MULTI-RADAR OBSERVATIONS OF POLAR MESOSPHERE SUMMER ECHOES DURING THE PHOCUS CAMPAIGN ON 20-22 JULY 2011

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Abstract

During the PHOCUS rocket campaign, on 20-22 July 2011, the observations of polar mesosphere summer echoes (PMSE) were made by three mesosphere-stratosphere-troposphere radars, operating at about 50 MHz. One radar, ESRAD is located at Esrange in Sweden, where the rocket was launched, two other radars, MAARSY and MORRO, are located 250 km north-west and 200 km north of ESRAD, respectively, on the other side of the Scandinavian mountain ridge. We compared PMSE as measured by these three radars in terms of their strength, spectral width and wave modulation. Time-altitude maps of PMSE strength look very similar for all three radars. Cross-correlations with maximum values 0.5-0.6 were found between the signal powers over the three days of observations for each pair of radars. By using cross-spectrum analysis of PMSE signals, we show that some waves with periods of a few hours were observed by all three radars. Unlike the strengths, simultaneous values of PMSE spectral width, which is related to turbulence, sometimes differ significantly between the radars. For interpretation of the results we suggested that large-scale fields of neutral temperature, ice particles and electron density, which are more or less uniform over 150-250 km horizontal extent were 'modulated' by waves and smaller patches of turbulence.

Keywords: mesosphere, PMSE, MST radar

1. Introduction

The aim of the PHOCUS project (Particles, Hydrogen and Oxygen Chemistry in the Upper Summer mesosphere) is to study mesospheric particles (ice and meteoric smoke) and their interaction with their neutral and charged environment. The PHOCUS sounding rocket was launched from Esrange, Sweden into strong noctilucent clouds (NLC) and polar mesosphere summer echoes (PMSE) on 21 July 2011. See an overview of the project and the main results in Gumbel et al. (this issue). Observations with three Mesosphere-Stratosphere-Troposphere (MST) radars, ESRAD at Esrange in Sweden, MORRO at Ramfjordmoen and MAARSY at

Andenes, both in Norway, were made for pre-flight diagnostics of PMSE (ESRAD) and in support of the rocket-borne measurements.

PMSE are strong radar echoes, which are closely related to NLC. See Rapp and Luebken, 2004 for a review of PMSE. However, while NLC are formed by ice particles, the PMSE occurrence requires perturbations in electron density produced due to complex interactions between ionospheric electrons and charged ice particles, including those of sub-visual sizes. Thus the PMSE study meets the objectives of the PHOCUS project.

In the past, MST radars in general (including ESRAD and the earlier radar, ALWIN, at Andenes), have been extensively used to study PMSE in terms of their characteristics, variations and trends (e.g. Bremer et al., 2006; 2009; Latteck et al., 2008; Smirnova et al., 2010; 2011; Swarnalingam et al., 2009a among many others). There are inter-comparison statistical studies of PMSE strength and occurrence measured with MST radars at different polar latitudes and even from different hemispheres (e.g. Kirkwood et al., 2007; Latteck et al., 2008; Morris et al., 2009; Swarnalingam et al., 2009b). Multi-radar studies of PMSE were performed using radars operating in different frequency ranges either co-located (e.g. Röttger et al, 1990; Strelnikova and Rapp, 2010) or located at some distance from each other (e.g. Belova et al., 2007; Hoppe et al., 1990; Kirkwood et al., 1995). However, it turns out that comparison of simultaneous PMSE data from radars, operating at about the same frequencies, at some hundreds of km distance apart is still missing. This paper is a first attempt to fill this gap. We will use data from the three radars, all operating at about 50 MHz, in order to study spatial and temporal variability of PMSE fields, waves and turbulence. This provides background information for interpretation of the in-situ measurements from the PHOCUS sounding rocket.

2. Experimental setups

At 07:01 UT on July 21, 2011, the PHOCUS sounding rocket was launched from Esrange into a strong layer of polar mesosphere summer echoes. PMSE observations have been made during the entire day by the ESRAD MST radar located at the same site. Two other 50-MHz radars: high-power MAARSY and medium-power MORRO located 250 km north-west and 200 km north of ESRAD, respectively, have observed PMSE from the other side of the Scandinavian mountain ridge. The radars belong to the same class of atmospheric radars, MST radars. However, the parameters of the radars and radar experiments differ from each other and are presented in Table 1. More detailed descriptions of the radars can be found in Kirkwood et al. (2007) for ESRAD, in http://tupac.phys.uit.no/~cesar/MORROradarSite/MORROradar.html for MORRO and in Latteck et al. (2012) for MAARSY.

3. Experimental results

3.1 PMSE strength

MST radars measure relative strength of backscatter, which is usually presented as signal-to-noise ratio (SNR) expressed in dB units. Because of its dependence on radar and experiment parameters as well as on the cosmic noise variation, SNR is not suitable for inter-comparison studies. Instead, radar volume reflectivity (VR), determined as the radar cross section per illuminated unit volume, is used as a measure of the absolute strength of PMSE and other echoes (e.g. Hocking, 1985). The determination of PMSE volume reflectivity requires stable radar performance and accurate calibration. Both ESRAD and MAARSY have been calibrated using different methods (Kirkwood et al., 2007; 2011; Latteck et al., 2012). However some technical adjustments were made to MAARSY during 2011, when it was operated with a large number of transmit-receive modules for the first time. Calibration of MORRO is not yet available. Therefore in this paper we present MAARSY and MORRO data in terms of signal-to-noise ratio but in order to give an idea about the absolute strength of PMSE, we provide radar volume reflectivities calculated for ESRAD. In Fig. 1 PMSE VR are presented for ESRAD for the entire day of 21 July 2011, together with SNR measured by MAARSY and MORRO.

Despite the difference in the strength we see similarities in the PMSE behaviour for all three radars. In order to find the altitude distribution of PMSE we averaged VR/SNR values over 24 hours. In Fig. 2 the altitude profiles of the mean PMSE strength are shown for the three radars. We cannot compare PMSE strengths at the three radar sites using this Fig. but we can choose the altitude range where the echoes are strongest for all three radars and use it for further analysis.

In order to find the relationship between PMSE measured by the different radars we calculated cross-correlations of their strength for each pair of radars at the same altitudes and presented them in Fig. 3. Firstly, the MORRO and MAARSY data were averaged over 600 m. Then we made suitable time integrations, interpolated all three radar data with 2 min time resolution and removed mean values.

As seen from Fig. 3, the correlations at some altitudes are moderately high with maxima of 0.5-0.6 at about zero lag. The strongest correlation is between PMSE variations at MORRO and MAARSY, which are situated closest to each other (150 km apart) and on the same side of the Scandinavian mountain ridge. These positive maxima imply that the main variations in PMSE (for 2 min data) occur at the same time for the three radars. All three cross-correlation functions show several pronounced maxima/minima for negative lags of several hour values. This is a signature of waves, which are present in the signals of all three radars. Because of the relatively long period of these waves (over 5 hours) we decided to use PMSE data for 3 days for further analysis: 20-22 July 2011, i.e. 1 day before to 1 day after the day of the rocket launch. For simplicity the analysis was restricted to one reference altitude of 85.2 km, where PMSE measured by all radars have maximum strength.

Fig. 4 shows behaviour of the echo power at this altitude over the course of three days for all three radars together with the cross-correlation functions calculated for each pair of radars. We see the signals vary in phase with each other even on short time scales consistent with relatively high maximum values of 0.6 for the correlation coefficients. Again as in Fig. 3 the presence of regular variations or waves is clear from the behaviour of the cross-correlations. The most pronounced ones are diurnal variations 'modulated' by waves with smaller periods of few hours, which have been chosen for further cross-spectrum analysis (Jenkins and Watts, 1969). This analysis allows one to quantify the relationship between PMSE signals measured by the three radars at each frequency (period). A useful quantity for this purpose is spectral coherence (also called magnitude-squared coherence (Welch, 1967)), which tells us whether the periodicities in any two time-series are related with each other. If the coherence-squared is close to 1 at a certain frequency then one could expect a real physical relationship between two signals at this frequency and that their phase difference remains constant in time.

For the coherence-squared and phase difference calculations we used the MATLAB functions mscohere and cpsd. In Fig.5 the results are presented. High spectral coherence for all three pairs of radars appears for periodicities (waves) with about 6-hour period. According to the phase difference, this wave seems to be the same wave which first arrived to ESRAD and then, propagating in a north-westward direction, it arrived simultaneously at MORRO and MAARSY. Waves with 2-hour period are present in the ESRAD and MAARSY PMSE data. Waves with periods between 2.5 and 8 hours are 'coherent' for MAARSY and MORRO with no phase difference between the sites.

As seen from Fig. 1, the PMSE signals show similar temporal and altitude behaviour for the three radars over the course of one day. We compared PMSE time-altitude maps for ESRAD, MORRO and MAARSY for a longer interval of three days. In order to accomplish a comparison of the quantities expressed in different units, one has to normalize them. The maps of PMSE power normalized for mean values and dynamic range (standard deviations) for the three radars are shown in Fig. 6. We did not succeed to find perfect normalizations because the quantities (signal powers) have distributions over amplitude, which are far from the Gaussian. As a result, the color scales of normalized powers differ slightly between the three. However, it is clear that PMSE measured by the radars at three different locations, 150-250 km apart, show remarkably similar behaviour in time and altitude. This relates not only to the diurnal variations but also variations on shorter time scales. For instance, there is wave-like behaviour on 20 July seen by all three radars, sharp displacement from the higher to the lower altitudes in early morning on 21 July and on the afternoon of 22 July, which is followed by PMSE completely disappearing.

3.2 PMSE spectral width

Another important characteristic of PMSE is their spectral width. It can be determined from the radar signal power spectrum, which, in turn, is calculated by applying FFT to the time-series of the radar backscattered power at sub-second time resolution. Here we define the PMSE spectral width as a half-maximum full spectral width (HMFW) and express it in velocity units (m/s), multiplying spectral width in Hz by a half radar wave length. Fig. 7 shows the time-altitude plots of PMSE spectral widths for all three radars. The MORRO and MAARSY spectral widths were corrected for beam broadening w_{beam} according to Eq. 46 in Hocking (1985), which reads as

$$w_{beam}(m/s) = \theta_{1/2} \cdot V_{hor} = \frac{1}{2\sqrt{2}} \cdot \theta \cdot V_{hor} \approx 0.35 \cdot \theta \cdot V_{hor} \;,$$

where $\theta_{1/2}$ is the half-maximum half-width of the effective radar beam (two-ways), θ is the 3 dB full beam width in radians and V_{hor} is the horizontal wind speed.

For the correction horizontal winds from the Andenes MF radar (Singer et al., 2008) were used. The data gaps in Fig. 7 appear partly due to the gaps in the horizontal wind data and partly because of spectral analysis failure due to low SNR. The ESRAD spectral width was calculated using the full correlation analysis (FCA), based on the spaced antenna technique, and is not affected by beam broadening. Because of several data gaps we cannot apply a correlation and cross-spectrum analysis for the PMSE spectral widths as was done for the echo strengths. Instead, in Fig. 8 we presented spectral width behaviour at 85.2 km altitude for all three radars. Like the echo strengths, instantaneous values of spectral widths can be similar (0-1 UT, 8-9 UT, 12-17 UT, 19-20 UT and 22-24 UT) for ESRAD, MAARSY and MORRO. However they also can differ significantly as at about 3-7 UT for the three radars and at 9-11 UT for MORRO and MAARSY.

As for backscattered power, we averaged PMSE spectral widths over 24 hours and the results are presented in Fig. 9. The PMSE median spectral widths at all three radars show similar behaviour for 79-89 km altitude range: they increase with increasing altitude. (Below and above this range the averaged values are not reliable because of a small amount of data.) Moreover, the averaged spectral width values at MORRO and MAARSY are close to each other at these altitudes. However the ESRAD spectral widths at lower heights are smaller than those for the two other radars. This might be due to underestimated beam-broadening corrections for MORRO and MAARSY.

4. Discussion and summary

High and positive cross correlations were found between PMSE measured by the three radars for one- and three-day intervals. The PMSE signals behave similarly on time scales as short as 2 hours (Fig. 4). Kirkwood et al. (1995) compared PMSE measured by the CUPRI 50 MHz radar and EISCAT 224 MHz radars, at Esrange and Ramfjordmoen, respectively. Based on more than 50 hours of joint observations, they found that morphology of PMSE is close at the two different frequencies and at the two sites. Here we made more accurate comparisons for PMSE at the same frequency between three sites and found that PMSE altitude-time maps look very similar. We can conclude that the processes producing the echoes have a horizontal extent more than 250 km, the maximum distance between the sites. These processes should include low neutral temperature field, ice particle and electron density fields.

Additionally, we showed that all three radars recorded the same waves. Some such waves were seen during one day of observations, other ones were observed during three days (e.g. wave with 6-hour period).

Spectral width of PMSE is related to the strength of turbulence (in the turbulent theory of PMSE generation). We see from the comparison of the spectral widths at the three sites that turbulence can be rather similar at all sites during some intervals. There are also examples when turbulent fields have smaller extent than the distance between sites. Turbulence is produced locally in the mesosphere but its sources (e.g. breaking gravity waves) may originate from the lower heights. Then the echo spectral widths reflect interplay between the turbulence sources and local conditions.

However, on average, turbulence strength shows the same behaviour for all three sites: it increases with altitude. This is consistent with the results based on ESRAD observations over the whole PMSE season as well as on PMSE observations by the MARA MST radar located in Antarctica (S. Kirkwood, private communications). It will be interesting to study further the processes responsible for such altitude behaviour.

In summary, taking together the behaviour of PMSE strengths and spectral widths at the three radars, we could suggest the following interpretation. There are large-scale fields of neutral temperature, (charged) ice particles and electron density, which are more or less uniform over 200-250 km horizontal extent and which vary in time in the same way. In these fields, smaller patches of turbulence are embedded and moreover, everything can be modulated by waves. Finally, this produces the PMSE patterns seen by our three radars. It would be interesting to test this interpretation by using satellite data on neutral temperature and ice particles (e.g. AIM satellite). However, this may be a task for further research.

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References

Belova, E., P. Dalin, and S. Kirkwood, Polar mesosphere summer echoes: a comparison of simultaneous observations at three wavelengths, Annales Geophysicae, **25**, 2487-2496, 2007.

Bremer, J., Hoffmann, P., Höffner, J., Latteck, R., Singer, W., Zecha, W., Zeller, O.: Long-term changes of mesospheric summer echoes at polar and middle latitudes, J. Atmos. Solar Terr. Phys., 68, 1940–1951, 2006.

Bremer, J., Hoffmann, P., Höffner, J., Latteck, R., Singer, W., Zecha, W.: Long-term changes of (polar) mesosphere summer echoes, J. Atmos. Solar Terr. Phys., 71, 1571–1576, 2009.

Gumbel, J., J. Hedin, M. Khaplanov, and the PHOCUS Team, the PHOCUS project: particle interactions in the polar summer mesosphere, this issue.

Hocking, W. K.: Measurement of turbulent energy dissipation rates in the middle atmosphere by radar techniques, Radio Sci., 20, 1403–1422, 1985.

Hoppe, U. P., Fritts, D. C., Reid, I. M., Czechowsky, P., Hall, C. M., & Hansen, T. L. (1990). Multiple-frequency studies of the high-latitude summer mesosphere: Implications for scattering processes. Journal of Atmospheric and Terrestrial Physics, 52(10), 907-926.

http://tupac.phys.uit.no/~cesar/MORROradarSite/MORROradar.html

Jenkins, G. M. and D.G. Watts, Spectral analysis and its applications, Holden-Day, San Fransisco, 1969.

Kirkwood, S., J. Cho, c. M. Hall, U.-P. Hoppe, D. P. Murtagh, J. Stegman, W. E. Swartz, A. P. Van Eyken, G. Wannberg and G. Witt: A comparison of PMSE and other ground-based observations during the NLC-91 campaign; Journal of Atmospheric and Terrestrial Physics, Vol. 57, No. 1, pp. 35-14, 1995

Kirkwood, S., I. Wolf, H. Nilsson, P. Dalin, D. Mikhaylova, and E. Belova, Polar mesosphere summer echoes at Wasa, Antarctica (73°S): First observations and comparison with 68°N, Geophys. Res. Lett., **34**, L15803, doi:10.1029/2007GL030516, 2007.

Kirkwood, S., Belova, E., Satheesan, K., Narayana Rao, T., Rajendra Prasad, T., and Satheesh Kumar, S.: Fresnel scatter revisited – comparison of 50 MHz radar and radiosondes in the Arctic, the Tropics and Antarctica, Ann. Geophys., 28, 1993-2005, doi:10.5194/angeo-28-1993-2010, 2010.

Kirkwood, S., Belova, E., Dalin, P., Mihalikova, M., Mikhaylova, D., Murtagh, D., Nilsson, H., Satheesan, K., Urban, J., and Wolf, I.: Response of polar mesosphere summer echoes to geomagnetic disturbances in the Southern and Northern Hemispheres: the importance of nitric oxide, Annales Geophysicae, **31**, 333-347, doi:10.5194/angeo-31-333-2013, 2013.

Latteck, R., Singer, W., Morris, R. J., Hocking, W. K., Murphy, D. J., Holdsworth, D. A., and Swarnalingam, N.: Similarities and differences of Polar Mesosphere Summer Echoes observed in the Arctic and Antarctica, Ann. Geophys., 26, 2795– 2806, 2008.

Latteck, R., W. Singer, M. Rapp, B. Vandepeer, T. Renkwitz, M. Zecha and G. Stober, MAARSY - the new MST radar on Andøya-system description and first results, Radio Sci., doi:10.1029/2011RS004775, 2012.

Morris, R. J., Klekociuk, A. R., Latteck, R., Singer, W., Holdsworth, D. A., & Murphy, D. J. (2009). Inter-hemispheric asymmetry in polar mesosphere summer echoes and temperature at 69 latitude. Journal of Atmospheric and Solar-Terrestrial Physics, 71(3), 464-469.

Rapp, M., Lübken, F.-J.: Polar mesosphere summer echoes (PMSE): review of observations and current understanding. Atmos. Chem. Phys. 4, 2601–2633, 2004.

Röttger J., Rietveld, M. T., La Hoz, C., Hall, T., Kelley, C., and Swartz, W. E.: Polar mesosphere summer echoes observed withthe EISCAT 933MHz radar and the CUPRI 46.9MHz radar, their similarity to 224MHz radar echoes and their relation to turbulence and electron density profiles, Radio Sci., 25, 671–687, 1990.

Singer, W., Latteck, R., & Holdsworth, D. A. (2008). A new narrow beam Doppler radar at 3MHz for studies of the high-latitude middle atmosphere. Advances in Space Research, 41(9), 1488-1494.

Smirnova, M., Belova, E., Kirkwood, S., Mitchell, N.: Polar mesosphere summer echoes with ESRAD, Kiruna, Sweden: variations and trends over 1997-2008, J. Atmos. Solar Terr. Phys., 72, 435-447, 2010.

Smirnova, M., E. Belova, and S. Kirkwood, Polar mesosphere summer echo strength in relation to solar variability and geomagnetic activity during 1997-2009, Annales Geophysicae, **29**, 563-572, 2011, doi:10.5194/angeo-29-563-2011.

Strelnikova, I., and M. Rapp: Majority of PMSE spectral widths at UHF and VHF are compatible with a single scattering mechanism, J. Atmos. Solar-Terr. Phys., 73, 2142-2152, doi:10.1016/j.jastp.2010.11.025, 2011.

Swarnalingam, N., Hocking, W. K., Argall, P. S.: Radar efficiency and the calculation of decade-long PMSE backscatter cross-section for the Resolute Bay VHF radar, Ann. Geophys., 27, 1643– 1656, 2009a.

Swarnalingam, N., Hocking, W. K., Singer, W., & Latteck, R. (2009b). Calibrated measurements of PMSE strengths at three different locations observed with SKiYMET radars and narrow beam VHF radars. Journal of Atmospheric and Solar-Terrestrial Physics, 71(17), 1807-1813.

Welch, P. (1967). The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. Audio and Electroacoustics, IEEE Transactions on, 15(2), 70-73.

Table 1. The radar and experiment parameters.

MST radars	ESRAD	MORRO	MAARSY
Location	Esrange, Sweden	Ramfjordmoen, Norway	Andenes, Norway
Geograph. coordinates	67.9°N 21°E	69.6°N 19.2°E	69.3°N 16°E
Frequency	52 MHz	56 MHz	53.5 MHz
Transmitter peak power	72 kW	90 kW	736 kW
Beam width	4.4°	5°	3.6°
Exp/Analysis	fca_4500/FCA	vertical beam	vertical beam
Altitude resolution	600 m	300 m	300 m
Time integration	~2 min	~25 s	~6 min

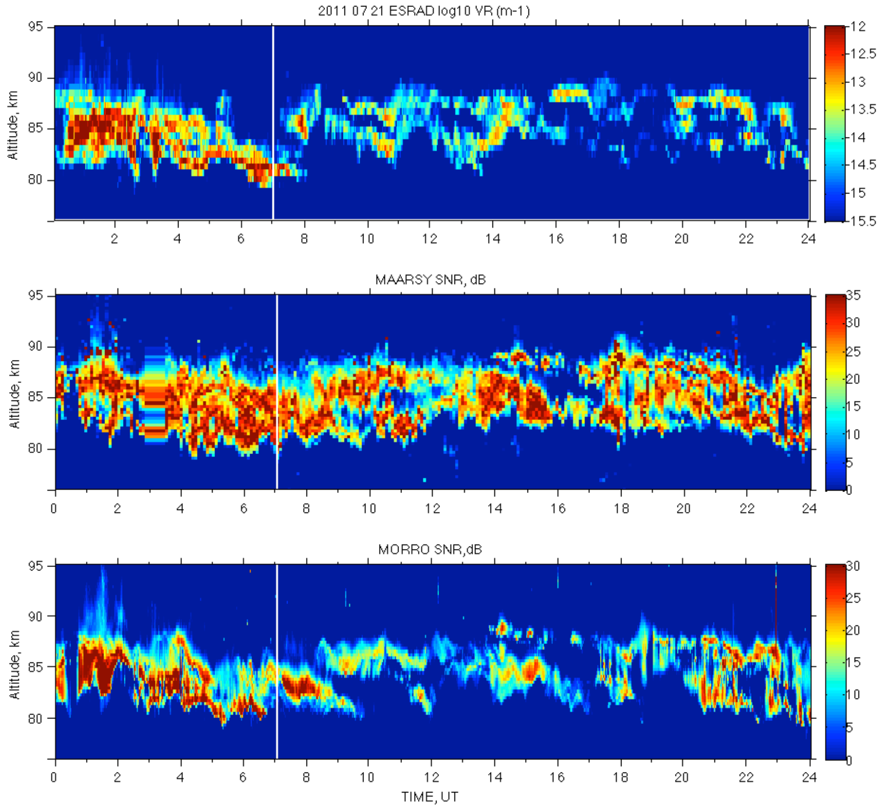

Figure 1. Volume reflectivities for ESRAD (top), SNR for MAARSY (middle) and for MORRO (bottom) for 21 July 2011. The white vertical line indicates the time of rocket launch.

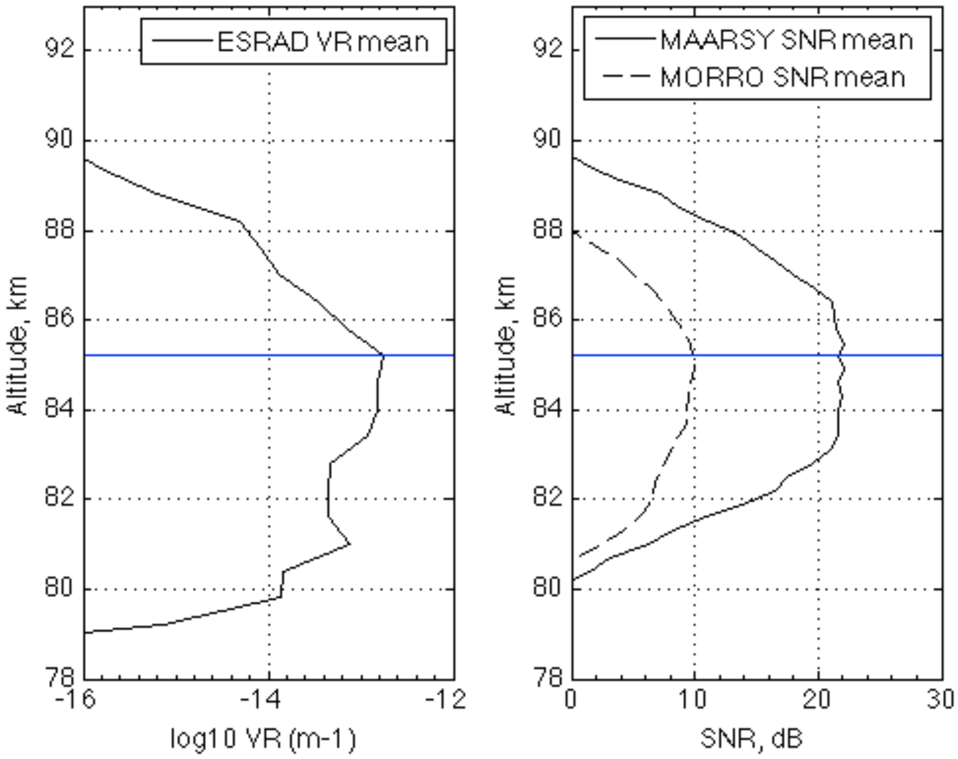

Figure 2. Altitude profiles of the PMSE mean values of volume reflectivities for ESRAD (left panel) and SNR for MAARSY and for MORRO (right panel) calculated over 24 hours for 21 July 2011. The blue horizontal line indicates the 85.2 km altitude chosen as a reference altitude.

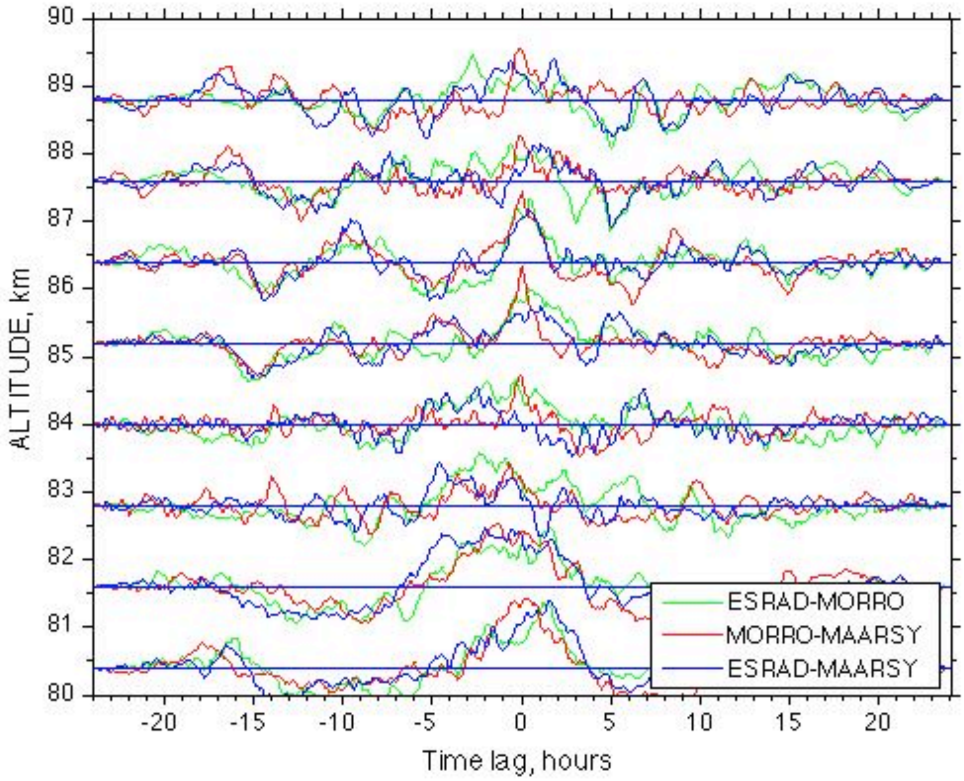

Figure 3. Cross-correlation functions (for each pair of radars marked by different colors) calculated at selected altitudes for 21 July 2011. Blue horizontal lines indicate both the altitude where cross-correlations were calculated (vetrical axis) and zero level for the cross-correlation function. The distance between two adjacent blue lines corresponds to 0.6 value of the cross-correlation.

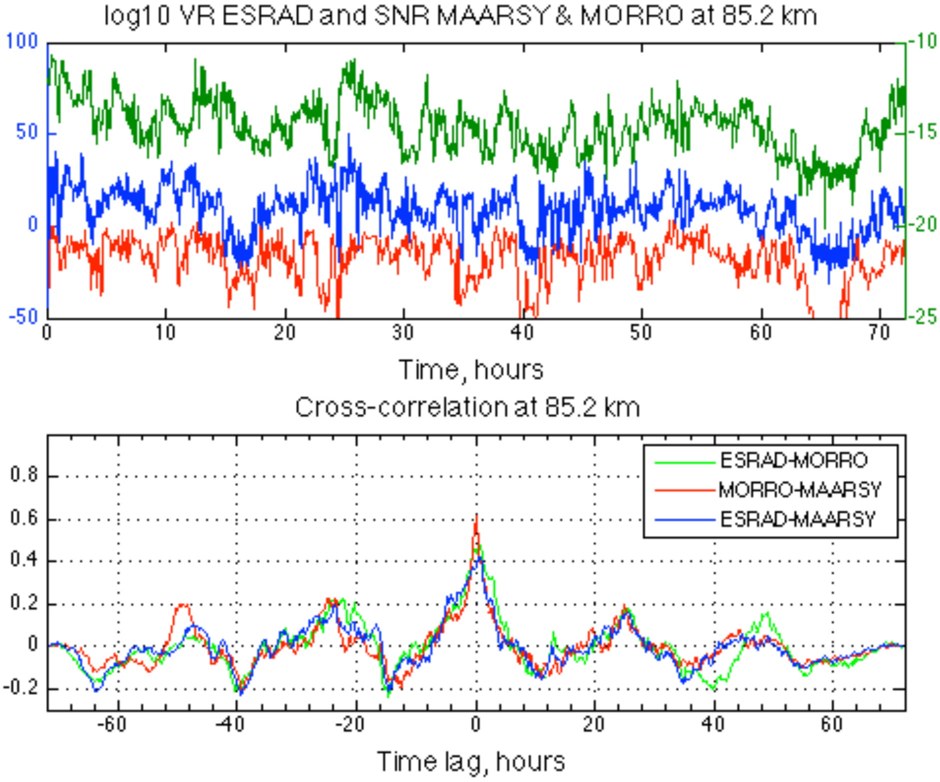

Figure 4. (Top) Log10 of volume reflectivity at ESRAD (green color and right vertical axis), signal-to-noise ratios at MAARSY (blue color and left vertical axis in dB units) and at MORRO (red color and left vertical axis) calculated at 85.2 km altitude over the course of 20-22 July, 2011. (Bottom) Cross-correlation functions calculated for each pair of signals shown on the top panel.

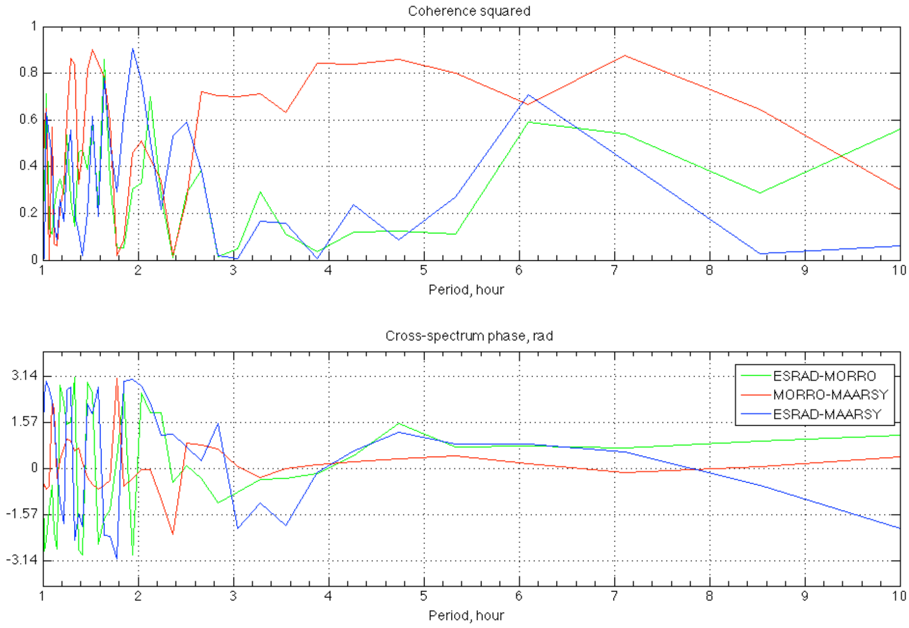

Figure 5. Spectral coherence squared (top) and cross-spectrum phase (bottom) calculated for each pair of radars from the cross-correlation functions shown in Fig. 4.

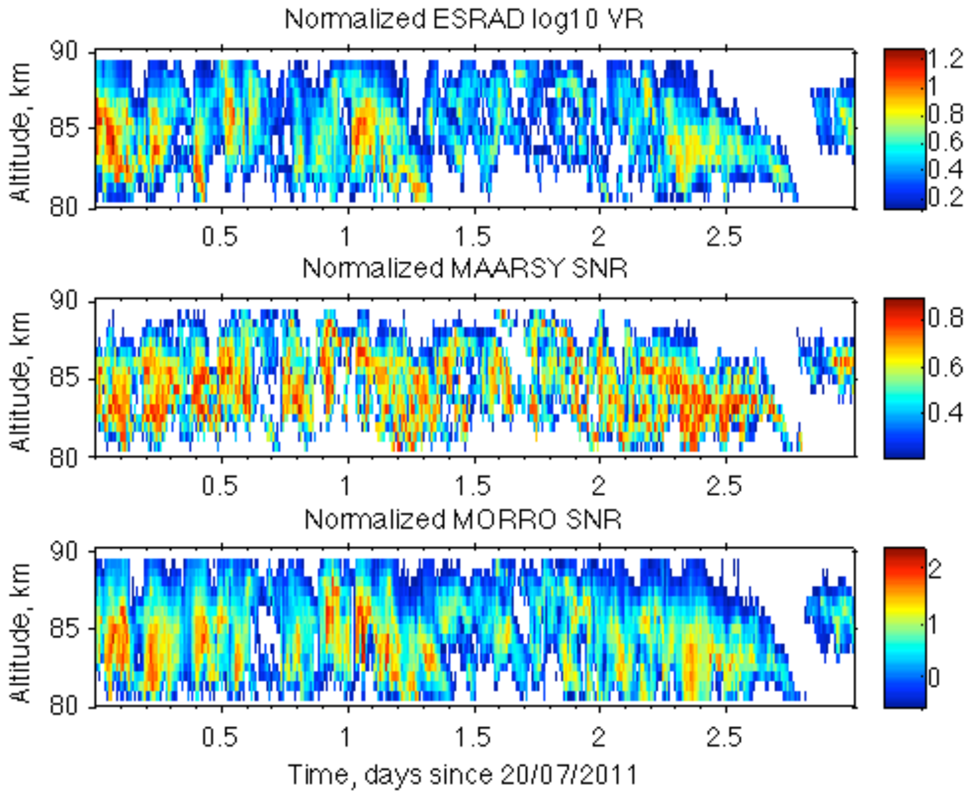

Figure 6. Normalized signal strengths at ESRAD (top), MAARSY (middle) and MORRO (bottom) over the three days of 20-22 July 2011

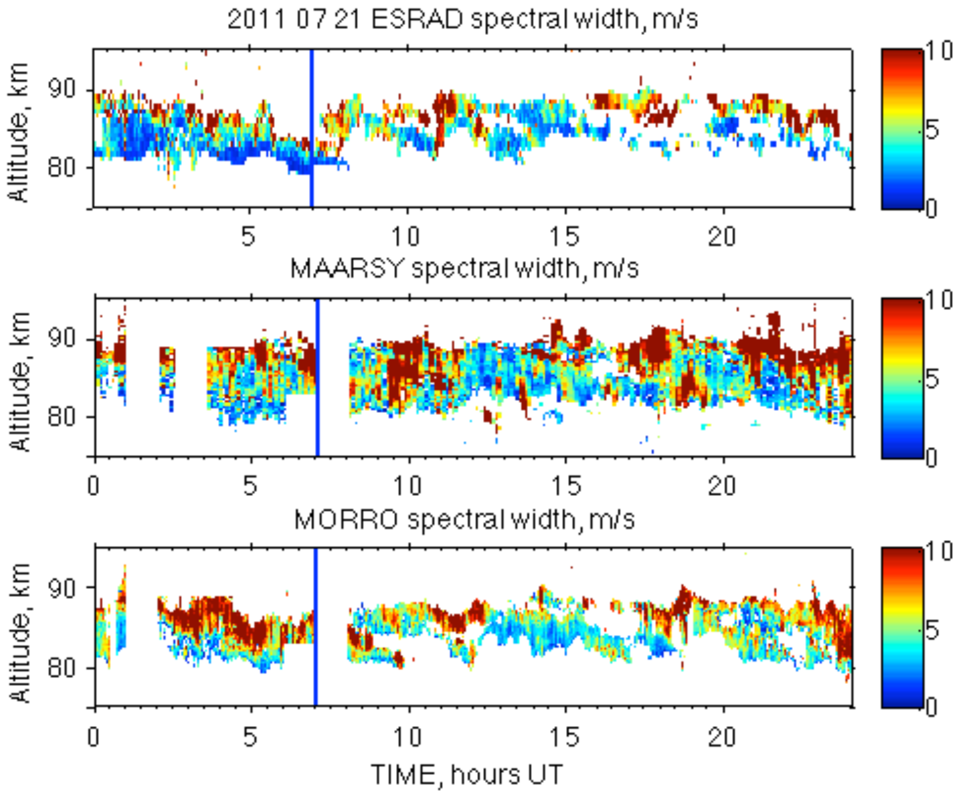

Figure 7. PMSE spectral widths corrected for beam broadening for ESRAD (top), MAARSY (middle) and MORRO (bottom) on 21 July 2011. The blue vertical line indicates the time of rocket launch.

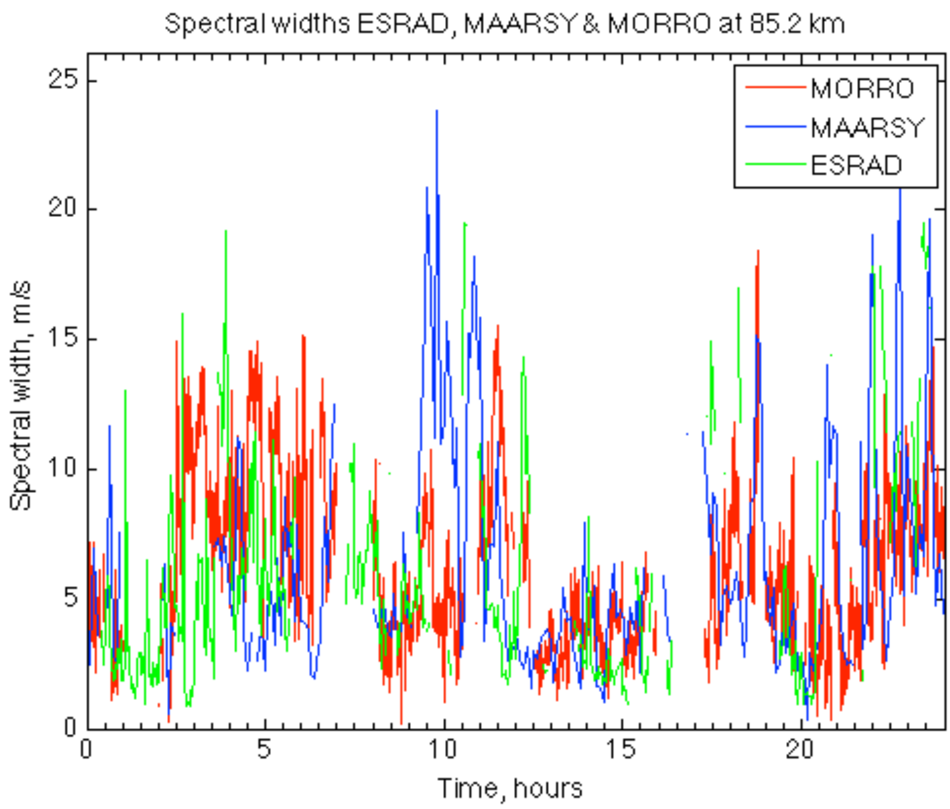

Figure 8. PMSE spectral widths for ESRAD (green), MAARSY (blue) and MORRO (red) at 85.2 km altitude on 21 July 2011.

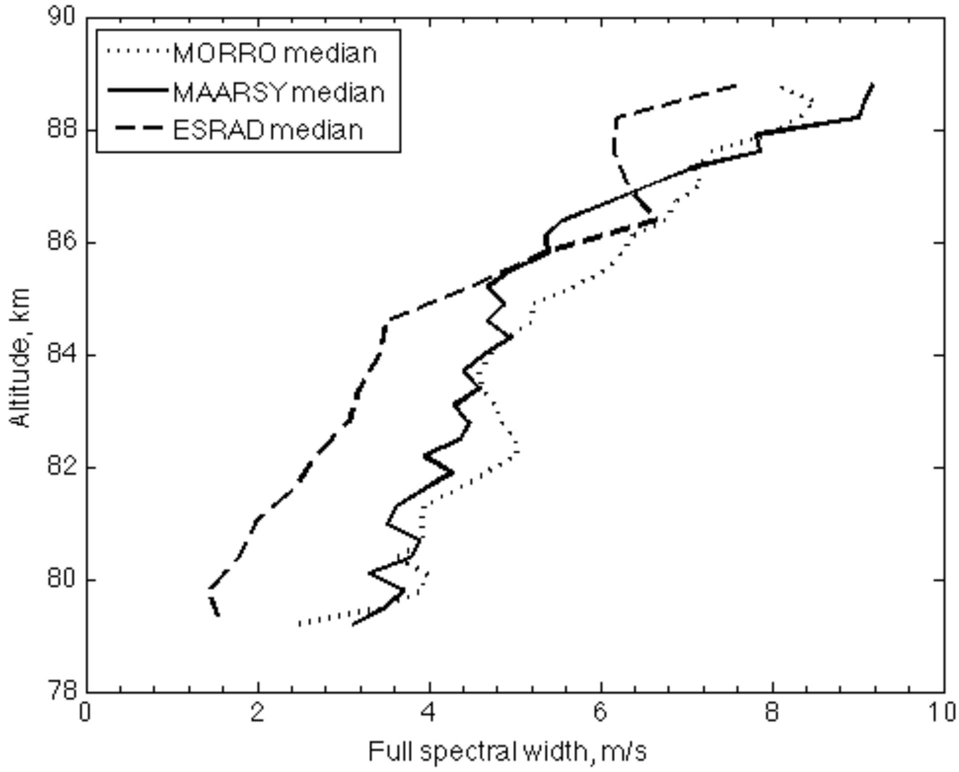

Figure 9. Altitude profiles of the median values of PMSE spectral widths calculated over 24 hours for the MAARSY, MORRO and ESRAD radars.