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Signatures of mesospheric particles in ionospheric data

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Abstract. The state of the ionosphere during the 2007 ECOMA/MASS campaign is described by in-situ observations by three sounding rockets launched from the Andøya Rocket Range and by ground based observations. The ground based measurements included the incoherent scatter radar EISCAT near Tromsø (both on UHF and VHF), as well as an MF radar, a meteor radar and an imaging riometer all located in the close vicinity of the rocket range. The pronounced electron density bite-outs seen by two of the rockets could not be detected from the ground, but the associated PMSE (Polar Mesospheric Summer Echoes) provide indirect evidence of pronounced perturbations of mesospheric electron densities.

Keywords. Atmospheric composition and structure (Aerosols and particles; Middle atmosphere – composition and chemistry) – Ionosphere (Ionospheric irregularities)

1 Introduction

At times the lower ionosphere behaves in an unusual way which can not be explained by the balance between ionisation and recombination alone. Notably at high latitudes electron density profiles were measured which displayed pronounced minima in the mesosphere which can only be understood by extremely large effective electron recombination rates (Ulwick et al., 1988). These so-called bite-outs can best be explained by particles much larger than molecules, efficiently scavenging free electrons. The altitude of these ionospheric structures usually coincides with the optically visible phenomenon of noctilucent clouds (NLC), which are formed by ice particles. Recent in-situ measurements have revealed that particles larger than molecules but too small to be optically detectable from the ground, presumably always exist in the 80 to 90 km altitude range and may therefore conceivably be responsible for a series of ionospheric irregularities. In summer smoke particles have long been expected to exist forming the nuclei of ice particles which lead to NLC (Havnes et al., 1996), but they are also found in winter (Lynch et al., 2005; Rapp et al., 2005; Amyx et al., 2008), and also at low latitudes (Strelnikova et al., 2007). Monitoring ionospheric parameters from the ground is one way to gain insight into the behaviour of these particles widely believed to be of meteoric origin. However compelling interpretation of ground based ionospheric data requires occasional comparisons with coincident in situ measurements. The projects ECOMA and MASS consist of a series of sounding rockets dedicated to detect and analyse particles in the mesosphere by various sets of instruments from different countries. A total of eight rocket soundings were hitherto performed from the Andøya Rocket Range, Norway, in three campaigns (September 2006, August 2007 and June 2008); we will here place emphasis on the 2007 campaign in which three rockets were flown, one (ECOMA) predominantly European and the other two (MASS, coded 41.069 and 41.070) provided by the USA.

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2 Data

2.1 Rocket data

The sounding rockets of the ECOMA/MASS series were to be launched into mesospheric conditions expected to be influenced by various types of particle-induced atmospheric perturbations. Both the ECOMA and MASS payloads carried four-frequency radio wave propagation experiments to establish electron densities with good absolute accuracy, whereas the probes – both for ions and electrons – provide the desired height resolution. The combination of these two

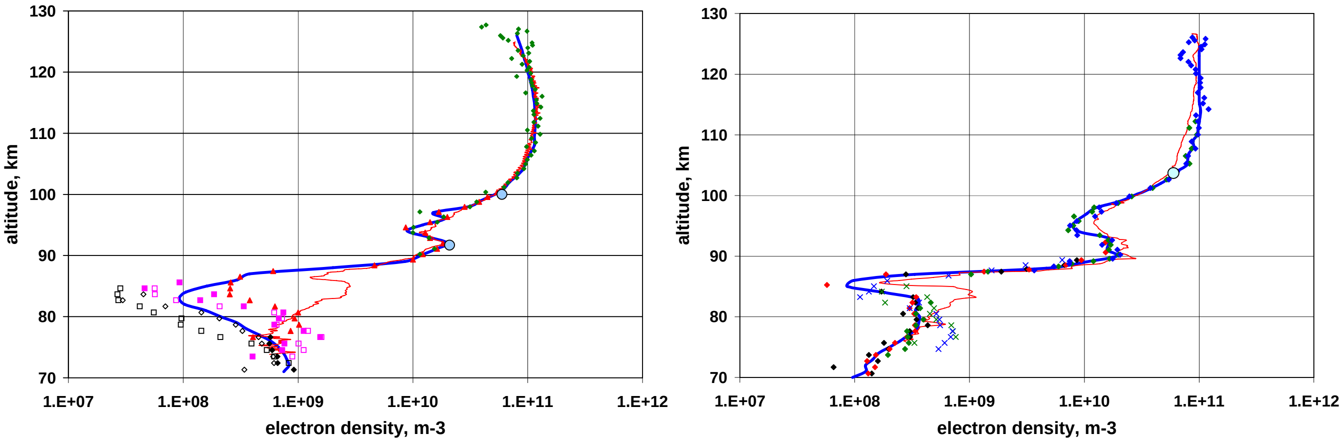

Fig. 1. Plasma densities measured by sounding rockets MASS-1 (left, 3 August 2007, 22:51 UT) and ECOMA-3 (right, same day, 23:22 UT). Bold blue lines represent the final electron densities in best agreement with the raw data (symbols), the fine red lines are ion densities normalised in the E-region to the wave propagation electron densities.

types of instruments yields the best results at altitudes where the neutral background density affects in-situ measurements by aerodynamic effects (Mechtly, 1974; Thrane, 1974). In the radio wave propagation method to determine electron densities one transmits linearly polarised waves of different frequencies between 1.3 and 7.835 MHz to the rocket. The likewise linearly polarised receiving antenna rotates with the spinning rocket and thus observes two minima and two maxima in each spin period. As the electron content between ground and rocket increases, the orientation of the maxima and minima rotates (Faraday rotation; Mechtly et al., 1967; Bennett et al., 1972; Jacobsen and Friedrich, 1979); the differential of this rotation is proportional to electron density. Since the ionosphere is a dispersive medium for electromagnetic waves, lower sounding frequencies are more affected (more sensitive), but are more absorbed (by electron-neutral collisions), or indeed reflected where the signal frequency equals the plasma frequency. Figure 1a and b shows the plasma densities of the flights MASS-1 and ECOMA-3. The electron densities were obtained from Faraday rotation and absorption from the various data sets (sounding frequencies). The smooth line is obtained by iteratively simulating the different sets of raw data with the final profile for best fit. Also indicated in the plots (circles) are the heights where total reflection of the 1.3 and 2.2 MHz signals occurred. Both profiles show a pronounced minimum in the 80 to 90 km region ("bite-out") the depth of it is difficult to ascertain and may indeed have been much deeper than indicated in the figures. As stated earlier the height resolution of this type of measurement is primarily determined by the rocket's spin and its velocity, but also by the wavelength of the sounding frequency. ECOMA-3 carried probes both for electron and ions, whereas in the case of the MASS payloads we can use the total current to the particle detector as a proxy for an ion probe (Robertson et al., 2009). For charge neutrality the difference between the number density of positive particles (fine red lines in Fig. 1) and electrons (bold blue lines) must be due to either negative ions (which is unlikely given the daytime-like conditions above 70 km when sunlight will efficiently photo detach electrons), or due to large particles scavenging free electrons (bite-out). With this interpretation we see a broad bite-out at the time of MASS-1 (22:51 UT) narrowing by the time of ECOMA-3 (23:22 UT). As expected, the bite-out of MASS-1 coincided with the height region where the detector recorded mainly negatively charged particles of >1 nm (Robertson et al., 2009). The bite-out of ECOMA-3 covered a considerably smaller height region and is not only seen by the particle detector, but also by the on-board photometer sensitive to particles <20 nm (Megner et al., 2009).

The probes aboard ECOMA-3 were mounted on sideways deployed booms, thus their data could also be used on the downleg, whereas no useful downleg data can be obtained from the MASS particle detector oriented along the rocket axis. The downleg data of ECOMA-3 display essentially the same features, notably also the peak at 90 km, but interestingly the ledge underneath is lower by about 2 km according to both the ion and the electron probes. Since the pronounced peak at 90 km in up- and downleg agrees, we believe that this is a real feature of the ionosphere – either temporal or spatial – and not a problem with the trajectory. In Fig. 2a and b we show the same rocket profiles, but compared to the EISCAT measurements. The integration time of EISCAT in this period was 0.5 min, the height resolution was set to 300 m and the beams were set to vertical. The data shown are 2.5 min averages with a running mean over 5 altitude levels. The UHF data are dotted where more than half the data in our bin of 25 independent measurements were invalid (i.e. negative); averaging only the valid (positive) data points results in an average always slightly above the threshold and is therefore not a reasonable approach to extend the altitude range. The

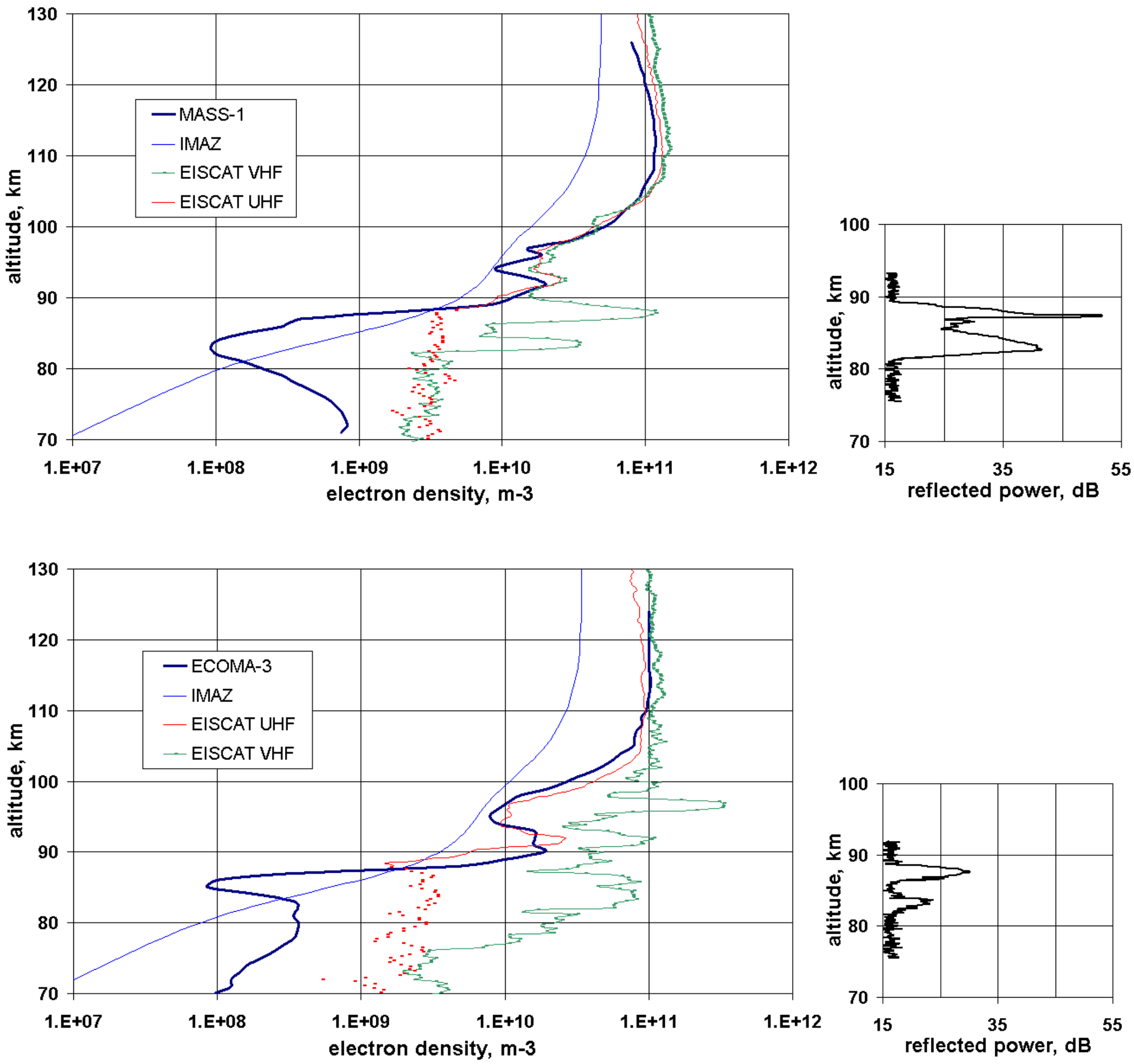

Fig. 2. Electron densities of MASS-1 and ECOMA-3 compared to the EISCAT results and an empirical model (smooth line). The panels on the right show reflected power measured by the ALWIN MST radar at the rocket range using the beam 7° off vertical to the northwest, i.e. largely coincident with the rocket trajectory. Clearly the features below 90 km of EISCAT VHF during MASS-1 are due to PMSE (cf. the right panel), whereas during ECOMA-3 below 100 km they are simply useless.

resulting effective threshold is about $3\times10^{9}\,\mathrm{m}^{-3}$, whereas in the conditions prevailing here the VHF data never reach their somewhat lower threshold. Above 100 km both EISCAT electron densities reasonably agree with the rocket profiles (despite the distance of 130 km), below that height the apparent large electron densities seen by the VHF radar are actually signatures of PMSE and not of electron density itself. In the case of MASS-1 this interpretation is supported by the PMSE seen by the local radar ALWIN (at 53.5 MHz) at the same altitudes (ALWIN=*AL*OMAR *Win*d Radar; Latteck et al., 1999). The EISCAT VHF data during ECOMA-3 are not only dominated by PMSE, but are simply noisy below 100 km. We therefore conclude that the present VHF data are not relevant for comparisons with the rocket borne electron density measurements, but rather are prime indicators of atmospheric perturbation leading to PMSE. Also indicated by smooth lines are the results of an empirical ionospheric model for the auroral zone (McKinnell and Friedrich, 2007; see below). The agreement is not obvious, but the model results represent the average behaviour for the geophysical conditions – other than NLC and PMSE – prevailing at the time of the rocket flights.

In Fig. 3 the electron densities of MASS-1, ECOMA-3 and MASS-2 are shown together with profiles measured during the PMSE season as defined by Bremer et al. (2003), i.e. between 19 May and 28 August. The profile of MASS-2 which was flown three days later shows no bite-out, nor is there a significant difference to the ion density (Robertson et

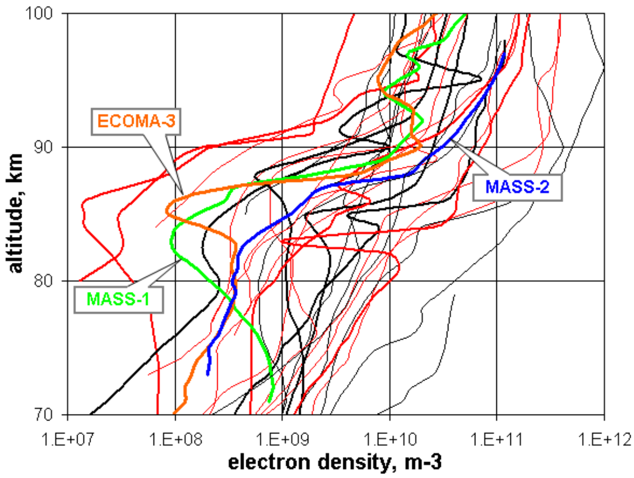

Fig. 3. High latitude electron densities measured in the PMSE season (zenith angles 48° to 96°, 31 May to 18 August). Profiles that were intentionally obtained during NLC or PMSE are marked in red, pronounced bite-outs by bolder lines.

al., 2009). The profiles in this figure were exclusively obtained by wave propagation methods (Faraday rotation) and the zenith angles range from 48° to 98°, but the overwhelming majority are from twilight conditions. Of the 29 rockets displayed in that figure, 17 were intentionally flown into conditions of either PMSE or NLC (in red). Many of the remaining profiles were also measured during NLC or PMSE, but at the time of the early rocket flights no suitable ground observations for these phenomena were available. Two features are evident: (1) bite-outs (thicker lines) are common but more rare in profiles of large electron densities when free electrons are produced faster than they can attach to particles; also, conceivably very thin bite-out layers may have been smeared by the limited height resolution of the Faraday method, and (2) peaks – at higher altitudes known as sporadic E-layers and presumably caused by metal ions – are also not uncommon. In fact the statistical analysis by Zhou et al. (2008) shows on a long term basis a clear correlation between lidar measurements of Fe and electron density peaks measured by the Arecibo incoherent scatter radar.

2.2 Ground-based data

Apart from lidar measurements by the co-located ALOMAR observatory, observations of the highly variable echoes seen by the ALWIN radar provided the main launch criteria. In addition, also the EISCAT VHF system operating at 224 MHz located near Tromsø some 130 km away shows these echoes believed to be caused by fine structure in the electron densities. ALWIN data therefore help to identify those EISCAT VHF values which cannot be interpreted as electron densities. For the reasons outlined above, we do not consider the EISCAT VHF data for the study of the ionospheric behaviour, but here concentrate on the electron densities obtained from EISCAT UHF only. Another ground based radar (almost) co-located with the rocket range is the MF radar at Saura some 10 km away which operates at 3.17 MHz (Singer et al., 2008). Although the prime objective of that installation is to provide wind data from the lower mesosphere to the lower thermosphere, the high flexibility of the installation also allows obtaining electron densities between 60 and 90 km. With this array of ground based data and the in situ results we are in a good position to verify the quality of these ground based measurements.

The classical instrument to observe the behaviour of the mesosphere's electron densities (the D-region) is the riometer. We will here concentrate on the imaging riometer AIRIS located a few kilometres from the rocket range, although a similar installation exists in Kilpisjärvi, Finland, and better covers the area above EISCAT (Browne et al., 1995). We only consider beam #25, i.e. the central beam looking vertically. We thereby ignore any conceivable horizontal gradient in the ionosphere between the location of the riometer and the location of the sounding rocket or EISCAT, but we gain data quality because the central beam is the narrowest. Also it is not affected by refraction and therefore best suited for comparisons with measured electron densities. A riometer measures excess absorption of natural extraterrestrial HF emissions relative to the quiet level (QDC) of this radio noise. Especially for small absorption values ($<$0.2 dB) a well-established QDC is important. The height predominantly contributing to the absorption is typically centred at 90 km, hence with a measured electron density profile covering from below 70 to beyond 120 km one can calculate practically the full radio wave absorption of the ionosphere. On the prime launch day (3 August 2007) we have two rocket flights with which to check/calibrate the riometer, namely MASS-1 at 22:51 UT and ECOMA-3 at 23:22 UT. For historical reasons we carry out the calculation for extraordinary wave component of the frequency 27.6 MHz; the relation to the frequency actually used (38.2 MHz) is simply the inverse of the squared frequency ratio. For the collision frequency we use a proportionality factor to pressure of $6.41\times10^5\ \mathrm{m^2\,s^{-1}\,N^{-1}}$ (Friedrich and Torkar, 1983), and for the pressure we employ an empirical atmospheric model based on data actually taken at Andøya (Friedrich et al., 2004). Table 1 lists the calculated integral absorption, L_i, the absorption, L_q, due to the quiet (solar controlled) ionosphere (Harrich et al., 2003) and the riometer absorption thus simulated ($L_r = L_i - L_q$). In the following we add 0.06 dB obtained from the flight MASS-1 to the nominal riometer readings to correct the offset of the QDC. Figure 4 displays the variation of the corrected riometer absorption and the geomagnetic index *ap*. The figure shows that, despite the correction, there still is a period between 13:00 and 15:00 where the riometer shows negative values which have no physical meaning and are therefore attributed to an inadequate QDC at that time of the day.

As mentioned earlier we have two useful, essentially continuous, ground-based electron density measurement installations, the Saura MF radar on the island of Andøya and the incoherent scatter EISCAT using UHF near Tromsø. Although the MF radar does indeed operate continuously, frequently the data are not good enough to derive electron densities due to interference from distant transmitters when the ionosphere is quiet, notably at night. On the other hand, large absorption shields the interference but reduces the height coverage. EISCAT operates on a campaign basis and was only switched on for the duration of the anticipated launch window (i.e. after 20:00 UT). In order to judge whether a particular electron density distribution is "normal" or "abnormal" one needs a reference or average behaviour for comparison. For this purpose we use the empirical Ionospheric Model of the Auroral Zone (IMAZ) which was established with a neural network and is based on about 300 000 EISCAT profiles together with over 100 rocket measurements from more than a full solar cycle (McKinnell and Friedrich, 2007). The inputs to this model are season, solar zenith angle and solar activity, geomagnetic time and a geomagnetic index, and – particularly – riometer absorption. For very quiet conditions the zenith angle and solar activity matter, whereas for disturbed conditions riometer absorption is the most relevant parameter below about 100 km and the magnetic index *ap* above that height. In Fig. 4 we show the IMAZ prediction for the period of our measurements (04:00 to 24:00 UT, 3 August 2007); in the time between 13:00 and 15:00 the prediction is not representative because it is based on zero dB riometer absorption caused by problems with the QDC. Clearly the E-region enhancement (>100 km) is not well predicted by IMAZ, because the index *ap* primarily reflecting the higher ionosphere, is (a) a global and not a local index, and (b) a three-hourly averaged values, whereas riometer absorption has the same time resolution as the EISCAT data (we here use 2.5 min averages). Also shown on further panels are the data of the MF radar and EISCAT. The 3 min Saura MF radar data are very intermittent, but on occasions reach down to 60 km, whereas useful EISCAT data under these rather quiet conditions usually only begin above 90 km. Meteoric smoke particles and particularly the even larger ice particles formed around them in the cold summer mesopause, are expected to be evident by electron density bite-outs near the mesopause (Reid, 1997; Rapp and Lübken, 2001; Brattli et al., 2009). In the presently available ground-based data we can not see the expected particle signatures (although Saura has on occasions observed bite-outs), but may look for precursors of perturbations associated with the expected phenomena. One such ominous feature is the pronounced electron density peak in the EISCAT UHF data occurring at just after 22:00 UT and slowly descending to 90 km by midnight. In the bottom panel of Fig. 4 the electron density measurements are normalised to what IMAZ – essentially based on riometer and *ap* – predicts. The aim of this procedure is to amplify perturbations in the electron density, such as the descending layer. This appears to be a promising approach, although with the present, mostly very small and thus uncertain riometer absorption values we encounter problems when the QDC is not sufficiently well established.

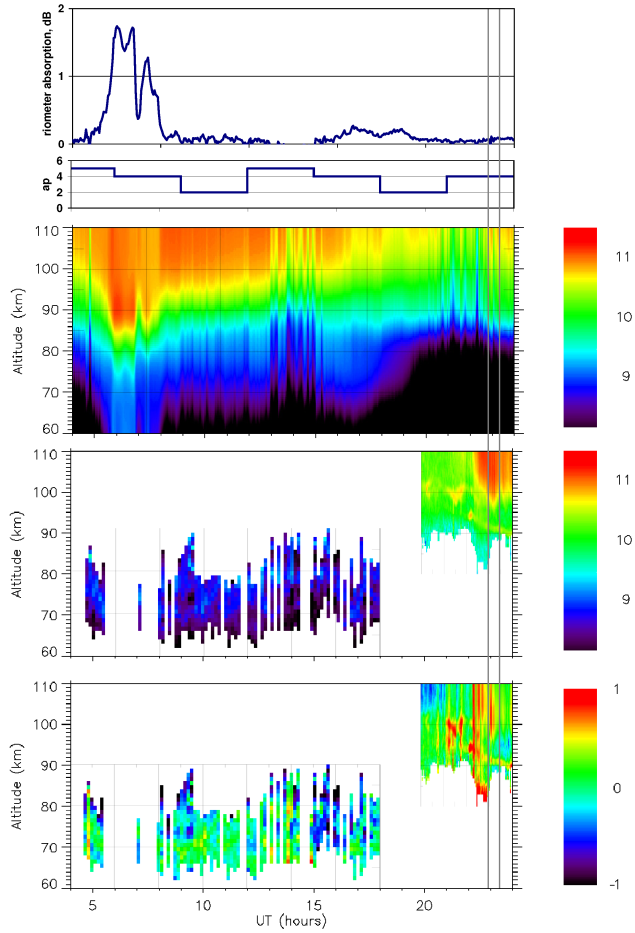

Fig. 4. Ionospheric conditions preceding the flights of MASS-1 and ECOMA-3 (grey vertical lines). The panels from the top are: Riometer absorption, magnetic index, electron density prediction according to the IMAZ model, electron densities from the MF radar (until 18:0 UT) and according to EISCAT UHF (20:00 to 24:00 UT), and the ratio between measurements and the IMAZ prediction. The electron desities are logarithmically colour coded in m^{-3} and the ratio in the bottom panel is on a logarithmic scale from 0.1 to 10.

3 Conclusions

In the 2007 ECOMA/MASS campaign the lower ionosphere was very variable over short periods of time and the in situ data show interesting structures, namely bite-outs and a layer, the latter presumably caused by metal ions. Whereas the layer was clearly detectable by EISCAT, the bite-out could not be seen by the ground based instruments, although the sensitivity of the MF radar is low enough as proven on other

Table 1. Absorption calculations to correct the riometer.

rocket	MASS-1	ECOMA-3
time, UT	22:51	23:22
solar zenith angle	93.17°	93.23°
calculated integral absorption L_i, dB	0.0711	0.0580
quiet absorption, L_q, dB	0.0091	0.0090
calculated riometer absorption, L_r(sim), dB	0.0620	0.0490
measured absorption (converted to 27.6 MHz, x-mode), dB	0.0019	0.0112
riometer offset, dB	**0.0601**	0.0378

occasions. Generally the height resolution of ionospheric radars is only marginally good enough to resolve thin electron density depletions. Furthermore the MF radar data are frequently impaired by interference, and the measurements by EISCAT reach that instrument's threshold for deep bite-outs. In the E-region the agreement with EISCAT is remarkably good, but in the polar summer the VHF data below 90 km reflect PMSE rather than electrons. The bite-outs seen by MASS-1 and ECOMA-3, but not seen by MASS-2, were as expected, associated with corresponding particle populations at the same altitudes (Robertson et al., 2009; Rapp et al., 2009). A relation between particle density and electron bite-outs is qualitatively understood, but quantitatively still a topic of further investigations (Rapp and Lübken, 2001). The present electron density profiles, together with a large set of comparable earlier measurements suggests that bite-outs, all centred at 85 km, are more likely to occur in low-density profiles, whereas at times of large ionisation the balance between production and attachment to smoke particles is more shifted towards free electrons. Particles observed at other times and latitudes do not lead to pronounced electron density perturbation because they appear over larger altitude range. Also ice particles prevalent in the polar summer are much larger than smoke particles and thus can be expected to more efficiently scavenge electrons.

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