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Polarisation in the auroral red line during coordinated EISCAT Svalbard Radar/optical experiments

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Abstract. The polarisation of the atomic oxygen red line in the Earth's thermosphere is observed in different configurations with respect to the magnetic field line at high latitude during several coordinated Incoherent Scatter radar/optical experiment campaigns. When pointing northward with a line-of-sight nearly perpendicular to the magnetic field, we show that, as expected, the polarisation is due to precipitated electrons with characteristic energies of a few hundreds of electron Volts. When pointing toward the zenith or southward with a line-of-sight more parallel to the magnetic field, we show that the polarisation practically disappears. This confirms experimentally the predictions deduced from the recent discovery of the red line polarisation. We show that the polarisation direction is parallel to the magnetic field line during geomagnetic activity intensification and that these results are in agreement with theoretical work.

Keywords. Atmospheric composition and structure (Airglow and aurora)

1 Introduction

Since the controversial measurements of Duncan (1959), which were questioned by Chamberlain (1959), the polarisation of the thermospheric atomic oxygen red line at 630 nm

has been ignored in the geophysics field for fifty years. It has been recently re-investigated (Lilensten et al., 2006) and measured by Lilensten et al. (2008). The red line emission at 630 nm is due to the transition between the O^1D and O^3P states with a corresponding energy threshold of 1.96 eV. In this study, the emission has been observed by a dedicated photo-polarimeter placed in the Svalbard archipelago (Latitude 78° North). Since initially no coordinated instrument was available the first observations were made only in the northward direction, in order to ensure a view perpendicular to the magnetic field line at 210 km, which is the altitude of the red line emission peak at high latitude at solar minimum (Witasse et al., 1999). Following Lilensten et al. (2006), the polarisation was foreseen to be perpendicular to the plane defined by the line-of-sight and the magnetic field.

Since then, three further experimental campaigns have been performed and another is being conducted during the winter 2010–2011. However, polar observations are very difficult due to harsh weather conditions and instrumental problems, hence only few measurements have been possible. Fortunately, we were successful in fulfilling our two goals: to reproduce the northward observations with the additional support of the ESR (EISCAT Svalbard Radar) incoherent scatter radar and to observe in other directions. Due to the difficulty of the observations, only four hours of data (two northward and two southward) are fully useable from about ten days of experiments during the 2009 campaign. The goal of this paper is (i) to report on these observations, (ii) to confirm our first discovery through an improved data processing and to recover the direction of the polarisation, (iii) to confirm our
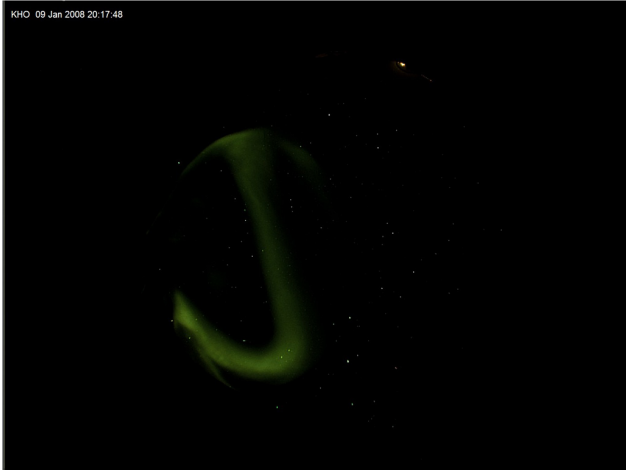
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Fig. 1. UCL (Univerisity College London) all-sky camera, for 9 January 2008, 20:17 UT. Northward direction is on the top of the image. Eastward on the left.

predictions for the zenith and southward observations (iv) to improve our interpretation of the phenomenon using coordinated measurements from the ESR incoherent scatter radar and (v) to compare with recent theoretical developments.

2 Presentation of the instruments

2.1 Steerable Photo-Polarimeter (SPP)

The SPP includes two detection channels with photomultipliers, front lenses and band pass interference filters centred around 630.0 nm with a width of 1 nm. A linear polarisation filter rotates in front of the first channel referred to as the "polarised channel" with a 4.02 s period and with a sampling rate of 20 points per second. Since the polarisation is measured between 0 and 180 degrees, the time between two identical linear polarisation measurements is then 2.01 s, which corresponds to a frequency close to the 0.5 Hz used in the data processing. This rotation period was chosen by considering the natural lifetime of the O^1D state (110 s). The modulations had to be small with respect to this time, nevertheless the design of a device with front optics rotating in four seconds was technically feasible for an instrument that was to be operated under harsh conditions. The reference direction for the polarisation measurements is the vertical and the aperture is 2°. The other channel with no polarising filter is referred to as the "reference channel". We installed the SPP at the Kjell Henriksen Observatory optical facility (KHO) close to Longyearbyen, Svalbard (78.15° N, 16.04° E geographic, 75.37° N, 110.99° E geomagnetic). In this work, North refers to geomagnetic North, i.e. 30° West of geographic North at the observatory location. In order to avoid spurious polarisation from the plexiglas dome, the instrument was placed outdoors on a platform with no covering dome. This was

an additional difficulty since the instrument was then subject to weather conditions (snow, ice, wind, temperature and humidity variations). Measurements of the instrumental noise and dark currents were performed regularly. Due to unexpected high atmospheric temperature episodes (see below), the background noise reached values up to 11 counts per exposure, which was subtracted during data processing. The instrumental polarisation has been measured in laboratory by using a calibration lamp and a diffuse Lambert screen and is found to be always smaller than 1 % with a direction close to the vertical.

2.2 EISCAT Svalbard Radar (ESR)

The EISCAT Svalbard Radar (ESR) is a high power UHF radar operating near Longyearbyen on the island of Spitsbergen, Svalbard. The funding, planning, construction and operation of the radar are undertaken by the EISCAT Scientific Association. The ESR is located 12 km South-East of Longyearbyen at 78°09′ N, 16°02′ E and 434 m above sea level, about 600 m North of the KHO optical facility. The ESR comprises a 42 m fixed antenna pointing parallel to the local magnetic field line and a 32 m steerable parabolic dish. The transmitter frequencies are in the UHF range from 498.0 to 502.0 MHz.

3 Geophysical conditions

We show three sets of data, from 11 December 2007; 9 January 2008; and 16 December 2009. These data have all been obtained for solar zenith angles larger than 108°, so that there is no possibility of Rayleigh scattering from the sun light[1]. For all three data sets, the weather conditions remained good with a clear sky. This has been carefully checked using records from the All Sky Colour Imager, belonging to the Atmospheric Physics Laboratory of University College London (Fig. 1). No clouds were seen in the pointing direction of the photo-polarimeter and no wind was recorded that could have blown snow in front of the instrument, possibly inducing light scattering. The configurations for the experiments discussed below are sketched in Fig. 2.

3.1 Northward direction: 11 December 2007 from 20:30 to 21:00 UT

The NOAA SEC PRF 1685 bulletin reports that the solar activity was "very low" to "low". The geomagnetic field was quiet to active on 11 December. No proton events were observed at geosynchronous orbit. The electron flux with energies larger than 2 MeV at geosynchronous orbit did not reach significant levels. The $f_{10.7}$ decimetric index value was 87. The Ap index was equal to 8 (9 for high latitude index) with

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[1]With a solar zenith angle above 108°, the direct light of the sun lights up atmospheric layers above 320 km.

a related Kp equal to 2 at the time of the experiment (same value at high latitude).

3.2 Zenith direction: 9 January 2008 from 19:00 to 21:00 UT

During this observation, the photo-polarimeter was operating in a two-position mode, alternating from northward to zenith pointing positions every 30 min. We extracted two hours of data with a full clear sky from this period. Very similar geomagnetic conditions as for 11 December 2007 prevailed, with no sunspots and a decimetric index equal to 80 and the same Ap (Kp) values. During this observing period, however, an aurora occured to the North.

3.3 Southward direction: 16 December 2009 from 22:00 to 24:00 UT

The solar activity was extremely low, at the beginning of December 2009, with only one sunspot, but slowly increased to reach 25 spots on 16 December. The SIDC (http://sidc.oma.be/) monthly bulletin stated that a first bout of flaring activity occurred on 9–10 December. The next active period started on 13 December. The background X-ray flux increased from below A-level to B-level on 16 December, related to the emergence of a sunspot group responsible for three C-class flares on 15 December. These flares, were associated with a non-geoeffective partial halo CME. During the whole period, the $f_{10.7}$ decimetric index remained around 70. The geomagnetic activity remained remarkably low: the Ap index remaining between 4 and 5 during the whole period. The solar wind was flowing at a mean velocity of 370 km s^{-1} and several aurorae were observed above Svalbard.

4 Data processing

4.1 Polarisation detection

As in the previous paper (Lilensten et al., 2008), following dark current correction of the SPP data, we perform a Fourier analysis and apply a low-pass filter at 1.5 Hz. After filtering, we fit each measurement cycle with a square sine function. The polarisation parameters are extracted from this fit. These parameters are the amplitude defined as the difference $Q = I_{\max} - I_{\min}$ between the maximum and the minimum intensities, the degree of polarisation defined by the following equation:

$$P = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \qquad (1)$$

and the direction of the polarisation. If polarisation is present, the signal should exhibit two maxima during a cycle, i.e. a 0.5 Hz signal, appearing exclusively in the polarised channel. In addition to this processing, we added the following criteria:
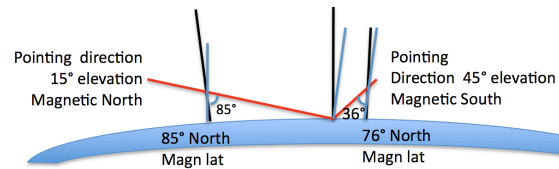

Fig. 2. Configuration of the experiments. The black lines indicate the local zenith. The blue lines are the local magnetic field directions. The red lines are the observation directions. The angles are shown where the line of sight intersects the magnetic field at 210 km altitude.

- Polarisation parameters are evaluated only when the power spectral density (PSD) maximizes between 0.4 and 0.6 Hz

- For a white noise, the probality for the PSD to maximize in this interval is 13.3 % ($= \frac{0.6-0.4}{1.5}$). Any signal with a probability density close to this value is then considered as noise. Practically, we consider any set of data with a probability density larger than 20 % when integrating for half an hour to be a true polarisation signature.

- The PSD must be significantly larger than its average. For a totally polarised signal, we should normally consider a 3σ criterion. Here, our signal is polarised up to 10 %, so that it is sufficient to consider as valid a power spectral density larger than $m_{\mathrm{psd}} + 0.3\sigma_{\mathrm{psd}}$ where m_{psd} represents the mean of the power spectral density and σ_{psd}^2 its variance computed on the set of data (one to two hours). However, we tested several values and found that $m_{\mathrm{psd}} + 0.6\sigma_{\mathrm{psd}}$ is the most appropriate threshold for event selection.

In order to double-check, we also computed the polarisation parameters from a one minute average, performed on the intensity measurements. The results were found to be not significantly different from the first analysis process. We also checked that the results presented here could not be due to the instrumental polarisation by simulating the instrument noise using a Monte Carlo method. The simulated data were processed in the same way as the real measurements. By default the noise is estimated using the following expression $N = 10 + \sqrt{(I)}$ counts (The standard deviation of a Poisson noise) which corresponds to the observed noise in the data.

4.2 Angle calibration

Reanalysing the previous measurements described in Lilensten et al. (2008), we found a problem with the calibration of the polarisation angles. We have therefore calculated a new calibration of the angles, using the fact that when looking to the South with a sufficiently low elevation around noon, the polarisation measured is due to single Rayleigh scattering of solar radiation. In this case, the angle between the polarisation direction and the vertical is given by:
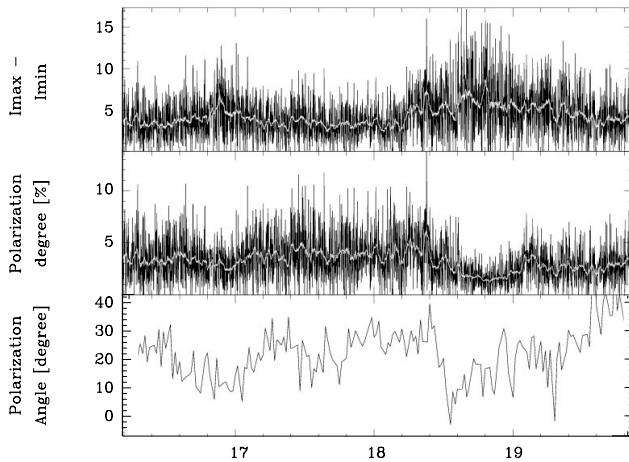
Fig. 3. 17 January 2007 with corrected polarisation direction. Hours are in UT. A faint aurora occurs slightly before 17:00 UT and a stronger one between 18:20 and 19:10 UT, corresponding to the polarisation direction rotations. Intensities are in arbitrary unit. The polarisation direction was named polarisation angle in Lilensten et al. (2008). We keep this terminology for this figure only.

$$\theta = \arctan\left(\frac{2 \times \cos(\alpha) \times \tan(\beta)}{\sin(2\alpha)}\right) \qquad (2)$$

where α is the angle in the horizontal plane between the line-of-sight and the solar azimuth, and β is the elevation of the line-of-sight from the southern horizon.

We analysed two examples to calibrate the polarisation angles: one observation made during the first campaign in 2006–2007 and another from one of the later campaigns. We chose the 15 January 2007 and the 8 December 2007, because during 2007 the SPP instrument had been considerably updated. At 12:01 UT the azimuth of the Sun as seen from Svalbard is 197°. For the December interval, the azimuth of the line-of-sight of the instrument was 150° and its elevation 15°, from which we derive an angle of 160° considering that the angle are taken from the vertical counted in the trigonometric direction. From the SPP data, we have verified that the measured polarisation direction of the Rayleigh scattered sunlight was close to 155°. Considering that the polarisation filter turns about 4° between each measurements, we can consider that the calibration of the angles is correct. This calibration has also been checked for all the later campaigns up to December 2009. During the first campaign in winter 2006–2007, no measurements with a low elevation to the South were performed. On 15 January 2007, however, measurements with an azimuth of 135° and an elevation of 60° were performed during a period of clear skies. Under the hypothesis of a single scattering, the angle of polarisation should have been 116° at 09:28 UT. However, the measured polarisation direction was found to be around 165°.

The effect of this calibration error is that Fig. 4 of Lilensten et al. (2008) presented polarisation directions which were in error by about 45°. During these observations (From 17 January 2007), two auroral events occurred. The intensity of the first one, at around 17:00 UT remained relatively small. The second event between 18:20 and 19:10 UT was much stronger. Re-analysing these data, we found that in both cases, the direction of polarisation decreased, eventually reaching values close to zero (i.e., parallel to the magnetic field line). During quiet periods, it oscillated between 20° and 35°. Using this new calibration, the corrected Fig. 4 of Lilensten et al. (2008) is displayed in Fig. 3. A recent paper (Bommier et al., 2011) theoretically explores the existence of the red line polarisation. This paper will be discussed later in more details but our revised polarisation measurements confirm their main result.

4.3 Rayleigh scattering

From our first observations, one uncertainty remained. Because the auroral arc was bright and spatially extended, the polarisation observed from the ground could have been partly due to the Rayleigh scattering in the lower atmosphere from parts of the auroral arc not intercepted by the SPP field of view. In order to exclude this possibility, we calculated the intensity and the polarisation due to the Rayleigh scattering using the all-sky images of the oxygen red line obtained from the UiO (University in Oslo) all sky camera. To test these calculations and get a maximal value, we chose images with bright auroral events and very asymmetric features not necessary corresponding to SPP observations. As an example, Fig. 4 shows data from 9 January 2008 around 20:00 UT which corresponds to this criterion. The volume scattering coefficient is given by Bucholtz (1995). At 630 nm, its value is equal to $\beta_{\text{ref}} = 6.6 \times 10^{-3} \text{ km}^{-1}$ at a pressure of 1013 hPa and a temperature of 288 K. Following this author, β can be corrected using the following equation:

$$\beta = \frac{PT_{\text{s}}}{P_{\text{s}}T} \qquad (3)$$

where P_{s} and T_{s} are the pressure and temperature at sea level and P and T at the altitude in question.

T is assumed to be constant with the altitude and equal to $-13\,^\circ\text{C}$. The sea level pressure was 1013 hPa. We assume a hydrostatic variation of the pressure with altitude. In order to perform these calculations, we have divided the cone seen by the instrument into 1 km thick slabs perpendicular to the line-of-sight . We calculate the Rayleigh diffusion into this cone by taking each pixel of the all sky image weighted by its solid angle coverage. We have calculated the total light diffused by each elementary volume in the cone in the direction of the instrument. The phase function for Rayleigh Scattering is not isotropic but is given by:

$$f_p = \frac{3}{4} \times (1 + \cos^2(\theta)), \qquad (4)$$

where θ is the angle between the incoming and diffused light. The light diffused by each pixel of the image and each elementary volume is summed taking into account the fact that it is partially polarised. The polarisation direction for each calculated element of diffused light is perpendicular to the diffusion plane and its polarisation degree is given by:

$$P = \frac{\sin^2(\theta)}{(1+\cos(\theta))^2} \qquad (5)$$

Applying this calculation to all-sky images between 19:00 UT and 20:00 UT on 9 January 2008, we find that the diffuse light intensity can only reach a few percent of the direct intensity. This diffuse light is generally polarised around 5 % but can reach 10 % for very asymmetric auroral features. Even under the worst conditions, however, the spurious polarisation light due to Rayleigh scattering from other parts of the sky can only affect the direct light by one or two parts in a thousand, which is insignificant. This means that the Rayleigh scattering from other parts of the sky cannot explain the observed polarisation nor contaminate it significantly.

5 Results

5.1 Northward direction: 11 December 2007

The elevation angle of the photo-polarimeter was 15°. Since the dip angle is about 82° and directed southward, the angle between the line-of-sight and the magnetic field line at 210 km altitude (where Witasse et al., 1999, predicted that the red line emission peaks) was about 85°. Only 30 min of observation, from 20:30 UT and 21:00 UT were performed with clear skies while the ESR was operating. The optical observations are shown in Fig. 5.

The power spectral density maximum lies between 0.4 and 0.6 Hz with a 33.9 % occurrence (Fig. 6), far above the 13 % level attributable to white noise in the polarised channel. For the reference channel, this value falls to 11.4 %, i.e. close to the white noise level. This validates the performance of the instrument since the PSD in the reference channel is close to pure random noise confirming that no parasitic process was acting to create fake detection.

The raw polarisation degree (four seconds resolution) varies between 3 % and 10 % (with a rough average of 5 %) when the red line intensity is weak and decreases down to about 2 % after 20:42 UT when an auroral event starts. When the data are averaged for 1 min, the polarisation degrees varies between 2 and 4 % and decreasing to 1 % when the event starts. This is in agreement with the first observations made in 2007 (Lilensten et al., 2008) once they have been re-analysed using the improved data processing.

The polarisation angle remains around 20° when the auroral emission intensity is very low at the beginning of the experiment. During the auroral intensification, the polarisation angle becomes close to zero, meaning a vertical polarisation
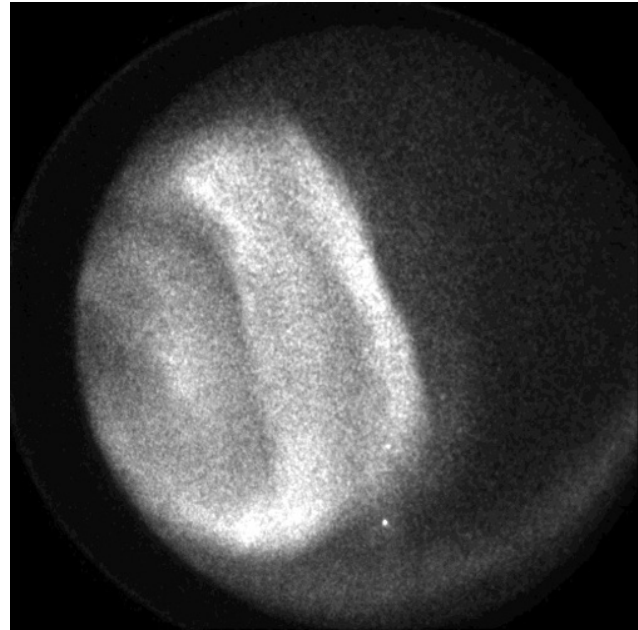

Fig. 4. UiO (University in Oslo) all-sky camera, red line 630 nm filter, for 9 January 2008, 20:17 UT. Northward direction is on the top of the image. Eastward on the left.

direction. This is in agreement with the theoretical predictions of Bommier et al. (2011). In this theoretical paper, the authors show that when the energy of the incoming electrons increases, the polarisation, initially perpendicular to the magnetic field, becomes parallel to the magnetic field just above the energy threshold between 2 eV and 3 eV. Considering the fact that the incoming particles have energies above 3 eV, the polarisation of the red line is predicted to be parallel to the magnetic field. Bommier et al. (2011) correctly concluded that actual auroral observations contain a mixture of real auroral polarisation and extraneous light pollution. When the auroral red line emissions become very intense, the light pollution becomes negligible and the polarisation is then seen to be vertical, in accordance with their theoretical calculations.

The ESR data (Fig. 7) are used to get an overview of the ionospheric conditions. However, the antenna cannot point as low as the spectro-photo-polarimeter. Its elevation angle was 30° North. The ionosphere was remarkably quiet. The electron density was very low (about 6×10^{10} m^{-3}) at around 200 km altitude where the red line should maximise. The auroral activity results in (i) an increase of this density at the end of the period at about 110 km, corresponding to electrons with energies of the order of a few keV; (ii) a slight increase of the electron temperature at 20:42 UT and (iii) a gravity wave episode during the second part of the period occurring in conjonction with the aurora. The fact that the aurora seen by the SPP at 15° elevation was hardly seen by the radar suggests that the precipitation was very localised. These ionospheric conditions are very comparable to those
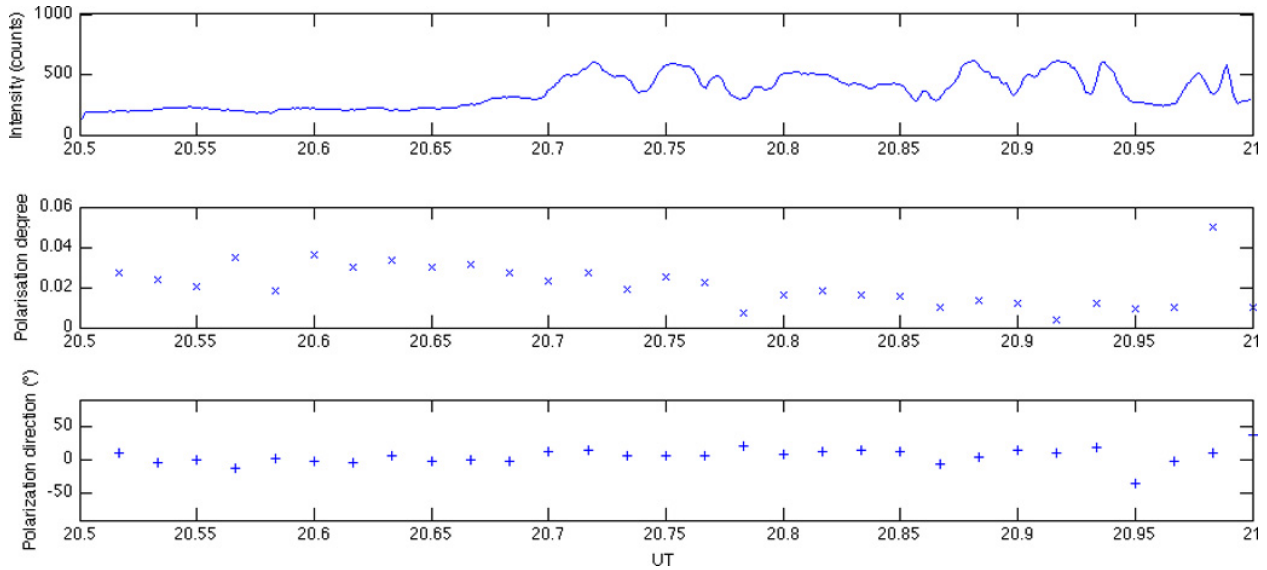
Fig. 5. Northward optical observations versus time (11 December 2007). UT is in decimal hour. Top panel: Intensity in counts; mid panel: polarisation degree; bottom panel: polarisation direction in degree from the vertical following the trigonometric direction.
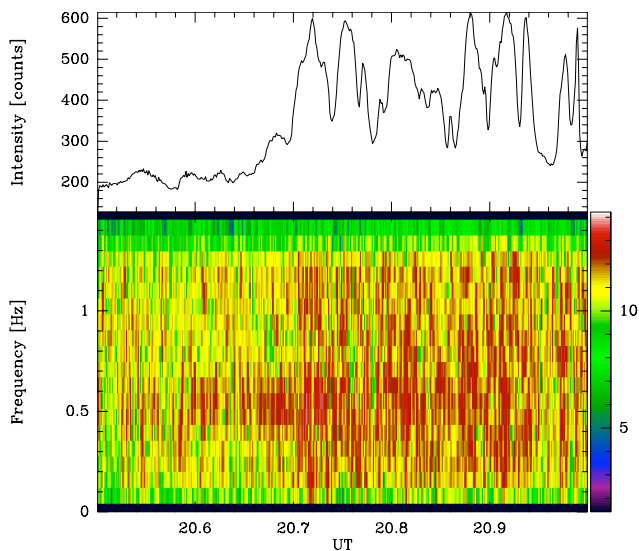

Fig. 6. Intensity of the red line and PSD (arbitrary unit) versus time during northward observations for the polarised channel.

which prevailed during the southward-looking experiment described in a following paragraph.

5.2 Zenith direction: 9 January 2008

The SPP was operated in a two-position scanning mode with one position to the North (see above) and the other toward the zenith. In the latter case, the angle between the line of sight and the local magnetic field line at 210 km altitude was 8°. For the sake of clarity we only show the zenith data in

Fig. 8. Measurements were performed while a strong aurora was crossing the line-of-sight.

For the polarised channel, the probabilities ($\mathcal{P}_{0.4-0.6}$) to get the maximum of the PSD between 0.4 and 0.6 Hz were observed to be respectively 16.9 % (Zenith), 30 % (North), 20.5 % (Zenith) and 26.1 % (North). Following the criteria defined in Sect. 4.1, the first zenith values can be seen to have no more meaning than pure white noise. The second zenith value (20.5 %) would appear to be significantly above above the noise threshold, which would not be surprising since the measurement was performed when strong aurora was crossing the line-of-sight. Considering, however, that the mean intensity during this period was about 600 counts and that the instrumental polarisation was measured as 0.9 %, the amplitude of the sine square function can reach 11 counts which is comparable to the noise of the instrument. Hence, we have to check that this measurement can be explained by the instrumental polarisation effects. Using the Monte Carlo simulation described in Sect. 4.1 with only instrumental polarisation, we found between 20:00 UT and 20:30 UT, a polarisation degree averaged over one minute equal to 0.94 %, a value very close to the 1.01 % mean degree in the data. This means that the PSD observed little additional polarisation beyond the levels associated with the instrumental noise. These results are then in perfect agreement with our prediction (Lilensten et al., 2006). For the reference channel, the values for $\mathcal{P}_{0.4-0.6}$ are respectively equal to 10.6 % (zenith), 13.45 % (North), 13 % (zenith) and 13.9 % (North) which are the values expected for white noise.

During this period, the ESR was running on a UK Special Programme and only the data from the 42 m dish were available for comparison with our optical observations. The
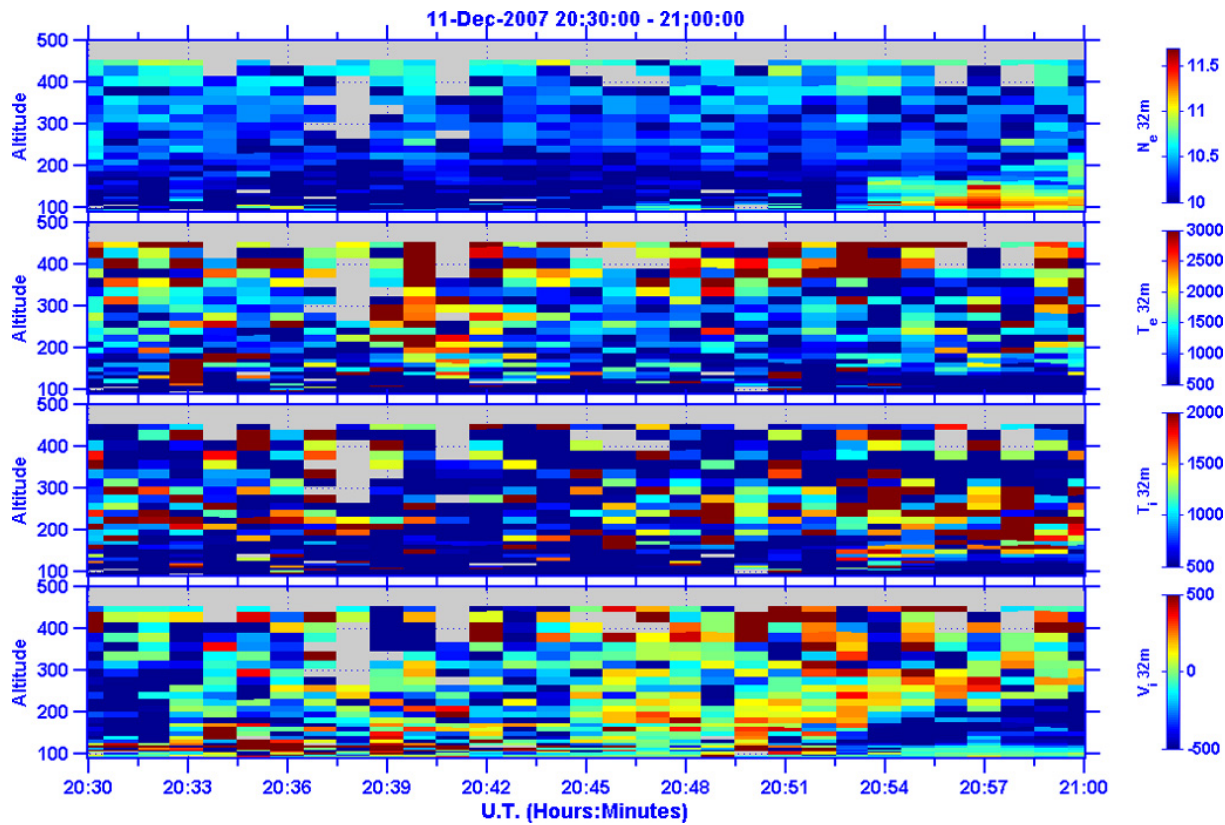
Fig. 7. ESR 32 m dish – northward observations. Upper panel represents N_e (log (N_e) with N_e in m^{-3}), second T_e (K), third T_i(K), and fourth V_i (m s^{-1}). Altitudes are in km. All the ESR figures are built in the same way.
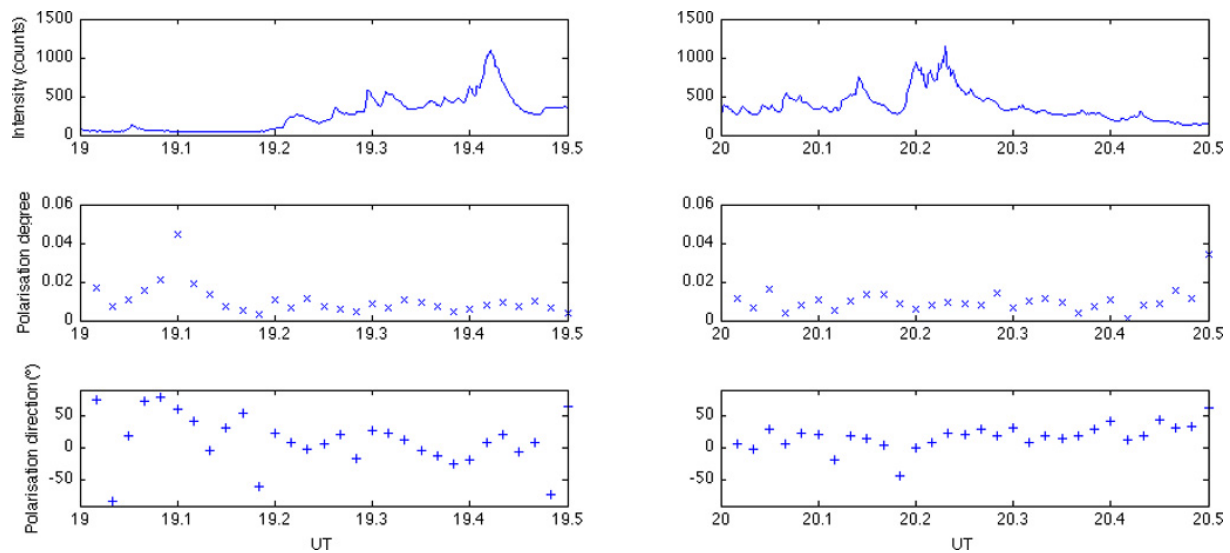

Fig. 8. Zenith optical observations during the first 30 min of each hour (9 January 2008). UT is in decimal hour. Top panel: intensity in counts; mid panel: polarisation degree; bottom panel: polarisation direction in degree from the vertical following the trigonometric direction.

data from this antenna, which points parallel to the magnetic field, are shown in Fig. 9. As expected, the auroral activity clearly shows up in the electron density. It starts

at about 19:25 UT and lasts until 20:30 with a 15 min interruption between 20:00 and 20:15 UT. The peak altitude of the electron density varies between 100 km and 190 km,
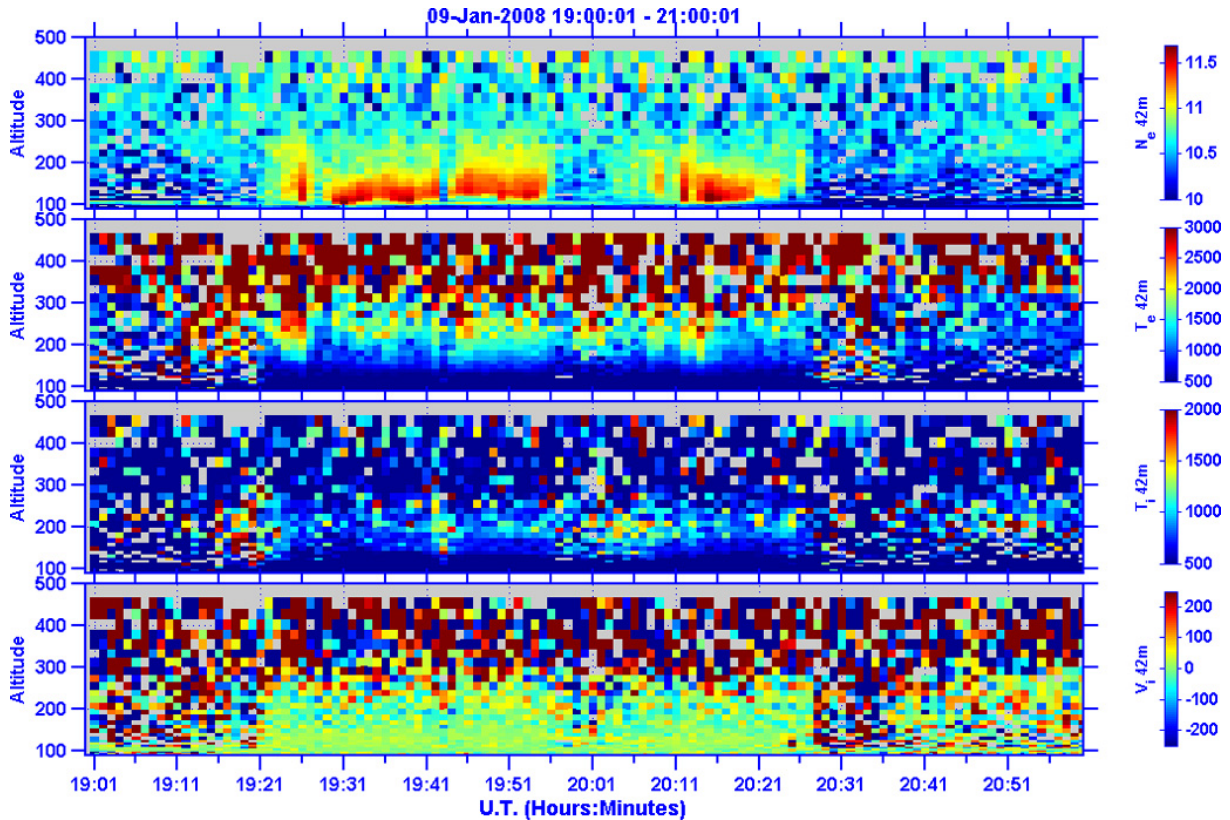
Fig. 9. ESR 42 m dish – zenith observations. Upper panel represents N_e (log (N_e) with N_e in m^{-3}), second T_e (K), third T_i (K), and fourth V_i (m s^{-1}). Altitudes are in km.

which is typical for electron precipitation with energies ranging between one keV and a few tens of keV. During the first northward-directed observation, the 42 m dish observed an aurora in the zenith. During the second period, the analysis of the radar data prove that the aurora had receded. However, the polarisation data showed no significant differences between the two periods. Since it is unlikely that any kind of measurement artefact could have affected the SPP in one period, but not the other, this re-inforces the conclusions that no significant polarisation is observed for the red line at the zenith.

5.3 Southward direction: 16 December 2009

There were several days of southward observations during the 2009 campaign. Only few of them are useable however, either due to fog or because of ice covering the instrument. All the useable southward data look similar. Here, we only show the data taken while the ESR was operating in a dedicated mode to support our optical observations. These observations were performed on 16 December 2009 from 22:00 UT to 06:00 UT on the next day. In this experiment, the elevation angle of the photo-polarimeter was 45°. The angle between the line-of-sight and the magnetic field line at 210 km altitude was about 36° The weather remained mostly

cloudy. The air temperature was chilly ranging between $-5\,°C$ and $-1\,°C$. The sea level pressure decreased steadily from 1012 hPa at 23:00 UT to reach 1006 hPa when the instrument was turned off. From 16:00 UT to midnight, the sky was clear especially in the southward direction. Clouds came back at 24:00 UT and periods of clear sky and clouds alternated until 02:00 UT in the morning, when fog set in until the end of the experiment.

The SPP optical observations are shown in Fig. 10. The differences between the two channels are hardly distinguishable. The polarisation degree is computed since the fit with a sine square always works. However, both the polarised and reference channel show the same polarisation amplitude. The phase shows no clear structure. Finally, $\mathcal{P}_{0.4-0.6}$ is equal to 14.1 % for the polarised channel and 13.7 % for the reference channel. These two values are not significantly different from each other and not significantly different from the white noise value. We can therefore conclude that there is no continuous polarisation during the period. However, after 23:30 UT a non continuous polarisation appears with a maximum around 1.5 % and a direction close to the vertical. This can be explained by two phenomena giving polarisation in the same direction:
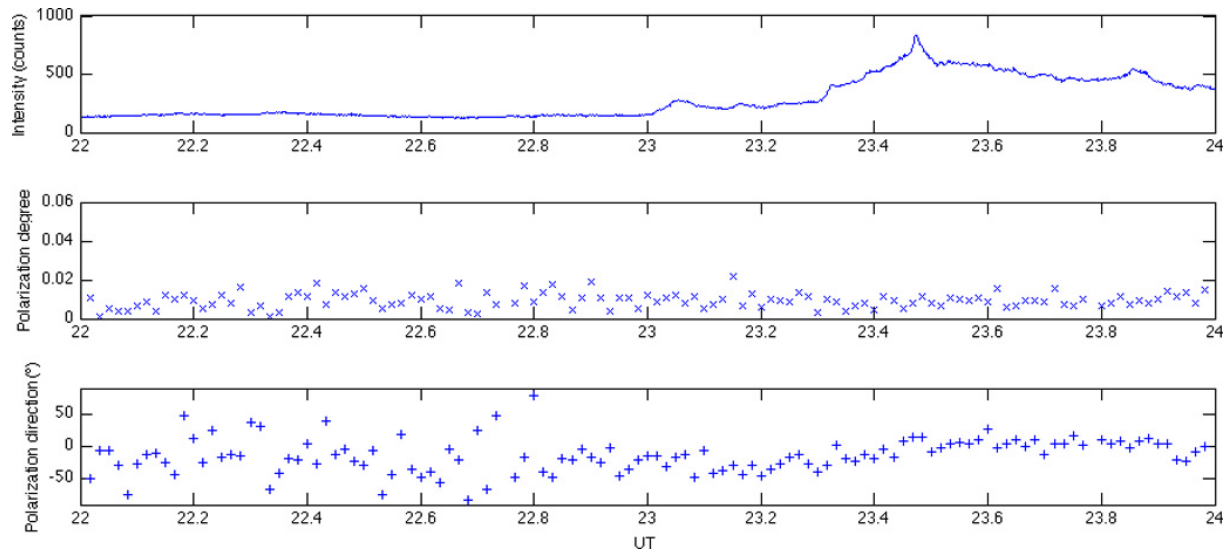
Fig. 10. Southward optical observations (16 December 2009). UT is in decimal hour. Top panel: intensity in counts; mid panel: polarisation degree; bottom panel: polarisation direction in degree from the vertical following the trigonometric direction.

- The instrumental polarisation is vertical and can reach 1 %. Considering that an auroral event occurs, this instrumental polarisation can be seen as explained in the zenith case.

- A residual polarisation due to the angle with respect to the magnetic field line. If the polarisation is 2 % perpendicular to the magnetic field line, which is the typical measured polarisation degree during an auroral event, an angle of 36° gives a polarisation degree of 1.2 % which is consistent with our measurements. Following Bommier et al. (2011), this polarisation should also be vertical.

The data from the ESR 32 m dish data are shown in Fig. 11. The pointing direction is parallel to the line of sight of the photopolarimeter. During the first part of the experiment (22:00 to 22:40 UT), weak precipitation occurs, creating an ionization layer around 220 km, i.e. the altitude where the red line maximizes. This is typical of the polar rain precipitation and very close to the conditions prevailing during the first part of the northward experiment: the characteristic energy of the precipitated electrons is around 500 eV. The second part of this southward pointing experiment is also similar to the second part of the northward pointing one, with precipitation creating a denser ionosphere at lower altitudes (down to 150 km). The ion and electron temperatures remain low (below 1000 K at 210 km) during the whole experiment, with some enhancements of the ion temperature at 23:30 UT. The ion velocity exhibits no wave signatures and no coherent structure.

These conditions are very similar to those encountered during the northward-pointing experiment. The fact that the polarisation effects were seen when looking northward but not when looking southward, is therefore not a consequence of different ionospheric/thermospheric conditions but indeed depends on the angle between the line-of-sight and the magnetic field line.

5.4 New northward data from Hornsund polish station

During the winter of 2010–2011, the SPP instrument was installed at the Polish polar station in Hornsund, 130 km South of Longyearbyen. The strong advantage of this station is that absolutely no light pollution exists at this place. The instrument was looking toward the North with an elevation of 23°. The first observation set comprises three clear nights, from the evening of 7 November to 10 November in the morning. As an example, we have studied on 8 November 2010 between 00:00 UT and 03:00 UT. Since there is no light pollution, the measured polarisation degrees can only be due to instrumental polarisation and of course to auroral polarisation. The data processing was the same as above, except the fact that some spikes appeared periodically every 6 min in the data, attributed to an electrical problem. The PSD on the polarised channel presents 21.06 % of the values in the 0.4 to 0.6 Hz interval versus 15.36 % for the non polarised channel. The polarisation degrees averaged on one minute are up to 3 % and the mean degree over two hours is 1.36 % with a direction close to the vertical. This is significantly less than at KHO but it confirms that the polarisation exists. To ensure that this measurement is also not due to instrumental polarisation we have simulated the data with default noise at a level of $10 + \sqrt{(I)}$ counts. In this case, the instrumental polarisation averaged over the same conditions can only reach 1.05 %. The measured polarisation is significantly higher confirming that the observed polarisation is due to auroral
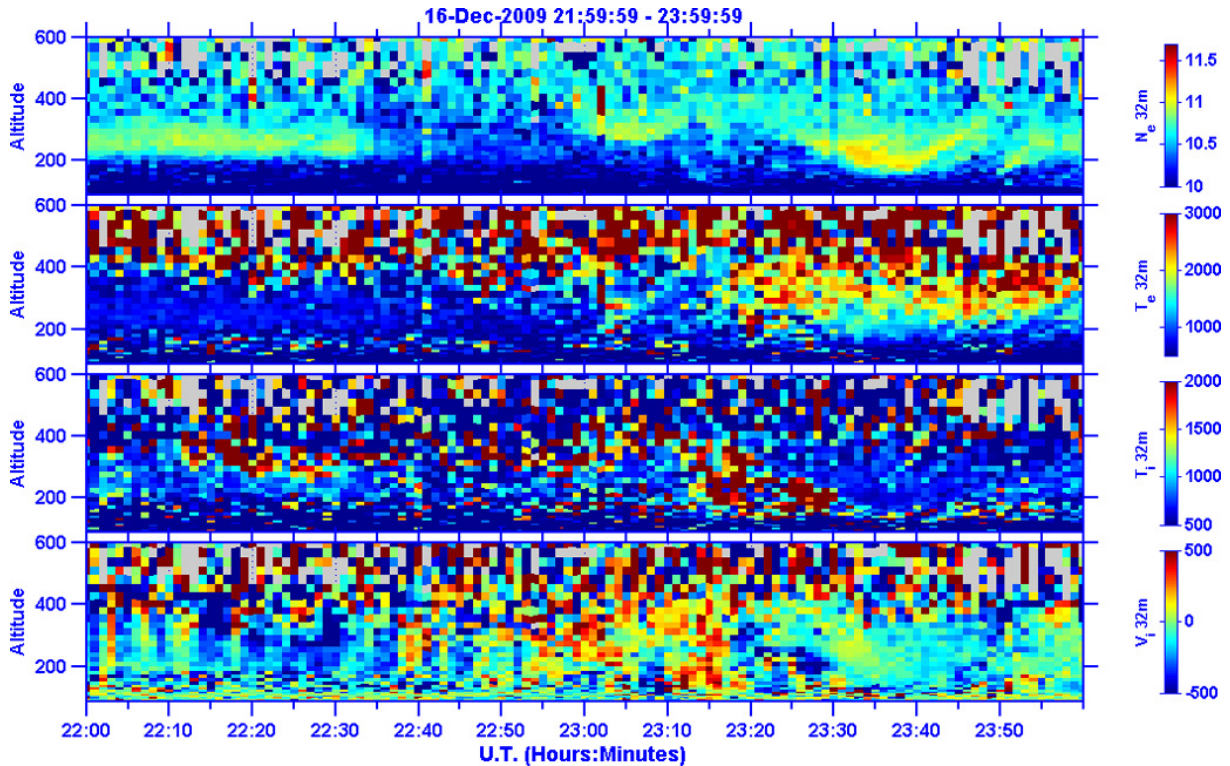
Fig. 11. ESR 32 m dish – southward observations. Upper panel represents N_e (log (N_e) with N_e in m^{-3}), second T_e (K), third T_i (K), and fourth V_i (m s^{-1}). Altitudes are in km.

light. The degree of the auroral polarisation is lower than found by Lilensten et al. (2008), with a direction close to the vertical. In the case of an auroral polarisation completely aligned with the instrumental one the degree would be 0.4 %, for the same averaging conditions. In reality, the polarisation degree is more probably between 0.5 % and 1.5 %. The maximum measured polarisation degree during these three nights is 2.24 % on the evening of the 7th which means that, allowing for the instrumental polarisation, the polarisation degree in the aurora would be 1.33 % if the auroral polarisation was completely aligned with the instrumental one. This is consistent with all of our observations at KHO.

6 Discussion and conclusion

In our first two articles (Lilensten et al., 2006, and Lilensten et al., 2008), we predicted and discovered that the auroral red line is partially polarised. We made some predictions and raised one possible artefact that could explain the polarisation measurement. This new set of observations fully confirms the theoretical works and rules the artefact out:

– In January 2007, we observed polarisation with the instrument pointing North. Our prediction was that the polarisation should maximize perpendicularly to the line-of-sight when looking perpendicularly to the mag-

netic field at 210 km altitude. The elevation angle of the optical instrument was 15° so that the angle between the perpendicular to the magnetic field and the line of sight was only 7°. We eliminated several artefacts such as light pollution from the city or from other sources. One possible artefact still remained after Lilensten et al. (2008): the observed polarisation could have been due to the aurora occurring outside the field of view being Rayleigh-scattered by the lower atmosphere. We have ruled out this possibility by a rigorous analysis calculating the Rayleigh scattering using the UiO all-sky camera. This analysis is confirmed by an alternating two-position experiment which shows no polarisation when looking to the zenith and polarisation when looking to the North.

– By re-calibrating our instrument, we have shown that the direction of polarisation typically ranges between up to 35° from the magnetic field line direction during quiet periods and rotates to align with the magnetic field line during auroral activity enhancements. This finding is fully supported by recent theoretical developments (Bommier et al., 2011).

– We predicted that, when looking at small angles to the magnetic field line, the polarisation should disappear. This is confirmed by the 2008 experiment looking to

Table 1. Summary of the SPP results. The polarisation data are presented as raw data without taking into account the instrumental polarisation and the light pollution.

Observation	Geophysical conditions	$\mathcal{P}_{0.4-0.6}$	polarisation degree (raw)	polarisation direction (raw)
Angle (θ) between the line-of-sight and **B**	$f_{10.7}$, A_p			
Northward (KHO), $\theta = 85°$, 11 Dec 2007	87, 8–9	33.9 %	$P = 2$–4 %	20°
Zenith (KHO), $\theta = 0°$, 9 Jan 2008	70, 4–5	16.9 % and 20.5 %	$P = 1$ %	$\sim 0°$ Noisy when signal is low
Southward (KHO), $\theta = 36°$,16 Dec 2009	80, 8–9	14.1 %	$P = 1$ %	$\sim 0°$ Noisy when signal is low
Northward(Hornsund), $\theta = 77°$ 8 Nov 2010	82, 4	21.06 %	$P = 1.36$ %	$\sim 0°$

the zenith, almost parallel to the magnetic field line. In 2009 with an angle of 36° between the line of sight to magnetic field, an intermittent faint polarisation occurred, confirming our prediction of a degree up to 1.5 % and a mean around 1 % close to the instrumental values.

– New observations at Hornsund have confirmed our measurements and the real mean 1 h degrees are found to be between 0.5 % and 1.5 % when each point is calculated on one minute average.

– We predicted that these polarisation measurements could provide a new window to monitor the geophysical activity. The present experiments confirm this, openning the road for a new space weather proxy, measureable from the ground as well as from space. Polarimeters can be adapted on many optical instruments at relatively low cost, allowing deployment of large scale measurements. However, considering the small polarisation degrees measured, this will require devices with very low instrumental polarisation, less than 0.2 %, and very low photometric noise in order to provide measurements which are truly linked to the ionospheric conditions.

The main results of this paper are summarised in Table 1. These new campaigns have confirmed the first observations and increased our knowledge about the polarisation of the thermospheric red line: the polarisation exists, its parameters depend on the geomagnetic activity and it is related to the direction of the magnetic field line. Recent theoretical work started to shed light on this observational evidence. It now becomes necessary to perform long duration observations. These began to be carried out from the Polish Hornsund polar base where a full winter of observations have been performed from November 2010 to February 2011. For future measurements, balloon and space observations should be considered.

The use of polarisation as a tool to understand atmospheric emissions is also of prime importance for other planetary bodies, such as Mars or Jupiter, for which recent observations show evidence that the H_3^+ at 3.95 µm line is also polarised (Barthélémy et al., 2011).

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