EISCAT_3D

Research infrastructure for incoherent scatter radar studies of the environment

Document prepared by EISCAT Scientific Association

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Contents

Cover photograph: Northern Lights are the visual manifestation of geospace-atmosphere interactions at high latitudes and the research reason why the EISCAT radars originally were located in Northern Scandinavia. The first technical feasibility study of the next-generation radar EISCAT_3D was the Design Study in 2005–2009. It proposed a 3- or 4-element Yagi antenna as the mass-producible element in the phased-array antennas of EISCAT_3D. The picture shows a small group of such Yagi antennas in a mutual coupling test at the EISCAT Kiruna site. The final EISCAT_3D would consist of several tens of thousands of such antenna elements at the distributed radar sites. (Photographer: Lars-Göran Vanhainen)

1 Executive Summary

EISCAT_3D will be a world-leading international Research Infrastructure, using the incoherent scatter technique to study how the Earth's atmosphere is coupled to space. EISCAT_3D is a tool to allow plasma physics experiments in the natural environment, a key atmospheric monitoring instrument for climate and space weather studies, and an essential element in international global multi-instrument campaigns for studying the environment. Within the global network of Geospace observatories it will will be a key element for covering the auroral zone.

EISCAT _3D aims to establish a system of distributed phased array radars that enable comprehensive 3D observations of the atmosphere and ionosphere above Northern Fenno-Scandinavia, a unique location for research into the polar atmosphere. The use of new radar technology, combined with the latest digital signal processing will achieve ten times higher temporal and spatial resolution than the present radars and at the same time will offer for the first time continuous measurement capability. The flexibility of EISCAT_3D will allow the study of atmospheric phenomena at both large and small scales, unreachable by the present systems. The new system will be implemented for a wide range of users and applications. It will allow studies to close the gap between space research and environmental research. The continuous data coverage will facilitate the inclusion of detailed incoherent scatter radar data into climate and Earth system modelling.

EISCAT Scientific Association has successfully been running incoherent scatter radars in the Scandinavian Arctic for more than 30 years. EISCAT is currently funded and operated by research councils of Norway, Sweden, Finland, Japan, China and the United Kingdom and has its headquarters in Kiruna, Sweden. The EISCAT_3D project proposal is based on the results of design studies incorporating the latest ideas and advances in radio array technology, software radar techniques, and advances in available components and technology. The European Union has funded a design study and is currently funding a preparatory phase project for EISCAT_3D[1]. The entire preparation and design phase has been underpinned by discussions and consultations with the international EISCAT user community, with scientists in the region and with potential new users both locally and globally.

The European Strategy Forum on Research Infrastructures (ESFRI) selected EISCAT_3D for inclusion in the Roadmap 2008 for Large-Scale European Research Infrastructures for the next 20—30 years and the Swedish Research Council (VR) played a key role in facilitating this process. This new large-scale research infrastructure has applications in a wide range of research areas including Earth environment monitoring and technology solutions supporting sustainable development, well beyond atmospheric and space sciences.

EISCAT_3D will consist of a core site with transmitting and receiving radar arrays and of sites with receiving antenna arrays at different distances from the core. All sites require a quiet radio environment in the vicinity of the central observation frequency around 233 MHz. It is intended that the advanced radar

[1] The Preparatory Phase project is financed within the EU FP7 funding programme. The participants are University of Oulu, Luleå University of Technology, Swedish Institute of Space Physics, University of Tromsø, Science and Technology Facilities Council (UK), the Swedish Research Council, National Instruments and EISCAT Scientific Association as the project coordinator.

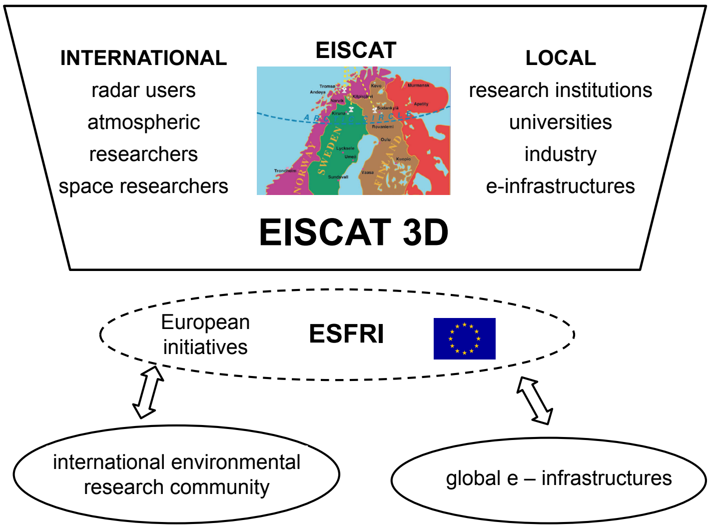

Figure 1: EISCAT_3D will transform the current EISCAT Scientific Association into an international Research Infrastructure for the environmental sciences.

facilities should also act as "magnets" to attract a variety of smaller supporting instruments, some of which will be deployed for a long duration, and some for specific shorter-term observations. EISCAT_3D will be built as a modular system, the first construction will start in 2014. It will require investment of the order of 120 M€. This comprises costs for local site and infrastructure preparation, for radar hardware and construction, and for implementing the core signal processing and software radar infrastructure needed to deliver calibrated and validated measurements to scientific end users. Several regional and national enterprises are expected to respond to invitations to tender both for the radio and the digital signal processing instruments.

The new EISCAT_3D facility with sites in Finland, Norway and Sweden will support local and international users in carrying out excellent research on an internationally competitive level. It offers to the scientific community state of the art instruments for dedicated observation campaigns in areas of research which are important for the understanding of our environment and climate. The continuous data can be used for long-term computer simulations and cooperation with local computing centers will enhance the competence in handling complex data products. EISCAT_3D will exploit the latest European e-infrastructures, connect to global e-infrastructures and offer a truly international forum for scientific discussion and collaborations.

EISCAT_3D will also act as a driver for the development and testing of new radar techniques and radio science, facilitate the education of young scientists and engineers in the EISCAT member countries and contribute to solving the environmental issues that mankind faces in the 21st century.

2 Introduction

The EISCAT Scientific Association has been world-leading in the studies of the upper ionised atmosphere by using the incoherent scatter (IS) radar facilities on the mainland of Northern Scandinavia (EISCAT UHF and VHF radar systems) and on Svalbard (the ESR radar). These radars, together with supporting instruments, are used for studying the high-latitude upper atmosphere and its connection to geospace in the Northern European arctic and sub-arctic regions.

Since EISCAT was formed in 1975 its suite of instruments has maintained world leadership in terms of experimental capability by continuous innovations and through a user community which has repeatedly developed new experiments and data analysis techniques. EISCAT data has until June 2011 been presented in 1951 refereed scientific publications. EISCAT discoveries have stimulated new ionospheric research. EISCAT users are teaching at universities in many countries and have supervised numerous Master and PhD theses.

The incoherent scatter (IS) technique is an advanced tool for studying the Earth's upper atmosphere. The IS method is based on the physical process of radio wave scattering from free electrons in the ionosphere, called Thomson scattering. Electrons have small cross sections for Thomson scattering and measuring them requires transmitting a high power radio wave and receiving with large aperture antennas. It was originally assumed that the observed Thomson scattering originates from the electron population in random thermal motion. Such a signal was expected to be incoherent in nature, hence the name for the IS method. However, ion acoustic plasma waves in the electrically conducting media of the ionosphere bring order in the electron population in such a way that there is a tiny coherence in the received signal. The power of the IS method originates from the fact that electrons in the ionospheric plasma are always coupled to the ions in their vicinity, and in the collisional plasma also to the neutral constituents in the air. Illuminating the air in the radar target volume by a high-power radiowave, it is possible to infer characteristics of the electron population from the spectrum of the backscattered radiowave, which in turn also reflects the characteristics of the ion and neutral populations. Today a well-developed incoherent scatter theory exists, so that the analysis of measured signals to physical parameters can be done using statistical inversion techniques.

The EISCAT science has expanded. Initially intended for studies of the physics related to the aurora and the magnetosphere, EISCAT observations are strongly tied to the past and present international Solar Terrestrial Physics programmes. EISCAT science has over the last three decades also moved into new areas, most of them relevant for environmental research. These include more detailed studies of the energy coupling between the upper and lower atmosphere, the linkages between the ionosphere and magnetosphere, investigations of the importance of turbulence and small-scale structures and sensitive detection of weak-coherence targets such as micrometeoroids and cm-scale space debris. Some of these studies also have practical importance for applications such as global positioning, communications and space situational awareness. Other studies are also of fundamental physical interest, like the processes of dusty and complex plasmas that are associated with polar mesospheric summer echoes and noctilucent clouds.

Many open questions are related to fundamental processes in plasma physics, on small spatial scales, that are much smaller than the radar beam width. With the new system it is possible to make use of the emerging new technique of radar interferometry as well as of statistical inversion methods for powerful computer analysis in order to reach a resolution that is smaller than the beam width.

A number of compelling scientific reasons suggest moving to continuous operations, or at least to a much higher level of operation than undertaken at the time: research on ionosphere-atmosphere coupling, on aurora physics, and on planetary waves, tides and winds. The possibility of continuous operations would also make it much easier for EISCAT to provide observational support for satellites, rocket campaigns and other types of diagnostic instruments and allow the EISCAT community to play a full role in the ground-based support of future satellite missions.

In summary, research development asks for observations that are beyond the capabilities of the present EISCAT systems and that no incoherent scatter radar is currently capable of providing in the same instrument. At the same time, the frequency bands used for EISCAT operations on the mainland are coming under increasing pressure from UMTS 900 mobile telephones (in the case of our UHF frequencies) and digital audio broadcasting (in the case of our VHF frequencies).

The EISCAT radars in mainland Scandinavia need to be replaced for technical reasons. The instruments started measurements in 1981. Although many parts of the radars (transmitters, signal processing, computers etc.) have been renovated during this time, some key sub-systems, particularly the large steerable antennas, are approaching the end of their working lives and modern systems offer a new generation of radar capabilities.

It was early realised that the large aperture for IS measurements can effectively be achieved by a phased-array antenna, where individual signals from separate antennas are summed with known phase delays so that various beam directions can be formed. Early systems had naturally fixed phase delays, so that only one directed beam could be generated at a time. Development in the speed of electronics has led to modern phased-array systems, where multiple beams can be formed and beam direction can be varied very rapidly. These are used in the new incoherent scatter radars, such as the AMISR systems at Poker Flat, Alaska, USA (PFISR), and at Resolute Bay, Canada (RISR). The latter has technical abilities beyond those, which could be provided by any of the existing EISCAT radars, either in their present form or through reasonable upgrades.

All this together convinced the EISCAT community to propose EISCAT_3D and to collectively aim considerably further in developing a phased array radar that is really unique and combines high sensitivity, volumetric imaging, interferometry and multistatic observations. The new system capabilities will go beyond those of the current generation of incoherent scatter radars, and will aim towards leading the technological development in this area.

Phased arrays are inherently modular, this is ideally suited to continuous operations and allows the system to be expanded incrementally. Employing electronic beam-forming and beam-steering, phased array systems are not

Figure 2: Artist's view of a core site of the EISCAT_3D phased array radar system.

only capable of steerability comparable with dish systems over a wide field of view, but also of pulse-to-pulse beam steering in arbitrary directions for applications such as large-scale imaging. With digital arrays, such as EISCAT_3D, there is also the possibility of much more complex antenna pattern control, such as volume illumination, split beams, and deep and adaptive nulls to provide fine scale measurements adjacent to strong coherent targets.

The construction of the new instruments is accompanied by adjusting the institutional structure of the organisation and by measures to expand the EISCAT_3D user community.

3 Science case

EISCAT_3D accounts for the increasing relevance that environmental research assigns to processes in the upper atmosphere, and the coupling between different atmospheric layers. The advanced EISCAT_3D incoherent scatter radar measurements will allow simultaneous observations over an unprecedented wide range of altitudes and cover tropospheric, ionospheric and magnetospheric phenomena, the understanding of which is important for environmental studies. At the same time, the measurements will reveal the influence on the atmosphere from the Sun, the solar wind and the influx of solid meteoroids. Finally, the advanced EISCAT_3D incoherent scatter radar measurements will allow detailed studies of these atmospheric phenomena regardless of the weather conditions.

3.1 Radar key capabilities

Incoherent scatter radars are unique. They provide several persistent and range resolved plasma parameters from the ionosphere: electron density, electron temperature, ion temperature and ion velocity. Many of these cannot be measured by any other ground-based technique. These parameters can be used to calculate additional properties of the upper atmosphere, such as electric fields and electrical currents, which can affect man-made systems on the ground. At lower altitudes in the atmosphere, the radar signal is scattered from turbulence, giving spectral width and Doppler velocity allowing calculation of the temperature and motion of the neutral upper atmosphere, which is of interest for a range of climate and weather-related studies. The key capabilities of the EISCAT_3D will be as follows.

Volumetric imaging: Digital beam-forming will allow the radar either to look in multiple directions simultaneously, or to “paint the sky”, repeatedly scanning a single beam thorough a range of directions, building up quasi-simultaneous images of a wide area of the upper atmosphere in three dimensions. This will resolve outstanding issues of spatio-temporal ambiguity (e.g. the dynamics of dusty plasmas in the mesopause region and moving auroral structures, tracking space debris and meteors), from which conventional radars and satellites suffer.

Multistatic configuration: In addition to a transmitter/receiver, EISCAT_3D will contain several passive receivers located at distances between 50 and 250 km from the central site. Like the central site, each remote site will be capable of generating multiple simultaneous beams or making imaging observations forming “all equivalent beams”. This will make it possible to construct height profiles of parameters such as vector velocity and ionospheric current density, or to look for anisotropic scattering mechanisms, in a manner that cannot be achieved by conventional radars. The volumetric vector velocities will be a unique property of EISCAT_3D, which no other IS radar in the world has. Such a capability is important for studying the variability, coupling, and energy dissipation between the solar wind, magnetosphere and atmosphere.

Continuous monitoring: EISCAT_3D will allow continuous operations, limited only by power consumption and data storage. It will be possible to have a uniform and standard observing program interleaved on a fine time scale with more specialised observational experiments. This will provide a uniform and unbroken observational record for the measurement volume over the radar, thereby monitoring the state of the atmosphere. This is particularly important for observing atmospheric parameters as a function of solar variability and for capturing unexpected Space Weather events that appear suddenly and are hard to predict.

Aperture Synthesis imaging: EISCAT_3D will have the unique capability to perform aperture synthesis imaging with multiple baseline angles and lengths by dividing the core site into a number of sub-arrays. This allows us to study small-scale (less than km) plasma physical processes like meteor head echoes, polar mesospheric summer echoes, small-scale auroras and naturally enhanced ion acoustic lines (NEIALs) produced by the coupling between energetic particles and plasma waves in the Earth’s space environment.

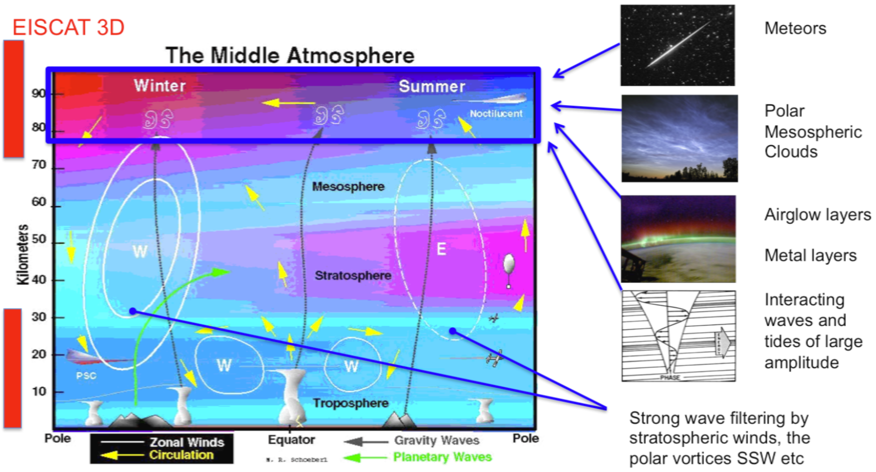

Figure 3: Atmospheric regions from the ground level to 100 km. Horizontal direction is from the winter pole to the equator and to the summer pole. Yellow arrows show global circulation. The left-hand red bars indicate altitudes, from where EISCAT_3D is expected to get scatter from atmospheric turbulence. The right-hand side shows some phenomena that are observed in the mesosphere (middle atmosphere).

3.2 Science topics

A full discussion of the science topics can be found in the EISCAT_3D Science Case document, which can be downloaded from `http://www.eiscat3d.se`. The following points summarise a few of the key topics:

3.2.1 Atmospheric physics and global change

Figure 3 shows schematically the atmospheric regions. The troposphere below about 12 km is a region, where normal weather phenomena take place. The stratosphere is an important region since it contains the ozone layer at 30–40 km altitude that absorbs most of the harmful short-wavelength UV radiation. The mesosphere contains the coldest region of the atmosphere, the mesopause at about 85 km altitude, where noctilucent clouds and polar mesospheric summer echoes (PMSE) are formed. The warm thermosphere is located above the mesopause.

The global circulation in the lower and middle atmosphere is also shown schematically in Figure 3. One distinct feature is the formation of the polar vortex, in which the circulation of the middle atmosphere isolates the polar air from that at lower latitudes. The EISCAT_3D radar will be located at or near the equatorward edge of the polar vortex. Atmospheric turbulence in the troposphere and lower stratosphere can give rise to scatter of the high-power VHF signal transmitted by EISCAT_3D.

The different altitude and latitude regions of the atmosphere are coupled in a complex way, in which energy is transported, converted from one form to another and dissipated in various parts of the system. In the lower and middle atmosphere, winds, waves (atmospheric gravity waves, planetary waves

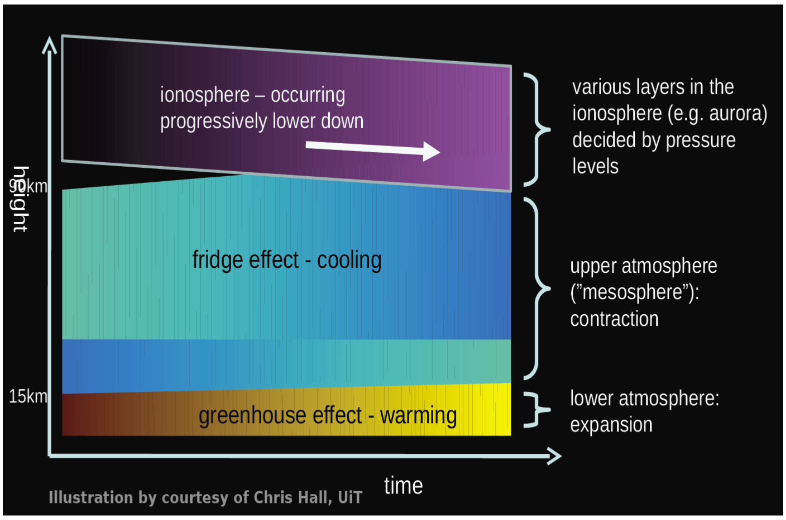

Figure 4: The man-made greenhouse warming in the troposphere results in expansion of the lower atmosphere. It has been theoretically predicted that this would lead to cooling of the mesosphere. No clear evidence of it has yet been obtained.

and tides) and turbulence play an important role. At present, we are far from understanding even the basic coupling processes, which could help us e.g. to separate the effects of natural and man-made variability in the long-term global change.

Six key questions about atmospheric physics and global change:

- Where do upgoing atmospheric gravity waves break into turbulence and how do they affect the temperature and global circulation?
- Do solar energetic particle events destroy stratospheric ozone?
- What is the process that links apparent variations in surface temperature to geomagnetic activity of solar origin (as some recent studies have suggested)?
- Are mesospheric thin layers and noctilucent clouds signs of global change, connected to human activity? How are they changing over time?
- How do stratospheric warming events affect the dynamics of the mesosphere and thermosphere?
- Is greenhouse warming of the lower atmosphere resulting in long-term cooling of the middle and upper atmosphere (see Figure 4)?

3.2.2 Influence of the Sun and the solar wind on the Earth's atmosphere

The stream of charged particles, the solar wind, blows continuously from the Sun. When it hits the Earth's magnetosphere, the magnetic fields of solar and

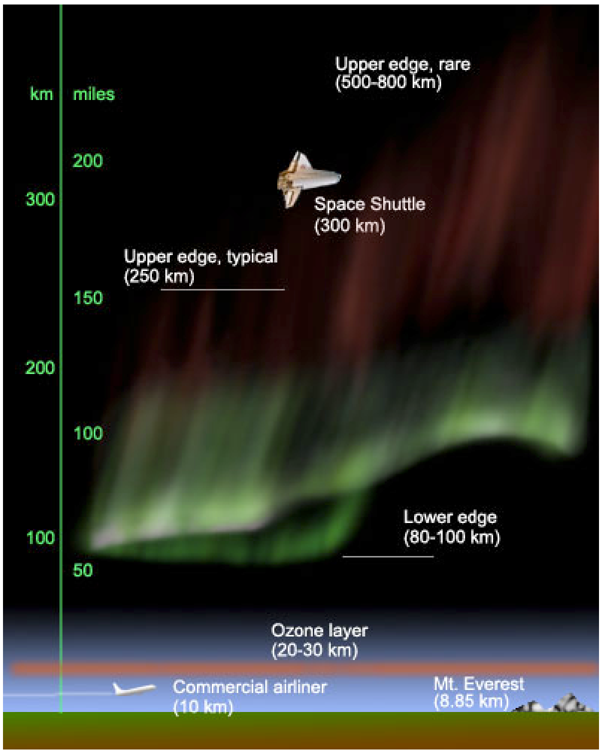

Figure 5: The ionosphere is a region covering altitudes from about 80 to 1000 km.

terrestrial origin can merge and let a huge amount of energy to enter the near-Earth space. The sudden releases of this energy stored in the Earth's magnetosphere (during magnetospheric substorms and magnetic storms) produce geomagnetic disturbances, aurora, and various Space Weather effects, which may disturb satellite orbits, satellite-based navigation systems and electrical power systems. The solar activity peaks during sunspot maxima periods, when solar energetic particles may have enough energy to penetrate down to the stratosphere. Solar radio bursts and bursts of X-rays are also to be expected.

The plasma sheet in the magnetosphere is connected via magnetic field lines to the high-latitude ionosphere to form the auroral oval, where intense electrical currents flow. EISCAT_3D will be located within this important region. The incoherent scatter method requires ionized atoms or molecules, accompanied by free electrons. The ionized part of the atmosphere, the ionosphere, starts from an altitude of about 70–80 km and continues into space (see Figure 5). IS radars can typically measure plasma parameters from 80 km to several hundreds of km. Horizontal currents flow at altitudes of 100–130 km, the ionization maximum is located at about 300 km and at the uppermost altitudes, above 500 km, ion outflows into the magnetosphere may take place.

By using a Heating facility co-located with EISCAT_3D, the basic plasma physical processes can be simulated in a natural plasma laboratory.

Three key questions concerning the influence of the Sun and the solar wind on the atmosphere:

- How much energy originating from the Sun and near-Earth space is deposited in the thermosphere during substorms and what effect does it have on the various atmospheric regions?
- Which are the most important generation mechanisms of ion outflows and what kinds of effect do they have on substorm onset?
- What is the plasma physics behind auroral arcs, small-scale structures, naturally enhanced ion acoustic waves and artificial aurora induced by the Heater?

3.2.3 Meteoroid entry into the Earth's atmosphere

Even though EISCAT_3D is designed to study the ionosphere and atmosphere of the Earth, it can also be used to study the solid objects, dust and meteoroids, that continuously hit the Earth's atmosphere. The disintegration of these objects is observed as meteors and it provides in the order of ten tons per day of extraterrestrial material that remains in the atmosphere for long time.

With the high power and large antenna aperture, incoherent scatter radars can be extraordinarily good monitors of extra-terrestrial dust and its interaction with the atmosphere. It is very important to make good measurements of the flux of meteoric material entering the upper atmosphere, because meteoric dust plays an important role in the chemistry and heat balance of the middle atmosphere, and thus forms a very important input into middle atmosphere models. The observations can also contribute to studies of how dust is distributed in the solar system, by measuring the trajectories of incoming meteors. In addition, thanks to the high power and great accuracy, mapping of objects such as asteroids that cross the Earth's orbit is possible.

Three key questions about meteoroid entry into the atmosphere:

- What is the mechanism behind the meteor formation, and what does it tell us about about the influence from meteoroids on the atmosphere?
- What kind of orbits do meteoroids have, and what do they tell us about meteoroid dynamics and the meteoroid mass flux into the atmosphere?
- What is the role of meteoric dust in the chemistry and heat balance of the middle atmosphere?

3.2.4 Space weather and service applications

Over the last decade, a vibrant international community has grown up around the study of space weather, focusing on the effects of varying conditions in geospace on human activity. For example, solar-terrestrial disturbances that heat the ionosphere lead to upwelling and expansion of the atmosphere, enhancing the thermospheric density at high altitudes and increasing satellite drag, while events such as coronal mass ejections (CMEs) and magnetospheric substorms increase the flux of highenergy particles which can damage spacecraft electronics. Auroral ionospheric currents can also induce current flow in ground systems such as power grids and pipelines. The ability to predict such events requires highly capable models, assimilating data from a global

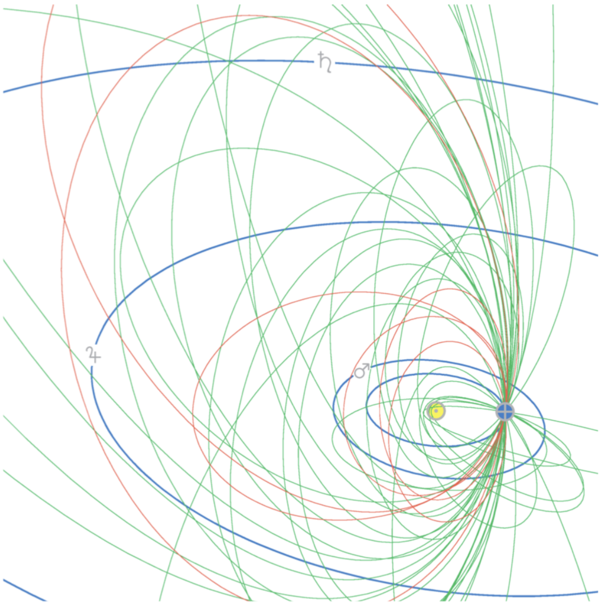

Figure 6: Calculated meteoroid orbits from EISCAT UHF tristatic vector velocity measurements. Sun (yellow), Earth (blue) and prograde (green) and retrograde (red) meteoroid orbits (Szasz, PhD thesis, IRF Kiruna, 2008). Knowledge of the meteoroid orbits is important for quantifying the amount of meteoroid mass that contributes to physical processes in the atmosphere.

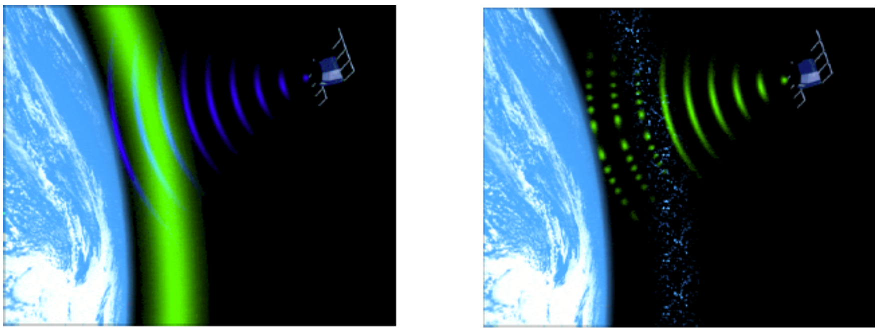

Figure 7: Schematic showing scintillation effects in beacon satellite data, as produced by a highly-structured ionosphere.

network of continuously observing instruments, of which incoherent scatter radars are the most powerful and versatile. EISCAT_3D will be a key European cornerstone of this endeavour.

Europe has recently begun making efforts to establish a Space Situational Awareness (SSA) programme, under the aegis of the European Space Agency. As well as improving the European monitoring and prediction of space weather, this programme is designed to provide an independent capability for monitoring spacecraft and the growing amount of “space debris”, ranging from large objects such as dead satellites to the millions of sub-centimetre fragments in Earth orbit.

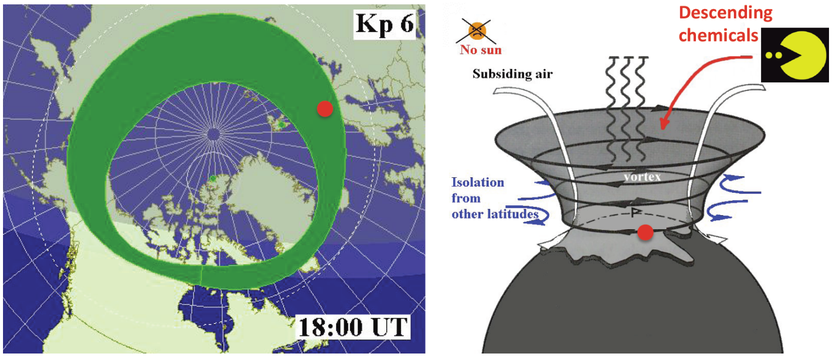

Figure 8: Left: Location of auroral oval (green) and EISCAT_3D (red point). Right: Schematic figure of the polar vortex in the winter hemisphere and EISCAT_3D (red point) (courtesy of M. Clilverd).

EISCAT_3D is very well suited to observing space debris. The wide spatial coverage and capability to generate multiple simultaneous, rapidly-moving beams, will enable EISCAT_3D to track individual objects, including multiple objects simultaneously, for an optimal characterisation of their orbital parameters and the monitoring of orbit perturbations due to Space Weather (e.g. magnetic storms) effects. In addition, the increased effective aperture (higher power and greater collecting area) of EISCAT_3D will give it an enhanced capability to track objects out to greater ranges and smaller sizes.

3.2.5 Radar techniques, coding and analysis

EISCAT has always been a testbed for new ideas in coding and data analysis, whose user community has pioneered many applications, including new radar codes, new types of data analysis and other applications of novel statistical inversion mathematics. Many of these new techniques, first developed at EISCAT, are now in standard use among incoherent scatter radars worldwide.

EISCAT_3D represents a further substantial step in the design of atmospheric radars. The system will be the first of a next generation of "software radars", whose advanced capabilities will be realised not by its hardware (which is relatively inexpensive and modular) but by the flexibility and adaptability of the scheduling, beam-forming, signal processing and analysis software used to control the radar and process its data. In this respect, EISCAT_3D will be a world leader in the development of new observing techniques, which will eventually be implemented by the next generation of incoherent scatter radars around the world.

3.3 Summary of the science case

The EISCAT_3D radar will be a unique facility because:

- It is located at the edge of the polar vortex, which isolates the polar air in the middle and upper troposphere and in the stratosphere from the air at lower latitudes. The breakdown of the polar vortex is an extreme

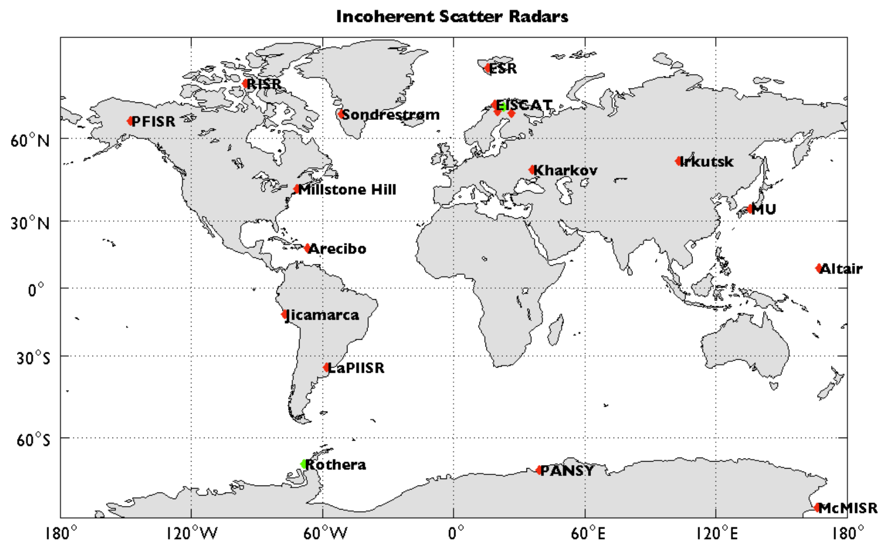

Figure 9: Existing and planned (LaPIISR, McMISR) IS radars.

event known as a Sudden Stratospheric Warming. Polar vortex is also associated with ozone depletion.

- It is located within the auroral zone, where typically the most energetic particles from the Sun and the near-Earth space precipitate and which is a key region for the solar influence on the Earth's upper atmosphere and Space Weather phenomena.
- In the northern part of mainland Scandinavia, a uniquely dense and versatile network of supporting instruments is in place: e.g. MST and MF radars, lidars, magnetometers, all-sky cameras and other optical instruments, wide-band and imaging riometers, rocket ranges and a Heating facility.
- To study global coupling, the EISCAT_3D measurements can be combined with the global network of incoherent scatter radars (see Figure 9), coherent scatter radars (SuperDarn network) and satellite measurements.

The key science questions are:

- How are atmospheric regions coupled vertically and latitudinally? What is the role of winds and different kind of waves (atmospheric gravity waves, planetary waves, tidal oscillations) in transporting energy between the regions and affecting the dynamics of the atmosphere? What is the role of atmospheric chemistry?
- How do the Sun and Space Weather (e.g. energetic particles, high-latitude intense electric fields and currents, electromagnetic radiation) affect the atmosphere to produce natural variability? How does the natural

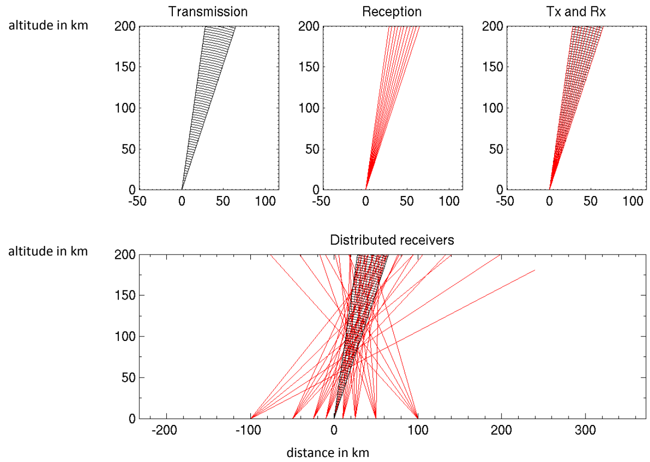

Figure 10: Volumetric imaging with EISCAT_3D. Modulation of the transmitted radar signal (Tx) subsequently illuminates layers at different distance from the transmitter. Receiving (Rx) in narrow beams provides the backscattered single from different angles. Combining the transmitted and received data (Tx and Rx) provides the back-scattered signal together with height and radial information hence from well-defined volumes in space ("voxels").

variability in the upper atmosphere influence the middle and lower atmosphere? Can the man-made global change be observed in the upper atmosphere?

4 Technical design

4.1 EISCAT_3D concept

EISCAT_3D will work at operating frequency in the high VHF band at 233 MHz to ensure optimum performance in low electron density conditions (i.e. both in the middle atmosphere and in the topside ionosphere). The ability for routine interferometric operation and for the temporary storage and advanced reprocessing of the lowest level data products represents a significant advance on existing incoherent scatter radar designs.

EISCAT_3D makes use of a phased array radar system to obtain volumetric imaging as illustrated in Figure 10. The unique feature of volumetric imaging is that it allows broad regions of the ionosphere and upper atmosphere to be mapped on a quasi-simultaneous basis. This is beyond the capabilities of the existing EISCAT radars, which are restricted to single radar beams produced by slowly-moving dishes. The availability of such images is key to disentangling the signatures of processes which are time-dependent from those which are spatially-dependent, an ambiguity that the current EISCAT radars cannot resolve. This resolution is particularly important during auroral processes where the ionosphere is rapidly changing over the observing radar instrument. While volumetric imaging can be used for imaging large areas of the upper atmosphere, it can also be used for imaging relatively small areas at high reso-

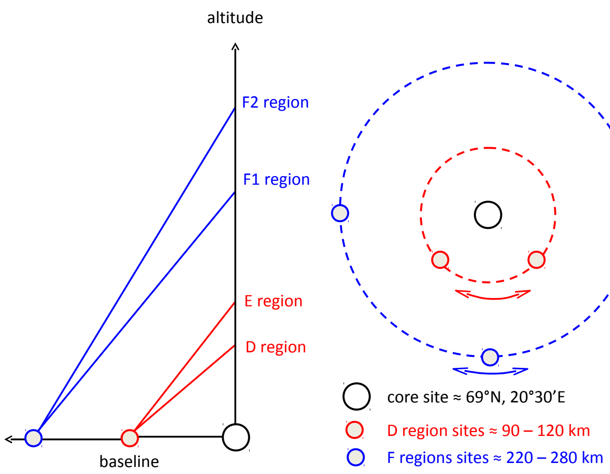

Figure 11: High power radio waves are transmitted into the atmosphere and partially scattered by the charged atmospheric particles. The core site and the surrounding distant sites receive back-scattered signals with less than a millionth of the transmitted power. Near distance sites are optimal for studying the atmospheres at low altitude, long distance sites for studying higher altitudes. Observations from different directions contain information about the direction of motion of the charged particles.

lution, promising interesting advances in the study of highly structured features such as auroral arcs and mesospheric thin layers.

4.2 Site configuration

The EISCAT_3D facilities will comprise one core site and at least four distant sites (see Figure 11) equipped with antenna arrays, other supporting instruments, platforms for movable equipment and high data rate internet connections.

At least two pair of distant sites with primary receiving capabilities will be located at baseline distances roughly 90–120 km and 220–280 km respectively, from the core site. These locations are best for measurements in the ionospheric D and E layers for one pair and F1 and F2 layers for the other. The most favourable geometry for tri-static observations depends on the number of remote sites which can be constructed. If four remote sites are constructed, the optimum configuration is along two baselines, running orthogonally to each other from the central site. If more than four remote stations are possible, the optimum configuration is likely to be based on concentric circles around the central site.

4.3 Radar system concept

The core site will comprise:

- A phased-array transmit/receive (TX/RX) system consisting of roughly 10,000 elements, covering an area with 200 m diameter.

- RF signal generation equipment and RF power amplifiers.
- Transmit/receive switching system.
- Beam-steering systems for transmission and reception.
- Incoherent scatter receiver subsystem.
- Outlier elements; receive-only phased-array antennas for narrow receiving beams and in-beam interferometry.
- Beam formers.
- Time and frequency synchronisation equipment.
- Digital signal processing equipment.
- Built-in test equipment.

The remote sites will comprise:

- Phased-array antennas with its associated receivers.
- Beam-formers.
- Time and frequency synchronisation equipment.
- Digital signal processing equipment.
- Built-in test equipment.

The total size of the central site will exceed 1 km, given that the dense inner core of antennas will be accompanied by a sparsely distributed array of outlying antennas. The approximate size of a remote site would be around 300 m in diameter.

The transmitter parameters are:

Centre frequency	233 MHz
Peak output power	10 MW
Instantaneous –1 dB power bandwidth	5 MHz
Pulse length	0.5–3000 μs
Pulse repetition frequency	0–3000 Hz
Wave modulation	Arbitrary waveform

The receiver parameters are:

Centre frequency	233 MHz
Instantaneous bandwidth	$\pm$15 MHz, at distant sites $\pm$5 MHz
Overall noise temperature	<50 K referenced to input terminals
Spurious-free dynamic range	>70 dB

The system parameters will be selected such that, over the multi-static field-of-view, the resolution along the transmitted beam direction(s) can be made better than 100 m at any altitude and the horizontal (transverse) –3 dB resolution at 100 km altitude is better than 100 m. The beam generated by the central core transmit/receive antenna array will be steerable out to a maximum zenith angle of $\approx 40^\circ$ in all azimuth directions and will have a side lobe window at low elevation. Tri-static observations will be feasible throughout the central core field-of-view at all altitudes up to 800 km. The beam from the central core antenna array will be steerable into any one of over 10,000 discrete pointing directions on timescale better than 1 μs.

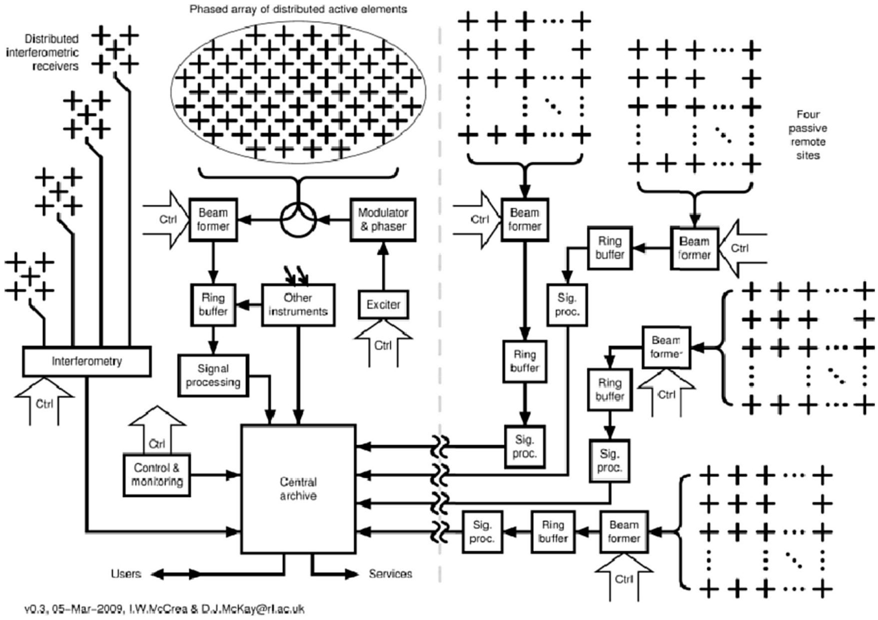

Figure 12: Block diagram of system concept. The transmitting array elements have single digital signal generator units as well as receiver units. Receive only units are the interferometric receivers located at the core and at the distant sites.

4.4 Other supporting instruments

The core site will comprise a heating facility to facilitate active ionospheric experiments in the region of the central site, using a high-power transmitter at a few MHz, separate from the main radar. Support for basic optical instrumentation at the core and selected distant sites will allow the observation of auroral or airglow emissions and Doppler shifts due to mesospheric and thermospheric neutral winds at the time and location of the radar observations. This can be facilitated by installing CCD equipped standard cameras with filter change capacity near the core site and at several distant sites, as well as a Fabry Perot imaging spectrometer at the core. Data storage and communication systems shall be located at, or close to, each site. Digital ionosondes at all sites will support the radar measurements and broaden the parameters obtained from continuous coverage.

4.5 Antenna requirements

In order to avoid snow coverage and to minimise maintenance, the antennas will be utilised without a raydome. This means that the mechanical design needs to be robust and changes in performance due to ice coverage need to be within a range that can be compensated by adjusting the measurement parameters. Test measurements have shown that modified versions of standard type Yagi antennas can meet the requirements, and a suitable antenna, known as the “Renkwitz Yagi” was developed during the FP6 Design Study. These are the antennas shown in the small array on the cover picture of this document.

In order to avoid interference between antennas, the minimum spacing of transmit antennas should be of the order of one metre, so that the 100×100 element transmitter array would cover a range of 200—300 m diameter. Receiver antennas reach optimum performance with wider spacing.

5 Construction and operation

5.1 Sites and frequency requirements

The current design plan is for one core and four distant sites. The core site with full transmitting and receiving capability will be located within roughly 100 km of a point at 69° North and 20.5° East, which is close to the intersection of the Swedish, Norwegian and Finnish boarders. This location is suitable for studying the atmospheric phenomena that appear east of the Scandinavian mountain range at low altitude, and also for observing at high altitude together with supporting instruments requiring clear skies, because the cloud cover statistics are much better than in more westerly locations. The configuration also permits measurements along the geomagnetic field lines that are followed by the downleg path of sounding rockets launched from Esrange.

A number of sites (see Table 1) have been surveyed as potential locations for EISCAT_3D facilities. During a site survey, at each location the criteria for a potential antenna site are:

- For the transmitter site: an open area of roughly 500 m diameter that is relatively flat and dry. There should also be possibilities to place smaller antenna arrays, for interferometry purposes, at roughly 120° angular separation and extending out to a distance of about 1 km from the system midpoint. Additionally, at any point in the area the maximum horizon elevation angle should not exceed 30°.
- For the receiving sites: an open area at least of size 300×300 m, that is relatively flat and dry, and with an incline of about 10—20 m in the direction towards a possible transmitter site.
- The absence of TV/radio transmitters and cell phone base stations in the neighbouring area.
- Possible availability of infrastructure such as electric power and data communications for the site.
- A remote location far away from any town or village in order to minimise potential radio noise sources. There should preferably be no houses in sight from the radar sites.

Optimum operation requires 30 MHz clear spectral interval at the core and at least one additional site. These spectral intervals have to be safeguarded for reception by the radar over the whole expected lifetime, 30 years. The conditions for clear spectral interval require minimum distance about 50 km from Digital Audio Broadcasting (DAB) transmitters in the neighbouring frequency interval (exact requirements depend on geographic conditions). The reserved band for radar transmission is narrower than that for reception. A transmission

Table 1: Location of sites that have been surveyed for EISCAT_3D.

Location	Country	Coordinates	
Abisko	Sweden	68°20′ N	18°58′ E
Andøya	Norway	69°12′ N	15°54′ E
Järämä	Sweden	68°23′ N	21°5′ E
Karasjok	Norway	69°39′ N	25°17′ E
Kautokeino	Norway	69°5′ N	23°13′ E
Kilpisjärvi	Finland	69°6′ N	20°45′ E
Masi	Norway	69°34′ N	23°34′ E
Øverbygd	Norway	69°1′ N	19°17′ E
Porjus	Sweden	67°4′ N	19°35′ E
Ramfjordmoen	Norway	69°35′ N	19°14′ E
Säytsjärvi	Finland	69°21′ N	27°12′ E
Skibotn	Norway	69°20′ N	20°18′ E

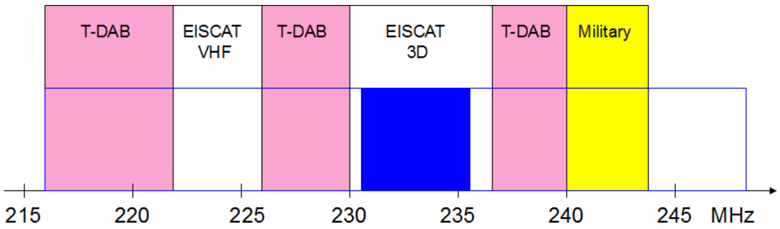

Figure 13: EISCAT frequency intervals shown in comparison to frequency allocations in Norway. EISCAT_3D will transmit in a 5 MHz frequency interval centered around 233 MHz as indicated with the blue interval. Full exploitation of the backscattered signal would require reception within a 30 MHz interval as sketched with the open blue block. The frequency allocation shown is for Norway, with terrestrial digital audio broadcasting (T-DAB). T-DAB is not implemented in Sweden and Finland.

bandwidth of 6 MHz for EISCAT_3D development has already been allocated in Norway (at Ramfjordmoen).

5.2 Construction

In the optimum scenario, construction of EISCAT_3D could begin in 2014. This requires that the remaining issues relating to site selection, land purchasing, frequency clearance and infrastructure provision should have been resolved, and that a certain level of initial investment is in place. Because phased arrays are inherently modular, it is possible that construction could be phased, according to the available funding. This type of phased construction would mean either that only a subset of the sites were built in the first phase, or that smaller arrays were initially built, which could later be extended. Our aim must, however, be to build a fully science-capable radar in the first phase of construction, implying that most of the functionality in the core site should be implemented from the beginning. We envisage that there will be opportunities

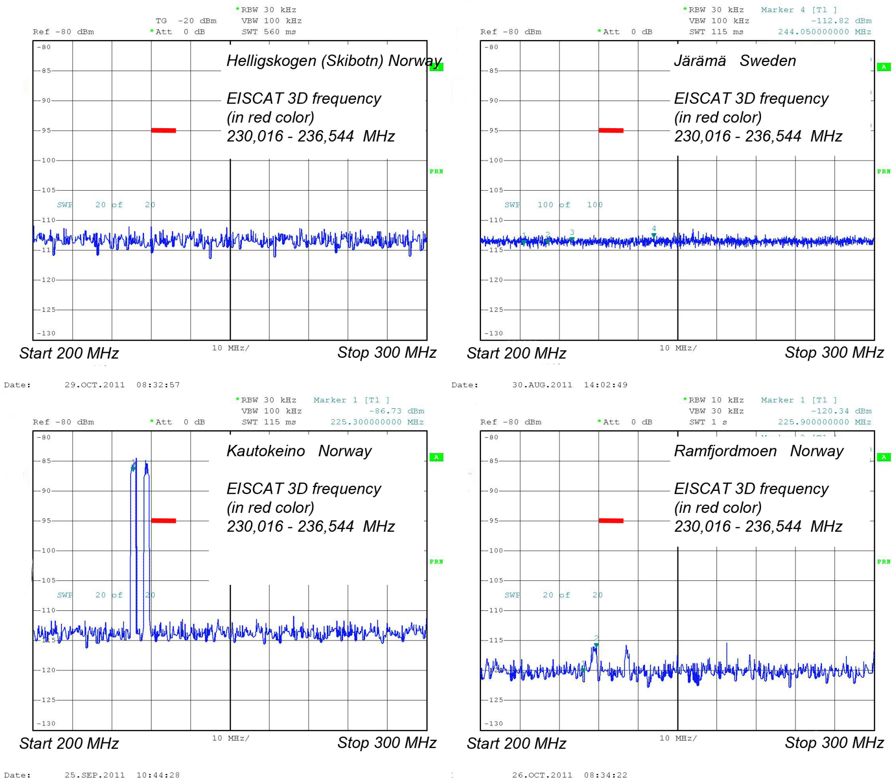

Figure 14: The radio frequency environment of four of the sites that have been surveyed. At the Kautokeino site (lower left panel) the presence of T-DAB transmitters in the area is very obvious. At Ramjordmoen (lower right panel), the Tromsø T-DAB transmitter is detected even though it is located on the other side of the Tromsdalstind mountain. At the area near Skibotn (upper left panel), the T-DAB transmissions have not started yet. The clean radio frequency environment in the Järämä area (top right panel) is not expected to change.

for local businesses on all scales, including Swedish companies, to become involved in the construction and operation of the new facility.

5.3 Operational characteristics

System control, monitoring, and data access will take place over the internet. Absolute time at all sites will be maintained to better than 100 ns. A formal experiment scheduling system will allow scheduling protocols and experiment files to be uploaded and tested well in advance of the scheduled execution times, and executed automatically according to a pre-set schedule. An override facility will enable experiments to be initiated by overriding the nominal schedule, either manually or automatically, in response to certain criteria being satisfied, either based on the instrument's own real-time analysed data or based on data provided from outside (by the other instruments on site, by satellite measurements, or solar observations).

5.4 Data products

The system will generate very large volumes of data and, because of this, flexible data storage capabilities will be deployed during during the construction phase. The full array produces a data rate of several TB/s, the expected stored data volume in the initial phase of operation is of the order of 1000 TB per year. For initial standard data products beam-formed data will be stored in ring buffer of relatively long duration (hours to days) and at least one set of time-integrated correlated data will be calculated from each set of beam-formed data, and permanently stored in a Web accessible master archive. This ring-buffer system will be replaced and modified as software and data storage capabilities advance further. At least one, and often several, analysed data sets will be permanently stored corresponding to each set of correlated data. The primary data products will also be used to derive routine value-added parameters (such as velocities, conductivities, currents, and heating rates), which will be made available together with the analysed data sets.

A Appendix: Background

A.1 EISCAT Scientific Association

The European Incoherent Scatter Scientific Association is an international research organisation whose headquarters are located in Kiruna, Sweden. The organisation currently operates three incoherent scatter radar systems:

- the mainland UHF system, using frequencies around 928 MHz, with a transmitting/receiving radar near Tromsø (Norway) and receive-only sites at Kiruna (Sweden) and Sodankylä (Finland).
- the VHF radar system, using frequencies around 224 MHz, with a single large transmitting/receiving antenna close to Tromsø
- the EISCAT Svalbard Radar, at frequencies around 500 MHz, consisting of two transmitting/receiving antennas, close to Longyearbyen on Spitsbergen

Radar operations of some 3000–4000 hours per year are distributed equally between Common Programmes (CP) and Special Programmes (SP). The CP data comprise six synoptic observing modes which are run regularly on a long-term basis, with data being made available to the international community. The SP modes are defined by individual scientific users, and are run to support specific national studies, with data access being reserved to the proposing scientists for the first year.

The association was first established in 1975, and radar operations have been conducted since 1981. The current members of EISCAT are the China Research Institute of Radio Propagation (PR China), Suomen Akatemia (Finland), National Institute for Polar Research (Japan), Solar-Terrestrial Environment Laboratory (Japan), Norges Forskningsråd, (Norway), Vetenskapsrådet (Sweden) and the Natural Environment Research Council (UK). Member organisations make long-term commitments, usually for five years, to fund the association through an annual subscription, and the size of their contributions is reflected in their share of the observing time. In addition, EISCAT associates such as CNRS (France), Roshydromet (Russia) and the Ukrainian Academy, buy time on the radar on a "pay-per-use" basis.

The EISCAT Scientific Association has around 20 full-time staff members, distributed between the headquarters and the radar sites mentioned above. The Director, Dr. Esa Turunen, and the Head of Administration, Mr. Henrik Andersson, are both located in the Kiruna HQ. The site staff are mostly employed via agreements with local "host institutes" (the University of Tromsø, the University of Oulu or the Swedish Institute of Space Physics) reflecting the close relationship which exists between EISCAT and the Nordic institutes involved in upper atmosphere research.

A.2 Evolution of the EISCAT_3D idea

The plan to replace the present dish-based EISCAT radars with a new system based on phased arrays was first suggested in 2001, when EISCAT Council established a "Futures Committee" to consider the changes needed to secure the organisation for the twenty-first century. Originally known as E-PRIME, the idea was to construct two active phased arrays close to EISCAT's current site at Tromsø, and to provide a much improved support infrastructure for other instruments operated at the EISCAT radar sites. Over the next three years, these plans were revised by the EISCAT Scientific Oversight Committee, until the present EISCAT_3D concept emerged.

In 2004, EISCAT submitted a proposal to the European Commission for a four-year study to finalise the design of the new facility. Funding was awarded under the European 6th Framework programme, and the Design Study was conducted between April 2005 and April 2009. Five partner institutes participated in the Design Study, and all continue to be members of the EISCAT_3D consortium.

The Design Study produced a high-level design for the entire EISCAT_3D system with low-level specifications of most of the important sub-systems, including antennas, beam-formers, transmitters and data handling systems. A small demonstrator array was constructed at EISCAT's radar site at Kiruna to receive signals from the existing EISCAT VHF antenna, and to demonstrate an operational "proof of concept" for the design study conclusions. All of the design study outputs are available on the EISCAT_3D project website at `www.eiscat3d.se/project/fp6`.

A.3 The EISCAT_3D partners

EISCAT_3D has been planned, and is being executed, as a project of the EISCAT Scientific Association, whose members are the relevant funding bodies for STP research in China, Finland, Japan, Norway, Sweden and the UK. EISCAT also has associates from Germany, France, Russia and Ukraine who exploit the facilities on a "pay-per-use" basis. The EISCAT_3D project has been strongly supported by the European Union, with the Design Phase and Preparatory Phase being funded by the EU 6th and 7th Framework Programmes, as well as direct national contributions by a number of the EISCAT member countries. In addition, EISCAT_3D has been adopted as one of the 44 ESFRI Roadmap projects (see Section A.4), projected new facilities recognised by the European Commission as providing the future cornerstones of the European Research Area. EISCAT_3D is one of the ten projects in the ESFRI "Environment Cluster" — a collection of planned European projects covering all aspects of the Earth's environment from the outermost limits of the atmosphere to the monitoring of the Earth's crust and the deep ocean bed.

The actual work of designing and preparing for the new facility is being done by a consortium of organisations, led by the EISCAT Scientific Association, which have strong links to the current EISCAT radars, either by virtue of having active and long-standing science users, or an important role in the technical development of the project. In the Preparatory Phase, there are nine partners:

- The EISCAT Scientific Association
- The Swedish Research Council (Vetenskaprådet)
- The University of Oulu, Finland
- The University of Tromsø, Norway

- The Technical University of Luleå, Sweden
- The Swedish Institute of Space Physics
- STFC Rutherford Appleton Laboratory, UK
- The Swedish National Infrastructure for Computing
- National Instruments (Belgium)

The project has also established close collaborations with LOFAR (the LOw Frequency Array for European radio astronomy) the Square Kilometer Array (SKA) and the US National Science Foundation, based on shared science interests and the possibilities for use of similar hardware and techniques across multiple projects. In addition, we are collaborating with the other ESFRI environmental programmes in developing proposals for a common system of e-infrastructure (networking, storage, high-performance computing and data handling techniques) which will underpin all of these future facilities.

Although the EISCAT_3D consortium is concentrated on northern Europe, and in the existing EISCAT countries, the project team has a strong commitment to creating a facility which is truly international — as the current EISCAT Scientific Association is. Mechanisms will be put into place to ensure that EISCAT_3D is available to the entire European and global scientific community, and we plan to involve a wide range of future international users in the Preparatory Phase project. Any institute, regardless of location, can register as an "Associate Partner" of EISCAT_3D, and volunteers will be warmly welcomed to take part in activities such as lobbying national governments and research councils, identifying and contacting potential suppliers, iterating the science case, reviewing project documents and taking part in meetings and public events during the next four years.

A.4 ESFRI

The European Strategy Forum on Research Infrastructures (`ec.europa.eu/research/infrastructures/`) was set up in 2001 as an inter-governmental forum to establish a coherent approach to the planning, exploitation and development of European research infrastructures. ESFRI maintains and develops a roadmap of future projects which are seen as being significant for the development of European research on a 10–20 year timescale, grouped under four headings (physical sciences, environmental sciences, bio-medical sciences, and social sciences/humanities). The roadmap was established in 2006 with 35 projects and 9 further projects, including EISCAT_3D, were added in 2008. EISCAT_3D is one of ten ESFRI projects in the environmental category.

A.5 The EISCAT_3D Preparatory Phase

According to the European Commission, the purpose of a Preparatory Phase is to "provide catalytic and leveraging support [. . .] leading to the construction of the new infrastructure". This should involve the combination of legal, strategic, financial, governance and technical work required to bring the project to maturity. In the EISCAT_3D context, this means that the task of the Preparatory

Phase is to resolve all the issues which need to be addressed before construction can finally begin. This means securing frequency clearances in all of the host countries, finalising the site selection and obtaining construction permissions, organising the provision of infrastructure to the sites, engaging with potential new users, resolving any open technical issues remaining from the design study, identifying potential manufacturers and prototyping and testing new hardware. By far the major task, however, is to assemble the funding consortium which will actually pay for the construction and operations of the new facility, which will involve detailed negotiations with a range of governments, local authorities and funding agencies.

The five members of the original Design Study consortium continue to be strongly involved in the Preparatory Phase. The EISCAT Scientific Association is co-ordinating the whole programme, leading the legal, logistical and consortium-building activities, and providing the outreach for the project. Luleå University and the Swedish Institute of Space Physics are working on the development and prototyping of the antennas and transmitters respectively. The University of Tromsø is developing new imaging techniques for EISCAT_3D, while the Rutherford Appleton Laboratory is involved in developing the science case and some aspects of the project management. Three new partners have joined our Preparatory Phase team. The Swedish Research Council is assisting us with consortium building activities and, through their joint research unit SNIC (the Swedish National Infrastructure for Computing), helping us to implement our data system. National Instruments (Belgium) is helping with the design and prototyping of hardware and the solution of timing and sampling issues, and the University of Oulu is developing the advanced signal processing and software techniques to be used by the new radar.

The EISCAT_3D Preparatory Phase consists of 14 work packages:

WP1: Project Management and Reporting *leader EISCAT Scientific Association.* Provision of an overall management framework for the project, and handling of the reporting to the Commission.

WP2: Legal and Logistical Issues *leader EISCAT Scientific Association.* Clarification of site selection, frequency clearance and infrastructure issues needed for the construction of EISCAT_3D.

WP3: Science Planning and User Engagement *leader University of Oulu/-RAL.* Revision and extension of the EISCAT_3D science case and engagement with new user communities.

WP4: Outreach Activities *leader EISCAT Scientific Association.* Publicity for the project, engagement with project stakeholders, the media and the general public.

WP5: Consortium Building *leader EISCAT Scientific Association.* Negotiations with the funding bodies which will support the new infrastructure, production of detailed costings.

WP6: Performance Specification *leader EISCAT Scientific Association.* Determination of performance requirements for all system components, documentation of measurement and operational principles.

WP7: Digital Signal Processing *leader University of Oulu.* Development of sampling and low-level data handling hardware. Field-testing and demonstration of signal processing equipment.

WP8: Antenna, Front End and Time Synchronisation *leader Luleå Technical University.* Testing of antenna designs, specification of antenna and front end. Timing calibration of the radar system.

WP9: Transmitter Development *leader Swedish Institute of Space Physics.* Verfication of T/R switch design, prototyping and evaluation of exciter, pre-driver and beam-steering system.

WP10: Aperture Synthesis Imaging Radar *leader University of Tromsø.* Simulation of image recovery and assessment of inversion techniques. Definition of antenna configurations for imaging.

WP11: Software Theory and Implementation *leader University of Oulu.* Development of sampling, data processing and analysis software and integration with the hardware developed in WP7.

WP12: System Control *leader EISCAT Scientific Association.* Generalisation of existing EISCAT control language to make it usable for control of a distributed phased array radar.

WP13: Data Handling and Distribution *leader SNIC.* Implementation of requirements for networking, data processing, data distribution and archiving within the existing or planned Scandinavian infrastructure.

WP14: Mass-Production and Reliability *leader EISCAT Scientific Association.* Specification of sub-systems for affordable mass production, prototyping and reliability testing. Tendering specifications for next phase.

A.6 Solar-terrestrial physics and EISCAT

The interaction between the Sun and the Earth is vital to every aspect of human existence. As well as providing us with heat and light, the Sun supplies the energy which powers the motion of the Earth's atmosphere and oceans, governing our weather and climate. In addition, the Sun produces the solar wind — a stream of energetic particles which permeates the solar system, carrying with it a magnetic field which interacts with the internally-generated magnetism of the Earth and other planets. The science of Solar-Terrestrial Physics (STP) is concerned with understanding all aspects of the relationship between the Earth and the Sun. In particular, it seeks to understand all the different ways that energy from the Sun is deposited in the environments of the Earth and other solar system bodies, the processes by which that energy is converted from one form to another, and the combined effects of all these processes on our environment.

Because of this broad remit, STP overlaps with many other areas of science, including atmospheric physics, solar physics and plasma physics. It also has many practical goals, including the better prediction and mitigation of "space weather" to safeguard space-based technology, improved modelling of the Earth's ionised atmosphere for communications and global positioning applications, and a deeper understanding of the contribution of natural variability to long-term and short-term global change. In a world ever more dependent on space-based systems, and in which an improved understanding of our environment is at the top of the scientific and political agenda, Solar-Terrestrial Physics has become a key science area for the twenty-first century.

Progress in STP is largely driven by observations. Because the solar-terrestrial system is continuously varying, and the interplay between the various processes is so complex, current theoretical models can only bring us a certain distance in understanding how the Earth's environment responds to solar influences. Hence there is a major requirement for high-quality data from continuous, multi-point observations of all the key regions of the Sun-Earth system, from the solar photosphere and corona to the solar wind and magnetosphere, through the ionosphere and thermosphere, and down to the middle and lower atmosphere. This requires a number of different instruments, including satellites, radars, optical imagers, and ground-based magnetic measurements, working in combination to observe different aspects of the coupled system and provide the input data for the development of sophisticated modelling and forecasting techniques. Science on this scale can only be done by international collaboration and, although some observing instruments are relatively cheap, the development of leading-edge instruments such as spacecraft and radars requires multi-national funding and the co-ordinated effort of a worldwide research community.

For many decades, Europe has played a central role in the development of STP science. The European Space Agency (ESA) has sponsored key missions such as Cluster to explore the Earth's magnetosphere, and collaborated internationally in missions such as SOHO, to measure variations in the Sun's outer atmosphere and Ulysses to map the distribution of the solar wind; while further ESA missions such as Solar Orbiter and SWARM (to measure the Earth's magnetic field) are up-coming.

On the ground, the EISCAT (European Incoherent SCATer) scientific association has played a key role in providing world-leading radar systems for use by the European and international research community over the past 30 years (see Section A.1). As well as carrying out its own independent experiments, EISCAT has run extensive observing programmes in support of the space-based STP missions referred to above, and collaborated closely with the other incoherent scatter radars around the world, particularly with those funded and operated by the US National Science Foundation, as part of a global observing programme based around the Geophysical World Days, and including the International Polar Year of 2007–08.

The EISCAT radars in mainland Scandinavia were constructed in the late 1970s. Although many parts of the radars (transmitters, signal processing, computers etc.) have been renovated and replaced during this time, some key sub-systems, particularly the large steerable antennas, are approaching the end of their working lives. In addition, the UHF frequencies around 930 MHz, allocated to EISCAT when mobile communications were in their infancy, are now heavily used by mobile phone companies, to the extent that the available bandwidth is so small that the receiver sites in Sweden and Finland are effectively unusable at the frequencies for which they were designed. In addition, the technology of radar systems has evolved so much in the last 30 years that it no longer makes sense to propose a replacement of the EISCAT antennas.

Instead, a much better solution is to propose a completely new radar system, working at a new frequency and exploiting twenty-first century phased array technology to provide the kind of observations which have never been possible with the existing EISCAT radars. This development is exactly what the EISCAT_3D project proposes.

A.7 The global picture

In recent years, there has been a growing awareness that there are viable mechanisms through which processes in near-Earth space can affect the lower atmosphere, potentially feeding through into weather and climate variations. This understanding has made it increasingly clear that that observations of the upper atmosphere should be made in the same way as meteorological observations, emphasising continuous coverage over a broad spatial range. The World Meteorological Organisation, WMO, has recently issued guidelines for the density and frequency of upper atmosphere measurements for the first time (see http://www.wmo.int/pages/prog/sat/spaceweather-intro_en.php).

EISCAT_3D is a key element in the international network of spacecraft, radars and other instruments which will be co-ordinated to study the complex coupled chain of processes linking the Sun to the Earth. Because of the scale and cost of the EISCAT_3D facility, and the active global community working with it, EISCAT_3D will undoubtedly be the centrepiece of European activity in ground-based STP and the most advanced system of its kind in the world.

The global network of incoherent scatter radars is well-established, with the US operating long-standing facilities at Sondrestrom (Greenland), Millstone Hill (USA), Arecibo (Puerto Rico) and Jicamarca (Peru). Two new AMISR (Advanced Modular Incoherent Scatter Radar) facilities, which represent the current state of the art in ISR systems, have recently begun operating in North America, one at Poker Flat (Alaska) and the second at Resolute Bay (Canada), the latter being a “dual face” radar, one half of which is funded by the Canadian Space Agency.

In addition to its mainland radars, EISCAT operates the EISCAT Svalbard Radar on Spitsbergen. Up to now, this has been a two-dish radar with one fixed and one steerable antenna, but planning is underway to install a third, fully steerable 50 m dish, funded by the Chinese EISCAT associate. This would be a dual-use system, designed for incoherent scatter use and communications with the planned programme of Chinese lunar missions. China is also developing its own ISR system, close to Kunming, via the conversion of a former defence radar, which would join the international ISR network completed by the Russian ISR at Irkutsk and the Ukranian radar system at Kharkov. The Japanese MU and EAR radars, though mainly designed for middle atmosphere studies, are also capable of ISR experiments, and are occasionally used for upper atmosphere research. The new ALWIN MST radar, with potentially similar sensitivity, is now becoming operational at the Andøya Rocket Range in Norway, while the Japanese National Institute of Polar Research is constructing a similar middle atmosphere radar (PANSY) for deployment in Antarctica. A further major international ISR project is being planned for the Antarctic, with advanced discussions in progress concerning the deployment of a radar at the US McMurdo Base, and a second system at another location in Antarctica.

These new developments in ground-based observation will complement an impressive programme of planned STP and solar spacecraft missions, including SWARM (launching 2012), Radiation Belt Storm Probes and KuaFu (launch also planned for 2012), Magnetosphere Multi-Scale (launch planned for 2014), Solar Orbiter (launching around 2016) and Solar Probe (launching around 2018). A number of other possible missions are in the early stages of planning, including multi-point studies of the magnetosphere and a possible follow-on to the STEREO mission based on spacecraft permanently stationed at the L4 and L5 Lagrangian points.