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Localized absorption events in the afternoon sector

H. Ranta,[1] A. Ranta,[1] J. K. Hargreaves[2] and S. Browne[3]

[1]Geophysical Observatory, SF-99600, Sodankylä, Finland;
[2]Engineering Department, University of Lancaster, Bailrigg, Lancaster LA1 4YQ, U.K.

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Abstract—The westward expansion of a substorm is accompanied by IPDP magnetic pulsations which appear in the afternoon sector shortly after the onset of a substorm in the midnight sector. Observations suggest a close correlation between some localized riometer absorption events and IPDP pulsations. The size and movement of absorption events has been studied using imaging riometer measurements at Kilpisjärvi (69.05°N, 20.79°E, $L = 5.9$), which give much better spatial and time resolution than earlier riometer measurements using broad antenna beams. The absorption occurs in a rather small spot-like area varying in size from 30 km by 30 km to 180 km by 130 km. In all cases the absorption area was smaller than the field of view of the imaging riometer, which covers a 240 km square at height 90 km. These afternoon side absorption events are the most localized events yet observed by imaging riometer. Sometimes southward movement was seen, at about 12–22 km/min (200–367 m/s). Small scale structure was also observed within the events. © 1997 Elsevier Science Ltd. All rights reserved

INTRODUCTION

The westward expansion of a substorm is characterized by IPDP (intervals of pulsation of diminishing period) magnetic pulsations which appear on the evening side of the auroral zone shortly after the onset of a substorm, in the midnight sector (Fukunishi, 1969, Heacock, 1973, Lukkari *et al.*, 1975, Lukkari and Kangas, 1976, Lukkari *et al.*, 1977). These pulsations seem to be generated via ion cyclotron resonance involving protons having energy of 50–100 keV (Fukunishi, 1969, Gendrin, 1970, Heacock, 1973, Kangas *et al.*, 1974). From the statistics of the occurrence of IPDP events at different latitudes, Heacock *et al.* (1976) concluded that these events have a close connection with the plasmapause, as should be expected from the theoretical considerations of ion cyclotron instability (Kennel and Petschek, 1966). Although the idea of continuous increase in the amplification of waves with increasing cold plasma density has been shown to be incorrect (Lin and Parks, 1974, Gendrin, 1975), the bulge of the plasmasphere on the evening side is still a preferential region of amplification according to the theory by Perraut and Roux (1975). Several mechanisms have been proposed to interpret the rising frequency characteristics of IPDP pulsations. Contributions from inward drift of the interaction region (Gendrin *et al.*, 1967), energy-dependent azimuthal drift of protons (Fukunishi, 1969), changes in cold plasma density (Lin and Parks, 1974), and combinations of these (Heacock, 1973, Kangas *et al.*, 1974) have been considered. In contrast the calculations by Perraut and Roux (1975) show that for a given pitch angle anisotropy the frequency at which maximum amplification occurs depends only on the local proton gyrofrequency. The frequency of magnetic pulsations during each event is greatly controlled by the L-shell of the generation region (Lukkari *et al.*, 1977). This is in agreement with the theory by Perraut and Roux (1975). In this case the rising frequency of IPDP pulsations should be the result of the inward drift of the interaction region. But in some cases the location of maximum amplitude does not seem to depend on the frequency of pulsations and thus cold plasma changes and dispersion effects should also be considered, as was suggested by Lin and Parks (1974, Lin and Parks, 1976).

The observed similarities, according to the results obtained by Lukkari *et al.* (1977), in the temporal and latitudinal behaviour of short-period magnetic pulsations and riometer absorption events in the afternoon sector are so striking that there can be no doubt of a close relation between them. The appearance of enhanced electron precipitation in the afternoon sector should be related to the westward drift of protons responsible for the generation of IPDP waves, and the riometer absorption may be produced by high-energy electrons precipitated through parasitic interactions with ion cyclotron waves as proposed by Thorne and Kennel (1971), Thorne *et al.* (1974) and Davidson

(1978). The parasitic interaction depends strongly on cold plasma density as shown by Thorne and Kennel (1971). Thus it is to be expected that the narrow latitudinal width of electron precipitation is caused by sharp plasma density gradients at the plasmapause and/or in detached plasma regions.

Ranta *et al.* (1983) studied substorm related absorption events in the afternoon–early evening sector during magnetically disturbed periods. After onset in the midnight sector they observed absorption events occurring simultaneously in spatially confined regions at high and low L-values separately, $L > 6$ and $L < 4.8$. At high latitudes PiB pulsations (short irregular pulsations), and at low latitudes IPDP pulsations were seen simultaneously with the absorption events. They related the absorption at high latitudes to direct magnetospheric injection and that at lower latitudes to substorm-injected protons near the plasmapause region.

Grafe *et al.* (1984) studied the occurrence of riometer absorption and eastward electrojet in the afternoon sector. During magnetospheric substorms an enhancement of riometer absorption and a positive magnetic disturbance do not always occur simultaneously in the afternoon sector. The observations reveal that when a westward electrojet is observed on the poleward side of the eastward electrojet, a riometer absorption is always observed. The westward electrojet lasts a short time. Thus it seems probable that the higher energy component of electron precipitation (>40 keV) in the afternoon sector is related to a process which leads to the formation of a westward electrojet on the poleward side of the eastward electrojet.

Söraas *et al.* (1980) and Maltseva *et al.* (1981) have put forward a model to explain the extent and location of the IPDP generation region in the magnetosphere and to explain the upward sweep of the IPDP frequency. In their model energetic protons are injected at the onset of a substorm into the nightside magnetosphere covering a certain region in L and local time. The injection occurs along the so-called McIlwain's injection boundary. Its shape depends on magnetic activity, as given by Mauk and McIlwain (1974). The protons drift azimuthally westward from the injection boundary and generate ion-cyclotron waves in the evening-to-afternoon sector of the magnetosphere where favourable conditions are met: most probably at or inside the plasmapause. The energy of the protons responsible for wave generation does not change much during the IPDP event, as was also pointed out by Fraser and Wawrzyniak (1978). Based on the model the time delay between the arrival of drifting protons at different L-values can be calculated as a function of the local time, Kp index and the energy of protons (Pikkarainen *et al.*, 1986).

MEASUREMENTS

The development of riometer absorption events in the afternoon sector has been observed by the imaging riometer at Kilpisjärvi (69.05°N, 20.79°E, $L = 5.9$). The system operates at 38.2 MHz, and uses an array of 64 crossed half wave dipoles over a ground plane, with a set of Butler matrices to form 49 independent beams. The signals are received by time sharing into 7 riometers, the outputs of which are digitized (12 bits) every second. The time resolution is 1 s. The zenithal beam is 13 degrees wide between half power points and the best spatial resolution at 90 km is 20 km. The oblique beams are considerably wider. A view of the coverage at the 90 km is shown in Fig. 1. The eighth riometer is connected to a wide-beam antenna at the site which covers a circle with radius of 50 km at the 90 km level (Hargreaves *et al.*, 1995, Detrick and Rosenberg, 1990).

The absorption events were also observed by the network of riometer stations located between L-values 4–14 and between longitudes 30°E–20°W. A list of the riometer stations with their geographic coordinates and operating frequencies is given in Table 1. The locations of the stations are shown in Fig. 1.

The data between the time interval 12–18 UT from 2 September 1994 to 18 July 1995 were analyzed. In the wide-beam riometer data, there were 66 cases where the absorption values were $A > 1$ dB. Additionally there were 32 cases where the absorption was just observable, 98 events all together.

From this data set eight events listed in Table 2 were studied in more detail. During these events at the same time four IPDP type pulsation were observed at magnetic pulsation stations in Finland, Fig. 3. For the events the position of plasmapause was calculated using the empirical model of Carpenter and Anderson (1992).

During the event on 15 September 1994 in the interval 13–14 UT, EISCAT incoherent scatter radar measurements were carried out at Tromsø (E. Turunen, private communication). An extraordinary ionization event occurred at 1310–1314 UT when ionization was seen at very low altitude, below 70 km. This indicates that the energy of precipitating electrons was at least several hundred keV.

AFTERNOON SIDE ABSORPTION EVENTS

Figure 2 presents four examples of quick look plots of the wide-beam measurements together with the

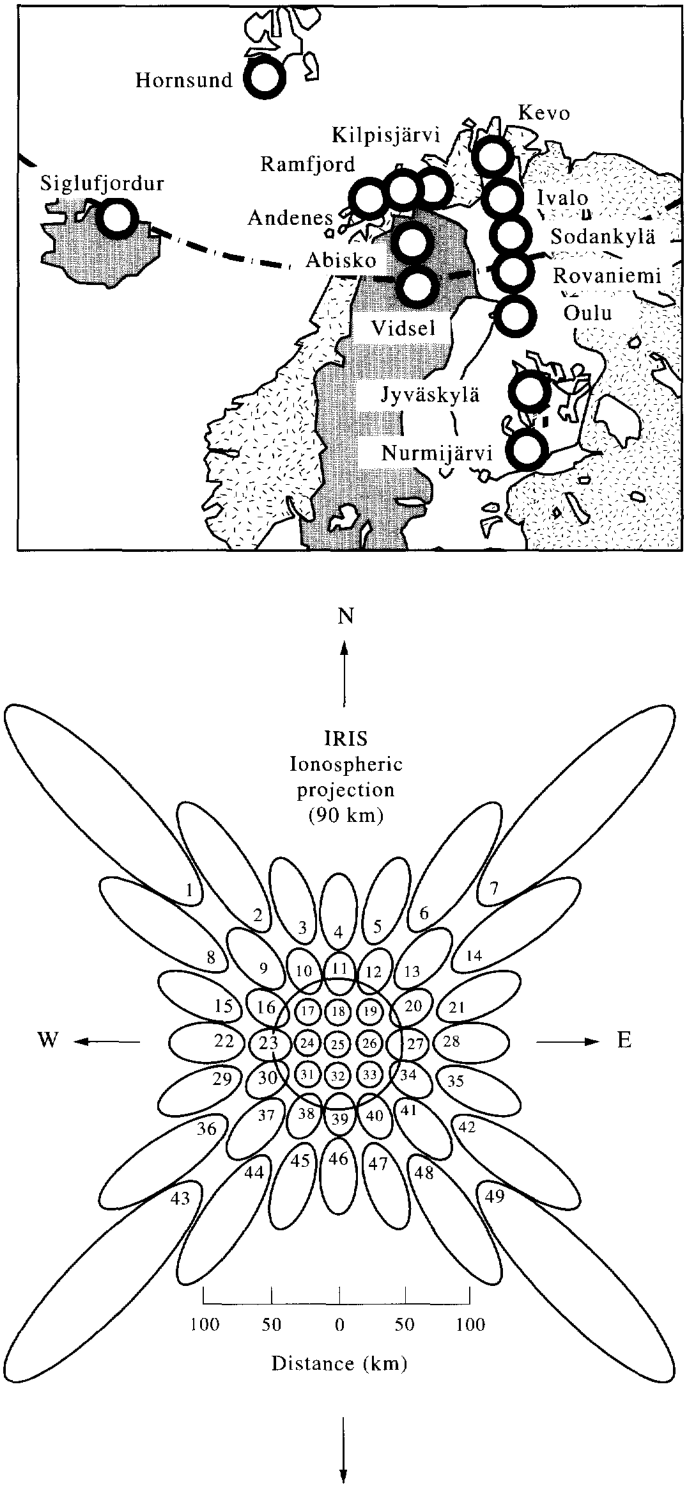


Fig. 1. (a) Riometer stations. (b) The patterns of antenna beams of the imaging riometer at Kilpisjärvi, at the height of 90 km.

Table 1. Riometer stations

Station	Frequency MHz	Geographic coordinates Latitude	Longitude
Hornsund	HOR 30.0	77°00′N	15°36′E
Kilpisjärvi	KIL 38.2	69 03	20 47
Ivalo	IVA 30.0	68 36	27 25
Sodankylä	SOD 30.0	67 25	26 24
Rovaniemi	ROV 32.4	66 34	26 01
Jyväskylä	JYV 32.4	62 24	25 22
Abisko	ABI 30.0	68 24	18 54
Siglufjordur	SIG 30.0	66 12	18 54 W

quiet day curves for the days 11 September 1994 (day 254), 20 March 1995 (day 79), 14 September 1994 (day 257) and 15 September 1994 (day 258).

The case on 11 September 1994 in the interval 14–15 UT is a typical afternoon side absorption event. The absorption is between 1 and 2 dB, the event lasts about 20 min and only a single peak is seen. The event on 20 March 1995 in the interval 13–14 UT was the strongest event during the studied time interval. The absorption observed even by the wide beam riometer was higher than 5 dB. During the event on 14 September 1994 in the interval 14–15 UT the wide-beam riometer also observes some structure in the absorption. Clearly two maxima are seen. Two different IPDP events were observed in magnetic pulsation data, Fig. 3, but they occur a little earlier than CNA. The case on 15 September 1995 in the interval 1230–1330 UT gives an example of an event where the absorption seen by wide-beam riometer is less than 1 dB, while, as will be shown later, the narrow beam instrument observes a very sharp rise in absorption. Figure 2 gives also the observed magnetic pulsations during the studied cases. During six cases a IPDP type pulsation, during four cases unstructured Pc1 pulsation, during one case structured Pc1 pulsation and during one case no pulsation was observed. The absorption and pulsation events do not occur equally at the same time.

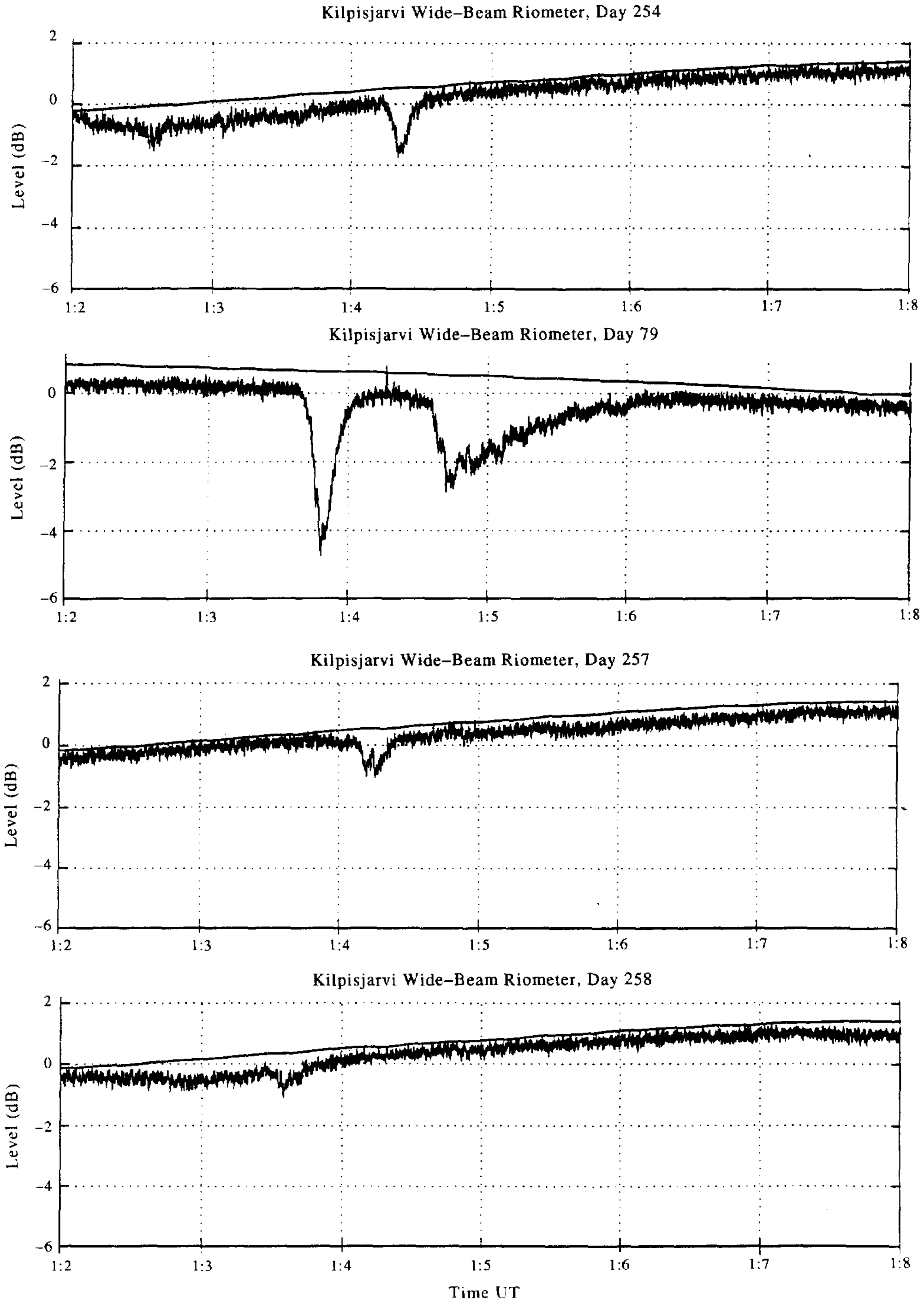
During each of these four events the broad beam riometer network (Fig. 1) observed absorption at Abisko because the antenna beams of the imaging riometer overlap the broad antenna beam of Abisko. At Rovaniemi weak absorption was observed on 12 and 14 September 1994. At Siglufjordur absorption was observed on 12 September 1994 at about 1520–1540 UT, indicating westward movement of the absorption area.

From the wide-beam measurements the duration of the afternoon side absorption events was determined for 33 clearest cases. The mean duration time was 15.7 min. In some cases the events overlap and two different events are seen in the wide-beam measurements as a single event. Therefore the mean duration time determined by the wide-beam antenna may be overestimated and the real duration time of an event can be shorter. Typically this type of event lasts from some minutes up to 30 min.

Figure 4 illustrates the behaviour of an absorption event in the afternoon sector on 14 September 1994 in the interval 1400–1432 UT. Each panel covers a 240 km square at the 90 km level, and the images are 30 s apart. North is to the top and east is to the right. The event starts at 1409:30 UT. To begin with the

Table 2. The selected absorption events in the afternoon sector 12–18 UT

Time	Kp index 12–24 UT	Time of absorption	Time of pulsation	Plasmapause L-value
11 September 1994	3 3 3 2	1415–1430 UT Pc1 1415–1505 UT	Pc1 1320–1425 UT	3.8
12 September 1994	3 3 2 2 1710–1740 UT	1436–1508 UT No Pc1 or IPDP	IPDP 1444–1515 UT	3.8
14 September 1994	3 2 1 2	1410–1424 UT IPDP 1358–1415 UT	IPDP 1345–1400 UT	4.3
15 September 1994	2 2 2 3	1230–1324 UT	Unstruct. PC1 1255–1310 UT	4.7
30 October 1994	5 4 5 4	1230–1250 UT	Pc1/IPDP 1145–1248 UT	3.0
20 March 1995	1340–1400 UT 1436–1600 UT	IPDP 1333–1405 UT Unstruct. Pc1 1430–1545 UT	4.7	
26 April 1995	2 3 2 2	1454–1510 UT	Unstruct. Pc1 1445–1525 UT	4.2
3 June 1995	3 3 3 4	1312–1318 UT 1328–1348 UT	Unstruct. Pc1 1310–1338 UT	3.9


Kilpisjarvi Wide-Beam Riometer, Day 254

Kilpisjarvi Wide-Beam Riometer, Day 79

Kilpisjarvi Wide-Beam Riometer, Day 257

Kilpisjarvi Wide-Beam Riometer, Day 258

Fig. 2. Recordings of wide-beam riometer at Kilpisjärvi on 11 September 1994, 20 March 1995, 14 September 1994 and 15 September 1994. The quiet day curves are also shown.

most intense absorption covers an area of 30 km by 30 km. Later the absorption covers a larger area of 240 km by 180 km. The event lasts 4.5 min. After 1 min the absorption reappears almost in the same area as before. In this case the absorption initially covers an area of 70 km by 120 km, reducing later to 30 km by 30 km. This event lasts 5 min. The maximum absorption during both cases is about 2 dB. No clear movement can be observed.

Figure 5 shows a similar display for the absorption event on 15 September in the interval 1326:20–1346:40 UT. The images in this case are 20 s apart. At the beginning of the event the absorption area is 40 km by 40 km. Later it expands westward to 155 km by 75 km. The maximum absorption during this event is 2.6 dB. No clear movement can be observed. After 1332 UT there are two different maxima in the absorption. The event lasts 14 min.

The colour panels for the absorption event observed on 11 September 1994 in the interval 1400–1431 UT are shown in Fig. 6. The images are 30 s apart. The event starts in the north at 1413 UT and lasts 13 min. At the beginning the absorption area covers the whole antenna area in the east–west direction, and in the

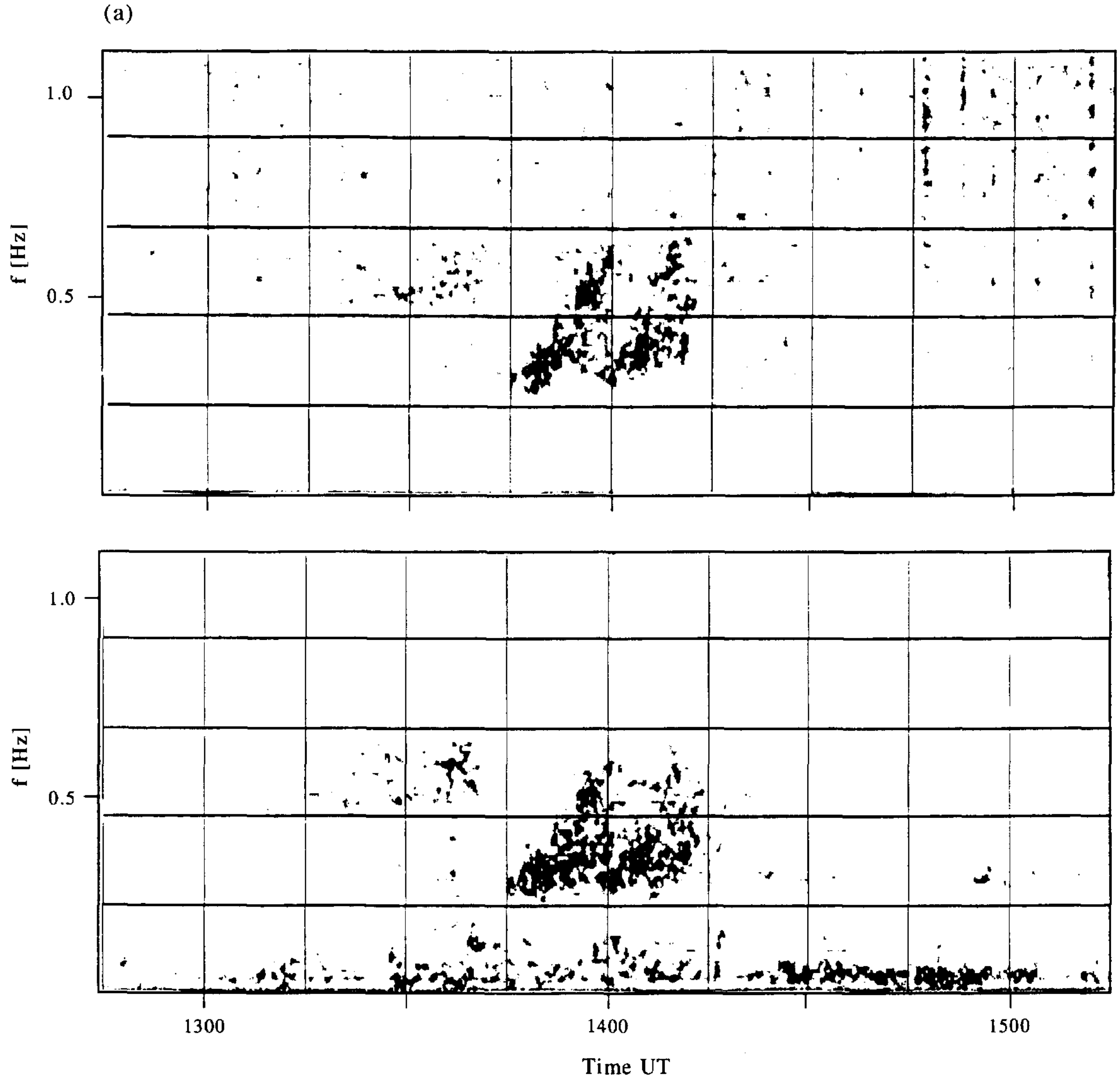


Fig. 3. Dynamic spectra of geomagnetic pusations recorded at Sodankylä (upper panel) and Oulu (lower panel) (a) on 14 September 1995 (b) on 20 March 1996.

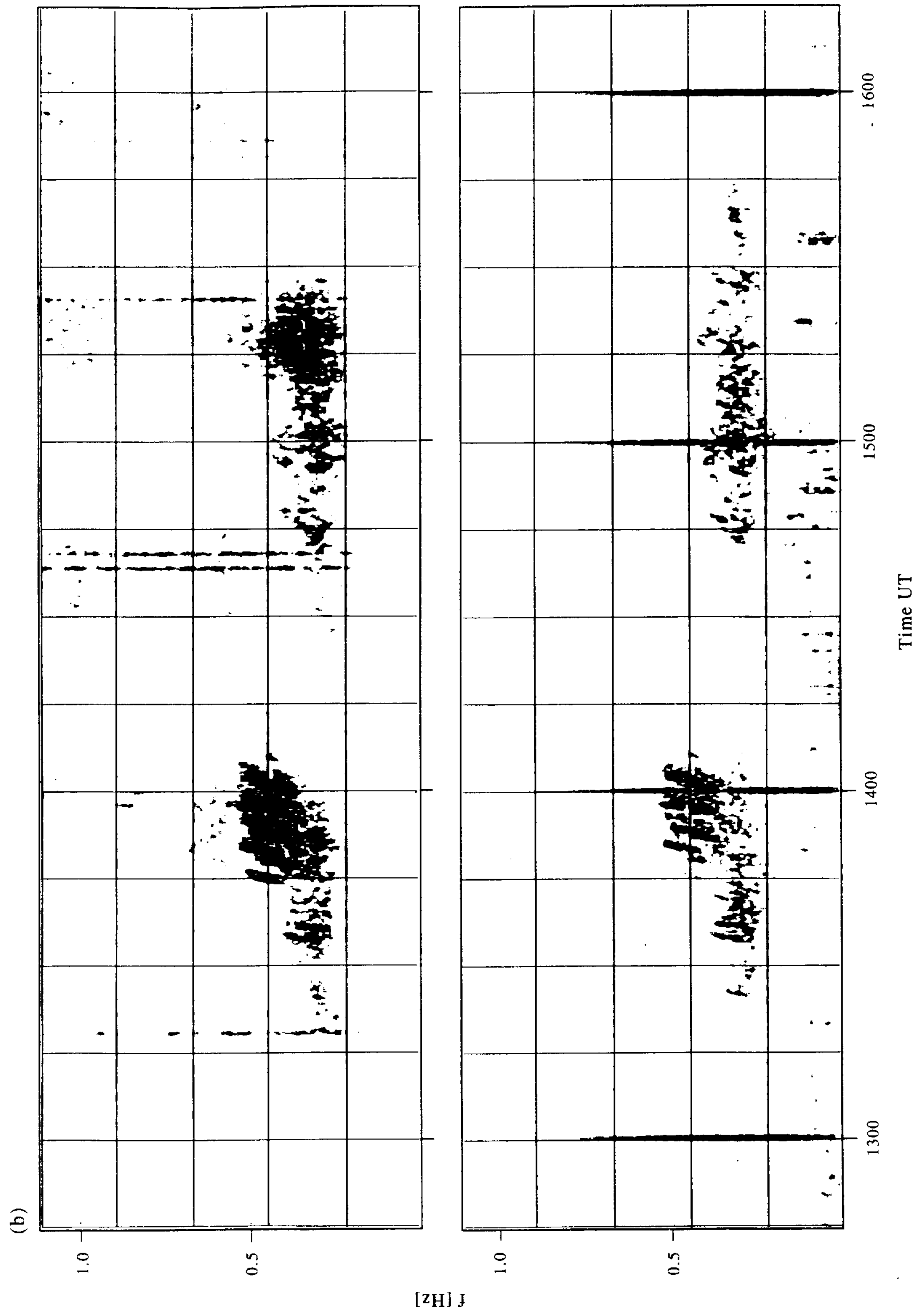


Fig. 3—*continued.*

north–south direction about 80 km. The absorption moves southward and westward, and later it covers about 200 km in the north–south direction. The southward velocity is about 22 km/min. The maximum absorption is 2.3 dB.

The colour panels for the strongest absorption event on 20 March 1995, in the interval 1330–1430 UT, are presented in Fig. 7. The maximum absorption is 6.2 dB. The absorption begins in the center of the antenna area and covers an area 180 km by 130 km. It moves southward and lasts 16 min. The southward velocity is about 12 km/min.

If one compares the wide-beam and imaging riometer observations, they show often different features. The events are highly localized, and often occupy such a small fraction of the beam of the wide-beam riometer that the event may not be seen at all. Clearly, the poor spatial resolution of wide-beam riometers in this type of event may often lead to erroneous conclusions in data interpretation, both in statistics and in estimating the size and apparent movements of precipitation regions.

According to Nevanlinna (1995), 60% to 70% of days during a year have luminous aurora between latitudes 65° and 70°. The absorption events studied here with a narrow-beam riometer occur on about 50% of auroral days, indicating 30% to 35% of days during the year. The stronger events are also observed by a wide-beam riometer, but only 30% of the auroral days.

Small-scale structure in the afternoon side absorption events can be seen in the colour plots produced by imaging riometer data. A better way to look at the fine structure of this kind of event is to study the signals from different beams. In Fig. 8 the data with 1 s time resolution is presented for 14 September 1994 in the interval 14–15 UT for the beams 04, 08, 24 and 35, and for 15 September 1994 in the interval 13–14 UT for the beams 02, 15, 22 and 42. The beams were selected to show best the small scale structure of ionization. On 14 September 1994 in the interval 14–15 UT during the first event at 1404–1420 UT all those beams observe three maxima. However the shape of the absorption bays is different in each beam. For example the maximum absorption in beam 04 was seen during the first maximum and in beam 35 during the second maximum.

On 15 September 1994 in the interval 13–14 UT during the first absorption event at 1309–1318 UT the absorption was observed only by beam 02, which saw very sharply decreasing absorption. The second event was seen by beams 15 and 22 at 1325–1342 UT. Both beams observed four maxima during this event; the highest absorption in both beams was seen during the second maximum. Beam 42 did not see any absorption in the interval 13–14 UT.

CONCLUSIONS AND DISCUSSION

The main results are summarized as follows.

1. The absorption area during the afternoon side absorption events is highly localized, often occupying a spotlike area from 30 km by 30 km up to as much as 180 km by 130 km. In all the cases studied the absorption area was smaller than the field of view of the imaging riometer, covering a 240 km square at 90 km level.
2. The afternoon side absorption events are the most localized events observed by imaging riometer so far.
3. A movement was not observed during each event. Sometimes southward movement was observed between 12 and 22 km/min (200 and 367 m/s).
4. The observed occurrence of afternoon side absorption events depends much on the antenna used. If narrow beam antennas are used, the events will be seen more often because of their localized nature.
5. Small scale structure is observed within the events.
6. The events may last from some minutes up to 30 min. The mean duration time of the events studied was 15.7 min.

Ranta *et al.* (1983) found that after an onset in the midnight sector absorption events occurred in the afternoon sector in spatially confined regions at high and low L-values. At high latitudes PiB pulsations and at low latitudes IPDP pulsations were seen simultaneously with the absorption events. During the events studied in this paper some IPDP pulsations were observed at the same time as absorption at Kilpisjärvi.

The area of the image obtained by the riometer system at Kilpisjärvi covers $L = 5.6$–6.3. For the events studied, model calculations, using the empirical model of Carpenter and Anderson (1992), give the position of the plasmapause as $L = 3.0$–4.7 which is 0.9–2.6 L-values to the south of where the events were seen. For comparison, the positions of the plasmapause for the 13 afternoon side absorption events studied by Ranta *et al.* (1983) and Pikkarainen *et al.* (1986) were calculated. In those cases also, the calculated position of the plasmapause was about 0.7–1.3 L-values south of the observed absorption and IPDP events.

This study supports the earlier findings that sometimes electron precipitation in the afternoon sector is related to the westward drift of protons responsible

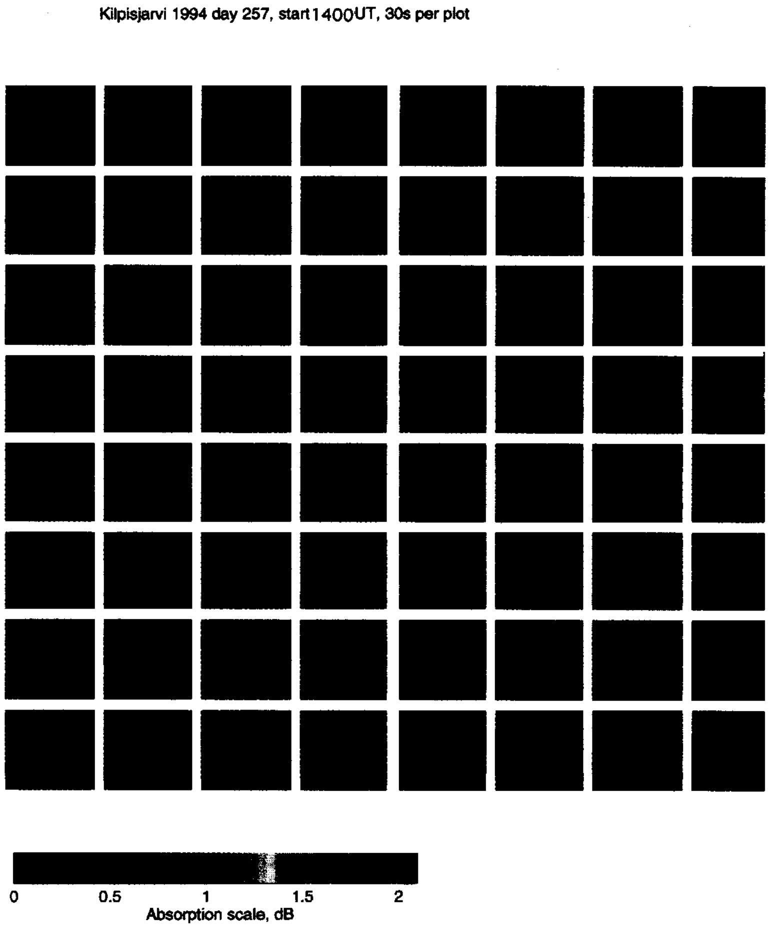


Fig. 4. Absorption images at Kilpisjärvi on 14 September 1994 in the interval 1400–1432 UT. The images are at every 30 s with the maximum absorption of 2.3 dB.

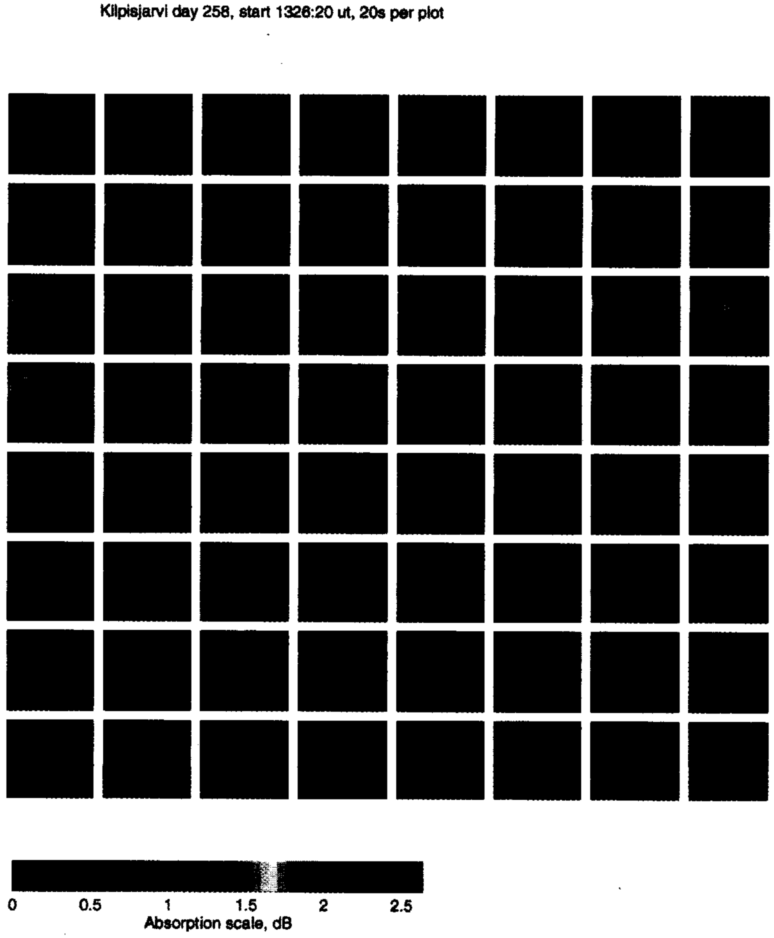


Fig. 5. Absorption images at Kilpisjärvi for the whole antenna area on 15 September 1994 in the interval 1326.20–1326.27 UT. The images are at every 60 s with the maximum absorption of 2.7 dB.

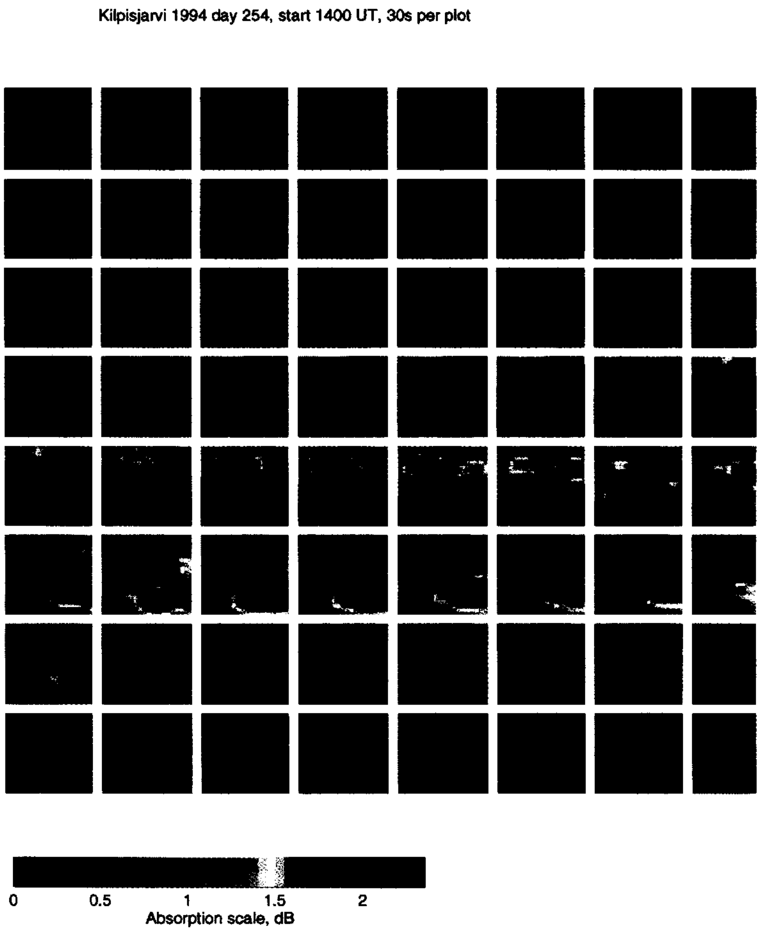


Fig. 6. Absorption images at Kilpisjärvi for the whole antenna area on 11 September 1994 in the interval 1400–1431 UT. The images are at every 30 s with the maximum absorption of 2.3 dB.

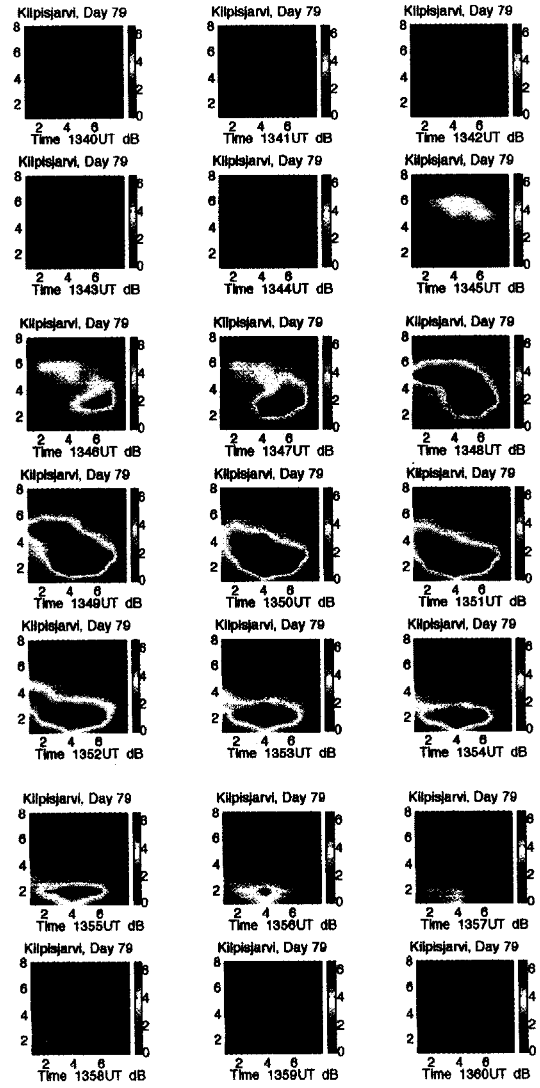


Fig. 7. Absorption images at Kilpisjärvi on 20 March 1995 in the interval 1330–1430 UT. The images are at every minute with the maximum absorption of 6.2 dB.

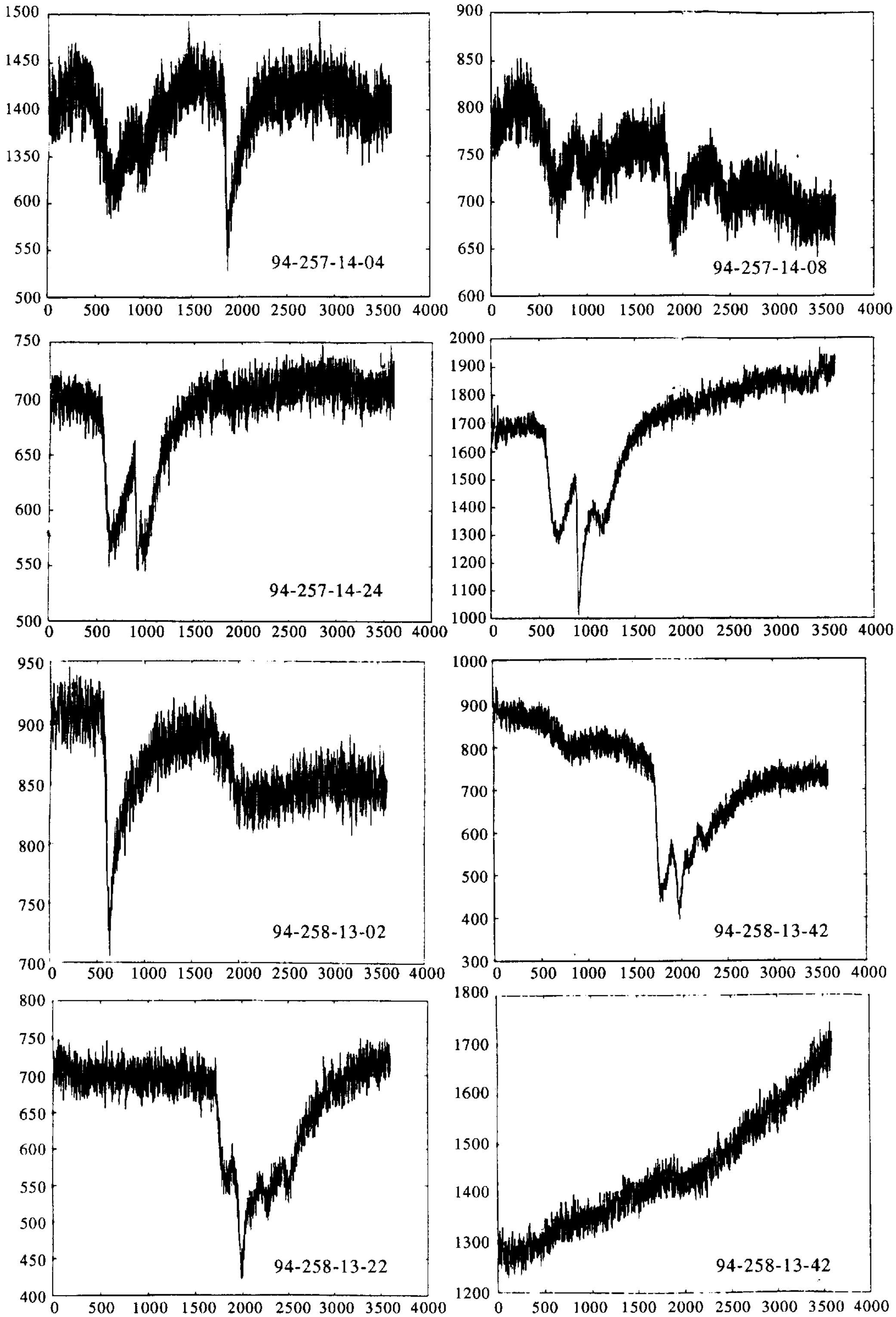


Fig. 8. The imaging riometer recordings at Kilpisjärvi with 1 s time resolution on 14 September 1994 in the interval 14–15 UT for the beams 04, 08, 24 and 35 and on 15 September 1994 in the interval 13–14 UT for the beams 02, 15, 22 and 42.

for the generation of IPDP waves. The EISCAT data during one of the events indicates hard, at least several hundred keV, precipitation. Structured regions of dense plasma of plasmaspheric origin are known to appear in the afternoon–evening sector at radii larger than those of the 'main' plasmasphere. Also there are variations in the real position of the plasmapause compared to the mean value of a model. The localized absorption area at higher L-shells as given by model calculations may indicate that the electron precipitation is caused by sharp plasma density gradients in detached plasma regions in the outer plasmasphere.

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