The Polar Atmosphere
studying space weather events with the EISCAT incoherent scatter radars

Atmospheric Physics

F7014R

A report submitted in fulfilment of the requirements for course F7014R - Polar Atmosphere, Luleå University of Technology

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Abstract

This report discusses the space weather conditions of the Halloween storms from 2003 with the support of EISCAT data. The data is analysed with GUISDAP and compared to the International Reference Ionosphere model. Furthermore heigh profiles of ion- and electron temperature and line-of-sight velocities are viewed.

Contents

1 Introduction

Over the last couple of decades our society learned how to use technology for improvement and well-being. It has had a major impact in everyone's everyday life and became a crucial part in development. In order to generate energy to power all our components we have even invented solar panels, to directly use the seemingly endless amount of energy of our sun. But it has a downside too: our sun is able to produce threatening conditions to our sophisitcated technology. Space weather is a real risk and needs to be understood in order to take appropriate precautions. In this report one of the most devastating space weather conditions is analysed and discussed: the Halloween storms of 2003, named due to their occurrence between middle of October to early November 2003. The solar activity was on its decline and yet it was able to produce outbreaks of 17 major flare eruptions. The consequences of the powerful storms on Earth were far reaching: from radio blackouts to power grid outages and damaging of satellites.
In chapter 2 an overview of the space weather conditions during the Halloween storms and the data acquisition for analysis is presented. Data is used from the EISCAT (see chapter 6) radar and from the International Reference Ionosphere (IRI). In addition to this, some analysis is also performed with GUISDAP, a package for MATLAB, using data from another space weather event (27.10.2016).
Chapter 3 presents the results and discussion of the analysed data. First, the effects of the storm are put into perspective with IRI, followed by a discussion of the height profiles of ion- and electron temperatures and line-of-sight velocities. Finally the data is compared to the space weather conditions during this time and how it is related.
In chapter 4 a brief summary of the outcomes of this report is presented.

2 Acquisition of Data and Analysis Method

2.1 Analysis with GUISDAP

For this section, raw data from an EISCAT experiment during the 27.10.2016 - 28.10.2016 was provided and analysed using GUISDAP, the standard software from EISCAT for (pre-)processing the data from the experiments conducted on the EISCAT radars. The final result is shown in figure 1.

The data used was an experiment from Svalbard with the experiment type ipy.

2.2 Conditions during the Halloween event

During mid October to early November 2003 (during the solar cycle 23) when the solar maximum just finished and the cycle was on its way to its solar minimum several sunspots formed with succeeding major space weather effects affecting the Earth. Due to their appearance during this time of the year they are called the *Halloween storms of 2003*.
During this period several aspects of these solar eruptive events included significant increases in active region size and potential energy flare occurrence rate and peak intensity, coronal mass ejection (CME) speed and energy, shock occurrence rate, SEP occurrence rate and peak intensity, and the geomagnetic storm intensity displayed extreme behaviour [Gopalswamy, 2007]. In total 143 well-defined solar flares from three active regions (54 from AR 484; 60 from AR 486; 29 from AR 488) were reported with 9 X-class flares with the largest flare of the solar cycle on 4 November 2003 [Gopalswamy et al., 2005]. All X-class flares were accompanied by major coronal mass ejections (CME) and in total 80 CMEs were recorded. Two of the flare events at the end of October were especially outstanding, originating from AR 486. On October 28th at 11:10 UTC an X17 solar flare was produced by it and a category R4 radio blackout was caused on Earth, accompanied by one of the most energetic CMEs every recorded with speeds of almost 2500 $\frac{\mathrm{km}}{\mathrm{s}}$ [Plunkett, 2005]. Shortly after, on October 29th at 20:49 UTC another X10

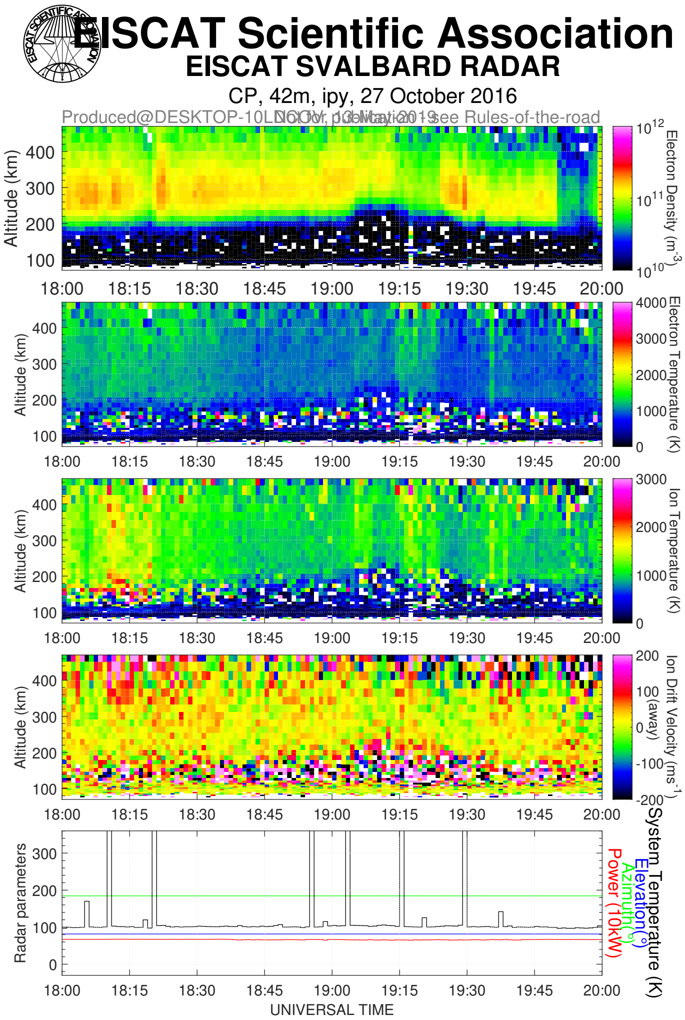

Figure 1: Resulting overview plot of the analysed EISCAT data from 27.10.2016, 18:00 - 20:00 UTC by GUISDAP

flare occured resulting in a class R4 radio blackout at Earth with an associated extremely fast CME ($2000\,\frac{\text{km}}{\text{s}}$) [Plunkett, 2005]. Another notable event during this time is the X28 flare which occured on November 4th causing an R5 radio blackout on Earth. Figure 2 shows visualised data of GOES including (from top to bottom) X-ray intensity, proton intensity and magnetometer measurements. Figure 3 shows overview plots including (from top to bottom) GOES X-ray flares, CME height-time plots, SEP intensity, solar wind speed and Dst (Disturbance storm time) index and the dashed line indicates normal quiet conditions. In both figures all three events are evident.

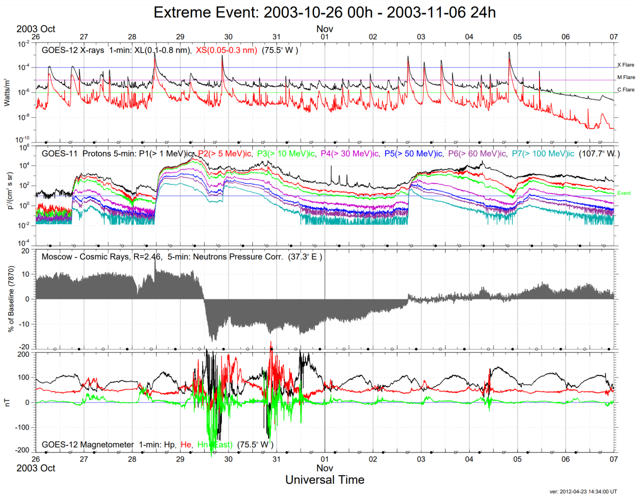

Figure 2: Data of GOES during Halloween storms in 2003. Source: https://satdat.ngdc.noaa.gov/

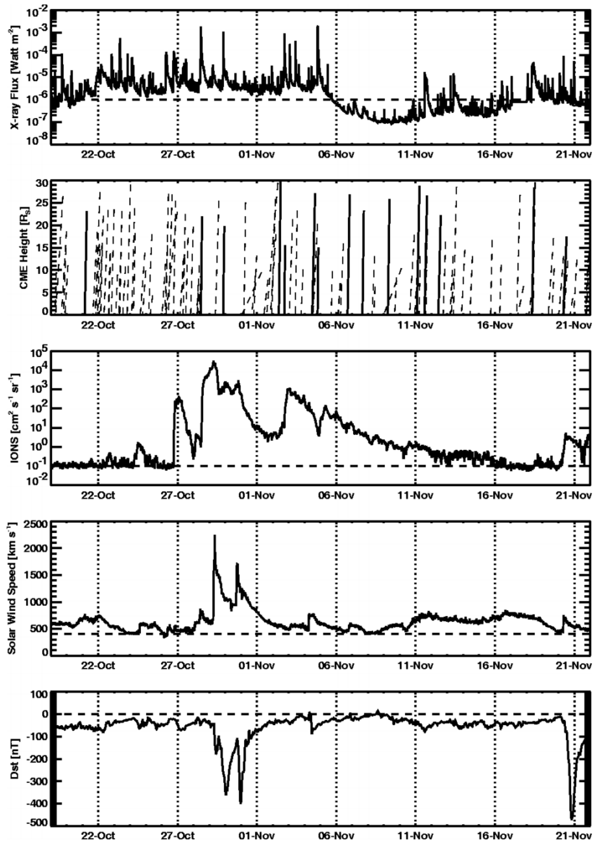

Figure 3: Detailed data of GOES during Halloween storms in 2003. Source: [Gopalswamy, 2007]

Shocks associated with fast and wide CMEs are thought to be good accelerators of electrons and ions [Gopalswamy et al., 2005]. The two major events on October 28th and October 29th produced SEP intensities of 33600 and 3580 pfu, respectively (1pfu = 1 proton per square-centimeter, second, steradian) [Gopalswamy et al., 2005].
During the two major events in late October measured solar wind speeds of >1850 km/s and 1700 km/s occured and presents some of the highest solar wind speeds ever measured in space [Skoug et al., 2004]. Figure 4 shows plasma and magnetic field measurements for 28 – 31 October 2003. From top to bottom, panels show proton speed and temperature, magnetic field magnitude, the GSE Z component of the magnetic field, and the magnetic field polar and azimuthal angles in GSE coordinates. Shocks are indicated by vertical dotted lines [Skoug et al., 2004].
The flare radiation caused enhanced ionization over a broad altitude range in the ionosphere from the D region (80–100 km altitude) all the way to the F region (the F peak is at about 300 km altitude) [Tsurutani et al., 2005]. Figure 5 shows the global ionospheric response to the flare on October 28th indicating a difference plot to a quiet day. The largest TEC (Total Electron Concentration) enhancement occurs at the subsolar region, with an electron column density increase of about 22 TECU and gets less away from noon and at higher and lower latitudes and is essentially zero at the nightside ionosphere [Tsurutani et al., 2005].

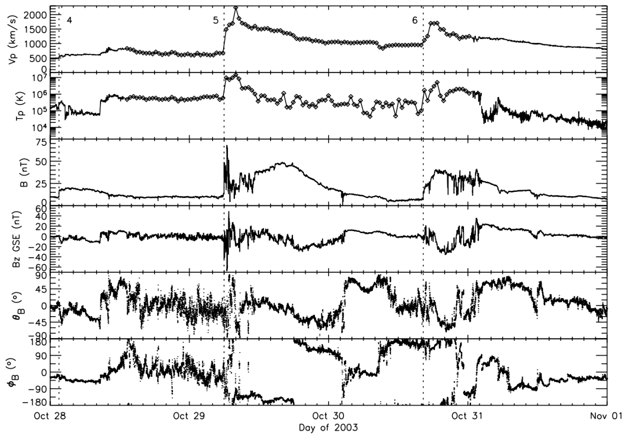

Figure 4: Plasma and magentic field measurements during October 28th to 30th 2003. Source: [Skoug et al., 2004]

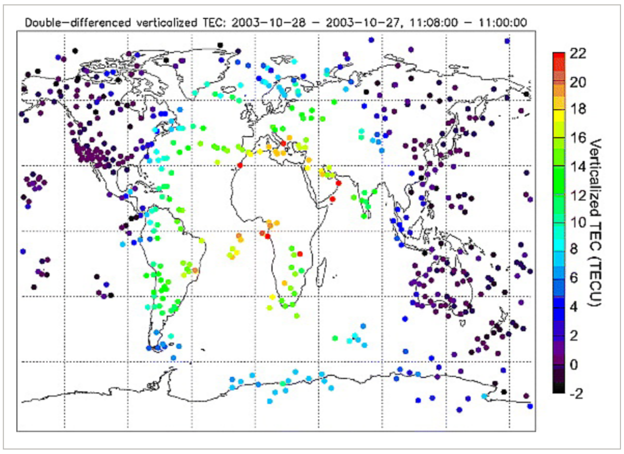

Figure 5: Global ionospheric response to flare on October 25th 2003. Source: [Tsurutani et al., 2005]

The beautiful phenomena of aurora was so strong during these events that it was even visible in Texas and Florida.

Figure 6: Aurora image taken near Houston Texas on Oct.29, 2003. Source: nasa.gov

2.3 EISCAT data base

To analyse the Halloween event 2003 with EISCAT data, two data sets were downloaded from the EISCAT Madrigal site [EISCAT, 2019]:

- 29th of October 2003, with particular analysis of the measurements at 20:48:49 UTC
- 4th of November, with analysis of the measurements at 15:14:57 UTC as well as a colour contour plot for the duration of the whole experiment (approx. 5 h). The colour plot can be seen in figure 7.

The reason why two data sets were analysed is because the results of the first data set (from the 29th of October) deviated greatly from the model, probably due to the fact that the solar activity and the geomagnetic storms were so intense during that time. In order to be able to relate the data a bit better to the models it was decided to analyse a second data set that originated also from the Halloween event but did not include the strongest activities observed.

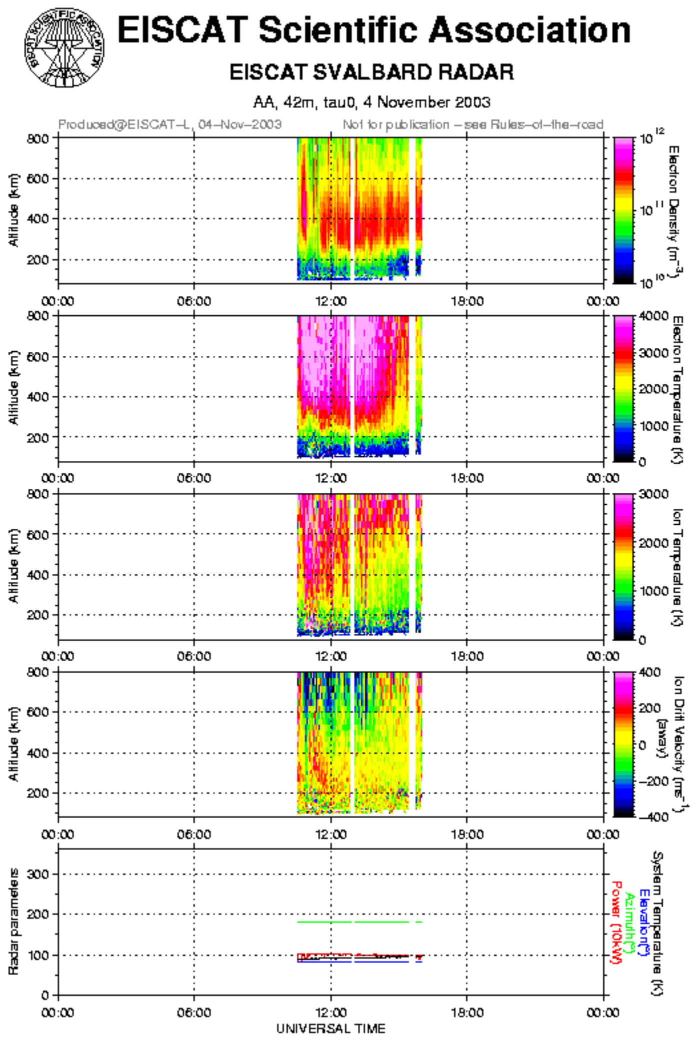

Figure 7: Colour plot of the EISCAT data measured on 04.11.2003

2.4 International Reference Ionosphere

To be able to compare the data measured by the EISCAT radars with theoretical models, the electron density and the ion and electron temperatures were modelled using the International Reference Ionosphere (IRI) model [NASA, 2019] for the exact location of the EISCAT radar in Svalbard and the specific times that the data was from, as mentioned above. The resulting height profiles are plotted along with the measured data with the use of MATLAB (see section 2.5) and can be found in section 3.

2.5 Analysis with MATLAB

For the data analysis the pre-processed data from Madrigal and the model data from the IRI were retrieved as `.txt` or `.csv` and imported into MATLAB. Then the height profiles for the electron number density N_e, the electron temperature T_e and the ion temperature T_i were plotted together to have a comparison between the model and the measured values. For the line of sight velocity only the data from EISCAT is shown because the IRI model does not provide any information about that. The results are found in section 3.

3 Results and Discussion

3.1 Effects of the storm on electron number densities

In the figures 8 and 9 the electron density numbers measured by the EISCAT radar are compared with the IRI model.

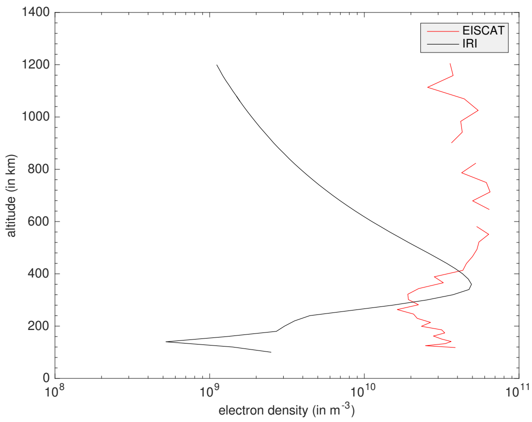

Figure 8: Electron number density N_e on 29.10.2003

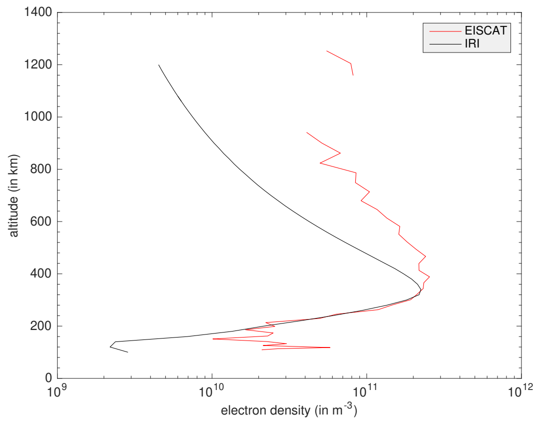

Figure 9: Electron number density N_e on 4.11.2003

Figure 8 shows one of the most extreme moments of the Halloween event, the 29th of October at 20:49 UTC where a G5 geomagnetic storm was recorded. The electron number densities differ greatly from the model, in particular for high altitudes (above 400 km) and also for lower altitudes (below 200 km). It is not entirely clear why the electron number density shows such a constant value between 600 km and 1200 km altitude, but one possibility is that the electron density actually comes from the solar wind that enters the Earth's atmosphere at the polar caps and penetrates quite far down until there is some shielding by the ionosphere itself at around 400 km. Below 200 km the measured values are once again higher than the simulated model values based on IRI, possibly also due to increased radiation during the solar event.

Figure 9 shows the electron density on the 4th of November at15:15 UTC, so during the Halloween event, but not explicitly during the most severe storms. Here it can be seen that while the measured electron densities are once again significantly higher for all altitudes except between 200 km to 400 km. However, in this case the similarities (i. e. the shape of the curve) remain, in particular the decrease in higher altitudes with decreasing atmospheric pressure.

3.2 Height profiles of ion and electron temperatures and line-of-sight velocities

Figures 10 to 13 show the electron and ion temperatures for the 29th of October and the 4th of November, respectively. Once again it can be seen that the data from the 4th of November fits better to the model data than the data from the 29th of October, where the electron temperature show significantly higher values and deviations from the model. Again this might be attributed to the high solar activity during this time. The low values of the ion temperature in high altitudes cannot be explained by this, although for the 4.11. there are some data points missing in that range that might give an idea of what is happening there.

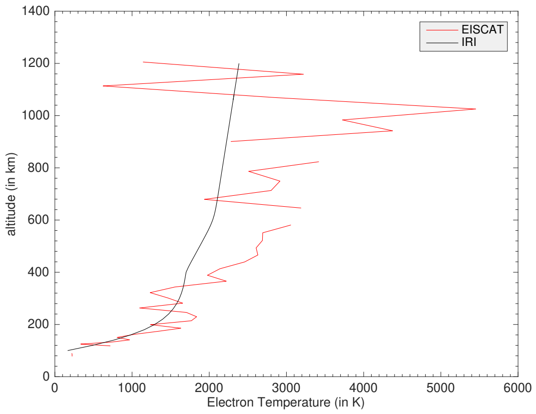

Figure 10: Electron temperature T_e on 29.10.2003

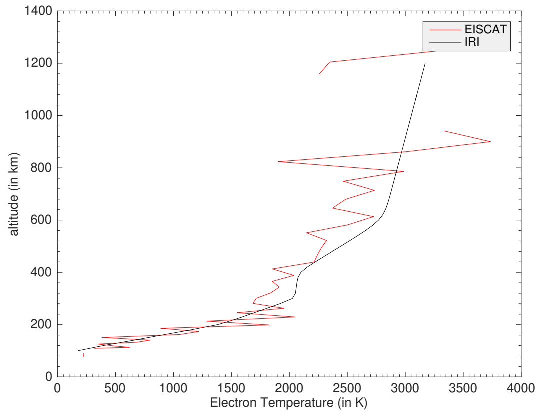

Figure 11: Electron temperature T_e on 4.11.2003

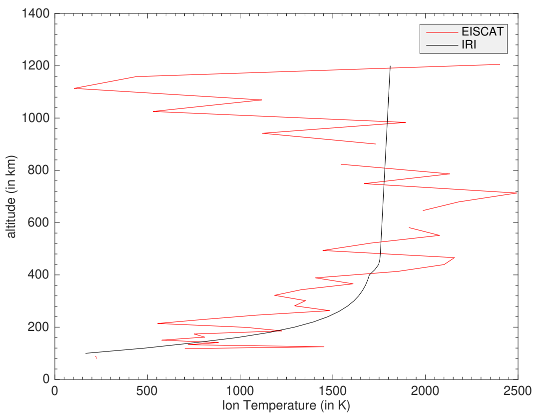

Figure 12: Ion temperature T_i on 29.10.2003

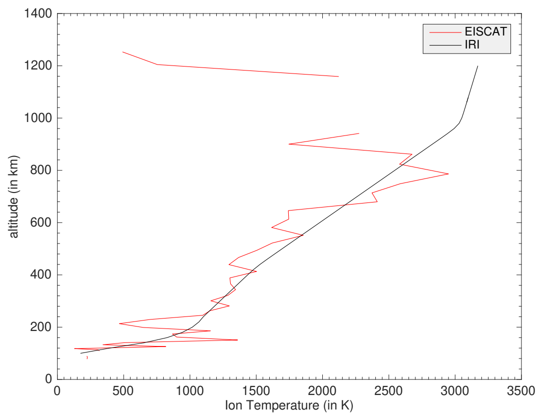

Figure 13: Ion temperature T_i on 4.11.2003

The line of sight (LOS) velocity is the velocity of ions in the direction of the radar beam and is defined positive in the direction away from the radar. The amplitude of the LOS velocity is quite high once an altitude of 600 km is reached. Above this altitude the vertical velocity component of ions is significant, which indicates that the interaction of ions with the atmosphere is high, along with mixture / penetration of the atmosphere by ions. The comparably low values at around 400 km could be related to the low electron number density seen in figure 8.

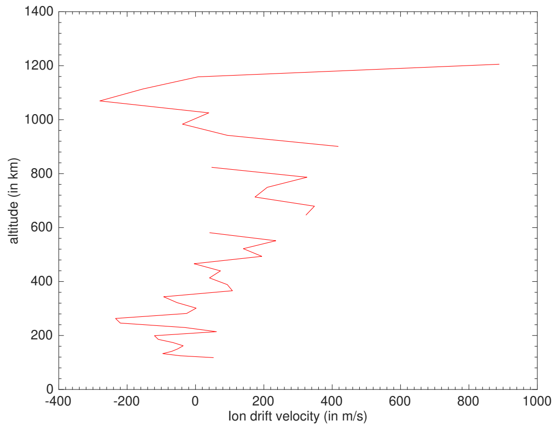

Figure 14: Line of Sight velocity on 29.10.2003

3.3 Space Weather Conditions

The facets of space weather cover radio blackouts (disturbances of the ionosphere caused by X-ray emissions from the sun), solar radiation storms (elevated levels of radiation that occur when the numbers of energetic particles increase) and geomagnetic storms (disturbances in the geomagnetic field caused by gusts in the solar wind that blows by Earth). As briefly described in section 2.2 the Halloween storms are an outstanding and intense event of space weather. During the events on 28th and 29th of October 2003 the X-ray emissions from the sun reached peaks of around $10^{-3}\,\frac{\mathrm{W}}{\mathrm{m}^2}$, as can be seen from figure 3 top panel causing R4 (severe) and R5 (extreme) radio black outs. The radio black outs occurred to the enhanced ionisation within the ionosphere due to the solar X-ray radiation causing HF radio signals to be absorbed, lost, bounced resulting in missing the receiver. This enhancement in electron number density during the events can also be evidently seen in the electron density in the figures 8 and 9. A high electron density can be also seen in figure 7. The succeeding radiation storm on October 28th reached category S3 (strong) and soon even S4 (severe) and the one from October 29th reached category S3, as can be seen in figure 2. During the S4 storm the crew onboard the ISS was asked to reside within the russian module which has the most effective shielding for five times 20 minutes [COMMERCE, 2004]. The geomagnetic storm due to the extreme solar wind of both events reached category G5. The variations in the magnetic field induced electric fields and drove geomagnetic induced currents in conducting networks and caused major power grid outages in Northern Europe which lasted for an hour.

4 Summary

In this report the space weather conditions during the Halloween storms in 2003 were discussed and analysed. The report showed how a plot for an arbitrary space weather event in October 2016 can look like with the help of the package GUISDAP provided by EISCAT.
Then the events of the Halloween storms are examined and the space weather conditions from the literature are listed. For investigating further parameters of the events data from the EISCAT data base and the IRI model is collected. From these data it was evident that during the Halloween events the electron number density was rising significantly. The electron temperature showed significantly higher values than compared to the model.
As expected the data mainly fitted to the space weather events from the Halloween storms in 2003.

5 Confirmation of participation

I, Veronika Haberle, hereby confirm that I have participated in this report.
I, Anja Möslinger, hereby confirm that I have participated in this report.

6 Acknowledgements

EISCAT is an international association supported by research organisations in China (CRIRP), Finland (SA), Japan (NIPR), Norway (NFR), Sweden (VR) and the United Kingdom (UKRI). EISCAT data are the intellectual property of the EISCAT Scientific Association. Except where clearly noted as Common Programme (CP), use of these data is restricted to the original experimenter (as noted in the description file available through the schedule system at http://www.eiscat.se/schedule/schedule.cgi) for one year from the date of the experiment. Otherwise, the data may be used freely for the purpose of illustration for teaching and for non-commercial scientific research, provided that the source is acknowledged and to the extent justified by the non-commercial purpose to be achieved. Substantial use of the data should be discussed at an early stage with knowledgeable scientists within the EISCAT Scientic Association in order to clarify matters of use, calibration and potential co-authorship. Ingemar Häggström, at EISCAT Headquarters, can provide advice on suitable contacts. Any further distribution of these data, including installation in any database, must be accompanied by this statement and subject to the same conditions of use.

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