EISCAT_3D: THE NEXT GENERATION INTERNATIONAL ATMOSPHERE AND GEOSPACE RESEARCH RADAR

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ABSTRACT

EISCAT_3D is the next generation international atmosphere- and geospace research radar in Arctic Europe. The EISCAT_3D construction started in September 2017 and the radar system is expected to be operational in the end of 2021. The EISCAT_3D facility will be distributed across three sites in Northern Scandinavia - in Skibotn, Norway, near Kiruna in Sweden, and near Karesuvanto in Finland. Each site will consist of about 10.000 antennas fed by a powerful 5 MW transmitter at Skibotn and a receiver at each of the three sites. EISCAT_3D is designed for novel measurement techniques, ones which have never been combined in one radar system: volumetric-, aperture synthesis- and multi-static imaging, tracking- and adaptive experiments, together with continuous operations. This unique versatility will enable tracking hard targets such as space debris, NEO:s and meteor head echoes in parallel with radar experiments to solve fundamental questions of cross-layer coupling in the atmosphere, solar-terrestrial interactions and plasma turbulence. In this presentation we review the current project status and outline the EISCAT_3D capabilities for contributing to Space Surveillance and Tracking (SST).

Keywords: EISCAT_3D, radar, space debris.

1. INTRODUCTION

EISCAT_3D will be a world-leading international research infrastructure using the incoherent scatter technique to study the atmosphere in the Fenno-Scandinavian Arctic and to investigate how the Earth's atmosphere is coupled to space. The EISCAT_3D phased-array multistatic radar system will be operated by EISCAT Scientific Association and as such be an integral part of an organisation that has successfully operated incoherent scatter radars for close to forty years. EISCAT_3D has the objective to provide to the scientific community monitoring data of the Arctic atmosphere during at least two consecutive solar cycles and the capability for carrying out in-depth dedicated observations to study the physical phenomena that determine the connection between geospace and the Earth.

Plans for the new system emerged from the existing EISCAT Scientific Association and its user community. This led to the Design Study for EISCAT_3D, funded by EU through Framework Programme 6 (2005–2009). In 2008, ESFRI (European Forum for Research Infrastructures) selected EISCAT_3D for inclusion in the 2008 update of its Roadmap for Large-Scale European Research Infrastructures, which made it possible for the project to enter the Preparatory Phase funded by EU through Framework Programme 7 (2010–2014). The Preparatory Phase resulted in a sufficient level of maturity with respect to technical, legal and financial issues for the project to apply for Preparation for Production (PfP) funding from EU through H2020-INFRADEV (2015–2017) to facilitate a smooth and swift transition into construction.

In the meantime, the scientific user communities in several of the EISCAT member countries applied for research infrastructure grants from their national funding agencies to support the construction and future operation of the radar.

In June 2017, when the total allocated level of national contributions exceeded 60M€, the EISCAT Council could finally take the decision to start construction of EISCAT_3D Stage 1. In the 2018 update of the ESFRI Roadmap, EISCAT_3D could therefore be promoted from Project to Landmark status.

In this paper we briefly describe the technical implementation status and timeline of EISCAT_3D Stage 1, the organisational structure of the EISCAT Scientific Association, as well as its statues, in order to outline a possible way towards enabling space debris observations as part

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Figure 1. Participants at the EISCAT_3D kickoff in September 2017 gathered in front of the EISCAT_3D PfP prototype subarray, with the cylindrical dish VHF antenna at EISCAT's Ramfjordmoen site in the background. (Photo: Craig Heinselman)

of regular EISCAT_3D activites.

2. EISCAT_3D STAGE 1

EISCAT_3D will be the first multi-static phased array incoherent scatter radar in the world. Space debris is listed in the EISCAT_3D Science Case [MAA+15] as one of its application areas, along with topics in the fields of space plasma physics, atmospheric and ionospheric research, and solar system research.

The construction of EISCAT_3D Stage 1 started in September 2017. Figure 1 shows participants at the construction project kickoff gathered in front of the EISCAT_3D PfP prototype subarray. When EISCAT_3D Stage 1 is commissioned in the end of 2021, it will consist of one transmit and receive site in Skibotn, Norway (69.340°N, 20.313°E) and two receive-only sites in Kaiseniemi, Sweden (68.267°N, 19.448°E) and Karesuvanto, Finland (68.463°N,22.458°E). An artist impression of a station is shown in Figure 2. The locations of the three sites Skibotn, Kaiseniemi and Karesuvanto currently under construction are shown on the map in Figure 3.

Hardware procurement is currently ongoing and each site will nominally be equipped with a 75 metre wide array of 109 antenna subarrays, each having 91 antennas, or a total of 9919 antennas.

The Skibotn transmitter site will be equipped with 5 MW (power) transmitter at a centre frequency of 233 MHz. The antenna array will be planar with the on-axis direction pointing towards zenith. The antenna array is phase steerable to 60° off zenith, with gain falling off approximately according to the projected geometric area $G(\alpha) = G_0 \cos(\alpha)$ where G_0 is 43-45 dBi (depending on final procurement) and α is the zenith angle.

EISCAT_3D will be the first incoherent scatter radar designed to have interferometric imaging [MAA+15, GCLB05] from the beginning, and for this purpose the Skibotn transmitter site will have 10 interferometric outlying receiver subgroups consisting of 91 antennas each. The longest baseline will be approximately 1.5 km. The planned distribution of outlying subgroups is given in Figure 3. This will enable imaging of small-scale ionospheric structures in the E-region of the ionosphere during auroral energetic electron precipitation in addition to estimating the angle of arrival of high signal-to-noise ratio space debris targets and meteor head echoes.

Figure 2. Visualization of an EISCAT_3D station with a 9919 element array (109 hexagonal subarrays with 91 antennas each). (Image: NIPR)

The system will have an all-digital beamformer, with a direct sampling 105 MHz digitizer connected to two polarizations on each one of the 9919 antenna elements. A level one beamformer will reduce the bandwidth to 30 MHz and form up to 10 dual polarization beams on each one of subarrays. These first level wide angle beams are then used by the second level beamformer to form up to 100 dual polarization 30 MHz beams. On the core site, most of these beams will be utilized for interferometry. On the receive sites, these beams will be used to form beams that intersect the transmitter beam across all altitudes of interest. The number of beams is sufficient to simultaneously cover all common volumes with the transmit beam, enabling tri-static observations at an extended range of altitudes simultaneously. Thanks to this, EIS-

CAT_3D will be the first radar ever to give simultaneous vector velocities along the entire beam.

The dual-polarization observation capability is a rather unique capability as well, as it has not been exploited in any other research radar of this class except for the Jicamarca Radio Observatory constructed in the sixties. Employing orthogonal polarization and phase coding for alternating bauds of an alternating code enables complete suppression of sidelobes and elimination of unwanted correlated signal, reduces the cycle length of a complete code set with a factor of two, and reduces the variance of autocorrelation function estimates by a factor of four in the high SNR case [GG09, GG11]. For incoherent scatter measurements this means that statistics can be collected up to four times faster than when using only a single polarization. For hard targets such as space debris the observed polarization properties can be used to infer useful properties such as the objects' shape, size, etc.

3. EISCAT SCIENTIFIC ASSOCIATION

EISCAT is registered as a non-profit organisation in Sweden since 1976. The organisation and management of EISCAT_3D will be based on the structure of the present EISCAT Scientific Association. The host institutes for the present EISCAT systems and the EISCAT Headquarters are the Swedish Institute of Space Physics, Kiruna, Sweden; University of Tromsø, Norway; and Sodankylä Geophysical Observatory at the University of Oulu, Finland. The host institutes provide parts, or all, of the staffing and operation of the current EISCAT sites. The same institutes have indicated their interest in EISCAT_3D.

The governing rules and management structure of EISCAT Scientific Association, including the function of the EISCAT Council, are laid down in an agreement between the EISCAT Associates. These rules are included in the governing rules and procedures book, the Blue Book[1] [Ass15].

The governing body of the present EISCAT Scientific Association is the EISCAT Council, which assumes overall responsibility for the activities of the Association. It consists of a Delegation of each Associate (presently member institutes or funding agencies in China, Finland, Japan, Norway, Sweden and United Kingdom) with a maximum of three people from each Associate. The Council makes decisions by simple majority of the delegations. However it may also, by unanimous decision, delegate matters for consideration to the Council Advisory Group or to other sub-committees which it may establish from time to time. In addition to the Associates, there are also affiliate institutes (funding EISCAT radar time but not full membership) in France, South Korea, and Ukraine.

The EISCAT Director is appointed by the Council. The role of the Director is to assume legal and financial responsibility for the management of the facilities and staff of the EISCAT Scientific Association. The Director also implements the decisions of the Council, and is responsible for implementing the budget approved by the Council according to the Council's instructions. The responsibility for the day-to-day scheduling of the scientific programme is also part of the role of the Director, who shall represent the Association in court and in all civil affairs unless otherwise decided by the Council.

The EISCAT scientific community, under the guidance of the Council, organises a Scientific Advisory Committee, funded by the Associates, which may also include external members. Typically Council appoints to the Scientific Advisory Committee two external members whose scientific expertise is relevant to the EISCAT scientific goals. The Scientific Advisory Committee advises the Council, the Council Committees and EISCAT executives on matters related to the scientific programme and the development, design and construction of facilities and experiments, the organisation of the observing programme and other aspects relevant to the scientific aims of the Association, including its overall scientific plans and goals.

4. SPACE DEBRIS OBSERVATIONS

In the EISCAT Data Policy, which is an appendix to the EISCAT agreement [Ass15] and subject to separate approval by the EISCAT Council, it is stated that ”EISCAT raw data containing radar echoes from satellites shall not be distributed to other agencies”.

The measurement technique and analysis implementation which needs to operate on low-level (raw) data will therefore have to be implemented as part of EISCAT_3D's Standard Experiment Programmes and Modes.

Furthermore, the EISCAT agreement states that:

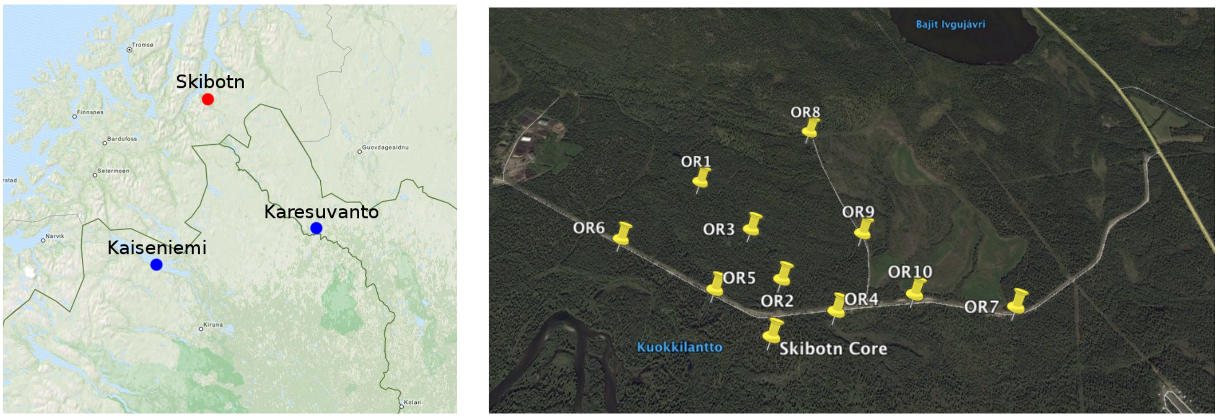
- 2.a. The aim of the Association is to provide access to radar [...] for non-military scientific purposes.
- 2.e. The Association may contribute to the international task of tracking objects in space (natural or man-made). For this activity, an agreed list of objects shall be maintained and the Association shall only conduct tracking of objects from this list.

The agreed list of objects is defined in the EISCAT Data Policy: ”The White List will be openly available and initially based on the Open Space-Track Catalog (www.space-track.org)”.

It should also be noted that: ”EISCAT shall strive to have full transparency in its operations and with respect to the data generated. All observation campaigns shall be clearly documented and the campaign log shall be available for inspection in accordance with the EISCAT Agreement.”

Full transparency could be maintained by requiring all orbit data to be published openly immediately and automat-

[1] https://www.eiscat.se/scientist/document/governing-rules/



a. b.

Figure 3. a. EISCAT_3D sites currently under construction. The transmitter/receiver site in Skibotn (Norway) is shown in red. Receiver sites in Kaiseniemi (Sweden) and Karesuvanto (Finland) are indicated in blue. b. Planned distribution of outlying receiver antenna subgroups near Skibotn, Norway.

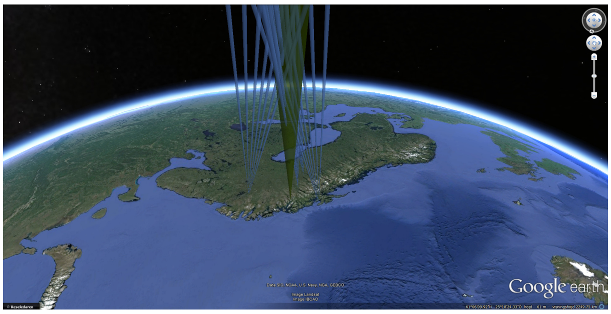


Figure 4. Visualization of the typical EISCAT_3D measurement volume at $68° - 69°N$ *above northern Fenno-Scandia.*

ically, to demonstrate that EISCAT and the user responsible for the measurement is behaving according to the agreement and that the White Listing procedure works as intended.

If the boundary condition of a White List of objects that needs to be updated and approved by the EISCAT Council is fulfilled and if hard target orbit analysis is implemented as a standard procedure, it seems likely that EISCAT_3D should be available for space debris observations whenever there is an interested (paying) client for these products. Since the radar is located on a high-northern latitude ($68° - 69°$N), space objects in polar orbits pass the measurement volume often.

5. DISCUSSION

Modeling [VMK+17] has shown that ionospheric ray-bending and group delay are severe enough at the operating frequency of EISCAT_3D, 233 MHz (low VHF) that these effects need to be addressed for SSA applications. However, it was also shown that because EISCAT_3D is an ionospheric research radar, the electron density profiles that these effects depend on can simultaneously be acquired with nearly every measurement of a hard target. This can be used to model the effect and correct for ionospheric propagation errors.

Preliminary results from an ongoing performance analysis to evaluate the capacity of EISCAT_3D for space debris observations is further detailed in these proceedings by Kastinen et al. *Next-generation Space Object Radar Tracking Simulator: SORTS++*. Using the MASTER catalogue [FGW+09] and the software toolbox SORTS++, which is the next-generation Space Object Radar Tracking Simulator (SORTS), it is demonstrated that EISCAT_3D will be able to maintain the orbits for tens of thousands of the objects in the catalogue.

A related overview of recent beampark space debris measurements with the currently available EISCAT radars by Vierinen et al., *2018 beampark observations of space debris with the EISCAT radars* is also available in these proceedings. The measurements were processed with a new range-velocity-acceleration matched filter bank, which doubles the coherent integration time compared with previous analysis. This has the effect of doubling the sensitivity of the measurements.

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