 magnetic local time (MLT) region and in the 3-8 L-Shell range (Douma et al., 2017). Microburst events are sub-second enhancements of energetic electrons observed in the high latitude regions of the inner magnetosphere. It is well established that microbursts are the results of pitch

angle scattering mechanisms which fill the bounce loss cone (BLC) and cause electrons to precipitate into the upper atmosphere.

In general, microbursts are associated with whistler mode chorus wave activity in the morning MLT region (Lorentzen, Blake, et al., 2001)(O'Brien et al., 2003)(Mozer et al., 2018). It has previously been theorized that microbursts are generated when electrons resonate with plasma waves in the magnetosphere, and recent models studying particle-wave physics have shown that it is possible for microbursts to be generated from resonant interactions between chorus plasma waves and relativistic electrons (Saito et al., 2012). Douma et al. (2017) have suggested that EMIC plasma waves may also play a role in microburst generation in the 13-22 MLT region. Meredith et al. (2014) have found that most EMIC waves occur in the 4-7 L-Shell range, and Usanova et al. (2012) suggest that EMIC waves driven by solar wind compression at the initial onset of moderate geomagnetic storms likely occur at  $>6$  L-Shell values. Although there have been links between microburst occurrence and EMIC wave activity, stronger correlations between microburst occurrence and VLF wave amplitude and frequency point to chorus waves as the primary source of microbursts (Douma et al., 2018).

Geomagnetic storm activity is thought to be the underlying cause of plasma wave-induced microburst activity, although there is still debate regarding when peak electron loss rates occur. Blum et al. (2015) used a superposed epoch analysis of multiple geomagnetic storms to show an increase in microburst flux magnitude and occurrence at the initial onset of storms. More recently, Douma et al. (2019) have found that microburst flux magnitude increases with increasing AE index intensity. While some studies show that microburst loss rates peak in the main phase of geomagnetic storms (O'Brien et al., 2004), others indicate that peaks in microburst flux magnitude and associated electron loss rates occur in the recovery phase (Lorentzen, Looper, & Blake, 2001).

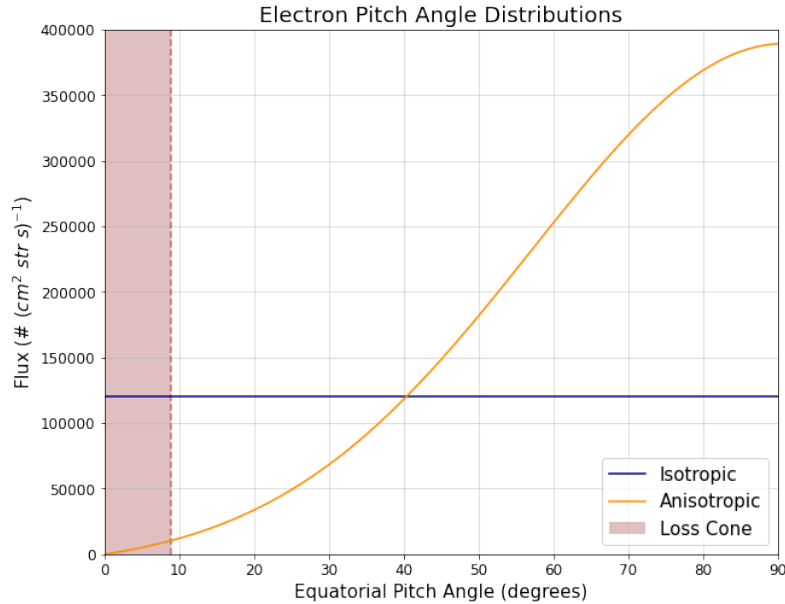
Recently, the first pitch angle dependent energy spectra and electron precipitation rates associated with microbursts were measured by the **ELFIN** satellite. Using this data, Zhang et al. (2022) and Tsai et al. (2022) found evidence for non-linear wave-particle resonance caused by ducted plasma waves at low latitudes. In previous studies, microburst associated electron loss rates have been estimated; however, the pitch angle distributions were assumed to be fully isotropic (Lorentzen, Looper, & Blake, 2001). Although these results have provided essential information regarding global electron loss rates from the radiation belts, an electron population pitch angle isotropy value could be applied to calculations of total loss rates to increase accuracy. Blake et al. (1996) discusses the potential for theoretical isotropy measurements using differential electron count rates from the HILT instrument onboard the SAMPEX satellite. In this study, we expand on the discussion in Blake et al. (1996) to calculate a qualitative isotropy index value. With this isotropy index, we then calculate the isotropy of microbursts occurring throughout the year 1993 and analyze the spatial, temporal, and flux magnitude dependencies of microburst pitch angle isotropy in the Earth's radiation belts.

## 2 HILT Observations

The SAMPEX satellite, originally launched from Lompoc, CA on July 3, 1992, was designed to detect energetic electrons and ions in Earth's radiation belts. The spacecraft orbited in a near-polar low Earth orbit (LEO) at an altitude of  $\sim 500$ -700km (Baker et al., 1993).

The HILT instrument, onboard the SAMPEX satellite, was composed of a  $4 \times 4$  array of  $10\text{cm}^2$  solid-state SiLi detectors which were grouped into four rows of four detectors. Each detector row recorded  $>1\text{MeV}$  electron counts at a time resolution of 100ms. The field of view constrained by the instrument aperture was 68 degrees by 68 degrees (Blake et al., 1996)(Mason et al., 1998).

The view of each individual detector row was slightly different from the other rows due to the geometry of the detector array, which caused each row to measure slightly different electron counts based on the distribution of electron pitch angles. Electron populations in the radiation belts can range from highly isotropic to highly anisotropic pitch angle distributions. Isotropic distributions are populations of electrons with evenly scattered pitch angles. In an isotropic distribution, there is an equal amount of perpendicular pitch angles and parallel pitch angles. Anisotropic distributions are populations of electrons with unevenly scattered pitch angles. Typically, anisotropic distributions in the radiation belts are composed mostly of perpendicular pitch angles and very few parallel pitch angles. The range of equatorial pitch angles that result in precipitation within one bounce is called the bounce loss cone (BLC), which typically ranges from 0 degrees to an upper limit of  $\sim 10$  degrees depending on the altitude and energy of the electron population. Generally, in isotropic distributions the BLC is full and in anisotropic distributions the BLC is less full. Since electron precipitation occurs when the BLC is full of electrons with parallel pitch angles, high isotropy distributions result in more direct electron precipitation into the upper atmosphere. Conversely, low isotropy distributions result in less electron precipitation. Example pitch angle distributions are shown in Figure 3.



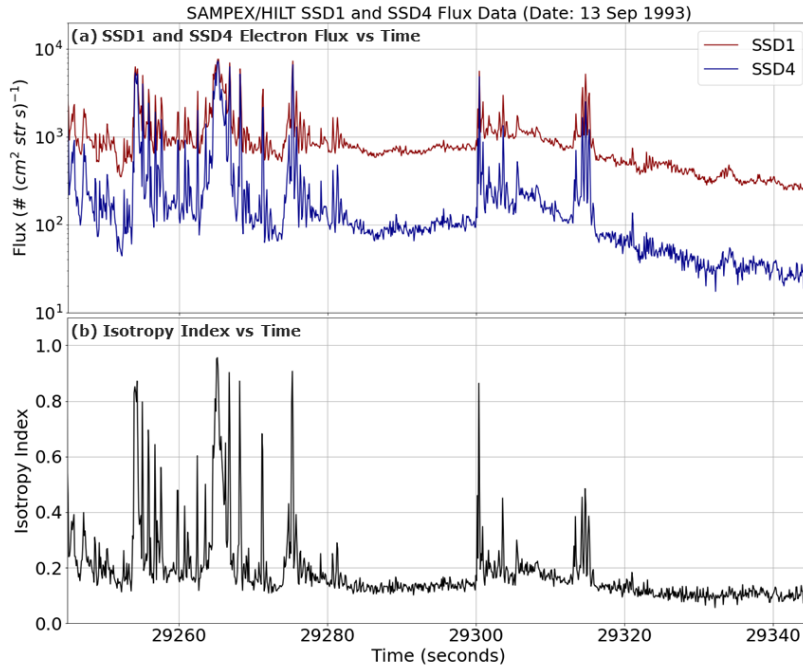
**Figure 1.** Example isotropic (blue) and anisotropic (orange) electron pitch angle distributions found in the inner magnetosphere. The BLC is indicated by the red shaded region. As shown above, the isotropic distribution fills the BLC while the anisotropic distribution is populated by pitch angles larger than those within the BLC region.

When the angle between the HILT boresight and the local magnetic field line is in the middle range between parallel and perpendicular, the geometry of the HILT detector array allows for a qualitative measurement of pitch angle isotropy for an electron population. Most microbursts were observed while the boresight was pitched less than 40 degrees relative to the local magnetic field line. Furthermore, at angles of less than 40 degrees, the boresight of the instrument is always within the BLC. Due to this, the 40 degree filter was applied to all data in the following sections. If all HILT detector rows count the same number of energetic electrons, the electron distribution is isotropic. If there is a large differential in counts across the detector rows, the electron distribution

is anisotropic. By taking the ratio of electron counts between solid-state detector row 1 (SSD1) and solid-state detector row 4 (SSD4), the isotropy index is calculated as shown in Equation (1):

$$I = N_{100,min}/N_{100,max} \quad (1)$$

Where  $I$  is the isotropy index (on a 0 to 1 scale),  $N_{100}$  is the number of electrons in 100ms,  $N_{100,min}$  is the  $N_{100}$  value from the detector row with lower counts, and  $N_{100,max}$  is the  $N_{100}$  value from the detector with higher counts. In this context, an  $I$  value approaching 0 indicates a highly anisotropic population and an  $I$  value approaching 1 indicates a highly isotropic population. To visualize the significance of the isotropy index, plots of SSD1 flux, SSD4 flux, and isotropy index versus time are shown in Figure 2. Microburst events are observed as rapid spikes in SSD1 and SSD4 flux. Note that during microburst events the two row fluxes spike up to relatively equal levels (more isotropic) and during quiet times the two row fluxes return to consistent but unequal values (less isotropic). Throughout this study, we will compare pitch angle isotropy during microbursts with pitch angle isotropy during non-microburst times, which will be referred to as the background population.



**Figure 2.** a) Electron flux from SSD1 (red) and SSD4 (blue) rows vs time. b) Isotropy index vs time. Rapid increases in row flux rates indicate when microbursts occur, and flat row flux rates indicate when microbursts are not occurring (referred to as the background population). During microburst events, isotropy index spikes close to 1 then returns to low values of  $\sim 0.1$  during quiet times.

To begin the analysis of the correlation between microburst events and increased pitch angle isotropy, we used a microburst detection algorithm developed by O'Brien et al. (2003):

$$(N_{100} - A_{500})/\sqrt{1 + A_{500}} > 10 \quad (2)$$

Where  $N_{100}$  is the number of electrons in 100ms and  $A_{500}$  is the centered rolling average of  $N_{100}$  over a 500ms time interval. This algorithm effectively detects rapid enhancements of electrons by measuring how much the electron count rates deviate from a rolling average. ~~For our analysis of microburst flux magnitude, we applied the microburst flux magnitude formula used in Blum et al. (2015):~~

$$M = N_{100} - B_{3000} \quad (3)$$

Where  $M$  is the microburst flux magnitude and  $B_{3000}$  is the centered rolling 10th percentile of  $N_{100}$  over a 3-second time interval. This provides the relative intensity of the microburst above the background flux levels.

### 3 Results

To determine the spatial and temporal dependence of microburst isotropy in the inner magnetosphere, the study was conducted in two parts. ~~In Section 3.1, correlations between microburst isotropy, magnitude, MLT, and L-shell over the year 1993 were observed. In Section 3.2, a superposed epoch analysis of the variation of microburst isotropy with respect to storm phases was conducted for 6 intense geomagnetic storms that fit a typical Dst profile.~~

#### 3.1 Statistical Study

First we explore the dependence of microburst isotropy on microburst intensity by plotting microburst isotropy with respect to microburst flux magnitude. A 2-dimensional histogram of this trend is plotted in Figure 3.

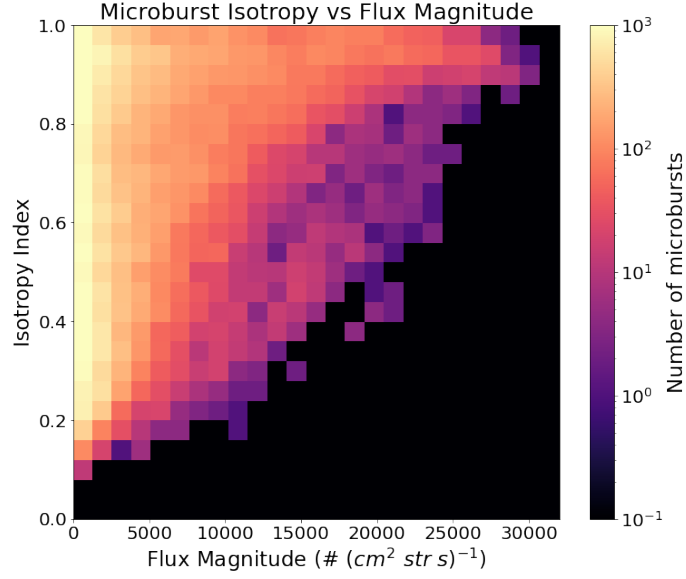
With isotropy index plotted on the y-axis and flux magnitude plotted on the x-axis, the colorbar indicates the number of microbursts observed at each respective isotropy-magnitude coordinate. ~~Due to the exponential decay of microburst counts as magnitude increases, the colorbar was scaled logarithmically.~~

~~Results from this analysis show that for low flux magnitudes there is a wide spread in microburst isotropy index ranging from 0.1 to 1. As magnitude increases towards the upper limit of  $\sim 30,000$  electrons  $(\text{cm}^2 \text{ str s})^{-1}$ , only high isotropy microbursts are observed. This would indicate that high flux magnitude microbursts result in significant electron precipitation into the atmosphere and low magnitude microbursts have varying degrees of impact on electron precipitation.~~

~~To analyze the spatial dependence of microburst isotropy within the radiation belts, occurrence distributions and isotropy values vs MLT-L were plotted in Figure 4.~~

Panels a) and b) are dial plots of microburst occurrence and background sampling rates throughout the year 1993. As shown previously, microbursts most often occur in the morning magnetic local time region (which these results agree with). The background sampling distribution shows good coverage of MLT and L-Shell values throughout the orbit of the SAMPEX spacecraft during the time period used in this study.

Panels c) and d) are dial plots of the median microburst and background isotropy index for each respective MLT-L bin. To eliminate any orbit effects, we compare relative isotropy of microbursts with the background population. By taking the difference between plots c) and d), the microburst isotropy relative to the background population ~~is examined, which~~ is plotted in Figure 5.



**Figure 3.** 2D histogram of microburst isotropy index vs microburst flux magnitude using data from the year 1993. Due to the logarithmic scaling of the colorbar, any zero value pixel was altered to a  $10^{-1}$  value to plot correctly in the figure. At low flux magnitudes, microbursts are observed at a wide range of isotropy indices. At high flux magnitudes, microbursts are observed to be highly isotropic.

From Figure 5, it can be determined that the largest difference in isotropy occurs in the evening magnetic local time region and the lowest difference occurs at noon. It is important to note that the peak isotropy difference in the evening MLT regions is due to the high microburst isotropy index values seen in Figure 4c. This indicates that, although microbursts are most frequent in the morning MLT region, individual microbursts are on average more isotropic in the evening.

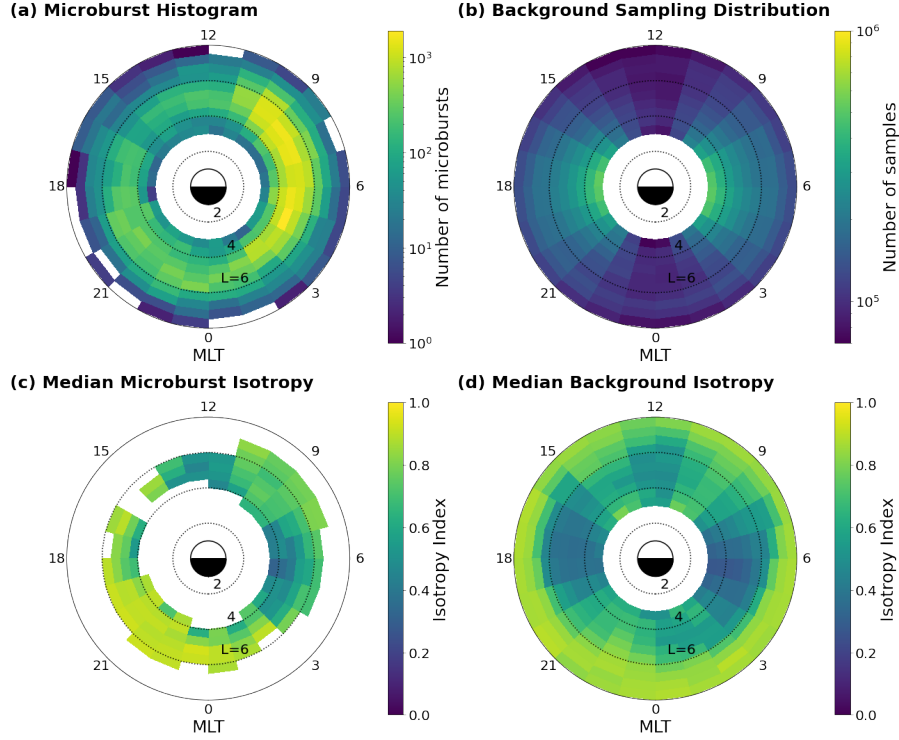
### 3.2 Storm-time Analysis

To analyze the storm-time dependence of microburst isotropy, we use the Disturbance Storm-time (Dst) index to define geomagnetic storm phases. The Dst index is a ground-based data set which measures the hourly disturbance of the global ring current at equatorial latitudes. By recording the Dst fluctuations during geomagnetic storms, the relative strength and time evolution of individual storms can be determined.

Out of 9 intense storms in the year 1993 with  $Dst_{min} < -100\text{nT}$  we removed 3 storms with atypical profiles, including multiple main phases. Table 1 details the start and end dates in addition to MLT-sampling and Dst profile information for the 6 selected storms. Due to the near-polar orbit of the spacecraft, SAMPEX primarily sampled MLT values on opposite sides of the earth for each individual storm (ie. 12 and 24 MLT). Figure 6 shows Dst index vs time throughout the duration of each storm.

Generally, geomagnetic storms are separated into three distinct phases: initial phase, main phase, and recovery phase. The initial phase of a geomagnetic storm is defined as the region from the initial increase in Dst index to the maximum Dst index. The main phase is defined as the region of time from when the Dst is at a local maximum to when it is at a local minimum during the storm. The recovery phase is defined as the region





**Figure 4.** a) Dial plot (histogram) of microburst occurrence; b) Dial plot (histogram) of the background sampling distribution; c) Dial plot of median microburst isotropy; d) Dial plot of median background isotropy. All panels use data from the year 1993 and are plotted as a function of MLT and L-Shell.

**Table 1.** List of intense geomagnetic storms selected from 1993

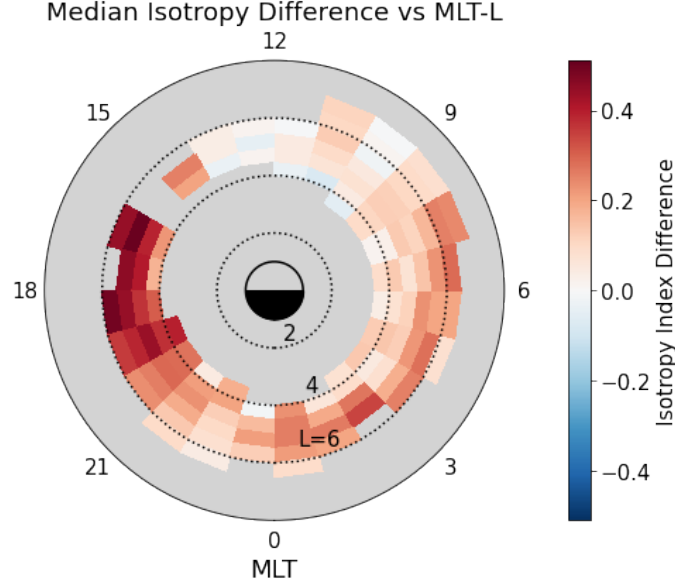
Time of $Dst_{min}$	Event Start	Event End	Notes
Feb 17, UT 14	Feb 16	Feb 23	MLT: 12-24; $Dst_{min}$ : -103 nT
Mar 09, UT 06	Mar 08	Mar 11	MLT: 09-21; $Dst_{min}$ : -145 nT
Mar 11, UT 18	Mar 11	Mar 13	MLT: 08-20; $Dst_{min}$ : -124 nT
Apr 05, UT 06	Apr 03	Apr 10	MLT: 05-17; $Dst_{min}$ : -191 nT
Sep 13, UT 06	Sep 11	Sep 18	MLT: 07-19; $Dst_{min}$ : -189 nT
Nov 04, UT 06	Nov 02	Nov 09	MLT: 12-24; $Dst_{min}$ : -127 nT

of time after the Dst minimum in which the Dst index slowly recovers and returns to values near 0 nT.

To analyze how microburst isotropy varies with storm phase, we used the above criteria to determine the storm phase boundaries during each individual storm and binned isotropy measurements by storm phase. A superposed epoch study was then conducted by taking the median isotropy index of all microbursts and background for each of the three storm phases, which can be observed in Figure 7.

Similarly to Section 3.1, by taking the difference between plots (a) and (b), the storm-time dependence of microburst isotropy relative to the background population can be determined in plot c). While the median background isotropy remains fairly even throughout initial and main phases, the median microburst isotropy changes to lower values dur-





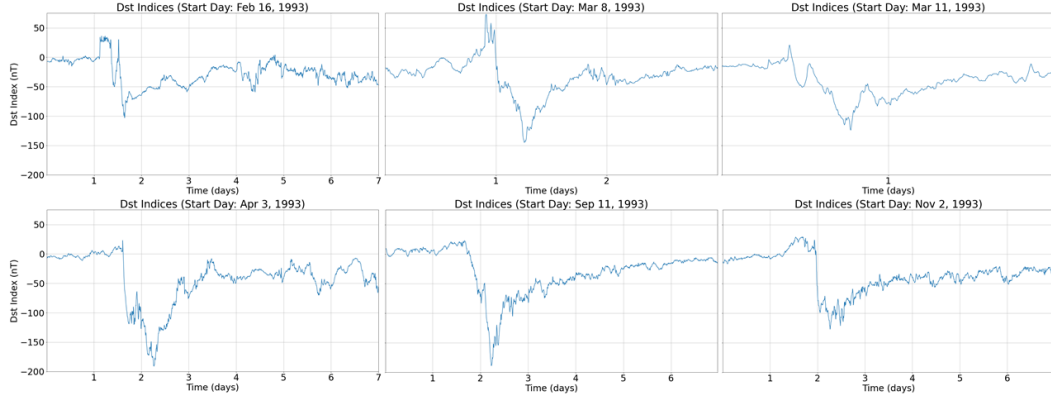
**Figure 5.** Dial plot of the difference in isotropy index between microbursts and the background population as a function of MLT and L-Shell in the year 1993. Red regions indicate where microbursts are more isotropic than the background population, white regions indicate zero difference, and blue regions indicate where microbursts are less isotropic than the background population.

ing the recovery phase. Results of this epoch study indicate that microburst isotropy relative to the background population is highest at the initial onset of intense geomagnetic storms, remains relatively constant through the main phase, and drops ~~substantially~~ as storms progress into the recovery phase.

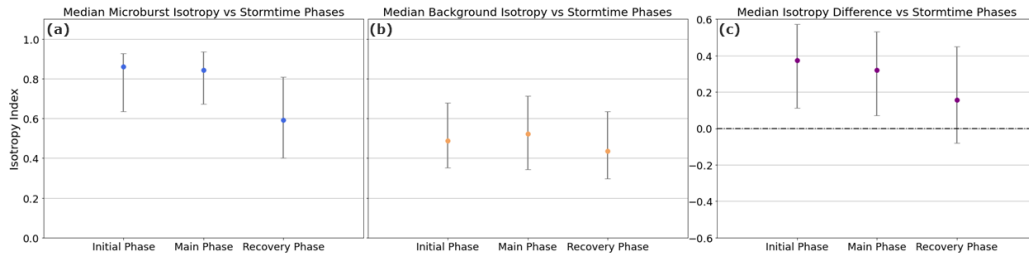
## 4 Discussion

In the context of previous electron precipitation research, this study provides information that will allow for a more accurate calculation of electron loss rates into the upper atmosphere. In Section 3.1, we have shown that the microburst isotropy index is positively correlated with microburst flux magnitude. Based on the theory that isotropic microbursts fill the BLC and therefore increase electron precipitation, this indicates that more intense microbursts also result in more precipitation. Although past papers have found correlations between microburst flux magnitude and geomagnetic activity, this is the first result showing a positive correlation between microburst isotropy and microburst flux magnitude. This finding provides the potential for future studies to more accurately quantify the effects of individual microbursts with specific flux magnitudes. In previous studies, full isotropy was assumed to calculate electron loss rates. Now, pitch angle isotropy can be considered using this isotropy-magnitude trend.

Results from Section 3.1 also suggest that the electron pitch angle diffusion of microbursts generated in the evening MLT region may be more effective than in other MLT regions. For example, in Figure 5 it is apparent that microbursts occurring in the 4-6 L-shell and 16-20 MLT region are more isotropic relative to the background population compared to morning-side microbursts. This indicates that for individual microburst events in the evening MLT region, electron ~~pitch angles~~ are more effectively scattered into the BLC. EMIC wave activity is known to occur in the noon and evening MLT regions, which



**Figure 6.** Dst profiles of the 6 storms selected for analysis



**Figure 7.** Dst storm-time analysis: a) plot of median microburst isotropy vs storm-time phases; b) plot of median background isotropy vs storm-time phases; c) plot of median isotropy difference vs storm-time phases. Upper limit and lower limit error bars indicate 25th and 75th percentiles, respectively.

could indicate that these more isotropic microbursts may be caused by EMIC waves rather than chorus waves (more often observed on the morning side). While the general consensus is that chorus waves are much closer linked to microburst activity, our results indicate that the rare cases of EMIC wave driven microbursts found by Douma et al. (2018) may be more isotropic than microbursts generated by chorus wave activity. Further studies must be conducted to establish a more substantial link between microburst isotropy and the wave mode producing microbursts in different MLT regions.

In Section 3.2, we found that the microburst isotropy index was highest in the initial and main phases and dropped during the recovery phase of intense geomagnetic storms. Based on the assumption that all microbursts are fully isotropic, Lorentzen, Looper, and Blake (2001) have found that microbursts are higher in flux magnitude and cause more precipitation in the recovery phase and the results from O’Brien et al. (2004) imply that electron loss due to microbursts peaks in the main phase. Now that we have developed an isotropy index for individual microbursts, this could be applied to the calculations from past papers to mitigate errors based on previously necessary assumptions. Past papers studying peak electron loss rates have been focused on various types of geomagnetic storms, so a replication of this study focused on small or moderate geomagnetic storms may be required.

Lastly, it is important to note that microbursts were found to be more isotropic than the background population in each section of the study. While this was expected, it supports the fundamental idea that microburst events in the Earth’s magnetosphere

contribute to electron precipitation by means of a rapid pitch angle scattering mechanism that fills the BLC (Zhang et al., 2022). These findings also reveal that, while microbursts are generally more isotropic than the background, there is a great deal of variability in isotropy between individual microbursts. By finding a qualitative measurement of microburst pitch angle isotropy, we have developed a new tool for understanding when and where microbursts most effectively fill the BLC and impact electron loss rates from the radiation belts.

## 5 Summary

In this study, we use a combination of SAMPEX/HILT electron measurements and ground-based Dst index measurements from the year 1993 to characterize pitch angle distributions of MeV-energy electrons. In the first part of Section 3.1, we compared microburst isotropy index with microburst flux magnitude. In the second part of Section 3.1, we looked at the variation of microburst and background isotropy versus MLT and L-Shell. In Section 3.2, we looked at the storm-time dependence of microburst and background isotropy during intense geomagnetic storms. Our results can be summarized by the following points:

1. Microburst isotropy is strongly correlated with microburst flux magnitude. At low microburst magnitudes, the isotropy index was widely varying; spanning from values of 0.1 to 1 isotropy index. At high microburst magnitudes, the microburst isotropy index converged on the upper limit of 1.
2. Similar to previous studies, we found that microbursts were most frequent in the morning MLT region. The microburst isotropy index compared to the background population was highest in the evening magnetic local time region and lowest in the noon region.
3. Microburst isotropy compared to the background population was found to be highest in the initial and main phases of geomagnetic storms and lowest in the recovery phase. This result suggests that microbursts more effectively scatter electrons into the BLC during the initial onset and main phase of intense geomagnetic storms.
4. Throughout the study, microburst isotropy was higher than the background isotropy. This finding supports the theory that microburst events act as rapid pitch angle scattering mechanisms that fill the BLC causing increased electron precipitation.

## References

- Anderson, K. A., & Milton, D. W. (1964, November). Balloon Observations of X Rays in the Auroral Zone, 3, High Time Resolution Studies. , *69*(21), 4457-4479. doi: 10.1029/JZ069i021p04457
- Baker, D. N., Mason, G. M., Figueroa, O., Colon, G., Watzin, J. G., & Aleman, R. M. (1993, May). An overview of the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX) mission. *IEEE Transactions on Geoscience and Remote Sensing*, *31*(3), 531-541. doi: 10.1109/36.225519
- Blake, J. B., Looper, M. D., Baker, D. N., Nakamura, R., Klecker, B., & Hovestadt, D. (1996, January). New high temporal and spatial resolution measurements by SAMPEX of the precipitation of relativistic electrons. *Advances in Space Research*, *18*(8), 171-186.
- Blum, L., Li, X., & Denton, M. (2015, May). Rapid MeV electron precipitation as observed by SAMPEX/HILT during high-speed stream-driven storms. *Journal of Geophysical Research (Space Physics)*, *120*(5), 3783-3794. doi: 10.1002/2014JA020633
- Douma, E., Rodger, C. J., Blum, L. W., & Clilverd, M. A. (2017, August). Occurrence characteristics of relativistic electron microbursts from SAMPEX

- observations. *Journal of Geophysical Research (Space Physics)*, 122(8), 8096-8107. doi: 10.1002/2017JA024067
- Douma, E., Rodger, C. J., Blum, L. W., O'Brien, T. P., Clilverd, M. A., & Blake, J. B. (2019, July). Characteristics of Relativistic Microburst Intensity From SAMPEX Observations. *Journal of Geophysical Research (Space Physics)*, 124(7), 5627-5640. doi: 10.1029/2019JA026757
- Douma, E., Rodger, C. J., Clilverd, M. A., Hendry, A. T., Engebretson, M. J., & Lessard, M. R. (2018, February). Comparison of Relativistic Microburst Activity Seen by SAMPEX With Ground-Based Wave Measurements at Halley, Antarctica. *Journal of Geophysical Research (Space Physics)*, 123(2), 1279-1294. doi: 10.1002/2017JA024754
- Lorentzen, K. R., Blake, J. B., Inan, U. S., & Bortnik, J. (2001, April). Observations of relativistic electron microbursts in association with VLF chorus. , 106(A4), 6017-6028. doi: 10.1029/2000JA003018
- Lorentzen, K. R., Looper, M. D., & Blake, J. B. (2001, January). Relativistic electron microbursts during the GEM storms. , 28(13), 2573-2576. doi: 10.1029/2001GL012926
- Mason, G. M., Baker, D. N., Blake, J. B., Boughner, R. E., Callis, L. B., Cummings, A. C., ... Williams, D. L. (1998, January). SAMPEX: NASA's first small explorer satellite. In *1998 ieee aerospace conference, vol. 5* (Vol. 5, p. 389-412).
- Meredith, N. P., Horne, R. B., Kersten, T., Fraser, B. J., & Grew, R. S. (2014, July). Global morphology and spectral properties of EMIC waves derived from CRRES observations. *Journal of Geophysical Research (Space Physics)*, 119(7), 5328-5342. doi: 10.1002/2014JA020064
- Mozer, F. S., Agapitov, O. V., Blake, J. B., & Vasko, I. Y. (2018, January). Simultaneous Observations of Lower Band Chorus Emissions at the Equator and Microburst Precipitating Electrons in the Ionosphere. , 45(2), 511-516. doi: 10.1002/2017GL076120
- O'Brien, T. P., Looper, M. D., & Blake, J. B. (2004, February). Quantification of relativistic electron microburst losses during the GEM storms. , 31(4), L04802. doi: 10.1029/2003GL018621
- O'Brien, T. P., Lorentzen, K. R., Mann, I. R., Meredith, N. P., Blake, J. B., Fennell, J. F., ... Anderson, R. R. (2003, August). Energization of relativistic electrons in the presence of ULF power and MeV microbursts: Evidence for dual ULF and VLF acceleration. *Journal of Geophysical Research (Space Physics)*, 108(A8), 1329. doi: 10.1029/2002JA009784
- Saito, S., Miyoshi, Y., & Seki, K. (2012, October). Relativistic electron microbursts associated with whistler chorus rising tone elements: GEMSIS-RBW simulations. *Journal of Geophysical Research (Space Physics)*, 117(A10), A10206. doi: 10.1029/2012JA018020
- Tsai, E., Artemyev, A., Zhang, X.-J., & Angelopoulos, V. (2022). Relativistic electron precipitation driven by nonlinear resonance with whistler-mode waves. *Journal of Geophysical Research: Space Physics*, 127(5), e2022JA030338. doi: <https://doi.org/10.1029/2022JA030338>
- Usanova, M. E., Mann, I. R., Bortnik, J., Shao, L., & Angelopoulos, V. (2012, October). THEMIS observations of electromagnetic ion cyclotron wave occurrence: Dependence on AE, SYMH, and solar wind dynamic pressure. *Journal of Geophysical Research (Space Physics)*, 117(A10), A10218. doi: 10.1029/2012JA018049
- Zhang, X.-J., Angelopoulos, V., Mourenas, D., Artemyev, A., Tsai, E., & Wilkins, C. (2022). Characteristics of electron microburst precipitation based on high-resolution elfin measurements. *Journal of Geophysical Research: Space Physics*, 127(5), e2022JA030509. doi: <https://doi.org/10.1029/2022JA030509>