Conjugate observations of EMIC waves

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Abstract.

We compare EMIC waves observed by the electric field instrument on Polar with simultaneous Pc1 pulsations detected at the subauroral Sodankylä station. We studied 44 passes where Polar was within ±1.5 hours in MLT from Sodankylä during a Pc1 pulsation event. In 70% of these passes a matching EMIC wave was observed in space. This shows that ground Pc1's indeed originate at high altitudes in the magnetosphere and have their source field line within a rather limited (±1-1.5 h) MLT range. It also limits horizontal ducting of waves in the longitude direction to less than about 1000-1500 km, and gives a lower limit of about 3 h on the MLT extent of a typical EMIC wave band in space. Out of 69 EMIC events, 75% were observed at Sodankylä. This restricts the scale of ionospheric modification on the amplitude and frequency of waves. In several passes two or three EMIC waves corresponding to different frequency branches were observed simultaneously. We discuss the location, frequency, amplitude and ground visibility of the EMIC waves of these three branches separately. The results emphasize the high-latitude dayside as a source of EMIC waves observed on ground.

1. Introduction

Geomagnetic Pc1/2 pulsations observed on the ground in the 0.1 - 5.0 Hz frequency range are due to electromagnetic ion cyclotron (EMIC) waves generated in the equatorial magnetosphere by the ion cyclotron instability involving protons and heavier ions in the energy range of about 10 - 100 keV [Brice, 1965; Cornwall, 1965]. Pc1/2 pulsations are frequently observed at mid- and high-latitude stations. The common form of Pc1/2 pulsations observed around the local morning at low- to mid-latitudes is structured pulsations (also called pearls), characterized by regular variations in amplitude. Unstructured pulsations are typically observed at high latitudes around local noon.

The growth of EMIC waves is organized to frequency bands limited by the gyrofrequencies of major ion species (H^+, He^+ and O^+). Also, wave propagation is affected by the abundance of the two heavy ions (He^+ and O^+). Waves generated above the equatorial gyrofrequency of He^+ ions, F_{He^+}, may encounter a stop band (cut-off frequency) where the left-hand (LH) polarized waves cannot propagate [Young et al., 1981]. However, the polarization may reverse to right-handed at a cross-over frequency and thereby enable the waves of this band to propagate through the stop band. Waves generated below F_{He^+} are guided along the magnetic field and propagate freely to the ionosphere unless a stop band formed by O^+-ions exists. A large amount of O^+-ions is found during storms or large substorms. During such conditions the wave band below F_{O^+} may also be amplified [Inhester et al., 1984; Thorne and Horne, 1997; Bräysy et al., 1998].

Ground-satellite conjugation studies comparing waves in space and on ground have been performed, e.g., using geosynchronous satellites [Bossen et al., 1976; Inhester et al., 1984; Perraut et al., 1984; Ludlow et al., 1989]. These observations were important in identifying the magnetic equator as a source region of Pc1/2 waves. Bossen et al. [1976] associated the large-amplitude LH polarized waves with f = 0.1-0.2 Hz observed by the ATS-1 satellite to simultaneous IPDP events observed on ground. Inhester et al. [1984] observed O^+-band waves in the Pc2 frequency range on the GEOS-2 satellite and at a ground station. These waves were connected with substorm injected O^+ ions in the late dawn sector. Perraut et al. [1984] compared EMIC waves on GEOS-1 and GEOS-2 satellites with observations at a conjugate ground station. They found that about half of the waves with $f > F_{He+}$ were observed on the ground while almost all waves with $f < F_{He+}$ propagated to the ground. Ludlow et al. [1989] reported of a single unstructured Pc1/EMIC wave event observed on a ground station and GEOS-1, separated by four units of L and 2.4 h in local time. In accordance with Perraut et al. [1984] the ground station observed mostly the lower frequency band while both He^+- and H^+-band waves were observed on the satellite.

The limited range of L-shells covered by geosynchronous satellites does not allow to study the location and width of EMIC wave source regions in radial direction. EMIC waves are often found at L-shells lower than the geosynchronous orbit. Due to the good waveguide properties the plasmapause [Mazur and Potapov, 1983] provides a favourable region for structured Pc1 pulsations [e.g. Webster and Fraser, 1985; Fraser et al., 1989; Erlandson and Anderson, 1996]. Also, during the storm main phase intense EMIC waves have been observed at very low L-shells [Bräysy et al., 1998]. On the other hand, the occurrence maximum of EMIC waves was found to be well beyond the geosynchronous orbit at about L = 8 - 9 in the afternoon sector [Anderson et al., 1992a]. Moreover, EMIC wave growth has been observed to increase in the outer daytime magnetosphere during magnetospheric compressions related to sudden increases in the solar wind dynamic pressure [Olson and Lee, 1983; Anderson and Hamilton, 1993]. EMIC waves at higher L-shells are mainly observed as unstructured Pc1's on ground [Mursula et al., 1996].

Satellite-ground conjunction studies of EMIC waves using polar-orbiting satellites [Ludlow et al., 1991; Hansen et al., 1995; Erlandson et al., 1996; Mursula et al., 1997, 1999] take advantage of the fact that satellite covers a wide range of L-shells at a roughly constant local time sector. Ludlow et al. [1991] studied conjunctions between DE-1 satellite and low- to mid-latitude ground stations (L = 1.8 - 3) and found seven cases where the satellite and ground stations observed waves simultaneously. All events were located close to L = 4.6 and around the magnetic equator. With one exception, all DE-1 events had most wave power below the local He^+ gyrofrequency. Hansen et al. [1995] studied seven cases of high-latitude Pc1 pulsations observed at an Antarctic station (70° MLAT) and on the Viking satellite. They concluded that the satellite field line must trace fairly close to such a high-latitude station in order for waves to be detected both by satellite and on ground. Waves which were recorded on field lines equatorward of the ground station were dominantly below F_{He^+} while events on field lines poleward were above F_{He^+}. Mursula et al. [1999] studied an event consisting of two bands of structured EMIC waves both of which were observed by the Finnish ground stations and by the Polar satellite in a conjugate position close to the plasmapause. The higher frequency band above F_{He^+} extended from the inner edge of the plasmapause through the plasmapause to outside the plasmapause (L=4.3 - 6.2) while the lower band below F_{He^+} was found in the plasmasphere and within the plasmapause (L=4.3 - 4.8).

In this paper we study the correspondence of Pc1/EMIC waves in space and on ground. We found 44 Polar passes in good conjunction with the Sodankylä (67.37°, 26.38° geog., 63.8° dipole INVlat, MLT = UT+2.6 h, L = 5.1) station at the time when Sodankylä observed Pc1 pulsations. 69 EMIC events were observed by the electric field instrument (EFI) onboard Polar satellite during these passes In section 2 we present the Polar satellite and the electric field instrument. In section 3 we describe two sample cases of wave events observed by Polar and ground, and present the statistical results of Polar observations. Section 4 discusses the main results, and final conclusions are presented in section 5.

2. Instrumentation

Polar has a highly eccentric polar orbit with apogee and perigee altitudes of 8.9 R_E and 1.8 R_E, respectively. The satellite spends most of its 18 hour orbit in the high-latitude polar area but crosses the plasmapause 4 times during an orbit. These crossing proceed slowly enough to allow monitoring of EMIC wave activity inside, at and outside the plasmapause. The Electric Field Investigation (EFI) instrument [Harvey et al., 1995] consists of two orthogonal pairs of wire booms in the satellite spin plane and one shorter pair of rigid booms parallel to the spin axis. The potential difference of each probe pair is measured to obtain the three components of the electric field vector from DC to over 20 kHz with a dynamic range of 0.02 - 1000 mV/m. EFI samples data over the whole orbit at the rate of

40 samples/s in its nominal operation mode.

Two coordinate systems were used in this study. In the field-aligned coordinate system, positive Z-axis (FACz) points in the direction of the Earth's magnetic field vector at the spacecraft's location, positive X-axis (FACx) lies in the plane of the Earth's magnetic field passing through the spacecraft's location and points towards the Earth, and Y-axis (FACy) completes the right-handed orthogonal system. In the spin plane coordinate system one coordinate (called "56"-axis) is perpendicular to the spin plane and two coordinates are in the spin plane. One of the spin plane coordinates (called "x-y"-axis) points in the direction which is as far away from the direction of the Sun as possible. The other spin plane coordinate ("z"-axis) points in the direction perpendicular to the x-y -axis and generally towards the north pole of the ecliptic. Satellite observations by double probe electric field instruments are always somewhat affected by the incomplete removal of the induced electric field and the related appearance of spin harmonics in electric field data. Nominal spin period of Polar is 6 seconds, resulting in spin harmonic bands in the Pc1 frequency range, in particular second and fourth harmonics at 0.33 Hz and 0.67 Hz, respectively. However, because of the narrow and known frequencies of the spin harmonics, EMIC waves can most often be easily recognized among them. Also the amplitude of spin harmonics is typically below that of EMIC waves.

3. Observations

The present study covers 32 months from the beginning of May 1996 to the end of December 1998. We have selected such Polar passes where the field line traced location of Polar was within ± 1.5 MLT hours and $\pm 5°$ INVlat from SOD (to be called the conjunction box) during a simultaneous Pc1 activity at SOD. We found 44 Polar passes fulfilling these conditions. We studied the Polar data during such passes even outside the conjunction box in order to find possible wave sources which might be further out from the SOD field line. In most passes a good conjunction was found both in the northern and southern hemisphere. Therefore the full half-orbit section in the same MLT sector was analyzed. Polar recorded 69 individual EMIC wave events on 37 passes, i.e., during most passes more than one wave event was recorded. A band of waves or wave bursts with a constant or steadily descending or ascending frequency is considered as one event, but waves at two (or more) different frequencies are treated as separate events even if they occur simultaneously. These 69 Polar EMIC events form the basis of our study. For each Polar event we registered the occurrence time and location (MLT, magnetic latitude, L-range), the frequency range and amplitude. In all events the frequency was smaller than the equatorial proton gyrofrequency, F_{H^+}, which was estimated using the Tsyganenko-89 model [Tsyganenko, 1989]. Amplitudes of Polar events were defined as the maximum peak-to-peak amplitude of the most intense electric field component. Events occurred at geomagnetically rather quiet times. The maximum Kp during the events was 4. The average Kp for the 44 passes was about 1.5, while for the whole time period from April 1996 to end of December 1998 it was 1.8.

3.1. Sample cases

Below we present two sample cases of EMIC observations during two passes. A third sample was discussed by Mursula et al. [1999].

April 16, 1998 On this day SOD observed two bands of Pc1 pulsations (see Figure 1a). An intense structured band appears at 0730-1000 UT with a mid-frequency decreasing from 0.6 Hz to 0.4 Hz during the event. Waves at roughly the same frequency reappear after 10 UT but much weaker and unstructured. The other band is much weaker and has a lower frequency of about 0.1-0.2 Hz. Figure 1

The Polar footprint is depicted in Figure 2. Here, a good conjunction occurred twice during a northbound leg, first, at about 0740 UT, when the satellite was in the southern hemisphere, and second, at about 09-10 UT, in the northern hemisphere. EFI observed two EMIC wave events from 0742 UT to 0748 UT when flying over the southern hemisphere (Figure 1b). These events are located at the plasmapause, as evidenced by increase of satellite potential from -3 V to -1 V at 0730-0750 UT (not shown). The first event at 0742-0744 UT (64° INVlat, 11 MLT) has its main power at about 0.5-0.6 Hz while F_{He^+} is about 0.7 Hz. The amplitude is about 6 mV/m. The frequency of this event matches well with the frequency of the simultaneous higher band seen at SOD. The second Polar event with 0.1-0.2 Hz is seen at 0746 UT (62° INVlat). The amplitude of this event is about 4 mV/m. F_{O^+} is 0.25 Hz during this event, implying that this is an O^+-band event. The frequency matches well with the frequency of the simultaneous lower band seen at SOD. In the northern hemisphere a very weak burst (not shown) of the O^+ waves of the second event was observed at 0912 UT at 63° INVlat, in good agreement with observations in the southern hemisphere and on ground. However, no sign of the He^+ waves of event one was found in the northern hemisphere. Instead, at rather high latitudes (68.2 - 71.9 INVlat), outside the plasmapause, Polar observed a third event, a long band of EMIC waves at a roughly constant frequency of 0.4 Figure 2

Hz, starting at 1000 UT and lasting for about 45 minutes (Figure 1c). The timing and frequency of this band corresponds to the weak band observed at SOD after 10 UT. This Polar event has an amplitude of almost 40 mV/m and F_{H^+} descends from 1.5 Hz to 1.0 Hz during this event.

October 27, 1996 The Pc1 pulsations observed at SOD are shown in Figure 3a and the Polar footprint over Scandinavia during this pass is depicted in Figure 4. The EFI instrument on Polar observed three EMIC wave events (see Figure 3b), the first event at 0835-0847 UT, the second at 0857-0915 UT and the third at 0932-0940 UT, all at different frequencies. While the first event was outside the plasmapause, the third event was already inside it. The first Polar event has a rather wide frequency band of about 0.6-1.2 Hz. Since F_{H^+} is about 1.4 Hz during this event these waves belong to the H^+-band. Simultaneously, two bands are observed in SOD, separated by a thin spectral cap at 0.5 Hz. The higher frequency band roughly matches the frequency of the Polar wave, although the Polar band extends to a slightly higher frequency. During this event, Polar is at noon MLT and at a rather high invariant latitude of about 68.5°, i.e., several degrees higher than SOD. The amplitude of this event, about 60 mV/m, is among the most intensive observed in this study. The second event in Polar is much weaker, having the maximum amplitude of about 4 mV/m. This wave occurs at a lower frequency between 0.45 Hz and 0.6 Hz. The estimated F_{He^+} is at the lower edge of this frequency range at about 0.5 Hz. At SOD, wave activity is greatly enhanced since about 0854 UT and the two bands observed earlier are now mixed with the maximum wave power between 0.4-0.6 Hz, matching the simultaneous

Figure 3

Figure 4

Polar wave frequency perfectly. The third Polar event with a high frequency of 1.8-2.3 Hz and an amplitude of about 2 mV/m is not seen at SOD. Instead, a very weak wave band extending up to about 1.4 Hz appears at SOD slightly before the Polar event. During this event $F_{H^+} = 3.9$ Hz and Polar is below the SOD latitude at about 62.5° INVlat.

3.2. Statistics of all Polar EMIC events

Figure 5 presents the MLT-invariant latitude distribution of the 69 Polar EMIC events. We have used the central values of corresponding parameters for each event. Waves corresponding to different wave bands are separated by marks as indicated. (Events with no matching wave observed at SOD are marked with crosses; to be discussed later). Polar observed in total 42 H^+-band, 23 He^+-band and 4 O^+-band wave events. Events occurred between 53° and 76° INVlat with more than half of them between 60° and 70° INVlat (median 67.4°). Within this latitude range there are events at all MLT sectors. Median invariant latitudes of H^+, He^+ and O^+ wave bands are 70.6°, 63.7° and 60.8°, respectively. We emphasize that the distribution of Figure 5 is biased by the requirement of simultaneous pulsations at SOD and the uneven sampling of waves at different location due to the Polar orbit. Accordingly, it does not give a normalized distribution of EMIC waves in space. It is well known [Troitskaya and Guglielmi, 1970; Mursula et al., 1996] that the structured pulsations at a high latitude station have their maximum occurrence in the late morning sector and unstructured pulsations in the noon to afternoon sector. Since both of these pulsation types are included in this study, a clear dayside dominance of events is seen with about 85% of events between 0600 Figure 5 and 1800 MLT.

Prior to 0800 MLT all six wave events belong to the H^+-band while after 1600 MLT there are seven He^+-band events but only one H^+- and one O^+-band event. H^+-band waves all occur above 61° INVlat and great majority even above 65° INVlat. Hence most of them originate from field lines northward of SOD. He^+-band waves are centered at about 64° INVlat, i.e., fairly close to the latitude of SOD, but cover a wide range of latitudes from 53° up to about 73°. All the four O^+-band waves observed by Polar originate from field lines equatorward from SOD (57°-63° INVlat) and are located around noon MLT or in the early afternoon.

Figure 6 depicts a scatterplot of Polar events in INVlat-frequency plane. Figure 6
Median frequencies of H^+-, He^+- and O^+-band waves are 0.50 Hz, 0.60 Hz and 0.15 Hz, respectively. Median frequency of all events is 0.50 Hz. For both H^+ and He^+ band waves the average frequency decreases with increasing INVlat up to about 65°-70°, remaining roughly constant above it, in agreement with earlier observation [Erlandson et al., 1990]. All the four O^+-band waves have frequency below 0.3 Hz. Lines in Figure 6 correspond to the equatorial ion gyrofrequencies as given by Tsyganenko-89 model at noon MLT with Kp = 1. Wave frequencies are reasonably well ordered within the corresponding frequency bands in each category although some deviations occur because of different geomagnetic disturbance levels and a different MLT sectors.

Figure 7 depicts the amplitudes of all Polar events with invariant latitude. Figure 7
The median amplitude of all events is 4.6 mV/m. The average event amplitude increases with increasing latitude between 60°-67° INVlat, in particular in case of H^+-band waves. The median amplitude of waves observed within 5° INVlat

equatorward of SOD is 2.2 mV/m while for those waves within 5° INVlat poleward it is 6.9 mV/m. Note also that the increase of amplitude is saturated at about 67°-70° INVlat, i.e., roughly at the same latitude where the frequency decrease is saturated. Ten high-amplitude events were found with amplitude exceeding 40 mV/m. Previously, very high-amplitude EMIC waves have been reported at rather low latitudes during the main phase of a geomagnetic storm [Bräysy et al., 1998]. Here all high-amplitude waves occur at high latitudes from 66° to 76° INVlat and during rather quiet times. Except for one, all high-amplitude events are H^+-band waves and have a low frequency between 0.1 and 0.5 Hz.

3.3. Statistics of matching Polar events

In 52 cases out of 69, Polar EMIC events had wave power at the same frequency as a Pc1 pulsation band simultaneously observed at SOD. We assume that in these events Polar indeed observed the EMIC wave source responsible for SOD pulsations, and we call them matching events. Instead of an exact frequency match, we required a sizable overlap between the frequency bands at the two locations. The frequency band observed by a ground station can be slightly different from that observed by a satellite due, e.g., to ionospheric filtration which can suppress the wave power at certain frequencies and enhance at others, thus modifying the frequency distribution. [Prikner and Fligel , 1991]. Also, the different response functions of the two instruments tend to modify the wave frequency. While the response function of the EFI instrument is flat, the sensitivity of the magnetic search coil sensor at SOD has a maximum around 0.5-1.0 Hz, and decreases at higher and lower frequencies. The remaining 17 Polar events had no matching wave at SOD. These non-matching events are marked by crosses in Figures 5-8.

Out of the 42 H^+-band Polar events, two thirds (28 events) were matching events (see Table). There were 35 H^+-band events at latitudes poleward of SOD, out of which 71% (25 events) were observed at SOD. In particular, all H^+-band waves occurring poleward of SOD up to about 67° were observed at SOD. On the other hand, out of 7 H^+-band events occurring below SOD latitude only three were observed at SOD although they are closer to SOD (all above 61°) on an average than waves poleward of SOD. Remarkably, out of the 23 Polar He^+-band events only one was not seen on ground, although the He^+-band waves cover the widest latitude range from 53° to 72°. Out of the four O^+ events, the two closest waves were seen at SOD.

Table

It is clear from Fig. 5 that many non-matching events are fairly far away from SOD at least in latitude. We have studied this question in more detail in Figure 8 which depicts the scatterplot of Polar events in ΔMLT-ΔINVlat plane, where ΔMLT and ΔINVlat are the corresponding differences between Polar and SOD during wave observation. Fig. 8 shows that most non-matching events are either equatorward of SOD or more than 10° poleward of SOD. Within the strict conjunction box of ±5° INVlat and ±1.5 MLT (black rectangle in Fig. 8) there are only 5 non-matching events which all are at latitudes below SOD. As discussed above, four of these are H^+-band events and one O^+-band event. It is interesting to note that all Polar events within the northern half of the conjunction box were observed on ground. As discussed above, there is a clear difference in amplitude between H^+-band events equatorward and poleward of SOD. The median amplitude of the 7 H^+-band events in the southern half of the conjunction box was only 2.1

Figure 8

mV/m while that of the 9 events in the northern half was 9.1 mV/m. On the other hand, the median amplitude of the 9 He^+-band events in the southern half of the conjunction box was 2.0 mV/m while that of the 7 events in the northern half was 3.5 mV/m, implying a less dramatic increase of average amplitude for He^+-band than H^+-band events.

4. Discussion

4.1. Satellite observation of ground Pc1 pulsations

We have analysed here 44 passes of the Polar satellite in a good conjunction with the Sodankylä station at a time when Pc1 pulsations were observed at SOD. During 7 passes no EMIC waves were observed by the Polar EFI instrument. Moreover, during 6 passes EMIC waves were observed on Polar but none of them were matching with those simultaneously observed at SOD. During the remaining 31 passes Polar observed EMIC waves out of which at least one band matched with pulsations observed at SOD. This gives a good overall probability of about 70% for Polar to observe SOD waves in the magnetosphere during those orbits where Polar is flying within about 1.5 h MLT from SOD. This implies, e.g., that the Polar orbit is quite well suited for the research of Pc1 pulsations, traversing a large range of latitudes fairly quickly and thus covering most of the magnetospheric regions where EMIC waves are generated.

The first sample case (April 16, 1998) of Pc1/EMIC waves presented above gives a good demonstration of the observational capability of the Polar satellite. During one pass, Polar observed waves of all the three most important frequency bands of magnetospheric ion cyclotron waves, i.e, H^+-, He^+- and O^+-band waves.

The higher frequency waves seen at SOD from 0730 UT to 10 UT belong to the He^+-band, and the weak, lower frequency waves to the O^+-band, as verified by the first two Polar events. Interestingly, the waves appearing at SOD after 10 UT with nearly the same frequency as earlier correspond to the H^+-band waves observed by Polar. This shows that using wave observations of one ground station alone one can not make reliable conclusions about the location or the frequency branch of EMIC waves. The three Polar EMIC wave events were ordered in latitude so that O^+-band waves were at the lowest latitude of about 62° INVlat, the He^+-band waves in the beginning of the event at about 64° INVlat, and the H^+-band waves around 70° INVlat. This ordering is as expected from the latitudinal change of the equatorial ion gyrofrequencies. Note al so that the mid-frequency of the He^+-band at SOD is decreasing with time from about 0.6 Hz at the start to about 0.4 Hz at the end of the event. This suggests that the source of these waves is moving to a higher latitude. A simple estimate using dipole geometry and the observed change of mid-frequency yields that the source was a couple of degrees higher at the end of the event. Polar reached such latitudes only at the very end of the SOD band at about 0940 UT when the band was very weak (see Fig. 1a) which can explain why Polar missed the He^+ band waves in the northern hemisphere.

More fundamentally, the 70% observation probability of SOD waves by Polar shows for, in a quantitative and statistically significant way, that Pc1s observed on ground indeed correlate with those observed at high altitudes. This correlation, together with generally earthward propagation of EMIC waves [Erlandson et al., 1992; Fraser et al., 1996], shows that Pc1s observed on ground indeed originate at high altitudes in the magnetosphere (close to the top of the field line around the equator). Moreover, the observation of such a large fraction of SOD waves by Polar within the 3 hour MLT width means that most of the SOD waves have their footpoint within this MLT range from SOD. This severely limits horizontal ducting in the longitude direction, in particular the fraction of those waves that were ducted to SOD within the horizontal waveguide from outside the ±1.5 h MLT range. This result is supported by the study of Ludlow et al. [1991] who, observing seven cases of simultaneous waves by a network of ground stations (L=1.7 to L=3.1) and the DE-1 satellite at L=4.6, concluded that the satellite did not see the ground pulsations if the MLT difference between DE-1 and the ground station was more than 1.5 hours.

The high hit probability of Polar also implies that the wave source region must be rather extended in MLT direction. Namely, if the wave MLT extent is not typically a large fraction of the 3-hour MLT range, the probability of Polar to observe the waves is effectively reduced. Using low-altitude satellite observations, Mursula et al. [1994] argued that the EMIC wave source during quiet magnetospheric conditions is rather limited in latitude (typically 0.5°-1° INVlat) but extends several hours in MLT. The present observations support this view and set a lower limit of about 3 hours on the MLT extent of a typical Pc1 band.

4.2. Ground observation of satellite EMIC waves

Out of the 69 Polar wave events, 52 events, i.e., 75% were observed at SOD. Nearly half of the Polar events (33) were within the conjunction box and a very large fraction (28 events) of these events were detected at SOD. This implies an almost perfect observation capability of SOD for waves which have their source region within the conjunction box from SOD. As a comparison, Hansen et al. [1995] studied 21 intervals of Pc1 pulsations by a mid-altitude Viking satellite. Using the same conjunction condition they found 7 events of matching waves. Taking the Polar observation probability of 70% and the fraction (48%) of matching waves inside the conjunction box we reach a very similar value of 34%.

Taking into account that the EMIC waves propagate from the equatorial source region to lower altitudes [Erlandson et al., 1990] the high observation capability of SOD sets a strict upper limit to the scale of modification that the ionosphere may have on waves. In particular, it is excluded that a large fraction of EMIC waves would suffer in the ionosphere, e.g., due to the filtering effect of the IAR [Polyakov and Rapoport, 1981], a frequency shift by more than half of the typical frequency width of a wave band (about 0.1 Hz). Using the average frequency of about 0.50 Hz, this implies a maximum possible frequency shift of about 20%. Prikner and Fligel [1991] observed a frequency shift for Pc1 waves of about 0.05 Hz for an average frequency of 0.5 Hz, i.e., considerably below the above estimated upper limit.

One third of all H^+-band events were not found at SOD. Most of these non-matching H^+-band events were located at very high latitudes of more than 73° INVlat. On the other hand, only one He^+-band event was missed at SOD. This difference in detection probability between He^+- and H^+-band waves is partly due to the different latitudinal occurrence distribution of these waves or due to effect of heavy ions. As seen in Fig. 2, the occurrence of He^+-band waves is centered around SOD latitude while H^+-band waves mostly occur poleward of SOD.

The perfect observation probability of 100% was obtained for He^+-band waves within the conjunction box. The lower observability of H^+-band waves is in accordance with the results of Perraut et al. [1984] who detected all of the satellite He^+-band waves but only half of the H^+-band waves by a ground station in near conjunction with geostationary satellite. Perraut et al. [1984] suggested that H^+-band waves are partly missing from ground due to reflection of waves at bi-ion frequency (F_{bi}) produced by He^+-ions [Roux et al., 1982]. In the present study, four H^+-band events in the conjunction box were missing on ground. In two events the wave frequency observed on Polar was above the local F_{He^+}, in two below. On the other hand, only one matching H^+-band event out of the ten in the conjunction box was above the local F_{He^+}. This difference is in line with the suggestion by Perraut et al. [1984], but the number of non-matching events is too small for definite conclusion. All the four non-matching H^+-band events in the conjunction box were found at latitudes below SOD (see Fig. 8). (This is because the Polar orbit crosses the lower invariant latitude field lines at a lower magnetic latitude, i.e., closer to the top of the field line where waves are more often above the local F_{He^+}). Instead, all H^+-band events in the conjunction box above SOD were observed. In fact, 18 out of 20 H^+-band waves occurring up to 8° INVlat poleward of SOD were observed. Such a latitudinally uneven detectability of H^+-band waves on ground seems to contradict the bi-ion reflection mechanism. Note that the average amplitude increases with latitude (Fig. 7) compensating possible losses during longer ionospheric ducting. Note also that the amplitudes of non-matching H^+-band waves above SOD were lower than average at respective latitudes.

4.3. Wave occurrence

There are 29 matching Polar events (56% of all matching events) within the $\pm 5^\circ$ latitude range of the conjunction box, 3 events at lower and 20 events at higher latitudes. Interestingly, a very large fraction (more than 90%) of those matching events which are outside this latitude range are found within 4 hours from noon (see Fig. 5). Between 08 and 16 MLT half (21 events) of the matching events are within the $\pm 5^\circ$ latitude range, half are outside it. On the other hand, outside the noon sector (00-08 or 16-24 MLT), only two events out of ten are outside the $\pm 5^\circ$ latitude range. This shows that the reason for the noon maximum for wave occurrence on ground is the fact that waves are produced in this MLT sector at a considerably larger latitude range than outside it. Also, since most (19 out of 21) of the matching waves outside the $\pm 5^\circ$ latitude range are at latitudes higher than SOD, the source of the noon maximum of EMIC waves is at high latitudes. This source may be related to the cusp/cleft region or to the effect of varying solar wind ram pressure and, possibly, IMF direction. Anderson and Hamilton [1993] showed that sudden compressions of magnetic field enhanced EMIC wave activity in the dayside sector at high latitudes. Olson and Lee [1983] and Hansen et al. [1995] have studied the effect of varying solar wind pressure on EMIC frequency.

We found that all morningside events (prior to 08 MLT) were H^+-band waves while most eveningside events (after 16 MLT) were He^+-band waves. These results are consistent with observations by Anderson et al. [1992b] using AMPTE/CCE close to the equator, who found a dominance of H^+-band events in the morning sector and an increase of the fraction He^+-band events with MLT in the afternoon.

Also, Perraut et al. [1984] found very few He^+-band waves in the dawn sector at geosynchronous orbit. Horne and Thorne [1994] studied the convective instability in outer magnetosphere theoretically and found that the dawn events indeed tend to have high normalized frequency, resulting in very few emissions below F_{He^+}, well in accordance with present results and those of Anderson et al. [1992b]. A similar conclusion was reached by Xue et al. [1996].

5. Conclusions

We have studied the correspondence of Pc1 pulsations on ground at the subauroral Sodankylä station and EMIC waves observed by the Polar satellite in the fair conjunction (±5° INVlat, ±1.5 h MLT) with Sodankylä during ground Pc1 activity. We note that the requirement of ground Pc1 activity sets a bias which forbids us to obtain correctly normalized EMIC occurrence probabilities at Polar. Out of 44 Polar passes studied, matching Pc1/EMIC waves were observed during 37 passes, yielding a high hit probability by Polar of about 70%. Accordingly, most Pc1s observed on ground indeed originate at high altitudes in the magnetosphere and have their source within a rather limited (±1-1.5h) MLT range. This severely limits horizontal ducting of waves in the longitude direction to less than about 1000-1500 km. The high hit probability by Polar also implies a lower limit of about 3 hours on the MLT extent of a typical Pc1 band in space.

Out of the 69 Polar EMIC wave events, 75% were observed at Sodankylä. Nearly half of the Polar events were within the above mentioned conjunction box and about 85% of these were detected at Sodankylä. This high observation probability by Sodankylä restricts the scale of modification on the amplitude and frequency of waves. E.g., it excludes a frequency shift of waves in the ionosphere typically by more than half of the frequency width of a wave band, i.e., roughly by more than 20%.

Out of the 37 Polar passes with EMIC waves, on 10 passes we observed waves of two or three different frequency branches. We showed sample passes where all the three main magnetospheric EMIC wave branches (H^+-, He^+- and O^+-branches) were simultaneously present at different invariant latitudes. The four O^+-band Polar events had the lowest median latitude (60.8° INVlat), the lowest median frequency (0.15 Hz) and a low median amplitude (2.9 mV/m). Out of these waves only the two waves closest to Sodankylä were observed on ground. Out of the 23 He^+-band waves (INVlat(med) = 63.7°, f(med) = 0.6 Hz, A(med) = 2.1 mV/m), all except one were observed on ground. On the other hand, only two thirds of H^+-band events (INVlat(med) = 70.6°, f(med) = 0.5 Hz, A(med) = 5.9 mV/m) were observed on ground. The observability of H^+-band waves on ground was not higher for waves closer to Sodankylä than further away. A larger fraction of Polar H^+-band waves missed on ground was above local He^+ gyrofrequency than of those waves seen on ground, supporting the effect of He^+ stop band on H^+-band waves.

Most (54%) Polar EMIC events seen at Sodankylä are within ±5° INVlat from Sodankylä. However, the latitude distribution of matching Polar events extends to considerably higher latitudes at noon sector (08-16 MLT) than at other MLT sectors. This explains the dayside maximum of Pc1 pulsations on ground at high latitudes. Possible EMIC sources are the cusp/cleft region or variations in solar wind pressure and possibly IMF.

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Figure Captions

Figure 1. April 16, 1998 sample event. a) Pc1 pulsation activity at SOD at 0730-1100 UT. b) EMIC observations by Polar at 0740-0750 UT. c) EMIC observations by Polar at 1000-1100 UT.

Figure 2. Polar footprint on April 16, 1998.

Figure 3. October 27, 1996 sample event. a) Pc1 pulsation activity at SOD and b) EMIC observations by Polar, both at 0830-1000 UT. Thick lines below the spectrogram indicate the duration of the three EMIC events.

Figure 4. Polar footprint on October 27, 1996.

Figure 5. The scatterplot of invariant latitude of Polar events against MLT. Dash-dotted line indicates the latitude of SOD station.

Figure 6. The scatterplot of frequency of Polar events against invariant latitude.

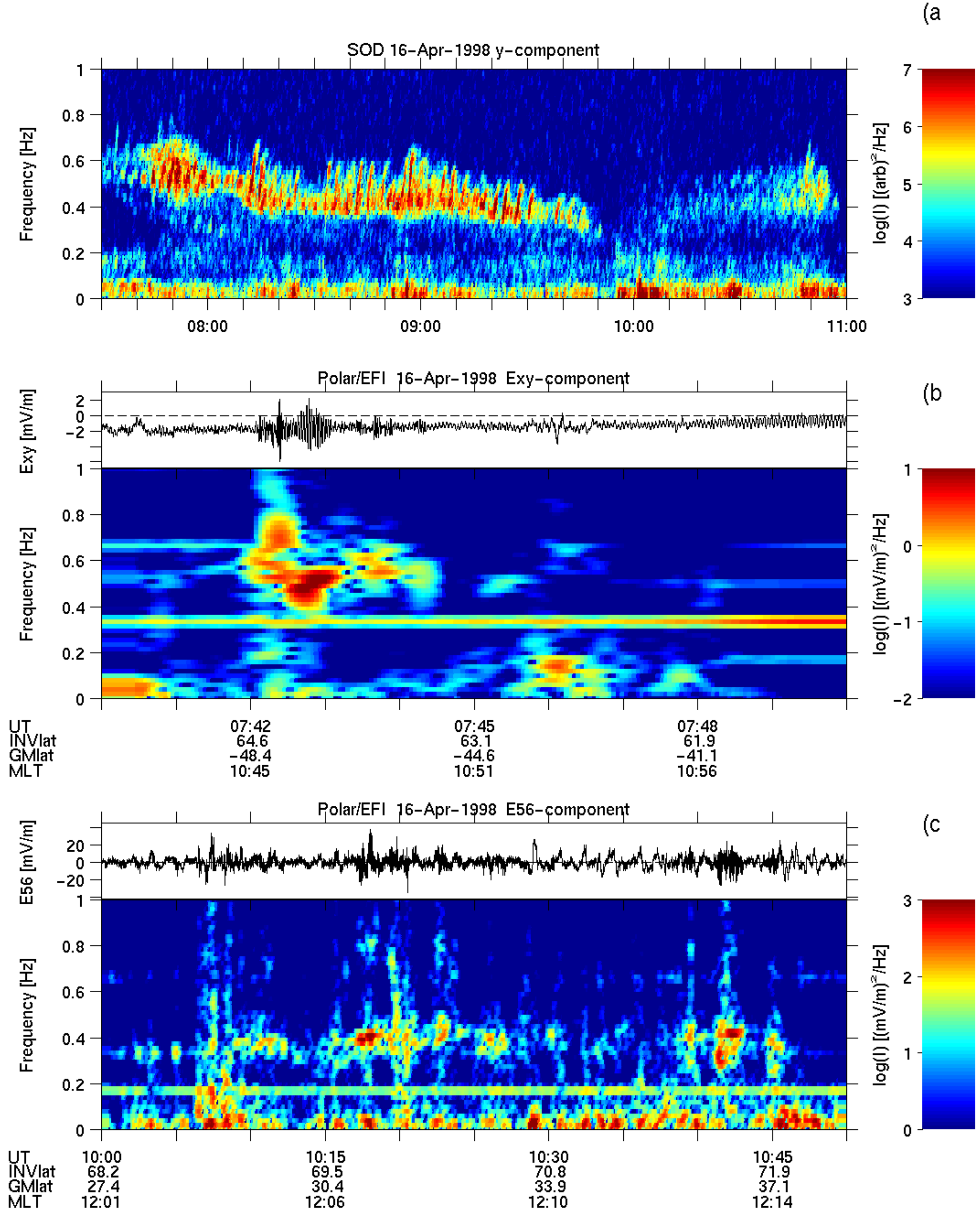
Figure 7. The scatterplot of amplitude of Polar events against invariant latitude.

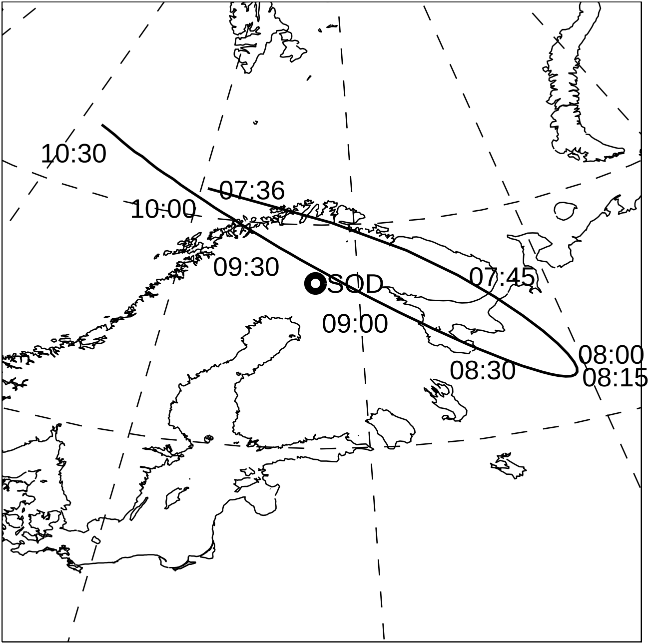
Figure 8. The scatterplot of Polar events in ΔMLT-ΔINVlat plane, where ΔMLT and ΔINVlat are the corresponding differences between Polar and SOD during wave observation.

Tables

Type	H^+	He^+	O^+	Total
Matching events	28/11	22/16	2/1	52/28
Non-matching events	14/4	1/0	2/1	17/5
All events	42/15	23/16	4/2	69/33

Table 1. Summary of the Polar events (all events/events inside the conjunction box).


(a
SOD 16-Apr-1998 y-component
Frequency [Hz]
08:00
09:00
10:00
11:00
log(I) [(arb)^2/Hz]
(b
Polar/EFI 16-Apr-1998 Exy-component
Exy [mV/m]
Frequency [Hz]
log(I) [(mV/m)^2/Hz]
UT 07:42 07:45 07:48
INVlat 64.6 63.1 61.9
GMlat -48.4 -44.6 -41.1
MLT 10:45 10:51 10:56
(c
Polar/EFI 16-Apr-1998 E56-component
E56 [mV/m]
Frequency [Hz]
log(I) [(mV/m)^2/Hz]
UT 10:00 10:15 10:30 10:45
INVlat 68.2 69.5 70.8 71.9
GMlat 27.4 30.4 33.9 37.1
MLT 12:01 12:06 12:10 12:14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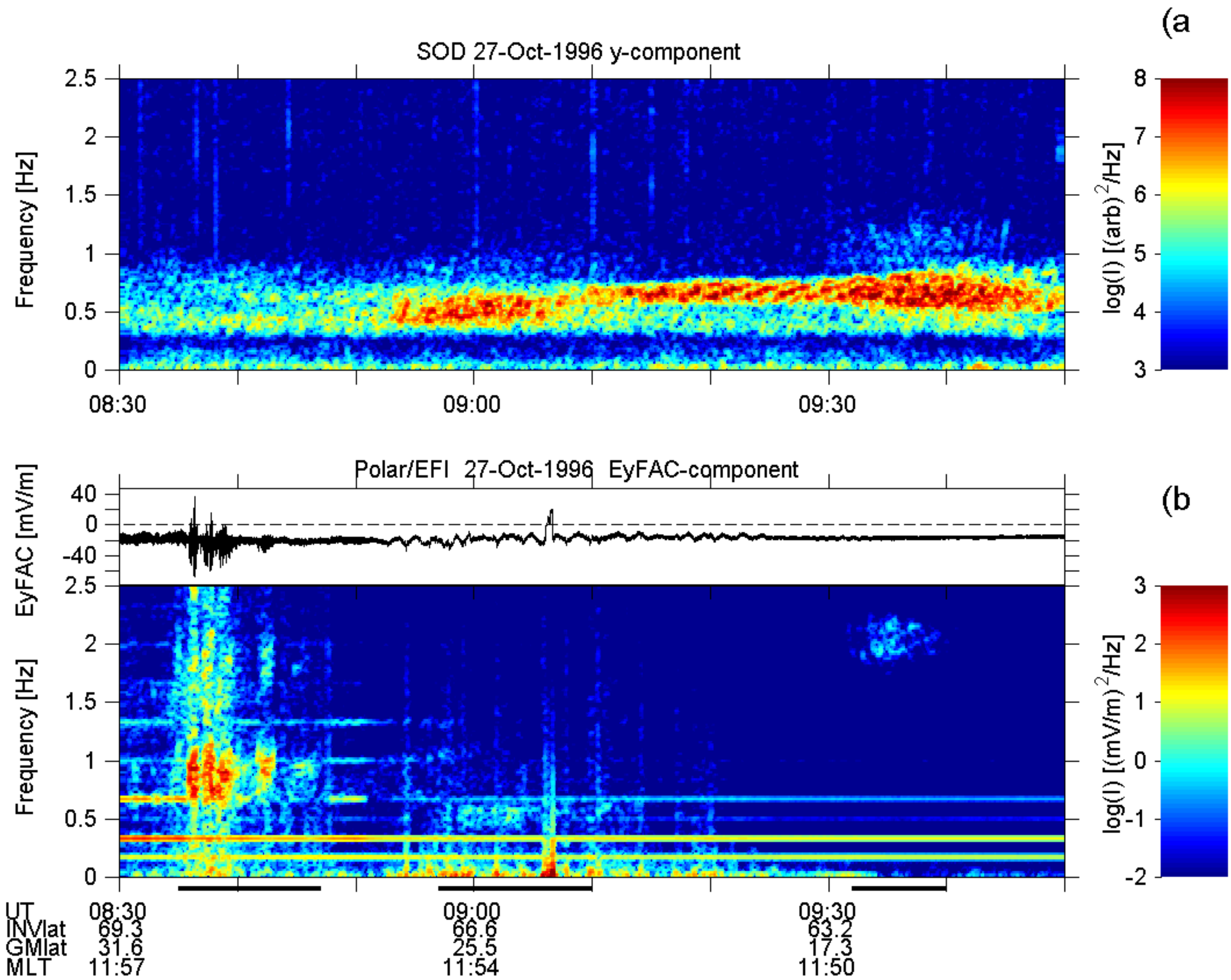
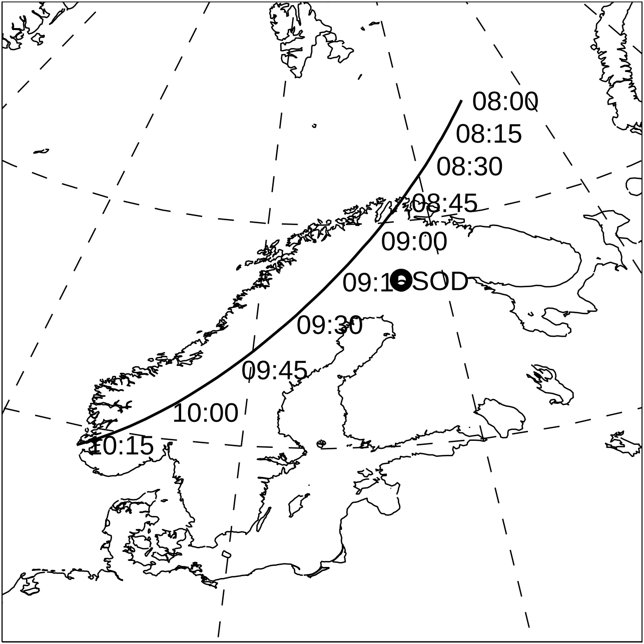
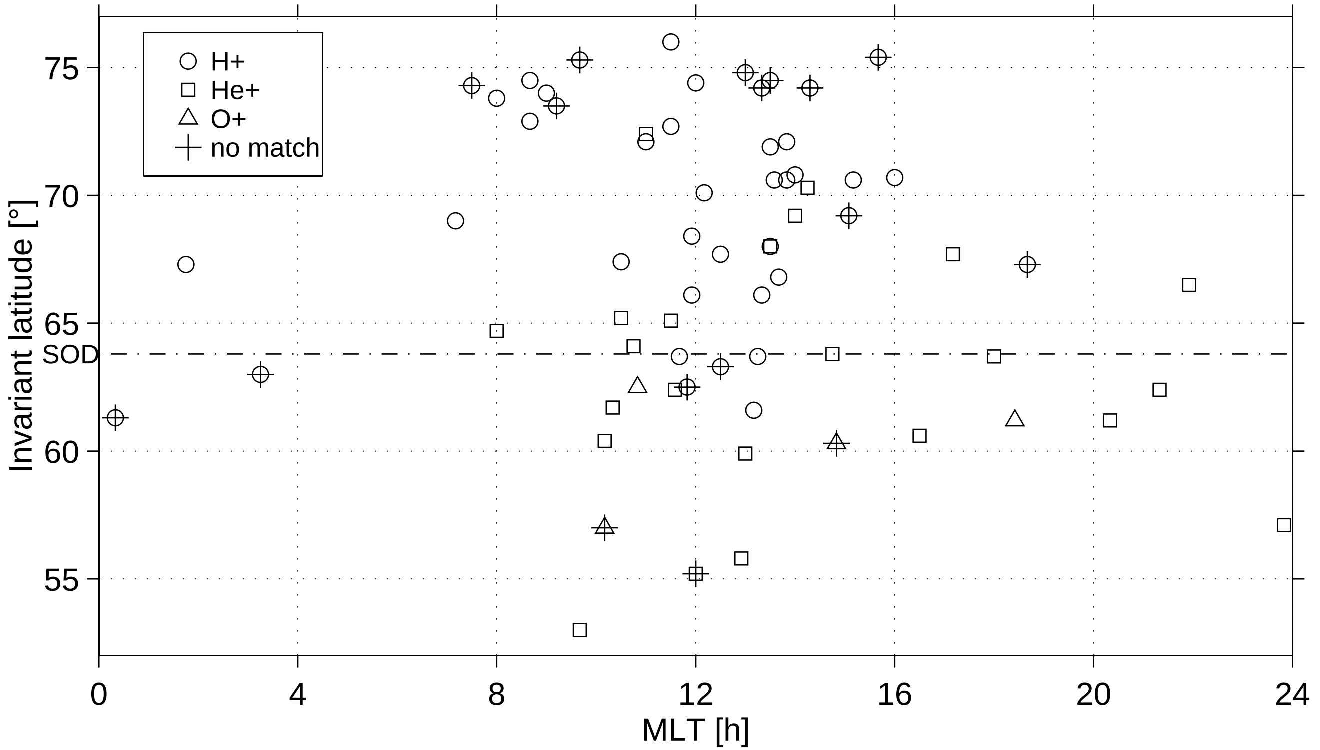
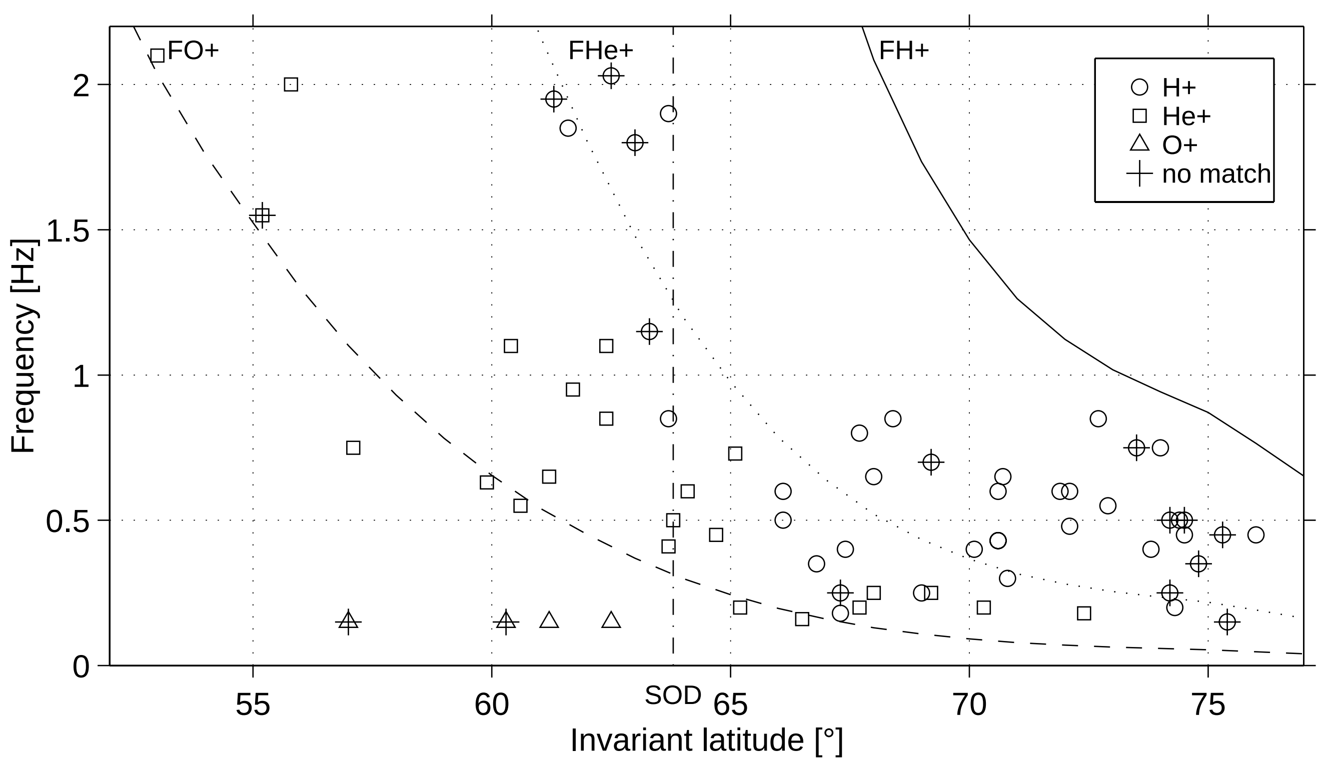
07:36
10:00
09:30
SOD
07:45
09:00
08:00
08:30
08:15

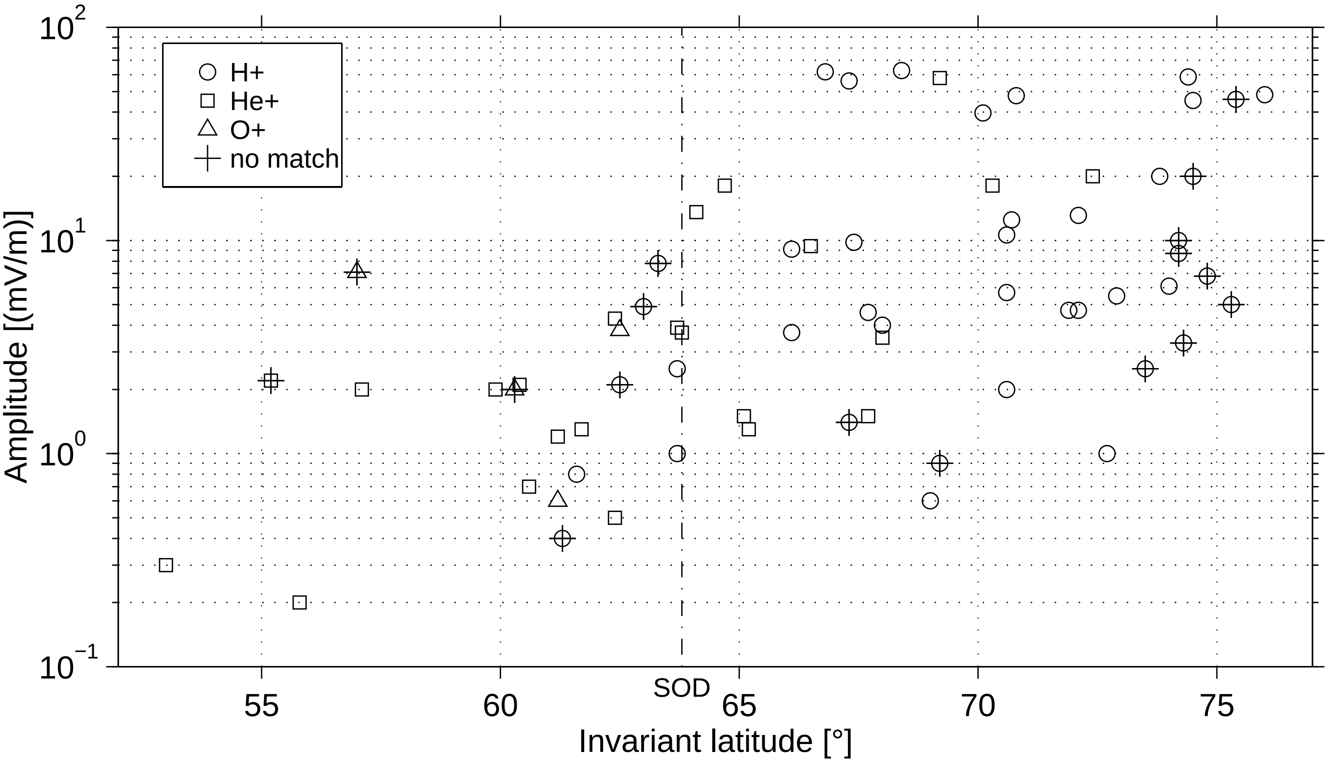

(a
SOD 27-Oct-1996 y-component
Frequency [Hz]
log(I) [(arb)^2/Hz]
08:30
09:00
09:30
(b
Polar/EFI 27-Oct-1996 EyFAC-component
EyFAC [mV/m]
Frequency [Hz]
log(I) [(mV/m)^2/Hz]
UT 08:30 09:00 09:30
INVlat 69.3 66.6 63.2
GMlat 31.6 25.5 17.3
MLT 11:57 11:54 11:50


08:00
08:15
08:30
08:45
09:00
09:15
SOD
09:30
09:45
10:00
10:15

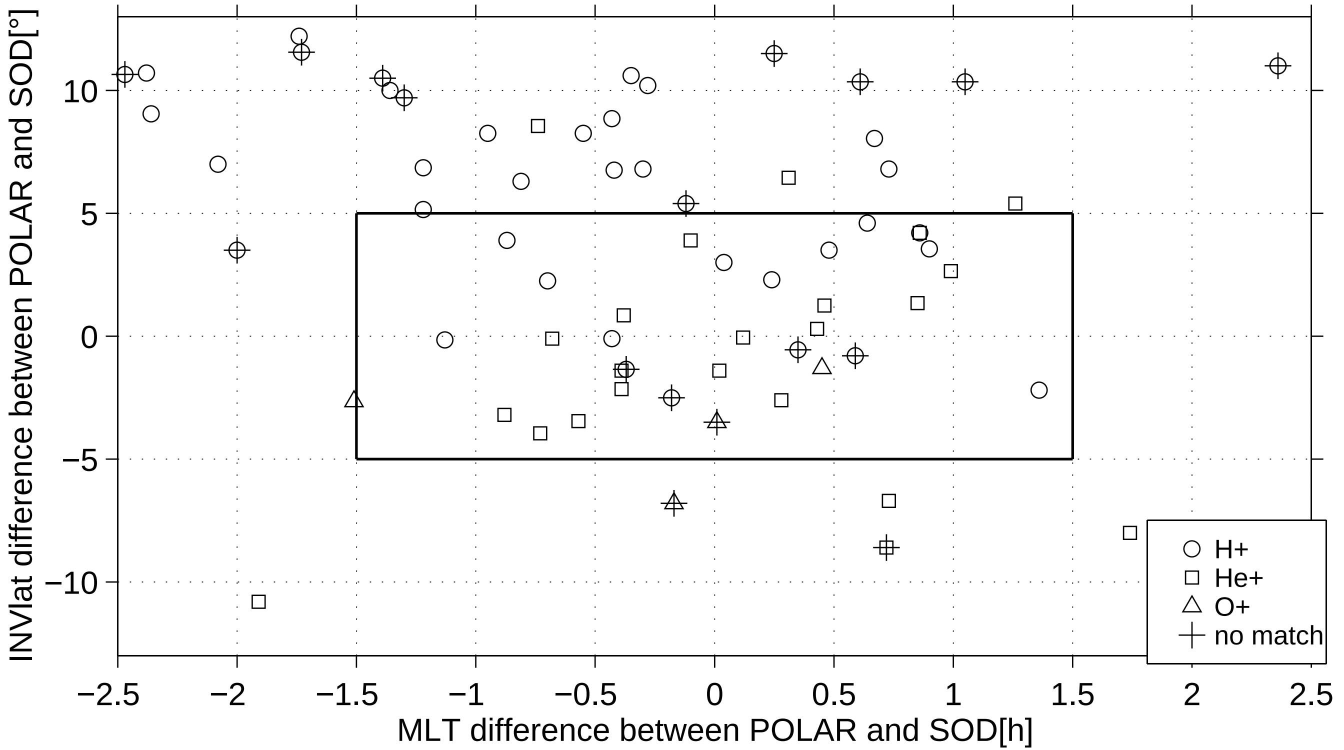


H+
He+
O+
no match
75
70
65
SOD
60
55
Invariant latitude [°]
0
4
8
12
16
20
24
MLT [h]


FO+
FHe+
FH+
H+
He+
O+
no match
SOD
Frequency [Hz]
Invariant latitude [°]
0
0.5
1
1.5
2
55
60
65
70
75



H+
He+
O+
no match
Amplitude [(mV/m)]
10^{2}
10^{1}
10^{0}
10^{-1}
SOD
55
60
65
70
75
Invariant latitude [°]


INVlat difference between POLAR and SOD[°]
10
5
0
−5
−10
−2.5
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
2.5
MLT difference between POLAR and SOD[h]
H+
He+
O+
no match