



Article

THEMIS observations and riometry: A data comparison with a view to proxy and prediction

Birch, Martin John and Hargreaves, J.K.

Available at <http://clock.uclan.ac.uk/19921/>

Birch, Martin John and Hargreaves, J.K. (2016) THEMIS observations and riometry: A data comparison with a view to proxy and prediction. Journal of Atmospheric and Solar-Terrestrial Physics, 137 . pp. 66-75. ISSN 1364-6826

It is advisable to refer to the publisher's version if you intend to cite from the work.
<http://dx.doi.org/10.1016/j.jastp.2015.11.005>

For more information about UCLan's research in this area go to <http://www.uclan.ac.uk/researchgroups/> and search for <name of research Group>.

For information about Research generally at UCLan please go to <http://www.uclan.ac.uk/research/>

All outputs in CLoK are protected by Intellectual Property Rights law, including Copyright law. Copyright, IPR and Moral Rights for the works on this site are retained by the individual authors and/or other copyright owners. Terms and conditions for use of this material are defined in the [policies](#) page.

November 18, 2015

THEMIS observations and riometry: a data comparison with a view to proxy and prediction

M.J. Birch¹

J.K. Hargreaves^{2,1}

(1) Jeremiah Horrocks Institute for Mathematics, Physics and Astronomy,
University of Central Lancashire, Preston, UK.

(2) Department of Physics, Lancaster University, UK.

Abstract

1
2 A comparison has been made between radio absorption events observed by riometer at
3 selected times of day and bursts of electrons observed in the midnight sector by THEMIS
4 satellites. The correlation is found to be good for absorption in the noon and midnight sectors
5 but poor around dawn and dusk. For noon and midnight the absorption can be estimated
6 from the THEMIS electron flux to better than a factor of 2 in most cases. In the noon sector
7 the absorption follows the THEMIS event by about 30 minutes on average (though with
8 considerable variation from case to case), but by night the absorption precedes the electron
9 flux by about 8 minutes on average. Thus, the flux at THEMIS can be predicted from the
10 absorption in the night sector, the accuracy being better than a factor of 3 in most cases.
11 The flux observed also depends on the location of the satellite, reducing with increasing
12 distance down the tail. It is estimated that the source of the tail events observed in this
13 study was at about $6R_e$, and comparisons are made with the established general pattern of
14 the substorm in auroral absorption.

15 **1 Introduction**

16 Auroral radio absorption was first identified as a distinct phenomenon by Reid and Collins
17 (1959), and early studies established its character as a sub-storm phenomenon, the absorption
18 events being stronger and more frequent during periods of enhanced solar and geomagnetic
19 disturbance (Holt et al., 1961). Its incidence in local time and magnetic latitude was first
20 defined by Hartz et al. (1963), Driatsky (1966), and Hargreaves and Cowley (1967).

21 Jelly et al. (1964) and Parthasarathy et al. (1966) developed associations between the level of
22 radio absorption and the incoming flux of electrons of energy greater than 40 keV observed by a
23 low-orbit satellite, and later work based on incoherent-scatter radar has shown that the amount
24 of absorption is consistent with the resulting increase of electron density in the lower ionosphere
25 (Hargreaves and Devlin, 1990; Birch et al., 2013).

26 The above comparisons between electron flux and absorption used observations on satellites
27 passing over, or close to, the site of the riometer used for the absorption measurement. However,
28 in verifying auroral absorption as a substorm driven phenomenon, Parthasarathy and Reid (1967)
29 showed that dayside absorption was also related to increased particle activity in the midnight
30 sector, though with a time delay, and Hargreaves et al. (1968) verified this using data from Vela
31 satellites some $17 R_e$ down the magnetotail. It became clear from these studies that in a given
32 absorption substorm the activity originated from the tail region on the night side of the Earth.

33 An objective of the present study is to explore these relationships in greater detail and to
34 investigate whether the more recent observations of tail conditions using the Time History of
35 Events and Macroscale Interactions during Substorms (THEMIS) group of satellites (Angelopoulos,
36 2008) might enhance knowledge of these connections or even be useful in predictions.

37 **2 Observations**

38 The THEMIS satellites were launched in February 2007. A group of five, they were designed
39 to study magnetotail phenomena and dynamics, particularly during substorms. Among the
40 various sensors are the Electrostatic Analyser (ESA) and the Solid State Telescope (SST). The
41 ESA covers the electron energy range from 7 eV to 31.2 keV, whereas the SST covers the electron
42 energy range from 31 keV to 719.5 MeV. We shall use mainly the 41.0 keV and 93.0 keV SST
43 energy channels in this study. The SST comprises two identical instruments per satellite, each
44 instrument measuring electrons in two opposite directions thereby forming four reception cones

45 in all. Each satellite has a spin axis which is nearly orthogonal to the ecliptic plane and completes
46 one revolution in about 3 seconds. The spin of the spacecraft, and the alignment and angular
47 coverage of the reception cones, mean that the two SST instruments together provide almost
48 omnidirectional measurement of the incoming electron flux, except for cones 39° wide centred
49 on the vertical and an annulus 13° wide centred on the horizontal.

50 A 49-beam imaging riometer (IRIS), the Imaging Riometer for Ionospheric Studies (Browne
51 et al., 1995), is used for the absorption measurements. Situated at Kilpisjärvi, Finland (ge-
52 ographic latitude 69.05°N , longitude 20.79°E , L-value 5.9), it is slightly equatorward of the
53 statistical maximum of the absorption zone. Our comparisons use only the vertical beam to
54 determine the ionospheric radio absorption at the operating frequency of 38.2 MHz. Some refer-
55 ence will also be made to observations by the European Incoherent Scatter (EISCAT) radar near
56 Tromsø, Norway (geographic latitude 69.9°N , longitude 19.23°E , L-value 6.0), which is about
57 112km north-west of IRIS.

58 **3 A comparison between THEMIS and IRIS peaks.**

59 **3.1 Method of peak selection**

60 Comparisons with THEMIS satellite observations are restricted to periods when at least one
61 spacecraft is between 2100 and 0300 LT and within $3R_e$ of the ecliptic plane. (Though there
62 was no range constraint down the magnetotail, all the observations were between 5.5 and $16R_e$).
63 Within these constraints, THEMIS passes through the tail were selected for four time sectors,
64 specifically when IRIS was located in the midnight, dawn, noon and dusk sectors (22-24, 4-6,
65 10-12 and 16-18 UT, or approximately $23.5-1.5$, $5.5-7.5$, $11.5-13.5$ and $17.5-19.5$ LT at Kilpisjärvi
66 where the local time is 1.39 hours later than UT, and magnetic local time is 0.9 hours later than
67 LT). The period from January to April 2008 was selected, a period when the satellites were
68 predominantly in the tail region. This period includes an EISCAT radar run on 2008 March 9
69 (see Section 5).

70 For each time sector, plots of the 41 keV flux observed at THEMIS were inspected visually,
71 and events were selected for which the peak magnitude and time of occurrence could be clearly
72 identified. The corresponding plots of the 38.2 MHz radio absorption at IRIS were then inspected
73 for activity within about an hour of each THEMIS event. If present, the magnitude and time
74 of the associated absorption events were noted. The approach to the data analysis is illustrated

75 by Figure 1 which shows a THEMIS-A event on 2008 February 15 with IRIS in the noon sector.
76 The THEMIS-A flux peaked at $487 \text{ cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$ at 11:00 UT, and the absorption peaked
77 at 0.4 dB at 11:21 UT. Not all the THEMIS passes were suitable for such a comparison, some
78 being dominated by strong features of characteristic form, presumably due to the permanent
79 Van Allen belts, and these were rejected from the data set.

80 **3.2 Basic statistics of the occurrence of associated features**

81 The initial data inspection identified 194 instances with at least one THEMIS satellite between
82 2100 and 0300 LT within $3R_e$ of the ecliptic plane. Of these, 62 were (or seemed likely to be)
83 affected by the strong features mentioned above. Of the remaining 132 selections, 104 showed
84 a measurable flux event at 41 keV, and inspection of the riometer data for those times showed
85 a clearly associated absorption event of at least 0.1 dB on 66 days. Inspection of the list of
86 substorm onsets identified from the SuperMAG electrojet (SME) index (Newell et al., 2011a,
87 2011b) revealed that on all but 3 of the 66 days a magnetic substorm occurred within or close
88 to the selected time period. Table 1 summarises these statistics in terms of the four selected
89 IRIS sectors. For each comparison the event maxima (as seen in both the particle flux and
90 the absorption) were noted, and also the times of these peaks. The observed electron densities
91 indicate that in nearly all cases the satellite was in the plasma sheet when within $10R_e$.

92 Table 2 provides a more detailed summary of the data and shows the probability of the
93 absorption being at least 1.0 and 0.3 dB over a selection of flux ranges in each of the four
94 sectors. (On some days a flux event was observed by more than one satellite, and where that
95 occurred all are included separately; Table 2 therefore shows more flux values in total (138) than
96 Table 1 (104)). These results confirm that the relation between the two quantities is strongest
97 for the noon and midnight sectors, as illustrated in Figure 2. For example, at noon, for a flux
98 between 100 and $330 \text{ cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$ at 41 keV we expect a 6% chance of seeing at least 1.0
99 dB absorption and a 69% chance of at least 0.3 dB. In no case (within our selection) was there
100 an occurrence of more than 0.3 dB if the THEMIS flux remained below $10 \text{ cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$
101 at 41 keV.

102 **3.3 Adjustment of flux for satellite position**

103 Figure 3 shows a mass plot of the observed flux and absorption values for the noon sector.
104 Because of the difficulty of specifying very small values of absorption, those values less than 0.1

105 dB are indicated by diamonds. In many cases, an event was observed by more than one satellite
 106 at different locations in the magnetotail, and where such multiple readings were obtained the
 107 values are connected by horizontal lines. It is noted that there can be considerable variations
 108 between these multiple values.

109 In order to determine whether these variations in flux may be due to differing locations
 110 within the nightside region, variations of flux with satellite position were investigated. No
 111 evidence was found for any systematic variation in the peak magnitude with the local time of
 112 the satellite. However, there is a significant variation with the radial distance in the ecliptic
 113 plane. This relationship was investigated using the 23 events which were observed by more than
 114 one satellite in the nightside region (2100-0300 LT, and within $3R_e$ of the ecliptic), all such
 115 examples being shown in Figure 4a, in which the associated observations are connected. There
 116 is clearly a tendency for the flux (F) to reduce with increasing distance, suggesting a linear
 117 relation of $\log(F)$ as a function of r of the form $\log F = c - kr$, r being the geocentric distance
 118 in the ecliptic plane, k the gradient, and c a constant.

119 A value for k was determined using a cumulative minimising technique in which the difference
 120 between each adjusted associated flux value was compared for a range of assumed values of k
 121 (Figure 4b). This suggests a value of k between 0.12 and 0.16; a value of 0.14 was therefore
 122 assumed. To remove the influence of distance, the observed fluxes (F_r) were therefore adjusted
 123 to $r = 10R_e$ (F_{10}) using the formula -

$$\log\left(\frac{F_{10}}{F_r}\right) = 0.14(r - 10) \quad (1)$$

124 (A relationship of the form $F_r \propto 1/r^3$ would also be a reasonable fit.)

125 In order to verify that the observed flux is related to the position of the satellite as well as
 126 the strength of the associated absorption event, a partial correlation analysis was performed on
 127 the data selections for the 22-24 UT and 10-12 UT periods. The analysis uses every observation
 128 in the data set, not just those having simultaneous observations from 2 or more spacecraft.
 129 The partial correlation coefficient is usually designated $\rho_{12,3}$ where 1 and 2 are the quantities
 130 correlated and 3 is the quantity "partialled-out" by the procedure.

131 The results of this analysis are summarised in Table 3, in which the observed flux is F , the
 132 absorption is A , and the radial distance of the satellite is r . The significance of the correlation
 133 coefficient is tested using Fisher's z -transform (Fisher, 1921; Moroney, 1951), the value of z
 134 being normally distributed with standard deviation $1/\sqrt{N-3}$, N being the number of values.

135 By this means the probability (u) of the correlation having arisen by chance may be estimated.
136 The parameters z and u are included in Table 3, which verifies that the associations of F with
137 both A and r are very significant, whereas there is no significant association between A and r .

138 **3.4 Detailed comparison of magnitudes.**

139 For comparison purposes, the observed flux is adjusted to $10R_e$ using equation (1). The
140 variation of peak absorption (A) with the adjusted peak 41 keV electron flux (F_{10}) is shown in
141 Figure 5 for the four IRIS sectors. Because of their relative uncertainty, low absorption values
142 (< 0.1 dB) are marked with diamonds and are not included in the correlation computations.
143 Correlation coefficients and other statistical quantities derived from these distributions are given
144 in Table 4. There is a clear distinction in these properties between the sectors. In the noon
145 and midnight sectors the correlation coefficients (0.74 and 0.73) are highly significant, and the
146 probability that they arose by chance is very small. In those sectors the absorption could be
147 predicted from the observed flux to within a factor of about 1.7 standard error. For the dawn
148 and dusk sectors the situation is quite different, with a small negative correlation which is of low
149 significance. These times are near the diurnal minima in the occurrence of auroral absorption
150 events, whereas the noon and midnight sectors are near occurrence maxima (Hargreaves, 1969).

151 **4 Peak-to-peak timing**

152 **4.1 The delay time between THEMIS flux peaks at 41 keV and IRIS absorp-** 153 **tion peaks**

154 The peak-to-peak delays between the bursts at THEMIS and the associated IRIS events for
155 the four time sectors (midnight, dawn, noon, and dusk) are summarised in Figure 6. In nearly all
156 cases where a valid comparison could be made it is clear that in the noon sector the absorption
157 followed the THEMIS event in nearly every case, the median time difference being 29 minutes
158 (with quartiles at 13 and 39 minutes). However, in the midnight sector the IRIS event preceded
159 that at THEMIS, with a median time difference of 8 minutes (with quartiles at 4 and 9 minutes).
160 The time differences are not so systematic for the dawn and dusk sectors, which is perhaps not
161 surprising given the lack of correlation between the magnitudes in those sectors. However, in
162 the dawn sector the flux precedes the absorption in 70% of the observations and the median
163 time difference is 20 minutes. The tendency for the flux to precede the absorption is probably

164 significant in this case also.

165 Adding together the midnight and noon median values predicts a typical delay of 37 minutes
166 from the night to the day absorption events. This is similar to the night-day difference estimated
167 from absorption observations at stations widely separated in longitude (e.g Hargreaves, 1967;
168 Pudovkin et al., 1968). Notable is the fact that in the midnight sector the absorption event
169 precedes the burst of energetic electrons detected by the THEMIS satellite. This suggests that
170 the source is closer to the field lines through Kilpisjarvi (at $L = 5.9$) than to those through
171 the satellite. Figure 7 shows the satellite locations in relation to the nose of the field line ($L =$
172 5.9) from Kilpisjärvi for each of the midnight sector events. The only consistency is that the
173 THEMIS event never precedes the absorption event observed at the ground, though they are
174 simultaneous on two occasions. The source location may be variable, but this result suggests
175 that it is usually close to 6 Earth radii. According to Liang et al. (2007) substorm dipolarisation
176 tends to occur near the duskward edge of the magnetotail, with which Figure 7 appears to be
177 consistent. At least half of the flux events plotted have the appearance of a spike, though several
178 are more complex in structure.

179 If the observed absorption precedes the flux, riometer observations near local midnight may
180 serve as a predictor of particle bursts in the tail. For the midnight sector, using the same
181 approach as in Table 2, but with absorption as the primary selection variable, there are 24
182 THEMIS observations unaffected by belt contamination when absorption was at least 0.1 dB,
183 21 of which were associated with measurable flux. These selections are summarised in Table
184 5. For a numerical prediction of the flux (at $10R_e$) from the observed absorption the regression
185 equation for F_{10} on A given in Table 4 should be valid. The standard error of estimate in this
186 case would be a factor of about 2.5. (The overall variation of flux observed in the 22-24 UT
187 sector was a factor of about 100.)

188 4.2 Time delay between satellites

189 The 23 cases when there were 2 or more THEMIS satellites in the selected tail region frequently
190 show a pattern of activity which is similar in general character though with differences in detail.
191 Figure 8 shows an example. For 16 such events, time differences for apparently similar, well-
192 defined features were studied. However, these fail to show any consistency regarding the direction
193 and speed of a presumed propagating event. This may be in part due to the time resolution of
194 the observations (either 1.6 or 3.2 minutes). Out of 29 comparisons from the 16 events, 62% of

195 the time differences were no more than 3 minutes and only two were more than 6 minutes.

196 **5 Spectral characteristics**

197 D-region observations were made using the EISCAT radar on the morning of 2008 March 9
198 (Birch et al, 2013). Some examples of the spectra derived from the electron-density profiles
199 are illustrated in Figure 9, together with the spectra observed by THEMIS-D. It is clear that
200 in the period from 0253 until 0638 UT there is reasonable agreement between the two spectral
201 estimates, even though the satellite is separated by 10 to 15 Earth radii in distance and 6 to 10
202 hours of local time from the estimated nose of the field line through the EISCAT radar. The
203 gradient of the spectrum is almost constant during this period, the flux steadily decreasing with
204 increasing energy. However, by 0736 UT the spectrum is beginning to harden, with a maximum
205 appearing between 50 and 100 keV, and by 0816 UT the change is pronounced.

206 To examine this matter further, the ratio between the fluxes at 93.0 and 41.0 keV was taken
207 as an indicator of the hardness of the spectrum. The values were taken at the peaks for each
208 energy, not necessarily at exactly the same time. Mass plots of hardness against the local time
209 at the satellite and against its geocentric distance show no clear trends, suggesting that the
210 observed variation of intensity with range is not accompanied by any systematic variation of
211 spectrum.

212 Figure 10 shows the time variation of hardness parameter from THEMIS-D and -E, and also
213 the same parameter derived from the EISCAT data, for the times when there was sufficient
214 precipitation for an estimate to be made. (THEMIS fluxes $< 0.1 \text{ cm}^{-2}.\text{s}^{-1}.\text{sr}^{-1}.\text{eV}^{-1}$ were
215 excluded from the spectral ratio computations, which resulted in the gaps in the plots.) As
216 indicated by Figure 9 there is reasonable agreement between THEMIS and EISCAT in the early
217 morning, but the ratios diverge after about 0700 UT, with the spectrum deduced from EISCAT
218 hardening considerably towards noon, a change which is not present in the THEMIS data. These
219 results are consistent with the tendency towards spectral hardening in the day sector reported by
220 Hargreaves and Devlin (1990). A likely cause is acceleration by interaction with whistler-mode
221 VLF waves as the energetic electrons move eastward under gradient-curvature drift (Horne et
222 al., 2003).

223 6 Discussion

224 Previous studies using THEMIS have compared results with properties of luminous aurora
225 (e.g. Gabrielse et al., 2009; Keiling et al., 2009; Mende et al., 2009; Nishimura, 2010; Pu et al.,
226 2010; Xing et al., 2010; Zou et al., 2010; Liu et al., 2011). The energies used in the present work
227 are considerably higher than those producing luminosity, and the comparison with auroral radio
228 absorption is more appropriate at these energies.

229 That the particles causing auroral radio absorption on the night side of the Earth might
230 be produced by the annihilation of magnetic field in the tail of the magnetosphere was first
231 suggested by Axford et al. (1965), and Reid and Parthasarathy (1966) found examples where
232 the pattern of particle flux on the IMP-1 satellite at $28R_e$ agreed closely with the variation of
233 radio absorption observed from the ground. Collis et al., (1984) showed that electron fluxes in
234 the range 20-160 keV at geosynchronous orbit ($6.6R_e$) could be predicted from riometer data to
235 an accuracy of 50% for the larger absorption events ($>2\text{dB}$), the samples being taken from the
236 whole day. More recently, Spanswick et al. (2007) have observed a close relation between rapid-
237 onset events (spikes excluded) seen with the CRESS satellite at $8R_e$ in the tail and absorption
238 at $L = 6.6$ observed by riometers near midnight in the Canadian sector. Clilverd et al. (2012)
239 and Ovalle et al. (2012) have made comparisons between riometers in the Antarctic and fluxes
240 observed by THEMIS in the tail, finding some clear associations between flux and absorption.
241 According to riometer studies, the latitude of maximum absorption occurrence is at about 67°
242 magnetic latitude ($L = 6.5$) during the period around midnight and into the morning, though
243 before about 2100 LT the maximum is more poleward at 72° or beyond (Hargreaves and Cowley,
244 1967). There is, however, considerable variation from case to case.

245 The timing of absorption events at the ground is also variable. As a rule they are seen
246 first at about $L = 5$ (magnetic latitude 63°), from whence they spread both poleward and
247 equatorward (Hargreaves et al., 1975). The latitude of the onset depends somewhat on the level
248 of geomagnetic activity as indicated by K_p , there being some equatorward displacement if K_p
249 is large. The progression of absorption from the night to the day side has been noted on many
250 occasions. There seems little doubt that the trapped electrons move eastward by the process
251 of gradient-curvature drift in the terrestrial magnetic field (e.g. Horne et al., 2003). However,
252 since the movement of structural features in the precipitated flux is eastward after midnight but
253 westward before that, some other factor must be involved in the precipitation process, perhaps
254 a propagating hydrodynamic wave (Hargreaves, 1968). This is still an open question, however.

255 A previous comparison between ≥ 45 keV electron flux observed at $17 R_e$ by Vela satellites
256 in the tail and auroral absorption at a number of riometers in the auroral zone (Hargreaves et
257 al., 1968) found that the absorption event at $L = 7$ in the midnight sector generally precedes the
258 increase of flux at Vela by 20 to 30 minutes, implying an outward motion. It was suggested that
259 the field lines reaching $17 R_e$ typically connect to the ground at about $L = 14$ (74° invariant
260 latitude). It was also estimated that the flux of energetic electrons entering the atmosphere was
261 considerably greater than the associated flux at $17 R_e$.

262 In many cases a weak bay-like event, the "pre-onset bay", is observed before the main event.
263 These can be extensive in longitude, and are first seen at a relatively high latitude, from which
264 they drift equatorward within the range $L = 16$ to 4, with most individual cases covering between
265 one and five or six units of L . The median speed over the ground is 100-200 m/s. It was suggested
266 (Hargreaves et al., 1975; Ranta et al., 1981) that this motion may be due to ExB drift of plasma
267 in the magnetotail under the influence of the cross-tail electric field. The main event often
268 appears first near the eastern end of the bay, which would generally be in the midnight sector.

269 The "spike event" is another absorption feature that may be significant. This is of short
270 duration and often marks the beginning of an absorption substorm as seen on the nightside of
271 the Earth. Spike events generally, though not always, move poleward, though there can also be
272 an east-west component. In the European sector, which includes Kilpisjärvi, the speeds are in
273 the range 200-3000 m/s over the ground (Ranta et al., 1981; Hargreaves et al., 1997; Ranta et
274 al., 1999). Taken together, these observed absorption features constitute the so-called "reversed-
275 y" event (Hargreaves et al., 1975). Features of spikey appearance were present in many of the
276 THEMIS events studied.

277 Recent observations by satellites in the tail, in some cases compared with ground-based
278 observations, have produced a range of ideas about processes and their locations, some at or
279 even beyond 25 Earth radii, others in the so-called "near-Earth" region at about 7-10 Earth radii
280 (Petrukovich and Yahnin, 2006; Lui, 2007; Xing et al., 2010). The present comparison between
281 auroral absorption features near midnight and energetic particle bursts in the tail, in which
282 the absorption event seen at about 6 Earth radii always precedes the THEMIS event, clearly
283 supports a near-Earth source for the main substorm event. However, the studies of pre-onset
284 absorption activity indicate that the onset is preceded by the inward movement of a feature
285 from a much greater distance, whose arrival closer to the Earth then triggers the main event.
286 The existence of two apparent sources of energetic particles was pointed out by Ashour-Abdalla

287 et al. (2011), the first one at a reconnection region producing particles of relatively low energy,
288 and a subsequent one producing particles of higher energy due to dipolarisation of the magnetic
289 field closer to the Earth. The implication of separate low- and high-energy fluxes produced at
290 different times and different locations within the magnetotail would appear to be consistent with
291 the pattern of auroral absorption and apparent sources as described above.

292 7 Summary

293 There is a significant association between the 41 keV electron flux observed by THEMIS in
294 the magnetotail and the auroral radio absorption at 38.2 MHz at Kilpisjärvi in the noon and
295 midnight sectors. The association is much weaker in the morning and evening sectors.

296 The electron flux also depends on the location, falling off exponentially in proportion to the
297 distance down the tail.

298 At noon and midnight the absorption could serve as a proxy for the tail flux within a factor
299 of 2 in most cases.

300 The tail flux usually precedes the absorption at noon but follows the absorption at midnight,
301 the median times being 29 and 8 minutes respectively, though there can be considerable variation
302 from case to case. The tail flux could therefore serve as a predictor of noon absorption, and
303 the midnight absorption as a predictor of tail flux. In the latter case the magnitude would be
304 predicted to an accuracy better than a factor of 3 in most cases.

305 The relative timing in the midnight sector suggests outward movement of the flux event
306 down the tail from a source close to $6R_e$.

307 A comparison with spectra derived from incoherent scatter radar observations shows rea-
308 sonable agreement between the spectra from THEMIS in the tail and the radar when in the
309 post-midnight to early morning sector. Thereafter the spectrum of precipitating electrons hard-
310 ens relative to the THEMIS measurement. No evidence was found for any systematic variation
311 of spectral hardness with location in the tail.

312 **Acknowledgements** The authors would like to thank Dr. B.J.I. Bromage (University of
313 Central Lancashire) for provision of the EISCAT VHF radar time allocation, the observations
314 from which were used to derive the EISCAT spectra used in Section 5. Assistance in the
315 reduction of the EISCAT data was provided by Dr. I. McCrea and other members of the EISCAT
316 Support Group at the Rutherford Appleton Laboratories, UK. Thanks are also extended to

317 Dr. J. Lewis (University of California, Berkeley), THEMIS software manager, for assistance in
318 deriving the ESA/SST fluxes and spectra. For the substorm list we gratefully acknowledge the
319 SuperMAG initiative and the SuperMAG collaborators.

320 **References**

- 321 Angelopoulos, V., 2008. The THEMIS mission. *Space Sci. Rev.*, 141, 5-34.
- 322 Ashour-Abdalla, M., El-Alaoui, M., Goldstein, M.L., Zhou, M., Schriver, D., Richard, R.,
323 Walker, R., Kivelson, M.G., Hwang, K.-J., 2011. Observations and simulations of non-local
324 acceleration of electrons in magnetotail magnetic reconnection events. *Nature Physics*, 7, 360-
325 365.
- 326 Axford, W.I., Petschek, H.E., Siscoe, G.L., 1965. Tail of the magnetosphere. *J. Geophys. Res.*
327 70, 1231-1236.
- 328 Birch, M.J., Hargreaves, J.K., Bromage, B.J.I., 2013. Properties of auroral radio absorption
329 patches observed in the morning sector using imaging riometer and incoherent-scatter radar.
330 *J. Atmos. Terr. Phys.*, 105-106, 262-272.
- 331 Browne, S., Hargreaves, J.K., Honary, B., 1995. An imaging riometer for ionospheric studies.
332 *Electronics and Communication Engineering Journal*. 7, 209.
- 333 Clilverd, M. A., Rodger, C.J., Rae, I.J., Brundell, J.B., Thomson, N.R., Cobbett, N., Ver-
334 ronen, P.T., Menk, F.W. 2012, Combined THEMIS and ground-based observations of a
335 pair of substorm associated electron precipitation events, *J. Geophys. Res.*, 117, A02313,
336 doi:10.1029/2011JA016933
- 337 Collis, P.N., Hargreaves, J.K., Korth, A., 1984. Auroral radio absorption as an indicator of
338 magnetospheric electrons and of conditions in the disturbed auroral D-region. *J. Atmos. Terr.*
339 *Phys.*, 46, 21-38.
- 340 Driatsky, V.M., 1966. Study of the space and time distribution of auroral absorption according
341 to observations of the riometer network in the arctic. *Geomagnetism and Aeronomy*, v6, p.828.
- 342 Fisher, R. A., 1921. On the probable error of a coefficient of correlation deduced from a small
343 sample, *Metron*, 1, 332.

344 Gabrielse, C., Angelopoulos, V., Runov, A., Frey, H.U., McFadden, J., Larson, D.E., Glassmeier,
345 K.H., Mende, S., Russell, C.T., Apatenkov, S., Murphy, K.R., and Rae, I.J., 2009. Timing
346 and localization of near-Earth tail and ionospheric signatures during a substorm onset. *J.*
347 *Geophys. Res.* 114, A00C13.

348 Hargreaves, J.K., 1967. Auroral motions observed with riometers: movements between stations
349 widely separated in longitude. *J. Atmos. Terr. Phys.* 29, 1139.

350 Hargreaves, J.K. Cowley, F.C., 1967. Studies of auroral radio absorption events at three magnetic
351 latitudes: 1. Occurrence and statistical properties of the events. *Planet. Space Sci.*, 15, 1571-
352 1583.

353 Hargreaves, J.K., 1968. Auroral motions observed with riometers: latitudinal movement and a
354 median global pattern. *J. Atmos. Terr. Phys.*, 80, 1461-1470.

355 Hargreaves, J.K., Hones, E.W., Singer, S., 1968. Relations between bursts of energetic electrons
356 at 17 Earth-radii in the magnetotail and radio absorption events in the ionospheric D-region.
357 *Planet. Space Sci.*, 16, 567.

358 Hargreaves, J.K., 1969. Auroral absorption of HF radio waves in the ionosphere: a review of
359 results from the first decade of riometry. *Proc. IEE*, v57, No8, p.1348.

360 Hargreaves, J.K., Chivers, H.J.A., Axford, W.I., 1975. The development of the substorm in
361 auroral radio absorption. *Planet. Space Sci.*, 23, 903-911.

362 Hargreaves, J.K., Devlin, T., 1990. Morning sector electron precipitation events observed by
363 incoherent scatter radar. *J. Atmos. Terr. Phys.* 52, 193.

364 Hargreaves, J.K., Browne, S., Ranta, H., Ranta, A., Rosenburg, T.J., Detrick, D.L., 1997.
365 A study of substorm-associated nightside spike events in auroral absorption using imaging
366 riometers at South Pole and Kilpisjärvi. *J. Atmos. Solar-Terrestrial Phys.* 59, 853-872.

367 Hartz, T.R., Montbriand, L.E., Vogan, E.L., 1963. A study of auroral absorption at 30 Mc/s.
368 *Canadian Journal of Physics*, 41, 581.

369 Holt, O., Landmark, B., Lied, F., 1961. Analysis of riometer observations obtained during polar
370 radio blackouts. *J. Atmos. Terr. Phys.*, 23, 229.

371 Horne, R.B., Glauert, S.A., Thorne, R.M., 2003. Resonant diffusion of radiation belt electrons
372 by whistler-mode chorus. *Geophys. Re. Letters*, 30, 9, 1493.

373 Jelly, D.H., McDiarmid, I.B., Burrows, J.R., 1964. Correlation between intensities of auroral
374 absorption and precipitating electrons. *Can. J. Phys.*, 42, 2411.

375 Keiling, A., Angelopoulos, V., Weygand J. M., Amm, O., Spanswick, E., Donovan, E., Mende,
376 S., McFadden, J., Larson, D., Glassmeier, K.H., Auster, H.U., 2009. THEMIS ground-space
377 observations during the development of auroral spirals, *Ann. Geophys.*, 2007, 4317-4322.

378 Liang, J., Liu, W.W., Spanswick, E., Donovan, E.F., 2007. Azimuthal structures of
379 substorm electron injection and their signatures in riometer observations, *JGR*, 112,
380 doi:10.1029/2007JA012354.

381 Liu, J., Angelopoulos, V., Kubyshkina, M., McFadden, J., Glassmeier, K.H., Russell, C.T.,
382 2011. Revised timing and onset location of two isolated substorms observed by Time History
383 of Events and Macroscale Interactions During Substorms (THEMIS). *J. Geophys. Res.*, 115,
384 A12309.

385 Lui, A.T.Y., 2007. Solving a four-decade-old mystery. *John Hopkins APL Technical Digest*, 27,
386 3, 233-238.

387 Mende, S., Angelopoulos, V., Frey, H.U., Donovan, E., Jackel, B., Glassmeier, K.H., McFadden,
388 J.P., Larson, D., Carlson, C.W., 2009. Timing and location of substorm onsets from THEMIS
389 satellite and ground based observations. *J. Geophys. Res.*, 27, 2813-2830.

390 Moroney, M. J., 1951. *Facts From Figures*, Pelican Books, Harmondsworth, U.K.

391 Newell, P. T., and J. W. Gjerloev, 2011. Evaluation of SuperMAG auroral electrojet in-
392 dices as indicators of substorms and auroral power, *J. Geophys. Res.*, 116, A12211,
393 doi:10.1029/2011JA016779.

394 Newell, P. T., and J. W. Gjerloev, 2011. Substorm and magnetosphere characteristic scales
395 inferred from the SuperMAG auroral electrojet indices, *J. Geophys. Res.*, 116, A12232,
396 doi:10.1029/2011JA016936.

397 Nishimura, Y, Lyons L., Zou, S., Angelopoulos, V., Mende S, 2010. Substorm triggering by new
398 plasma intrusion: THEMIS all-sky imager observations, *J. Geophys. Res.*, 115, A07222, doi:
399 10.1029/2009JA015166.

400 Ovalle, E.M., Vidal, S.E., Foppiano A.J., Weatherwax, A., Stepanova, M.V., Comparison of
401 antarctic riometer radio wave absorption and Themis missions energetic electron fluxes, *Ad-*
402 *vances in Space Research*, 49(11), 1538-1543, 2012.

403 Parthasarathy, P., Berkey, F.T. and Ventakeson, D., 1966. Auroral zone electron flux and its
404 relation to broadbeam radiowave absorption. *Planet.Space Sci.* 14, 65.

405 Parthasarathy, R., Reid, R.C., 1967. Magnetospheric activity and its consequences in the auroral
406 zone. *Planet. Space Sci.*, 15, 917.

407 Petrukovich, A.A., and Yahnin, A.G., 2006. The substorm onset location controversy. *Space*
408 *Science Reviews*, 122, 81-87.

409 Pu, Z.H., Chu, X.N., Cao, X., Mishin, V., Angelopoulos, V., Wang, J., Wei, Y., Zong, Q.G.,
410 Fu, S.Y., Xie, L., Glassmeier, K.H., Frey, H., Russell, C.T., Liu, J., McFadden, J., Larson,
411 D., Mende, S., Mann, I., Sibeck, D., Sapronova, L.A., Tolochko, M.V., Saifudinova, T.I., Yao,
412 Z.H., Wang, X.G., Xiao, C.J., Zhou, X.Z., Reme, H., Lucek, E., 2010. THEMIS observations
413 of substorms on 26 February 2008 initiated by magnetotail reconnection. *J. Geophys. Res.*,
414 115, A02212

415 Pudovkin, M.I., Shumilov, O.I. and Zaitzeva, S.A, 1968. Dynamics of the zone of corpuscular
416 precipitations. *Planet. Space Sci.*, 16, 881.

417 Ranta, H., Ranta, A., Collis, P.N., Hargreaves, J.K., 1981. Development of the auroral absorption
418 substorm: studies of the pre-onset phase and sharp onset using an extensive riometer network.
419 *Planet. Space Sci.*, 29, 1287-1313.

420 Ranta, H., Ranta, A., Hargreaves, J.K., 1999. Small-scale structure of ionospheric absorption
421 of cosmic noise during pre-onset and sharp onset phases of an auroral absorption substorm.
422 *Geophysica (Geophysical Society of Finland)*, 35, 45-57.

423 Reid, G.C. and Collins, C., 1959. Observations of abnormal VHF radio wave absorption at
424 medium and high latitudes. *J. Atmos. Terr. Phys.*, 14, 68.

425 Reid, G.C., and Parthasarathy, R., 1966. Ionosphere effects of energetic electron bursts in the
426 tail of the magnetosphere. *J. Geophys. Res.*, 71, 3267-3272.

427 Spanswick, E., Donovan, E., Friedel, R., Korth, A., 2007. Ground based identification of disper-
428 sionless electron injections. *Geophys. Res. Letters*, 34, L03101.

429 Xing, ??, 2010

430 Zou, S., Moldwin, M.B., Lyons, L.R., Nishimura, Y., Hirahara, M, Sakanoi, T., Asamura, K.,
431 Nicolls, M.J., Miyashita, Y., Mende, S.B., Heinselman, C.J., 2010. Identification of substorm
432 onset location and preonset sequence using Reimei, THEMIS GBO, PFISR, and Geotail. *J.*
433 *Geophys. Res.*, 116, A00117.

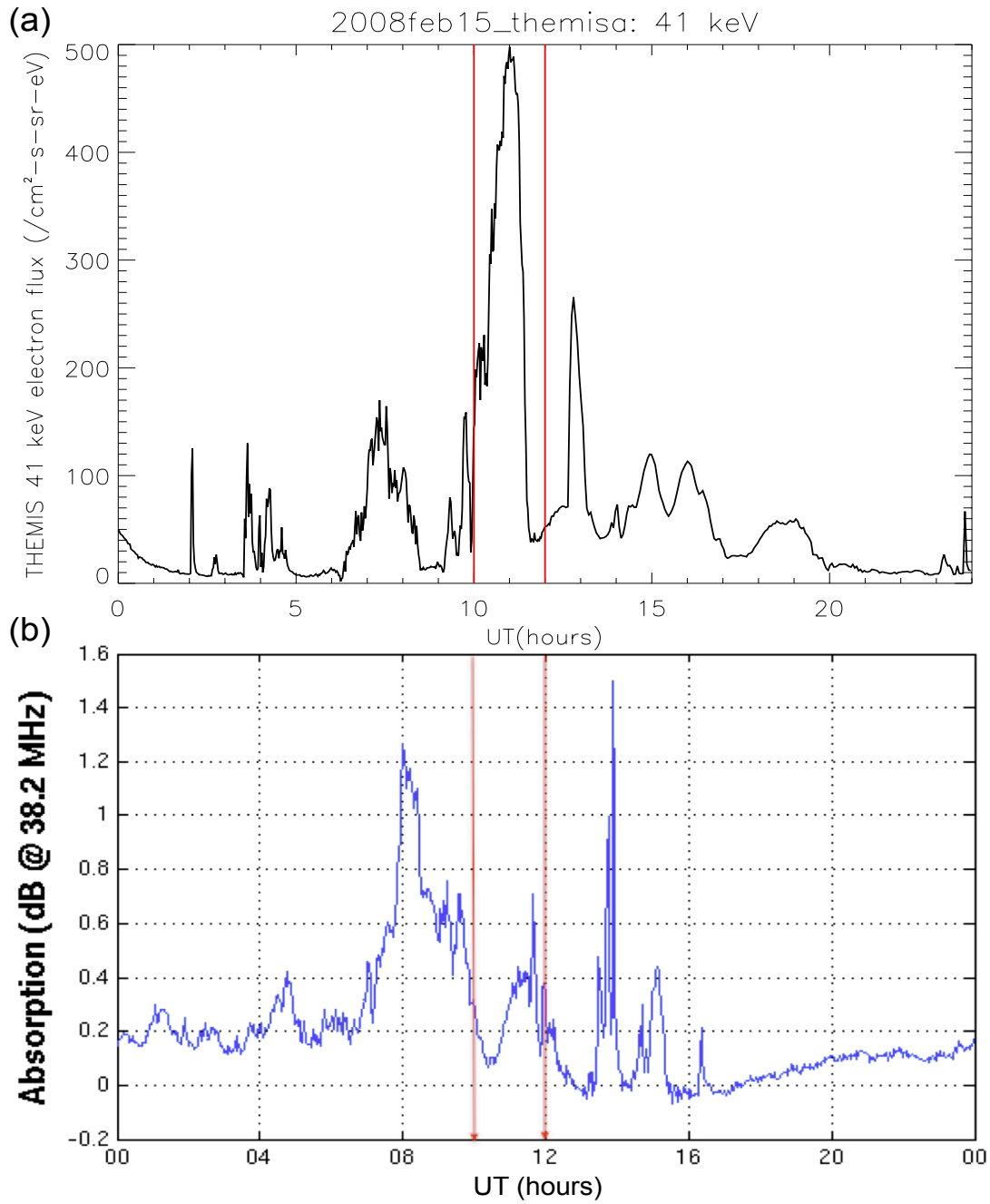


Figure 1: (a) THEMIS-A 41 keV electron flux ($\text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}\cdot\text{eV}^{-1}$) and (b) IRIS absorption (dB) on 2008 February 15. (Local noon at Kilpisjärvi is at 10.6 UT.)

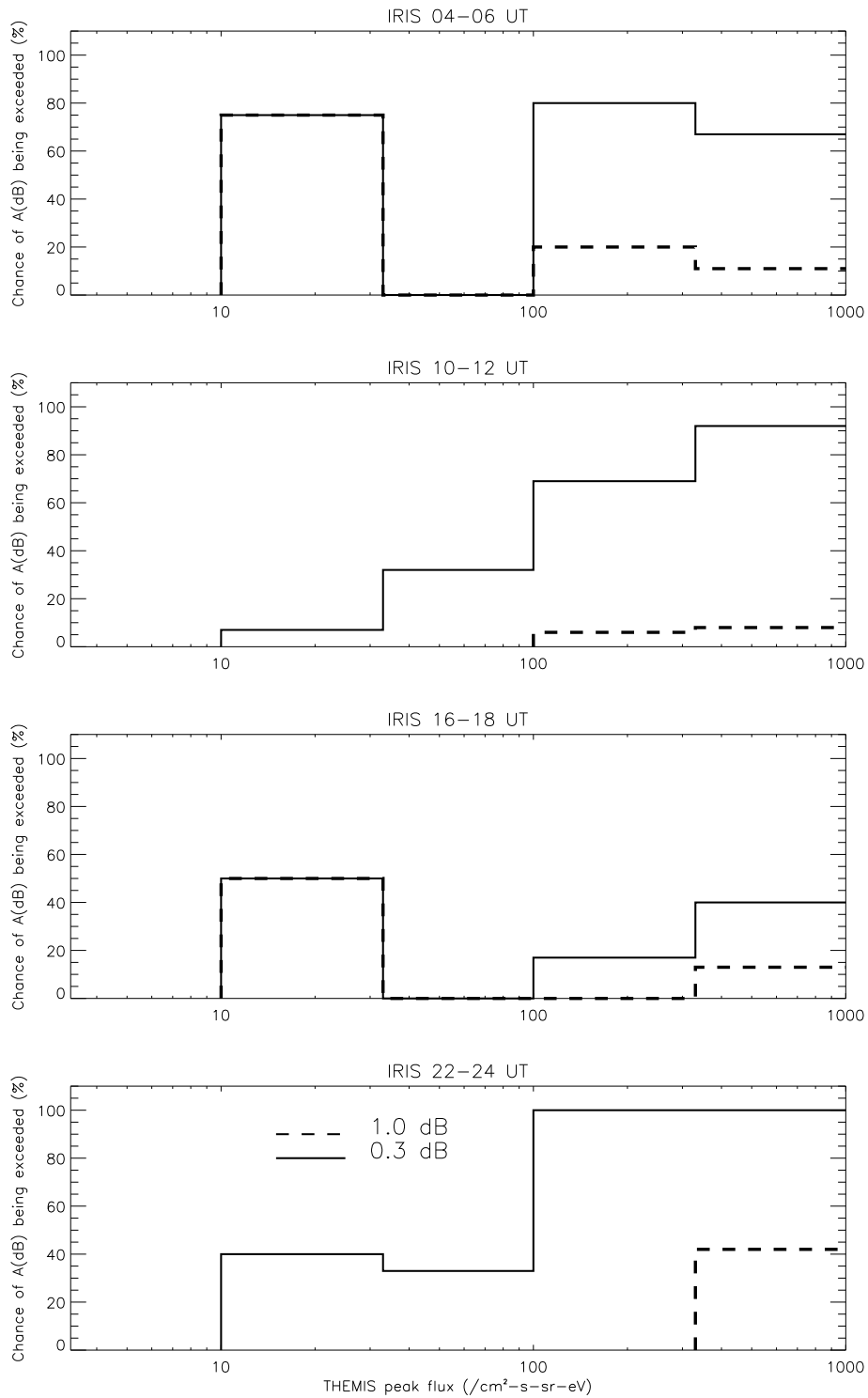


Figure 2: Probabilities of at least 0.3 dB and 1.0 dB in each of the four sectors for given ranges of 41 keV THEMIS flux

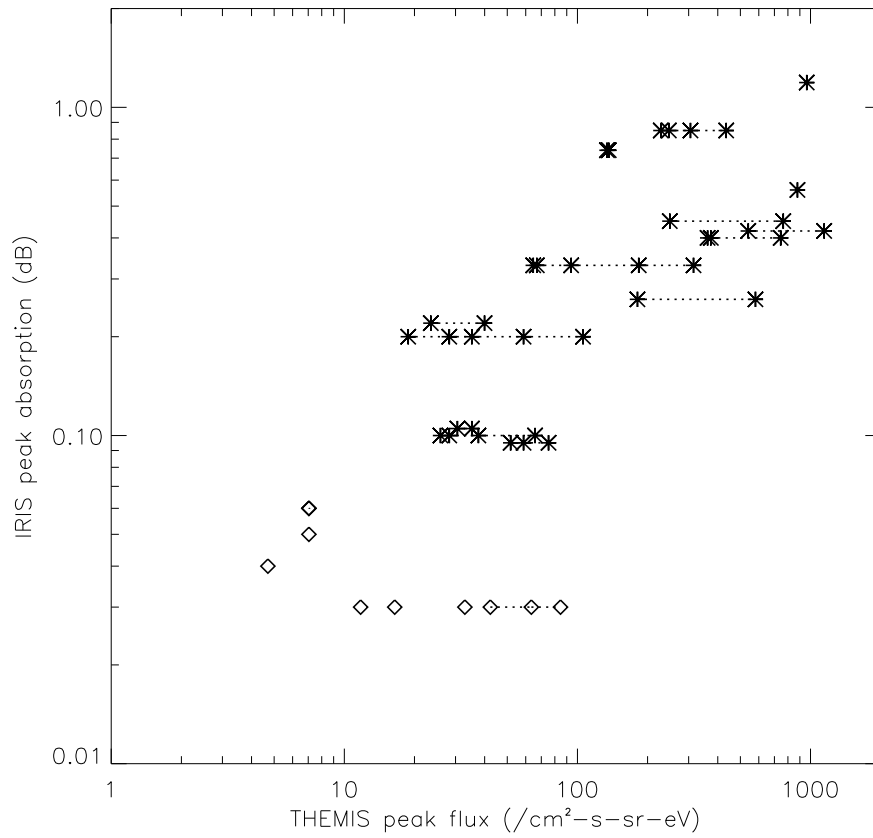


Figure 3: Peak absorption (A dB) against 41 keV peak flux ($F \text{ cm}^{-2}.\text{s}^{-1}.\text{sr}^{-1}\text{eV}^{-1}$) for all measurable values from the set of 42 days in the IRIS noon sector. (Groups of points at 0.1 dB have been offset in absorption, for clarity; values <0.1 dB are indicated by diamonds)

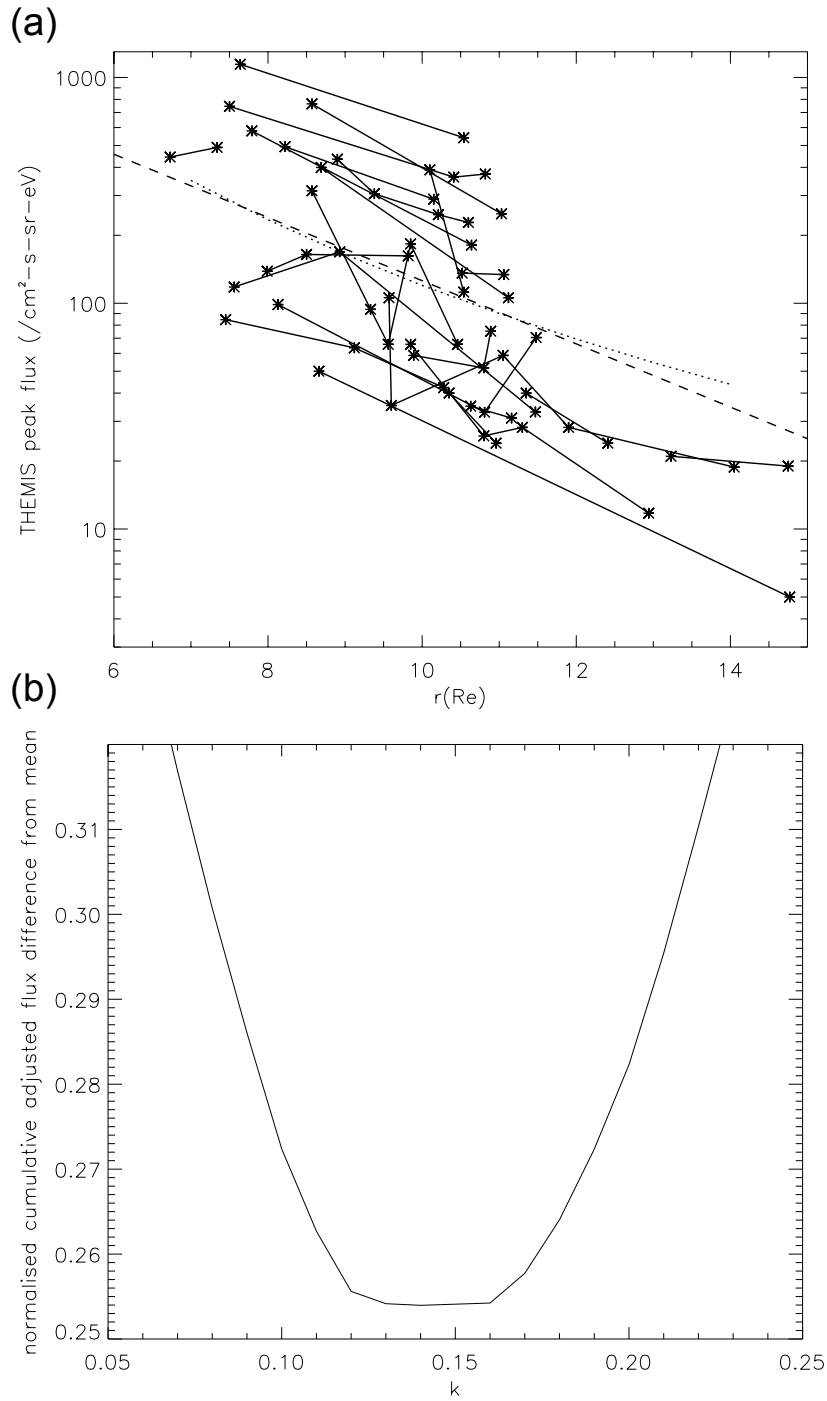


Figure 4: (a) Variation of 41 keV flux with geocentric radial distance in the ecliptic plane for the 23 events observed by 2 or more satellites. (The dashed line has gradient $k = -0.14$; the dotted line represents the relation $F \propto r^{-3}$.) (b) Variation of "normalised cumulative adjusted flux difference from the mean" against gradient k .

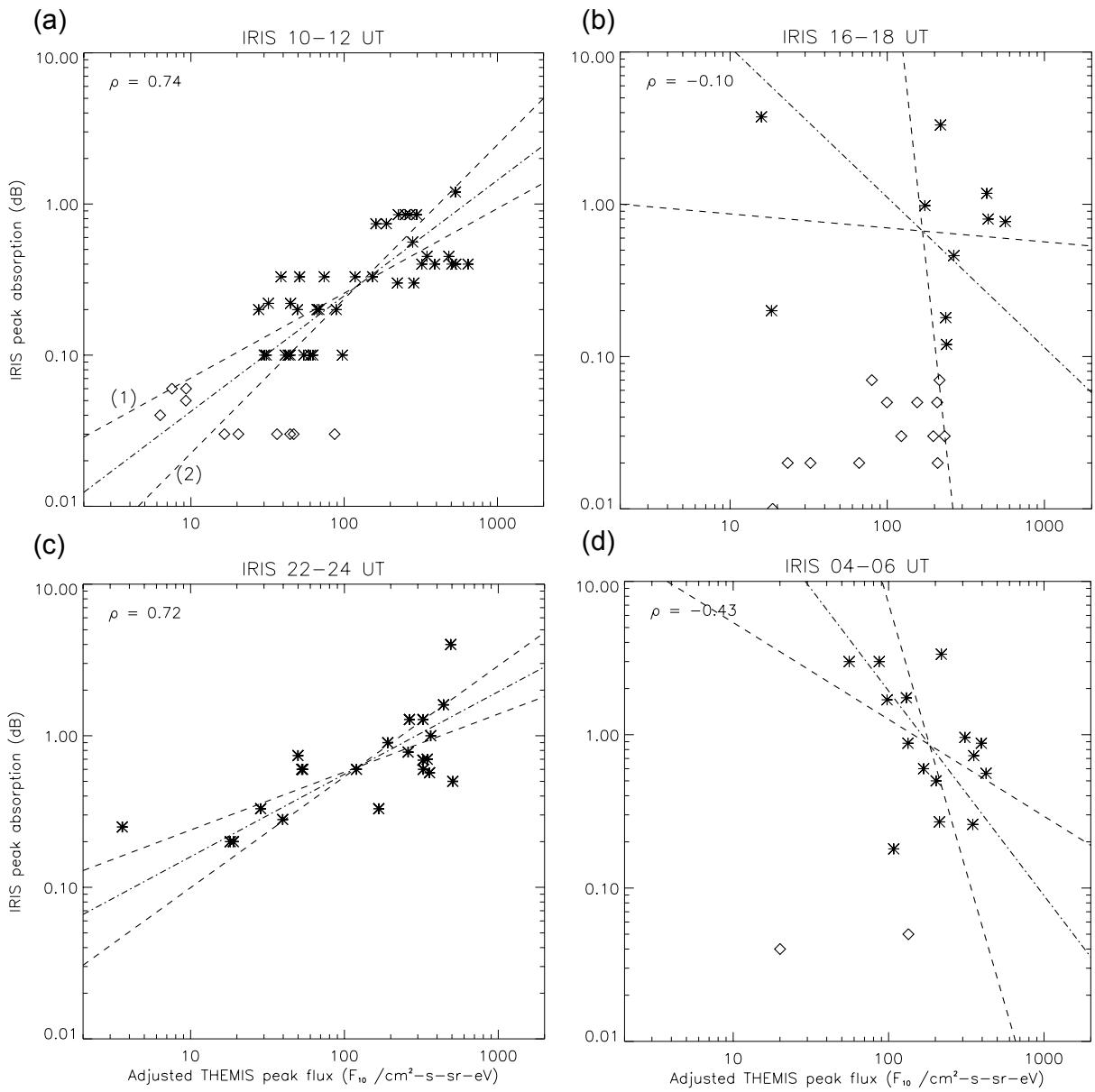


Figure 5: Variation of IRIS peak absorption (A) with THEMIS adjusted peak flux (F_{10}) for IRIS UT sectors: (a) 10-12; (b) 16-18; (c) 22-24; (d) 04-06. (Regression lines: (1) $\log(A)$ on $\log(F_{10})$; (2) $\log(F_{10})$ on $\log(A)$.)

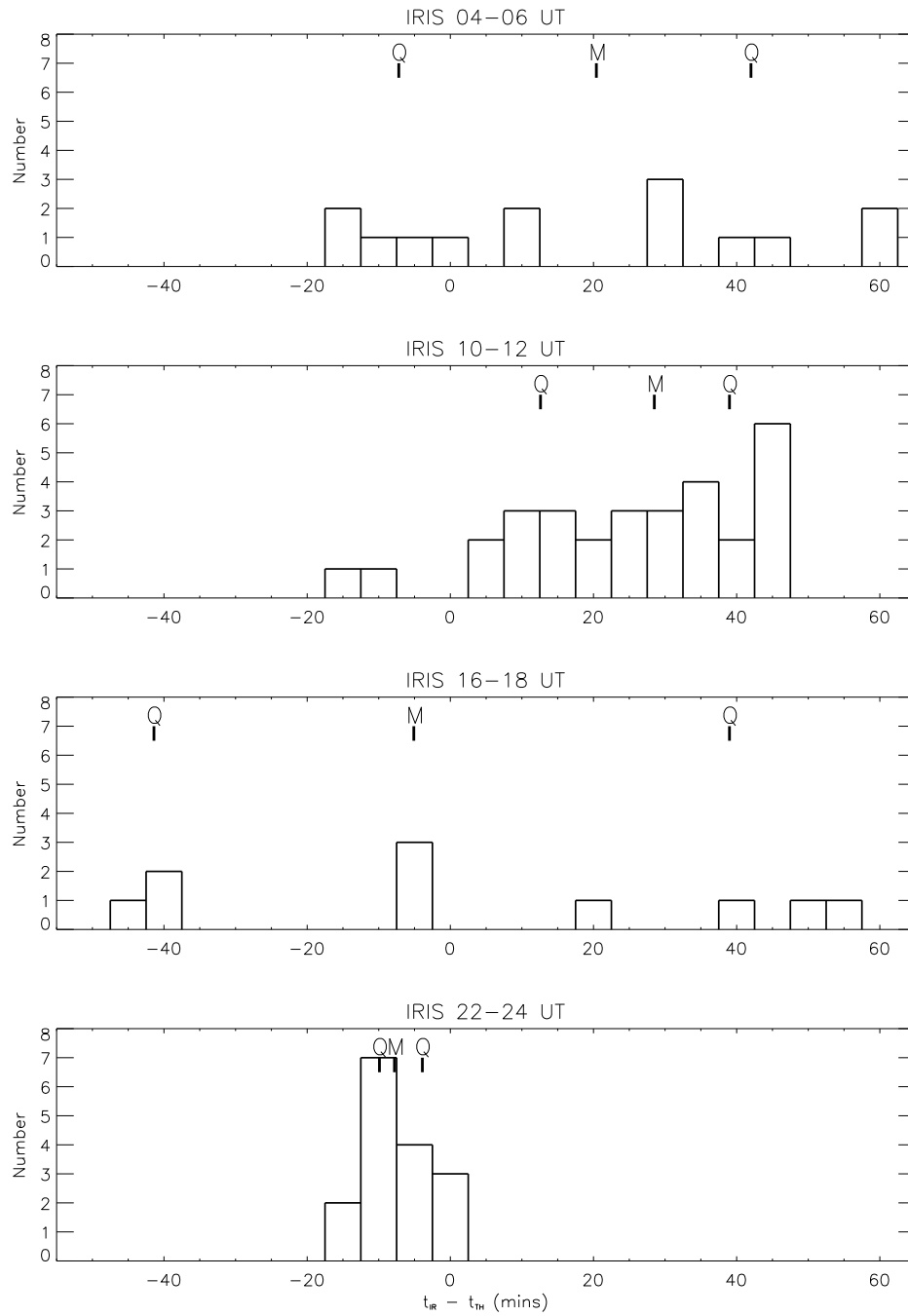


Figure 6: Summary of time differences ($t_{IR} - t_{TH}$ minutes) for the four IRIS time sectors (M = median; Q = quartiles).

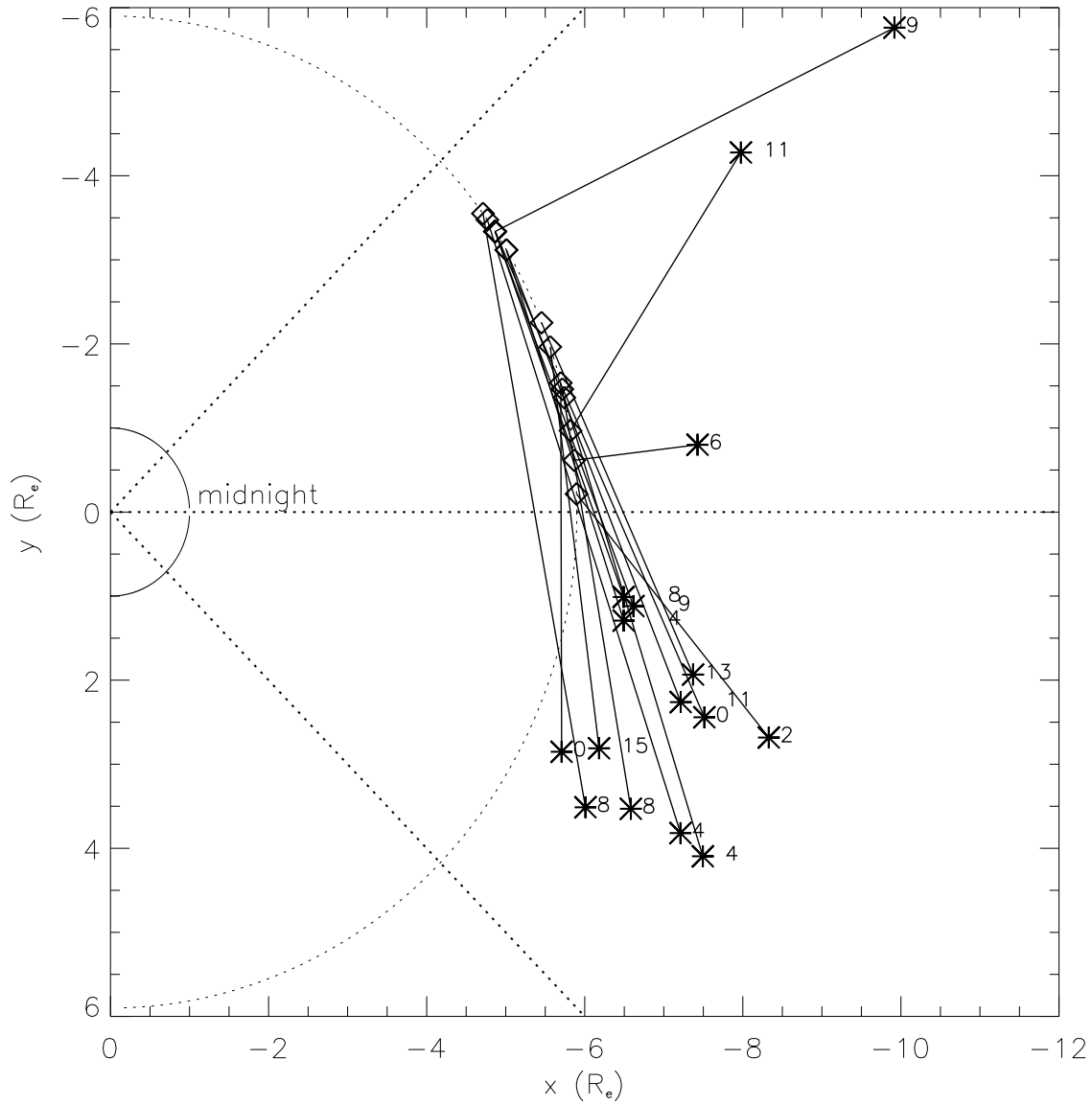


Figure 7: Comparison between nose of field line through Kilpisjärvi (diamonds, at $L = 5.9$) and THEMIS satellite location (asterisks) for individual cases in the midnight sector. The time differences in minutes are marked (the absorption peak precedes the THEMIS flux).

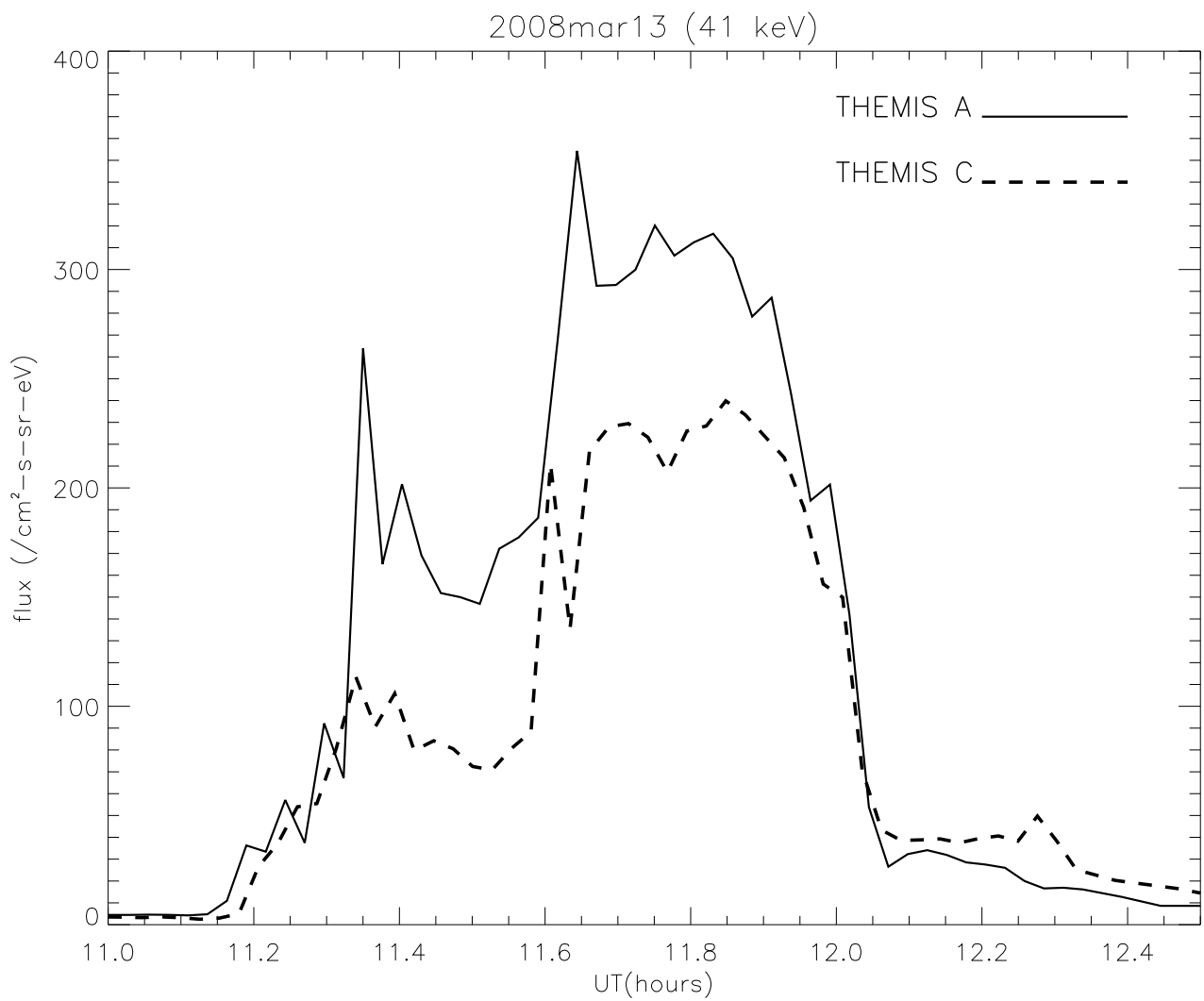


Figure 8: Comparison of 41 keV THEMIS flux profiles between satellites A and C for an event on 2008 March 13, the satellites being $2.62 R_e$ apart.

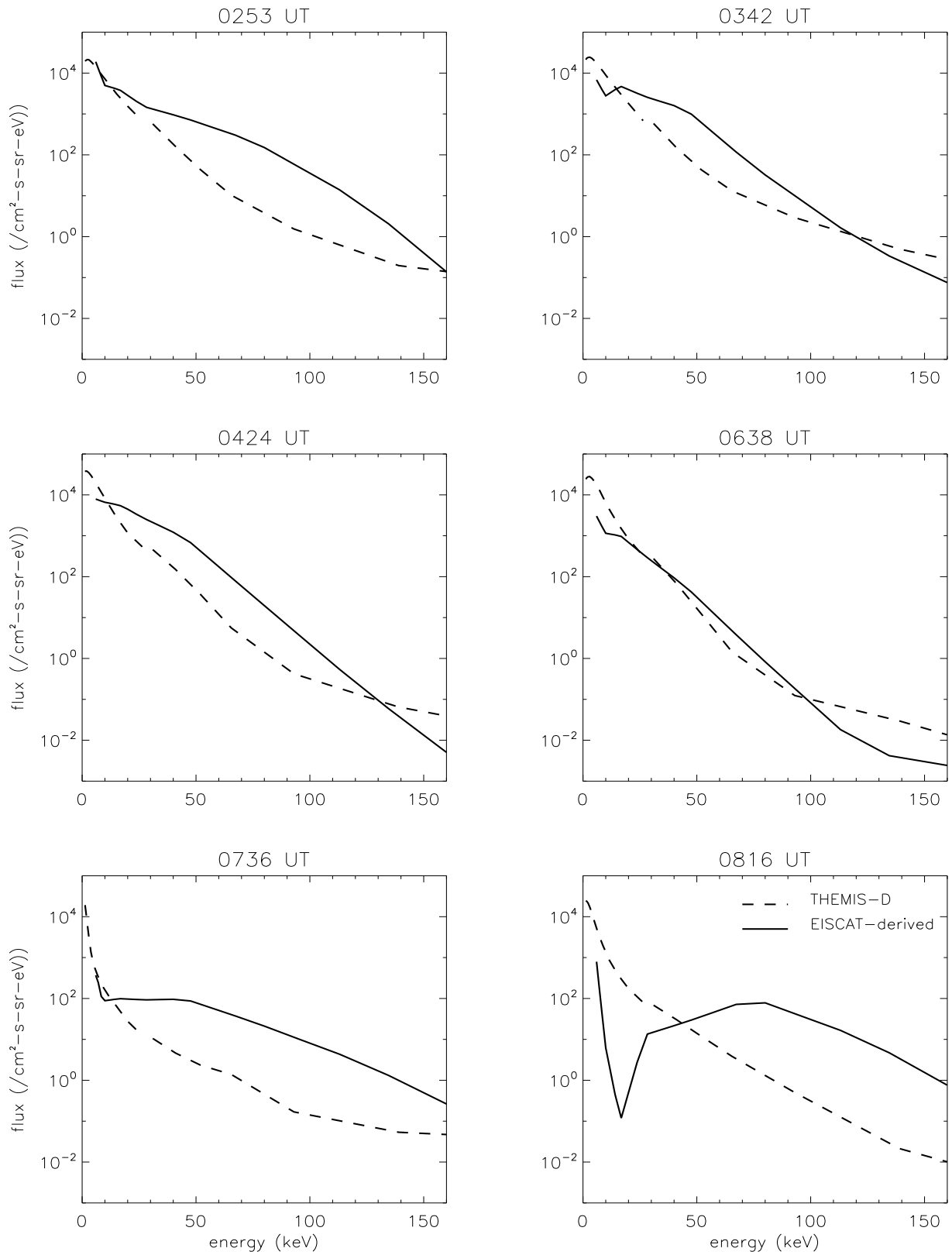


Figure 9: Comparison of THEMIS-D and EISCAT-derived spectra at selected times on the morning of March 9 2008 (solid lines: EISCAT-derived spectra; dashed lines: THEMIS-D spectra).

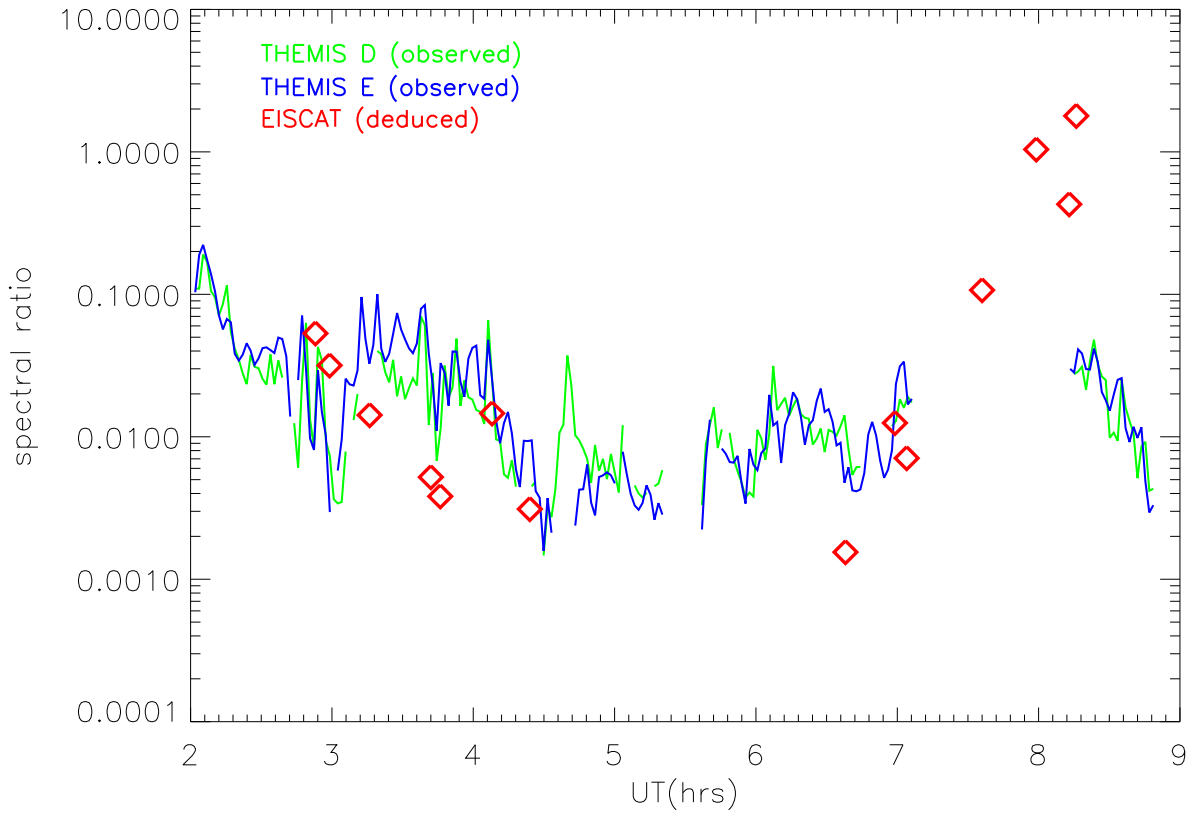


Figure 10: Comparison of spectral hardness: THEMIS D (green); THEMIS E (blue); EISCAT-deduced (red). (Fluxes $< 0.1 \text{ cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$ were discarded, which caused the gaps in the THEMIS profiles.)

IRIS UT range	04-06	10-12	16-18	22-24	Total
1. Days considered	52	42	46	54	194
2. Days rejected due to belt contamination	15	4	17	26	62
3. Days without radiation belt contamination (1 - 2)	37	38	29	28	132
4. Days from (3) with measurable 41 keV flux event	22	33	28	21	104
5. Days from (4) with clearly associated abs event ≥ 0.1 dB	16	18	12	20	66
6. Days from (5) without associated magnetic substorm	0	2	1	0	3

Table 1: General occurrence statistics for the four IRIS sectors. (6. According to SME index (<http://supermag.jhuapl.edu/substorms/>))

Flux range	No. of values	Median (dB)	Range (dB)	Chance (%) of abs being at least	
				1.0 dB	0.3 dB
IRIS 04-06 UT (18 samples)					
≥ 330	9	0.50	0.00 - 3.35	11	67
100 - 330	5	0.88	0.18 - 1.69	20	80
33 - 100	0			0	0
10 - 33	4	3.00	0.04 - 3.00	75	75
3.3 - 10	0			0	0
IRIS 10-12 UT (70 samples)					
≥ 330	12	0.42	0.26 - 1.19	8	92
100 - 330	16	0.70	0.20 - 1.00	6	69
33 - 100	19	0.10	0.03 - 0.85	0	32
10 - 33	14	0.10	0.02 - 0.50	0	7
3.3 - 10	6	0.05	0.03 - 0.06	0	0
1.0 - 3.3	3	0.05	0.05 - 0.05	0	0
IRIS 16-18 UT (26 samples)					
≥ 330	15	0.12	0.00 - 3.32	13	40
100 - 330	6	0.05	0.00 - 0.46	0	17
33 - 100	1	0.03	0.03 - 0.03	0	0
10 - 33	2	3.75	0.01 - 3.75	50	50
3.3 - 10	2	0.20	0.03 - 0.20	0	0
IRIS 22-24 UT (24 samples)					
≥ 330	12	0.90	0.50 - 4.00	42	100
100 - 330	3	0.60	0.33 - 0.60	0	100
33 - 100	3	0.28	0.00 - 0.74	0	33
10 - 33	5	0.20	0.10 - 0.60	0	40
3.3 - 10	1	0.25	0.25 - 0.25	0	0

Table 2: Detailed occurrence statistics for the four IRIS sectors (138 samples in total).

Correlated	Partialled-out	22-24 UT (22 values)			10-12 UT (29 values)		
		$\rho_{12,3}$	z	u	$\rho_{12,3}$	z	u
12	3						
logF, logA	r	0.56	0.63	0.4%	0.69	0.84	< 0.1%
logF, r	logA	-0.69	0.85	<0.1%	-0.64	0.75	< 0.1%
logA, r	logF	0.13	0.13	29%	0.20	0.20	16%

Table 3: Results of partial correlation analysis of observed flux (F), strength of absorption (A), and radial distance of satellite (r) for IRIS sectors 22-24 UT and 10-12 UT. ($\rho_{12,3}$ is the correlation coefficient between parameters 1 and 2 with parameter 3 partialled-out, and u is the probability, based on Fisher's z-transform, that the correlation arose by chance.)

IRIS sector	Noon	Dusk	Midnight	Dawn
UT	10-12	16-18	22-24	04-06
LT (approx)	11.5-13.5	17.5-19.5	23.5-1.5	5.5-7.5
Number of points	38	10	22	15
Correlation coefficient	0.74	-0.10	0.73	-0.43
A on F_{10} regression	$A = 0.019 \times F_{10}^{0.560}$	$A = 1.068 \times F_{10}^{-0.092}$	$A = 0.096 \times F_{10}^{0.390}$	$A = 23.09 \times F_{10}^{-0.632}$
A on F_{10} standard error factor	1.67	3.44	1.65	2.37
F_{10} on A regression	$F_{10} = 413.3 \times A^{0.980}$	$F_{10} = 160.5 \times A^{-0.106}$	$F_{10} = 230.9 \times A^{1.369}$	$F_{10} = 175.6 \times A^{-0.286}$
F_{10} on A standard error factor	1.97	3.78	2.56	1.79
Probability of chance occurrence	$<10^{-4}$	0.21	10^{-4}	0.14

Table 4: Regression results between A dB and F_{10} $\text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{eV}^{-1}$ for IRIS in the noon, midnight, dawn and dusk. sectors. (Probability of chance occurrence according to Fisher's z-transform [Fisher, 1921; Moroney, 1951].)

Absorption (A) range	No. of values	Median flux	Range of flux	Chance (%) of flux being in range		
				0 - 10	10 - 100	>100
$0.1 \leq A < 0.3$	6	3	0 - 10	100	0	0
$0.3 \leq A < 1.0$	12	140	0 - 400	8	33	58
$A \geq 1.0$	6	380	200 - 500	0	0	100

Table 5: Detailed occurrence statistics for the midnight IRIS sector, using absorption as the primary selection variable (24 samples in total). These flux values have not been adjusted to $10R_e$.