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Meteor head echo observations with the MU radar and future possibilities with EISCAT_3D

Johan Kero

Swedish Institute of Space Physics, 981 28 Kiruna, Sweden
kero@irf.se

EISCAT_3D is a three-dimensional imaging radar project for atmospheric and geospace research. It will consist of multiple phased arrays located in northern Fenno-Scandia. The multi-purpose experiment and data analysis approach will enable continuous meteor observations, unique in terms of coverage and quality. The aim of this paper is to establish a channel through which the EISCAT and IMO communities can interact. A presentation of the meteor head echo observations using the Shigaraki Middle and Upper atmosphere (MU) radar in Japan gives a flavor of some of the possibilities of EISCAT_3D.

1 Introduction

A radar is a detection system which transmits electromagnetic energy in the form of radio waves, and receives echoes from objects enabling determination of their range, direction, velocity, and other properties. The EISCAT (European Incoherent Scatter) Scientific Association is an international research organisation operating scientific radar systems in northern Fenno-Scandia. The EISCAT_3D radar system, hereafter called E3D, is a three-dimensional imaging radar project for atmospheric and geospace research. It will consist of multiple phased arrays of thousands of antennas.

E3D is not in construction yet, but in preparatory phase from 2010 through 2014. This means, in particular, that the radar performance specification is a living document. Any input and demands from the (potential) user community during the preparatory phase can be taken into account in the hardware design. Additional input and demands regarding experiment design and software will be of great use, also during construction, and, later on, for the operation of the radar. The E3D radar sites will be complemented by a set of supportive instruments. Multi-station video and spectral imagers would allow simultaneous head echo and optical meteor observations (Campbell-Brown et al., 2012).

Incoherent scatter radars are introduced in Section 2 and Section 3 is a review of meteor head echoes. The present EISCAT radar systems, current operations and the conceptual design of E3D are presented in Section 4. A brief overview of the 2009–2010 meteor head echo observation program carried out using the Middle and Upper Atmosphere (MU) radar in Japan is given in Section 5. Since MU is a phased array, the MU observation program gives a flavor of some possibilities of E3D.

It is of great practical and theoretical importance to measure the masses of meteoroids, to identify meteoroid populations, to determine the mass indexes of these populations, to constrain models of Solar System formation, and to estimate the hazards meteoroids present to spacecraft and manned space missions. The mass influx of extraterrestrial material onto Earth is the source of the neutral and ion metal layers in the middle atmosphere and plays an important role in atmospheric dynamics and processes as the formation of high-altitude clouds, possibly through coagulation of charged meteoric smoke particles acting as condensation nuclei for water vapor.

2 Incoherent scatter and HPLA radars

An incoherent scatter radar is a scientific instrument designed to enable reception and analysis of the very weak signal scattered off electrons in the ionosphere, the ionized part of the atmosphere at about 85 to 600 km altitude above ground (Nygrén, 1996). The peak transmitter power has to be of the order of 1 MW and the array or dish antenna aperture of at least around 1000 m^2. The large aperture means that the antenna gain pattern is focused into a narrow main beam with a full-width-at-half-maximum (FWHM) of the order of 1° at their VHF and/or UHF operating frequencies. Very High Frequency (VHF) is the frequency interval 30–300 MHz, while Ultra High Frequency (UHF) is in the range of 300 MHz–3 GHz. Corresponding wavelengths are 10–1 m (VHF) and 1–0.1 m (UHF).

Incoherent signal processing allows measurements of the electron density, ion and electron temperatures, ion collision frequency, ion composition, and ion drift velocity. The term "incoherent" is used to designate that the motion of the ionospheric electrons is random and lacks well-defined structure in contrast to a (coherent) meteor trail plasma. However, the altitude region of the lower ionosphere overlaps with the meteor zone, and incoherent radar systems can therefore advantageously be used to study radar echoes from coherent meteor plasma structures, too.

The high power density permits numerous head echo detections from very faint meteors. Sporadic meteors therefore dominate the size regime. A meteor head echo comes from the compact region of plasma close to and traveling along with a meteoroid, and is therefore highly transient and Doppler-shifted. Its characteristics are very different from those of a meteor trail echo, which is an echo from the already slowed-down columns of plasma drifting with the local wind speed.

Not all scientific High Power Larger Aperture (HPLA) radar systems are designed for incoherent scatter analysis. Some of them are optimized to study, e.g., coherent echoes from neutral wind structures in the middle and upper atmosphere. The MU radar, its sibling the Equatorial Atmosphere Radar (EAR) in Indonesia, and the Middle Atmosphere Alomar Radar System (MAARSY) in Norway are three such examples. Some defense agencies also operate HPLA radars as part of their ballistic missile early warning defense systems. One such radar successfully used also for meteor science purposes is ALTAIR—the Advanced Research Projects Agency Long-Range Tracking and Instrumentation Radar on the Kwajalein missile range (Close et al., 2002).

3 Meteor head echoes

A meteor head echo is caused by radio waves scattered from the intense region of plasma surrounding and co-moving with a meteoroid during atmospheric flight. The signal's Doppler shift and/or target's range rate can therefore be used to determine meteoroid velocity. The first head echoes were reported by Hey et al. (1947) from observations conducted in 1946 between October 7 and 11, covering the anticipated 1946 Draconid meteor outburst, using a 150 kW VHF radar system.

Since the 1990s, head echo observations have been made with most HPLA radar facilities around the world (e.g., Pellinen-Wannberg and Wannberg, 1994; Mathews et al., 1997; Close et al., 2000; Sato et al., 2000; Chau and Woodman, 2004; Mathews et al., 2007; Malhotra and Mathews, 2011). However, few published observations concern shower meteors (e.g., Chau and Galindo, 2008) before the 2009–2010 observation program with the MU radar described in Section 5.

Most incoherent scatter radar operating frequencies do not permit specular meteor trail echo detections. The reason is destructive interference of echoes from different parts of the trail because the wavelengths are shorter than typical meteor trail plasma radii. Non-specular trail echoes from field-aligned irregularities are, however, common if/when observations are carried out perpendicular to the geomagnetic field lines (Zhou et al., 2001). With the EISCAT radars, and E3D, such observations are difficult to conduct due to the very steep magnetic inclination (approximately 77–82°) at the high-latitude radar locations.

4 Present EISCAT operations

EISCAT currently operates the monostatic 224 MHz VHF and 930 MHz UHF radars near Tromsø, Norway and the 500 MHz EISCAT Svalbard Radar (ESR) near Longyearbyen on Svalbard. Previous meteor head echo observations have been conducted using the now non-operational passive 930 MHz UHF receivers in Kiruna, Sweden, and Sodankylä, Finland, in conjunction with the UHF monostatic transmitter/receiver (Kero, 2008; Szasz, 2008). Several supporting instruments are installed at the radar sites, the most prominent of which is an ionospheric heater at the Tromsø site.

The present EISCAT Associates include Norway, Sweden, Finland, Japan, China and the United Kingdom. Germany (until 2011) and France (until 2005) are earlier EISCAT Associates. The construction of E3D will probably lead to additional countries joining (and re-joining).

EISCAT radar operations are divided into Common Programme (CP) and Special Programme (SP) experiments and totals about 1000 hours per year and radar system. CP is run by EISCAT staff according to a pre-arranged schedule and the data is available to any scientist from an Associate country. SP time is apportioned to each Associate country according to the size of its financial contribution to EISCAT. Each country decides how its time is utilized, and time is usually applied for by particular individuals. Access to SP data is limited to these individuals for one year after the data are taken. Then the same rules apply as for the CP. EISCAT also invites applications for observing time on their facilities by individual scientists, research groups, and consortia throughout the world on equal basis. In 2012, 200 hours of experiment time was open for such international peer-reviewed competition.

Real-time graphs of ionospheric parameters from all EISCAT experiments are freely available on the web. Meteor analysis, on the other hand, has been conducted in a post-processing manner on subsets of archived raw data, primarily through SP experiments.

Virtanen et al. (2008) present a multi-purpose experiment and data analysis approach to be used as the standard, continuous, observational mode at E3D. This approach will enable meteor observations to be run in parallel to incoherent scatter data analysis, whenever the radar is running. Our aim is to provide real-time graphs of meteor data on the web and an open source library of analysis routines, similar to what already exist for ionospheric data.

According to the EISCAT Scientific Association, the Preparatory Phase will ensure that the E3D project reaches a sufficient level of maturity with respect to technical, legal and financial issues, so that the construction of E3D can begin immediately after the conclusion of the phase. The E3D Preparatory Phase is funded by the European Commission until September 2014. Further information is available on the website of the E3D project[1]

[1] http://www.eiscat3d.se/.

5 MU radar and EISCAT_3D

Kero et al. (2012c) have developed an automated analysis scheme for meteor head echo observations using the 1 MW, 46.5 MHz, interferometric, Shigaraki Middle and Upper atmosphere (MU) radar in Japan ($\lambda = 34\overset{\circ}{.}85$ N, $\varphi = 136\overset{\circ}{.}10$ E). An aerial view of the radar is given in Figure 1. The analysis technique can be adapted to real-time meteor flux monitoring with E3D and extended to incorporate the E3D's superior sensitivity, higher resolution, and multiple receiver sites.

The analysis scheme has made it possible at MU to determine meteoroid velocities and radiants of faint meteors with unprecedented accuracy and precision. Thus, the activity and flux of meteor showers can now be studied also with the head echo observation technique (Kero et al., 2011; 2012a). An extensive set of data (more than 500 hours of observing and over 100 000 meteors) was collected with the MU radar between June 2009 and December 2010 (Kero et al., 2012b). The predominant part of the mass distribution detected with MU is estimated to be in the range 10^{-9} to 10^{-6} kg.

Figure 2, adapted from Kero et al. (2011), shows an example in the form of a radiant plot of MU data collected between 2009 October 19, 14^{h} UT, to October 21, 9^{h} UT. Most numerous in the data are sporadic meteors. However, more than 600 of about 10 000 head echoes were associated with the Orionid meteor shower. These meteors constitute a very clear enhancement of meteor radiants with an atmospheric entry velocity around 67 km/s. The radiant density distribution is as compact as the distribution of all precisely reduced Orionids (66 photographic and 19 video meteors) of the IAU Meteor Data Center presented by Lindblad and Porubčan (1999). This indicates that the radar method provides precision and accuracy comparable to photographic reduction of much brighter meteors with longer detectable trajectories.

The Orionid activity within the MU radar beam reached about 50 per hour during radiant culmination. The flux of sporadic meteors in the MU radar data peaked at about 700 per hour. Also, several minor meteor showers, as the Southern Taurids and the Leonis Minorids, were observed.

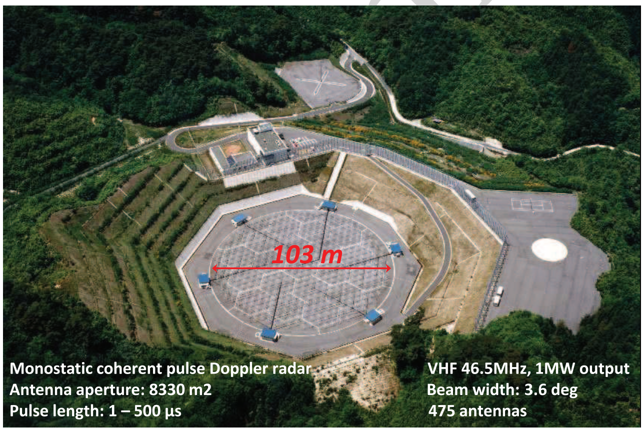

Figure 1 – Aerial view of the MU radar.

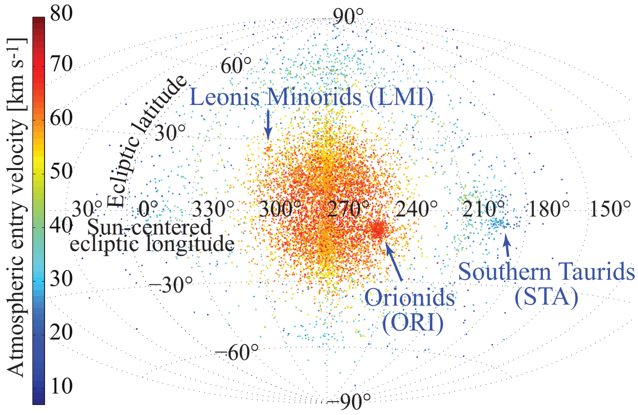

Figure 2 – The radiant distribution of about 10 000 meteors detected with the MU radar during a 33 h observation in the period 2009 October 19–21, plotted in Sun-centered ecliptic coordinates.

E3D will have far greater sensitivity than MU and enable investigation of a broader part of the influx as function of meteoroid mass. It will have several interferometric receiver stations providing meteoroid orbits with unprecedented accuracy down to very faint and sub-visual meteors. The continuous mode of observations will lead to a large database made available, e.g., through the IAU Meteor Data Center (MDC) at the Astronomical Institute of the Slovak Academy of Sciences, under the auspices of Division III of the International Astronomical Union (IAU).

A crucial advantage of meteor head echo observations compared to meteor trail echo observations is the absence of a strong echo height ceiling effect. This allows detection of low-mass, high-geocentric velocity meteoroids, which ablate at altitudes above the echo height ceiling of the meteor trail radar systems, and are therefore largely undetectable with these systems (Elford, 1993). E3D will enable investigation and correction of this dominant, and in meteor trail observations missing, part of the meteoroid influx.

6 Conclusion

E3D is a three-dimensional imaging radar project for atmospheric and geospace research. It will consist of multiple phased arrays in northern Fenno-Scandia, each array having a very large antenna gain-power product. E3D has the potential to become the most advanced instrument on Earth for meteor studies. It should be combined with multi-station video and spectral imagers.

The IMO community is cordially invited to share experiences from visual, radar, and multi-station video observations, and take an active part in the realization of the E3D meteor observation program.

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