

# Microburst Scale Size Derived from Multiple Bounces of a Microburst Simultaneously Observed with the FIREBIRD-II CubeSats

Mykhaylo Shumko<sup>1</sup>, John Sample<sup>1</sup>, Arlo Johnson<sup>1</sup>, Bern Blake<sup>2</sup>, Alex Crew<sup>3</sup>, Harlan  
Spence<sup>4</sup>, David Klumpar<sup>1</sup>, Oleksiy Agapitov<sup>5</sup>, Matthew Handley<sup>6</sup>

<sup>1</sup>Department of Physics, Montana State University, Bozeman, Montana, USA

<sup>2</sup>Space Science Applications Laboratory, The Aerospace Corporation, Los Angeles, California, USA

<sup>3</sup>The Johns Hopkins University Applied Physics Laboratory LLC, Laurel, Maryland, USA

<sup>4</sup>Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, New Hampshire, USA

<sup>5</sup>Space Sciences Laboratory, UC Berkeley, Berkeley, California, USA

<sup>6</sup>Los Alamos National Laboratory, Los Alamos, New Mexico, USA

## Key Points:

- The lower bound lat/lon scale sizes of the microburst at LEO were  $28.8 \pm 0.8$  km and  $50.8 \pm 11.4$  km, respectively.
- Deduced lower bound equatorial scale size was similar to the whistler-mode chorus source scale.

## Abstract

We present the first observation of a spatially large microburst with multiple bounces simultaneously made by the FIREBIRD-II CubeSats on February 2nd, 2015. This is the first such microburst simultaneously observed by two spacecraft, and we estimated its lower bound spatial scale sizes and bounce periods. Its lower bound latitudinal scale size was  $28.8 \pm 0.8$  km and the longitudinal scale size was  $50.8 \pm 11.4$  km in low earth orbit. We mapped these scale sizes to the magnetic equator and found that the radial and azimuthal scale sizes were at least  $504 \pm 14$  km and  $530 \pm 119$  km, respectively. These lower bound equatorial scale sizes are similar to whistler-mode chorus wave source scale sizes, which supports the hypothesis that microbursts are a product of electron scattering by chorus waves. Lastly, we estimated the bounce periods for 200-800 keV electrons and found good agreement with four common magnetic field models.

## 1 Introduction

The dynamics of radiation belt electrons are complex, and are driven by competition between source and loss processes. A few possible loss processes are radial diffusion [Shprits and Thorne, 2004], magnetopause shadowing [Ukhorskiy et al., 2006], and pitch angle and energy diffusion due to scattering of electrons by plasma waves [e.g. Abel and Thorne, 1998; Summers et al., 1998; Meredith et al., 2002; Selesnick et al., 2003; Horne and Thorne, 2003; Thorne et al., 2005]. There are a variety of waves that cause pitch angle scattering, including electromagnetic ion cyclotron waves, plasmaspheric hiss, and chorus [Millan and Thorne, 2007; Thorne, 2010]. Chorus predominantly occurs in the dawn sector (6-12 magnetic local times (MLT)) [Li et al., 2009] where it accelerates electrons with large equatorial pitch angles and scatters electrons with small equatorial pitch angles [Horne and Thorne, 2003]. Some of these electrons may be impulsively scattered into the loss cone, where they result in short-duration ( $\sim 100$  ms) enhancements in precipitating flux called microbursts.

Anderson and Milton [1964] coined the term microburst to describe high altitude balloon observations of  $\sim 100$  ms enhancements of bremsstrahlung X-rays emitted from scattered microburst electrons impacting the atmosphere. Since then, non-relativistic microbursts have been routinely observed with other balloon missions [Parks, 1967; Woodger et al., 2015; Anderson et al., 2017]. Relativistic microbursts have not yet been observed by high altitude balloons in the dawn sector with the following evidence. Millan et al. [2002] and Woodger et al. [2015] discuss balloon observations of longer-duration relativistic duskside precipitation and non-relativistic microbursts, but do not provide any observational evidence of relativistic microbursts in their balloon data. This lack of observation may be explained by relatively weaker pitch angle scattering of relativistic electrons by chorus [Lee et al., 2012]. Both relativistic and non-relativistic microbursts have been directly observed in low earth orbit (LEO) with, e.g. the SAMPEX  $> 150$  keV and  $> 1$  MeV channels [Nakamura et al., 1995, 2000; Blake et al., 1996; Lorentzen et al., 2001a,b; O'Brien et al., 2003, 2004; Blum et al., 2015] and FIREBIRD-II with its  $> 200$  keV energy channels [Crew et al., 2016; Anderson et al., 2017; Breneman et al., 2017]. To characterize the source of microbursts, Lorentzen et al. [2001b] found that microbursts and chorus waves predominantly occur in the dawn sector and Breneman et al. [2017] made a direct observational link between microbursts and chorus.

Understanding microburst precipitation is important to radiation belt dynamics since they have been modeled and empirically estimated to be capable of depleting the relativistic electron population in the outer radiation belt on the order of a day [O'Brien et al., 2004; Thorne et al., 2005; Shprits et al., 2007; Breneman et al., 2017]. An important parameter in the estimation of instantaneous radiation belt electron losses due to microbursts is their scale size. Parks [1967] used balloon measurements of bremsstrahlung X-rays to estimate the scale size of predominantly low energy microbursts to be  $40 \pm 14$  km. In Blake et al. [1996] a microburst with multiple bounces was observed by SAMPEX, and the microburst's latitu-

The highlighted sentence feels awkward and unnecessary. The following sentence contains all of the content and would need little or no transition if the highlighted sentence were deleted.

Your comment to the first reviewer under L51 states you've added a reference to Millan and Thorne 2007, but that reference does not appear in this paragraph.

dinal scale size was estimated to have been “at least a few tens of kilometers”. *Blake et al.* [1996] concluded that typically microbursts are less than a few tens of electron gyroradii in size (at  $L = 5$  at LEO, the gyroradii of 1 MeV electrons is on the order of 100 m). *Dietrich et al.* [2010] used SAMPEX along with ground-based very low frequency stations to conclude that microbursts have scale sizes less than 4 km.

Since February 1st, 2015, microbursts have been observed by FIREBIRD-II, a pair of CubeSats in LEO. Soon after launch, when the two FIREBIRD-II spacecraft were at close range, a microburst with a scale size greater than 11 km was observed [*Crew et al.*, 2016]. On the same day, FIREBIRD-II simultaneously observed a microburst with multiple bounces. The microburst decay was observed over a period of a few seconds, while the spacecraft were traveling predominantly in latitude. Here we present the analysis and results of the latitude and longitude scale sizes and bounce periods of the first microburst with multiple bounces observed with the two FIREBIRD-II spacecraft.

## 2 Spacecraft and Observation

FIREBIRD-II is a pair of identically-instrumented 1.5U CubeSats (15 x 10 x 10 cm) that are designed to measure electron precipitation in LEO. The FIREBIRD-II CubeSats are identified as Flight Unit 3 (FU3) and Flight Unit 4 (FU4) and were launched on January 31st, 2015 into a 632 km apogee, 433 km perigee, and 99° inclination orbit [*Crew et al.*, 2016]. FU3 and FU4 are orbiting in a string of pearls configuration with FU4 ahead, to resolve the **space-time ambiguity** inherent to single spacecraft missions such as SAMPEX. Each FIREBIRD-II unit has two solid state detectors: one is mounted just below the surface with a field of view of 90° (surface detector), and the other is beneath a collimator which restricts the field of view to 54° (collimated detector). Only FU3 has a functioning surface detector, so this analysis utilizes the collimated detectors. These detectors observe electron fluxes in six energy channels from ~ 230 keV to > 1 MeV, with an adjustable sampling rate of 18.75 ms by default and as fast as 12.5 ms.

Be more explicit than "space-time ambiguity". I understand what you mean, but someone with less experience in the field probably wouldn't.

Alternatively, pointing the difficulty of distinguishing between temporal and spatial structures on a single satellite might not be necessary at all.

On February 2nd, 2015 at 06:12 UT, FIREBIRD-II simultaneously observed a microburst with subsequent bounces during the transition between the main and recovery phases of a storm with a minimum Dst of -44 nT ( $K_p = 4$ , and  $AE \approx 400$  nT). Figure 1 shows the High Resolution (HiRes) microburst electron flux, sampled at 18.75 ms. Five peaks were observed by both spacecraft. The fifth peak observed by FU4 was comparable to the Poisson noise and was not used in this analysis. This microburst was observed from the first energy channel ( $\approx 200 - 300$  keV), to the fourth energy channel ( $\approx 500 - 700$  keV), and FU3's surface detector observed the microburst up to the fifth energy channel (683 - 950 keV).

The HiRes data in Fig. 1 shows signs of energy dispersion. The first peak does not appear to be dispersed, and subsequent peaks show dispersion consistent across energy channels. The black vertical bars have been added to Fig. 1 to highlight this energy dispersion. This dispersion signature and amplitude decay implies that the first peak was observed soon after the electrons were scattered, followed by decaying bounces.

At this time, FIREBIRD-II was at McIlwain  $L = 4.7$  and MLT = 8.3, calculated with the Tsyganenko 1989 (T89) magnetic field model [*Tsyganenko*, 1989]. They were above Sweden, latitude = 63°N, longitude = 15°E, altitude = 650 km. At this location, any background electron flux that was in the drift loss cone **was lost** to the South Atlantic Anomaly, enabling FIREBIRD-II to make this unique observation. Outside of this region, the drift loss cone flux will quickly hide the returning bounces. Locally mirroring electrons would have mirrored at 95 km in the opposite hemisphere, calculated with T89 and IRBEM-Lib [*Boscher et al.*, 2012]. From the analysis done by *Fang et al.* [2010], the peak in the total ionization rate in the atmosphere for 100 keV electrons is around 80 km altitude, while the total ionization rate from 1 MeV electrons peaks around 60 km altitude. It is, therefore, expected that a fraction of the microburst electrons will survive each encounter with the atmosphere. By plotting the

Change highlight to "was recently lost". As written it sounds like electrons in some locations are lost to the SAA and are not in others. The important point here is we are right next to the SAA so the DLC has not had time to refill yet.

peak flux as a function of bounce (not shown), it was found that 40 - 60 % of the microburst electrons were lost on the first bounce, similar to the 33% loss per bounce observed for a bouncing microburst observed by SAMPEX [Thorne *et al.*, 2005].

### 3 Analysis

At the beginning of the FIREBIRD-II mission, two issues prevented the proper analysis of the microburst's spatial scale size: the spacecraft clocks were not synchronized, and their relative positions were not accurately known. We addressed these issues with a cross-correlation time lag analysis described in detail in the supporting information (SI). From this analysis, the time correction was  $2.28 \pm 0.12$  s (applied to Fig. 1) and the separation was  $19.9 \pm 0.9$  km at the time of the microburst observation.

#### 3.1 Microburst Scale Sizes

After we applied the corrections detailed in the SI, we mapped the locations of FU3 and FU4 in Fig. 2. The locations where FU3 saw peaks 1-5 and where FU4 saw peaks 1-4 are shown as P1-5 and P1-4, respectively. The lower bound on the latitudinal extent of the microburst was the difference in latitude between P1 on FU3 and P4 on FU4 and was found to be  $28.8 \pm 0.8$  km. The uncertainty was estimated from the spacecraft separation uncertainty described in the SI. This scale size is the largest reported by FIREBIRD-II.

To calculate the longitudinal scale size of the microburst, we assumed that the scattered electrons observed in the last bounce by FIREBIRD-II, must have drifted east from their initial scattering longitude. Following geometrical arguments, the distance that electrons drift east in a single bounce is a product of the circumference of the drift shell foot print, and the fraction of the total drift orbit traversed in a single bounce and is given by,

$$d_{az} = 2\pi(R_E + A) \cos(\lambda) \frac{t_b}{\langle T_d \rangle} \quad (1)$$

where  $R_E$  is the Earth's radius,  $A$  is the spacecraft altitude,  $\lambda$  is the magnetic latitude,  $t_b$  is the electron bounce period, and  $\langle T_d \rangle$  is the electron drift period. Parks [2003] derived  $\langle T_d \rangle$  to be,

$$\langle T_d \rangle \approx \begin{cases} 43.8/(L \cdot E) & \text{if } \alpha_0 = 90^\circ \\ 62.7/(L \cdot E) & \text{if } \alpha_0 = 0^\circ \end{cases} \quad (2)$$

where  $E$  is the electron energy in MeV,  $L$  is the L shell, and  $\alpha_0$  is the equatorial pitch angle. Electrons mirroring at FIREBIRD-II have  $\alpha_0 \approx 3.7^\circ$  and so the  $\alpha_0 = 0^\circ$  limit was used.

The microburst's longitudinal scale size is defined as the distance the highest energy electrons drifted in the time between the observations of the first and last peaks. This scale size is given by  $D_{az} = n d_{az}$  where  $n$  is the number of bounces observed. The stars with energy labels in Fig. 2 represent the locations of electrons with that energy when the microburst was observed at P1, and drifted eastward to be last seen at P5 for FU3 and P4 for FU4. **Using this methodology, the larger longitudinal scale size was observed by FU3 and it was greater than  $38.5 \pm 8.8$  km for the 555 keV electrons and greater than  $50.8 \pm 11.4$  km for the 771 keV electrons, and is shown with the red dashed box in Fig. 2.** The uncertainty was estimated by propagating the uncertainty in the spacecraft separation through Eq. 1.

The microburst's longitudinal and latitudinal scale sizes and their uncertainties in LEO were mapped to the magnetic equator with T89. The radial scale size (latitudinal scale mapped from LEO) was greater than  $504 \pm 14$  km. The azimuthal scale size (longitudinal scale mapped from LEO) of 555 keV electrons was greater than  $451 \pm 103$  km and for the 771 keV electrons it was greater than  $530 \pm 119$  km.

This last paragraph lacks context. It would tie together better if you concluded with a sentence stating this is comparable to chorus scale sizes rather than leaving that entire thought for the discussion. As it is, I'm left with the question "so what?"

The highlighted sentence uses the word 'and' too much, maybe because you're trying to put more content into it than is comfortable.

Maybe try two sentences: "The larger longitudinal scale size was observed by FU3 and is shown with the red dashed box in Fig. 2. The minimum scale size was  $38.5 \pm 8.8$  km for the 555 keV electrons and  $50.8 \pm 11.4$  km for the 771 keV electrons."

Also, why are you quoting results for two energy channels here?

### 3.2 Electron Bounce Period

We used this unique observation of bouncing electrons to calculate the bounce period,  $t_b$  as a function of energy and compare it to  $t_b$  derived from four magnetic field models. The observed  $t_b$  and uncertainties were calculated by fitting the baseline-subtracted HiRes flux. The baseline flux used in this analysis is given in *O'Brien et al.* [2004] as the flux at the 10th percentile over a specified time interval, which in this analysis was taken to be 0.5 seconds. The flux was fitted with a superposition of Gaussians for each energy channel, and the uncertainty in flux was calculated using the Poisson error from the microburst and baseline fluxes summed in quadrature. Using the fit parameters, the mean  $t_b$  for the lowest four energy channels is shown in Fig. 3. The trend of decreasing  $t_b$  as a function of energy is evident in Fig. 3, which further supports the assumption that the subsequent peaks are bounces, and not a train of microbursts scattered by bouncing chorus.

The decaying peaks in the 231–408 keV electron flux observed by FU3's lowest two energy channels (see Fig. 1) were right-skewed. This implies that there was in-channel energy dispersion within those channels that is smeared out by the broad energy channels. Since  $t_b$  of higher energy electrons is shorter, a right-skewed peak implies that higher energy electrons were more abundant within each channel. A Gaussian fit cannot account for this in-channel dispersion, and as a first order correction, minima between peaks was used to calculate  $t_b$ , and is shown in Fig. 3.

To compare the observed and modeled  $t_b$ , we superposed  $t_b$  curves for various models including an analytical solution in a dipole [*Schulz and Lanzerotti*, 1974], and numerical models: T89, Tsyganenko 2004 (T04) [*Tsyganenko and Sitnov*, 2005], and Olson & Pfizter Quiet [*Olson and Pfizter*, 1982] in Fig. 3. The numerical  $t_b$  curves were calculated using a wrapper for IRBEM-Lib. This code traces the magnetic field line between mirror points, and calculates  $t_b$  assuming conservation of energy and the first adiabatic invariant for electrons mirroring at FIREBIRD-II. With the empirical  $t_b$ , the models agree within FIREBIRD-II's uncertainties, but the T04 model has the largest discrepancy compared to the other models.

### 3.3 Microburst Energy Spectra

Lastly, we investigated the energy spectra of this microburst. Using the fit parameters from section 3.2, we calculated the exponential E-folding energy,  $E_0$  to be  $\sim 100$  keV. This spectra is similar to the spectra shown in *Lee et al.* [2005] who used STSAT-1 and *Datta et al.* [1997] who used a sounding rocket. The energy spectra is soft for a typical microburst observed with FIREBIRD-II. There was no statistically significant change in  $E_0$  for subsequent bounces which further supports a single bouncing packet over a train of isolated bursts.

Wouldn't the low energy electrons be more likely to be lost, and therefore  $E_0$  would increase in each bounce? You even state above that higher energies have a peak ionization lower into the atmosphere.

The manuscript probably doesn't require any changes or further discussion on this point, but I'm personally curious.

## 4 Discussion

The twin FIREBIRD-II CubeSats have enabled a direct estimate of the lower bound scale size of a large microburst. This microburst was larger than the latitudinal scale sizes of typical  $> 1$  MeV microbursts reported in *Blake et al.* [1996],  $\approx 10$  times larger than reported in *Dietrich et al.* [2010], and  $\approx 2.6$  times larger than other simultaneous microbursts observed by FIREBIRD-II [*Crew et al.*, 2016]. Lastly, the scale sizes derived here were similar to the scale sizes of  $> 15$  keV microbursts observed with a high altitude balloon [*Parks*, 1967]. No energy dependence on the scale size was observed.

The microburst scale size obtained in Section 3.1 and scaled to the geomagnetic equator can be compared with the scales of chorus waves presumably responsible for the rapid burst electron precipitation. Early direct estimates of the chorus source scales were made by the coordinated measurement by ISEE-1, 2. The wave power correlation scale was estimated to be about several hundred kilometers across the background magnetic field [*Gurnett et al.*, 1979]. Furthermore, *Santolik et al.* [2003] determined the correlation lengths of chorus-type



whistler waves to be around 100 km based on multipoint CLUSTER Wide Band Data measurements near the chorus source region at  $L \approx 4$ , during the magnetic storm of 18 April 2002. Agapitov *et al.* [2010, 2011, 2017] recently showed that the spatial extent of chorus source region can be larger, ranging from 600 km in the outer radiation belt to more than 1000 km in the outer magnetosphere. The lower bound azimuthal and latitudinal scales obtained in Section 3.1 and scaled to the magnetic equator, are similar to the whistler-mode chorus source scale sizes reported in Agapitov *et al.* [2011, 2017].

No wave measurements from nearby spacecraft were available at this time. Nevertheless, during the hours before and after this observation, the Van Allen Probes' [Mauk *et al.*, 2013] Electric and Magnetic Field Instrument and Integrated Science [Kletzing *et al.*, 2013] observed strong wave power in the lower band chorus frequency range, inside the outer radiation belt between 22 and 2 MLT. Furthermore,  $AE \sim 400$  nT at this time, and relatively strong chorus waves were statistically more likely to be present at FIREBIRD-II's MLT [Li *et al.*, 2009]. With the evidence presented, we conclude that the microburst electrons were likely scattered by chorus, similar to the conclusions made in the past by e.g. Lorentzen *et al.* [2001a]; O'Brien *et al.* [2003]; Breneman *et al.* [2017].

The empirically estimated and modeled  $t_b$  in this study agree within FIREBIRD-II's uncertainties. The  $t_b$  curves are a proxy for field line length, and this agreement implies that they are comparable. This is expected since the magnetosphere is not drastically compressed at 8 MLT, but we expect a larger discrepancy near midnight, where the magnetosphere is more stretched, and more difficult to accurately model. This analysis can be used as a diagnostic tool to validate field line lengths in future studies.

## 5 Conclusions

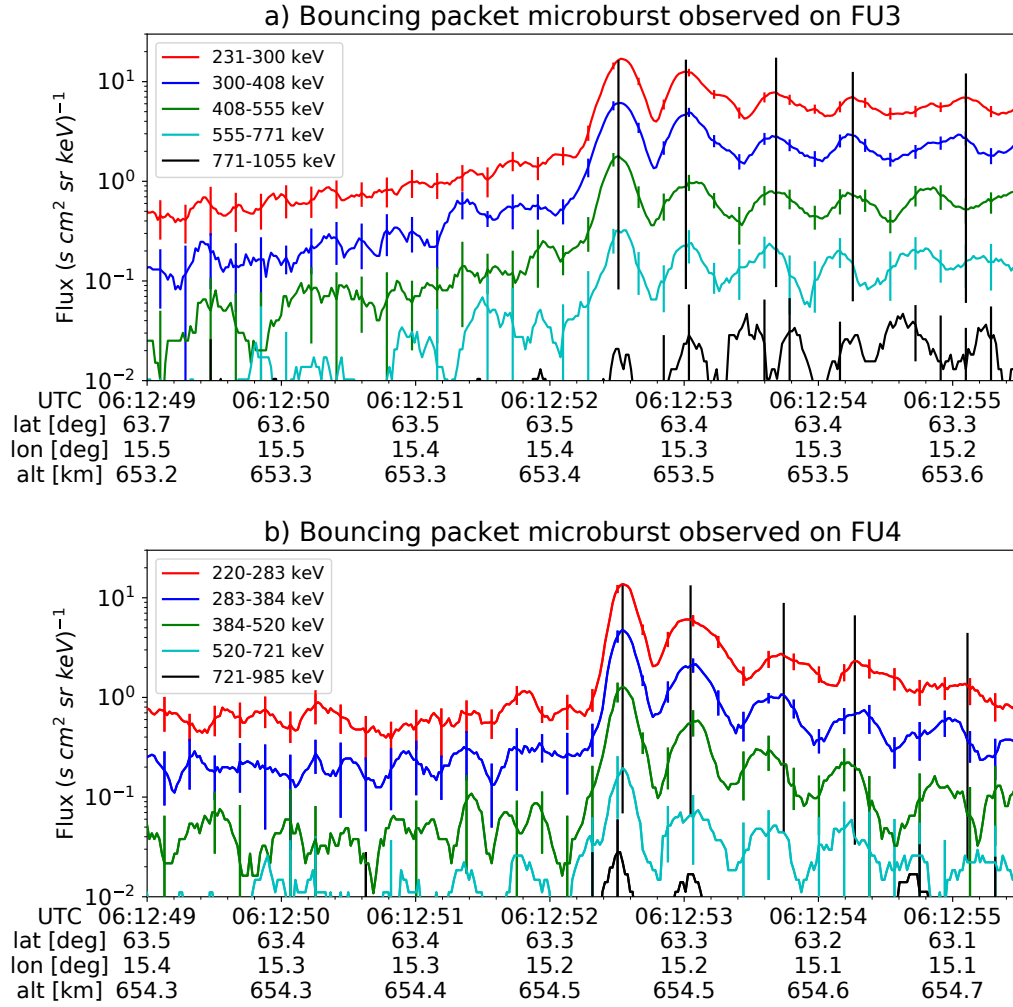
We presented the first observation of a large microburst with multiple bounces made possible by the twin FIREBIRD-II CubeSats. Its lower bound LEO latitudinal and longitudinal scale sizes of  $28.8 \pm 0.8$  km and  $50.8 \pm 11.4$  km make it one of the largest observed. No energy dependence on the scale size was observed. Furthermore, its lower bound LEO scale sizes mapped to the magnetic equator were  $504 \pm 14$  km radially and  $530 \pm 119$  km azimuthally, similar to the chorus source scale size. The bounce periods calculated with the Gaussian fit and minima methods are in good agreement with the four numerically estimated bounce periods, confirming that the energy-dependent dispersion was due to bouncing. The similarity of the microburst and chorus source region scale sizes, as well as magnetospheric location and conditions, further support the correlation between microbursts and chorus.

## Acknowledgments

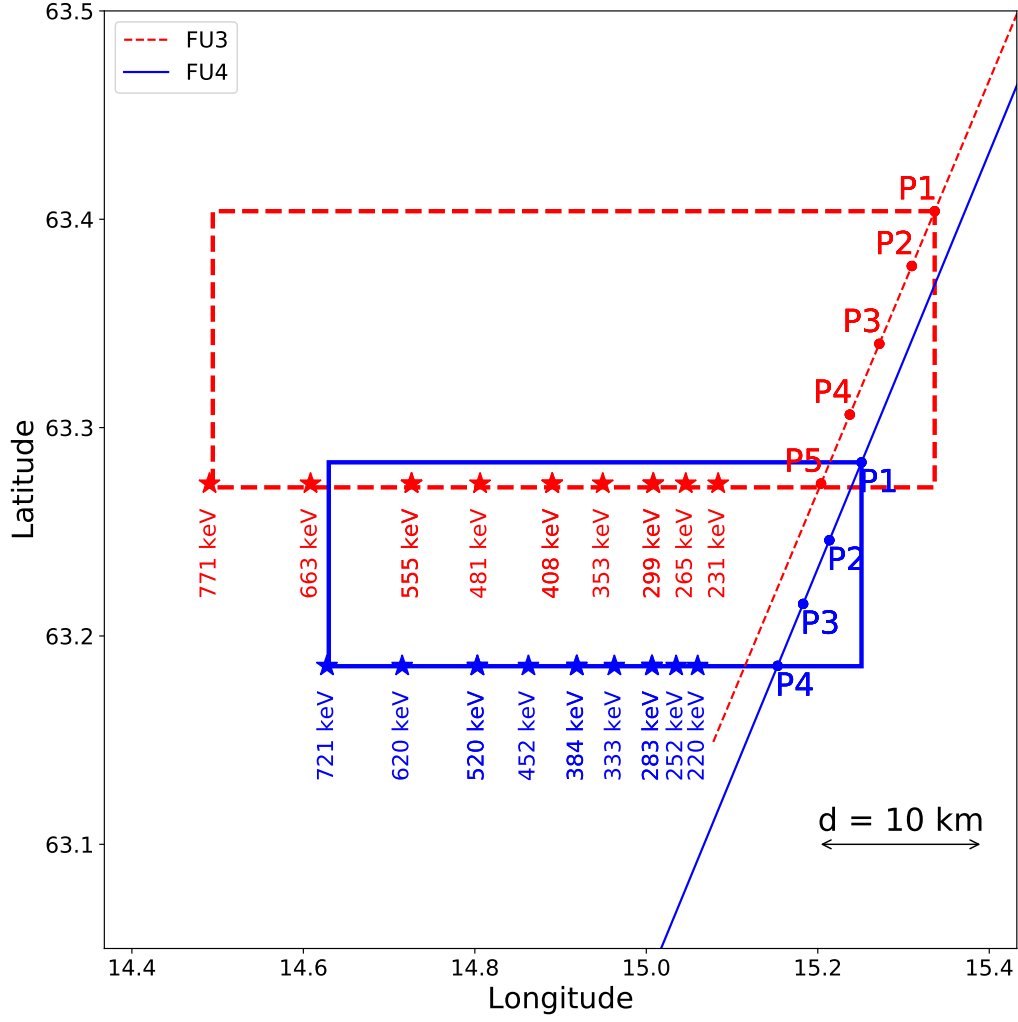
This work was made possible with help from the FIREBIRD team, and the members of the Space Sciences and Engineering Laboratory at Montana State University for their hard work to make this mission a success. In addition, M. Shumko acknowledges Drew Turner for his suggestions regarding the bounce period calculations, and Dana Longcope for his proofreading feedback. The FIREBIRD-II data are available at [http://solar.physics.montana.edu/FIREBIRD\\_II/](http://solar.physics.montana.edu/FIREBIRD_II/). This analysis is supported by the National Science Foundation under Grant Numbers 0838034 and 1339414.

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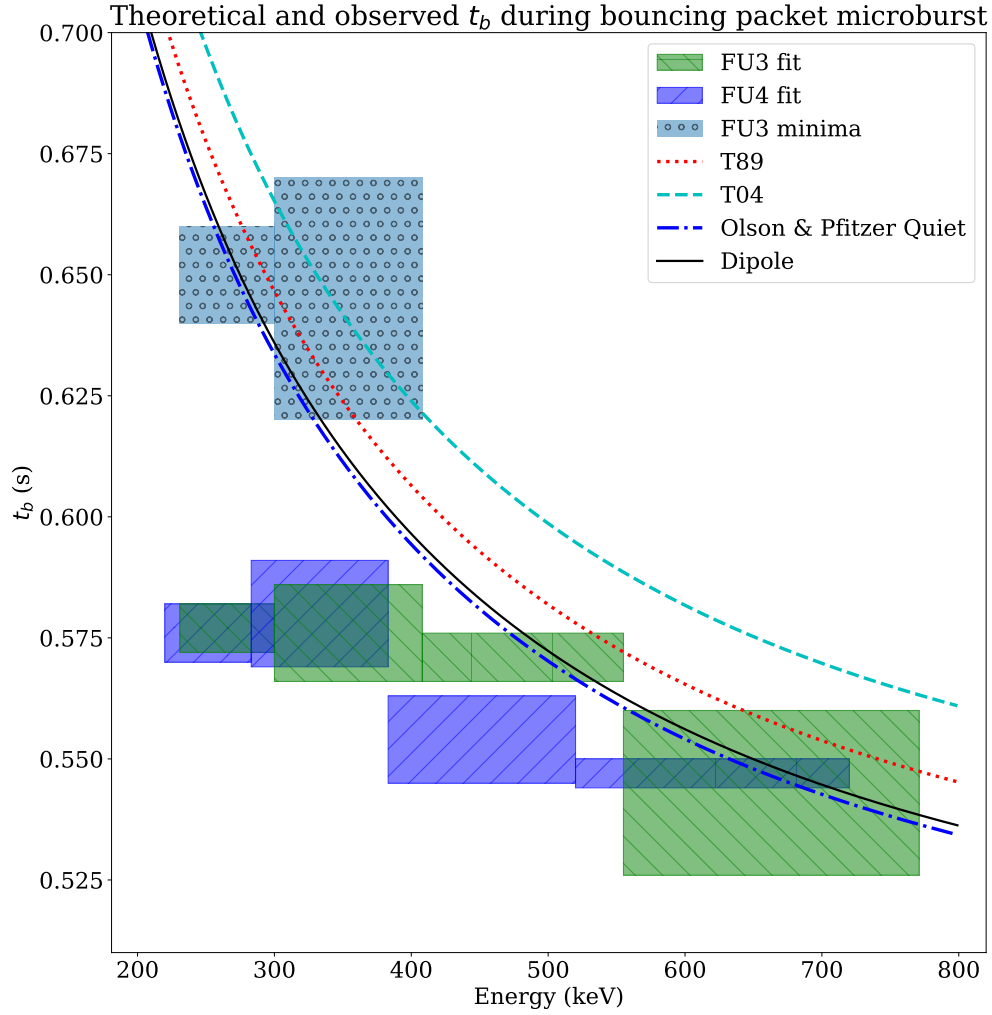


**Figure 1.** HiRes data of the microburst observed at February 2nd, 2015 at 06:12:53 UT, smoothed with a 150 ms rolling average. The subsequent bounces showed some energy dispersion. As discussed in the supporting information, a time correction of -2.28 s was applied to FU3. While the flux from five energy channels is shown, only channels with reasonable counting statistics were used for the spatial scale analysis. Vertical colored bars show the  $\sqrt{N}$  error every 10th data point and vertical black bars are lined up with the peaks in the 220-283 keV energy channel to help identify dispersion.



**Figure 2.** The topology of the FIREBIRD-II orbit and the multiple bounces of the microburst projected onto latitude and longitude with axis scaled to equal distance. Attributes relating to FU3 shown in red dashed lines, and FU4 with blue solid lines. The spacecraft path is shown with the diagonal lines, starting at the upper right corner. The labels P1-4 for FU4 and P1-5 for FU3 indicate where the spacecraft were when the  $N^{th}$  peak was seen in the lowest energy channel in the HiRes data. The stars with the accompanying energy labels represent the locations of the electrons with that energy that started at time of P1, and were seen at the last peak on each spacecraft. The rectangles represent the lower bound of the microburst scale size, assuming that the majority of the electrons were in the upper boundary of energy channel 4.





**Figure 3.** Observed and theoretical  $t_b$  for electrons of energies from 200 to 770 keV. The solid black line is  $t_b$  in a dipole magnetic field, derived in *Schulz and Lanzerotti* [1974]. The red and cyan dashed lines are the  $t_b$  derived using the T89, and T04 magnetic field models with IRBEM. Lastly, the blue dashed curve is the  $t_b$  derived using the Olson & Pfitzer Quiet model. The green and purple rectangles represent the observed  $t_b$  for FU3 and FU4 using a Gaussian fit, respectively. The blue rectangles represent the observed  $t_b$  calculated with the minima between the bounces. The width of the boxes represent the width of those energy channels, and the height represents the uncertainty from the fit.

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