EISCAT_3D

The next generation European Incoherent Scatter radar system

Introduction and Brief Background

The high latitude environment is of increasing importance, not only for purely scientific studies, but because of the direct effects on technological systems and climate which are principally mediated through interactions with solar produced particles and fields and whose effects are overwhelmingly concentrated in the polar and high latitude areas. These effects are of importance not only from a European dimension, but globally, since the European arctic and high arctic areas are the most accessible, and best supported by installed infrastructure and existing communities, of any place on the Earth from which the necessary observations and measurements can be made.

Mankind is entering a period where full knowledge and understanding of the Earth's environment as part of the linked Sun-Earth system is essential and it is important to exploit existing advantages to provide effective and continuous monitoring of the critical interaction regions. Incoherent scatter radar is the most effective, ground-based technique for studying and monitoring the upper atmosphere and ionosphere.

The radars of the EISCAT Scientific Association have defined the present state of the art within the World's incoherent scatter community for the last several years. EISCAT has been very successful in exploiting its two radars located on the Scandinavian mainland (one operating at 931 MHz and the second at 231 MHz) and, indeed, this success led directly to the design, construction, and operation of the EISCAT Svalbard Radar nearly 1000 km further north almost ten years ago.

Other radars exist at Irkutsk (Russia), Kharkov (Ukraine), Kyoto (Japan), Söndreström (Greenland), Millstone Hill (USA), Arecibo (Puerto Rico, USA), Jicamarca (Peru), and in Indonesia. Substantial recent investment by the USA will lead to the availability of new American sector high-latitude radars, to be located in central Alaska, and in northern Canada, by late 2007. These radars will have technical abilities beyond those which can be provided by the existing EISCAT radars either in their present form or through reasonable upgrades.

The EISCAT Scientific Association, in co-operation with the University of Tromsø, Luleå University of Technology, and the Rutherford Appleton Laboratory, has therefore started a four-year design exercise, supported by European Union funding under the Sixth Framework initiative, which builds on its past successes and aims to maintain its world leadership role in this field.

Mindful that the driving issues in ionospheric research continuously evolve, this document outlines the required specifications of a new concept in incoherent scatter radars which can both replace the two existing, but now aging, European mainland systems and also substantially extend the systems' capabilities as required to address the scientific and service requirements of the next fifteen to twenty years. The facility envisaged in this design study will surpass all other facilities, both existing and under construction, and will provide researchers with access to the World's most advanced and capable facility.

In order to best exploit and enhance European technological resources and to arrive at the best possible design to address the needs of the present, and expanding, European community, the design exercise must evaluate a number of different approaches which are now possible in order to meet the required performance as cheaply, and efficiently, as possible.

It will require the development of new radar and signal processing technology, together with crucial developments in polarisation control, built-in interferometric capabilities, the provision of remote receiving installations with electronic beam forming, signal processing, and automated data analysis.

The design study also includes a component to design communication, data distribution, and data archiving systems which leverage the available skills and existing network and Grid structures within the Community. These developments will allow European scientists and other users to access data from the new systems irrespective of their location within the community.

The new facility will greatly extend the range of available data, dramatically improving its temporal and spatial resolution as well as the geographic, altitude, and temporal extent. The design goals mandate improvements in the achievable temporal and spatial resolution (both parallel and perpendicular to the radar line-of-sight) by about an order of magnitude, to extend the unambiguous instantaneous measurement of full-vector ionospheric drift velocities from a single point to cover the entire altitude range of the radar and to increase the operational time by a factor of at least four (from 12 to 50%), and possibly to full-time.

The facility will provide high-quality ionospheric and atmospheric parameters on an essentially continuous basis for both academic researchers and practical consumers as well as providing near-instantaneous response capabilities for scientists and users who need data to study unusual and unpredicted disturbances and phenomena in the high-latitude ionosphere and atmosphere.

While users will sometimes visit the facility to obtain maximum access and response from the system, it will be possible for the radar to be operated entirely remotely and access to both the control and monitoring systems and the raw and processed data streams will be provided through secure network connections.

Besides supporting data consumers for service driven applications (such as Space Weather effect forecasting), the new facility will support studies of such topics as: ion outflow to the magnetosphere, auroral acceleration, small scale plasma physics, induced changes in the ionosphere, magnetic reconnection, sub-storms, ionosphere-neutral atmosphere coupling, mesospheric Physics, and solar wind acceleration.

Science Drivers

Interest in high latitude ionospheric physics has been concentrated for some years in the large scale convection processes occurring within the Polar Cap and at the poleward edge of the auroral oval. However, it has become increasingly clear that the processes which mediate even the largest scale effects are predominantly controlled by very the physics of small scale rapid interactions and this has led to a renewed interest in auroral electrodynamics and plasma physics.

Scientists now need to study short time-scale, small spatial scale targets and processes typified by:

- Quasi-coherent echoes from small plasma targets in E and F regions,
- Controlled experiments on PMSE using the EISCAT Heater,
- Routine D-region /middle atmosphere incoherent scatter measurements,
- Statistics of E-region micrometeor head echoes for planetology,
- Instantaneous E fields at many altitudes along a whole magnetic field line,

Users also need to study ionospheric topside processes which have proved very difficult in the European arctic sector, perhaps as a result of asymmetries in the Earth’s magnetic field which appears to lead to relatively low levels of precipitation in this area, almost a mirror image of the situation in the vicinity of the better known South Atlantic Anomaly. For these studies, good observations are required of, for example:

- H/He/O ratios the in polar ionosphere
- “Polar wind” plasma outflow

System Requirements

For applications of this type, the existing EISCAT mainland radar systems have almost reached their limits:

- Present best cross-beam resolution is ≈1 km at 100 km altitude (UHF), whereas the required resolution is now <<100 m,
- Present best along-beam resolution is ≈300 m (set by available transmitter band-width), whereas the required resolution is now <100 m,
- Present best temporal resolution in the D-region, lower E-region, and throughout the topside is of the order of many minutes, whereas it is clear that resolutions <10 s are often required to resolve the observed phenomena,
- True three-dimensional electric field measurements can currently only be made at one altitude at a time and integration time constrains, as well as antenna motion times, result in little correlation between measurements made sequentially at different altitudes. Measurements made using the radars in monostatic modes suffer from essentially the same problem and cannot unambiguously differentiate between temporal and spatial effects

when measuring rapid, small scale effects. Effective observations require the determination of true three dimensional parameters over at least 5-10 altitudes simultaneously.

EISCAT_3D

The EISCAT-3D design study is intended to develop a feasible design for a new radar to address the needs of the European, and Global, community for the next 15-20 years.

The four-year design study, which started on May 1, 2005, is supported by the European Union under the Sixth Framework program and European Union funding accounts for approximately half of the total cost of approximately 4M€.

The study is being conducted by a consortium led by the EISCAT Scientific Association, and including the University of Tromsø (Norway) Luleå Technical University (Sweden) and the Rutherford Appleton Laboratory (United Kingdom). Within EISCAT, the effort has required the temporary diversion of more than 10% of staff effort from radar operations and maintenance.

Completion of a successful design, and the timely availability of adequate construction funds (presently estimated to be in the region of 60M€), could see substantial parts of the new system in place, and producing good scientific data, as early as 2012.

EISCAT_3D Design (current plan)

Overall configuration

Common transmitter facility with RX capabilities:

- Close to the present Tromsø (NO) EISCAT site
- Operating frequency in the (225-240) MHz range
- Power amplifiers utilising VHF TV power FETs
- Phased-array system with > 16 K elements, Ppk > 2 MW
- Actual antenna configuration and performance TBD
- >3 outlier, RX-only array modules for interferometry
- Fully digital, post-sampling beam-forming on receive
- Comprehensive interferometric capabilities built-in

2 + 2 very large receive-only (”remote”) arrays:

- Actual sites TBD, four promising sites investigated...
- Filled apertures, long enough to provide ~1 km beam resolution at E- region altitudes above transmitter
- Medium gain (~10 dBi) element antennas
- Fully digital, post-sampling beam-forming
- Sufficient local signal processing power to generate at least five simultaneous beams
- 10 Gb/s connections for data transfer and remote control and monitoring

Radar field-of-view (FOV)

The beam generated by the central core transmit/receive antenna array will be steerable to a maximum zenith angle of ≈ 40o in all azimuth directions. At 300 km altitude, the radius of the resulting field-of-view is approximately 200 km. In the N-S plane this corresponds to a latitudinal coverage of ± 1.80° relative to the transmitter site.

The antenna arrays at the EISCAT_3D receiving facilities will be arranged to permit tri-static observations to be made throughout the central core FOV at all altitudes up to 800 km.

Beam steering

It will be possible to steer the beam from the central core TX/RX antenna array into any one of > 12000 discrete pointing directions, regularly distributed over its FOV and separated by on average 0.625° in each of two orthogonal planes. The beam steering system will operate on a < 500 μs timescale.

Central core parameters:	First phase	Fully instrumented
Number of elements:	16000	30000
Diameter [λ]:	87	116
Element separation [λ]:	0.6	0.6
P x A [GW m^{-2}]:	91	295
Half Power BW [degrees]:	0.62	0.46

For comparison, for the EISCAT VHF system in Mode 1 (full antenna, 3 MW):

P x A = 2.4 GW m^{-2}, HPBW = 0.6 x 1.7 degrees

Transmitter parameters

Centre frequency	220-250MHz, subject to allocation
Peak output power	at least 2 MW
Instantaneous -1dB power bandwidth	at least 5 MHz
Pulse length	0.5-2000 μs
Pulse repetition frequency	0-3000 Hz
Modulation	Arbitrary waveforms, limited only by power bandwidth

Receiver parameters

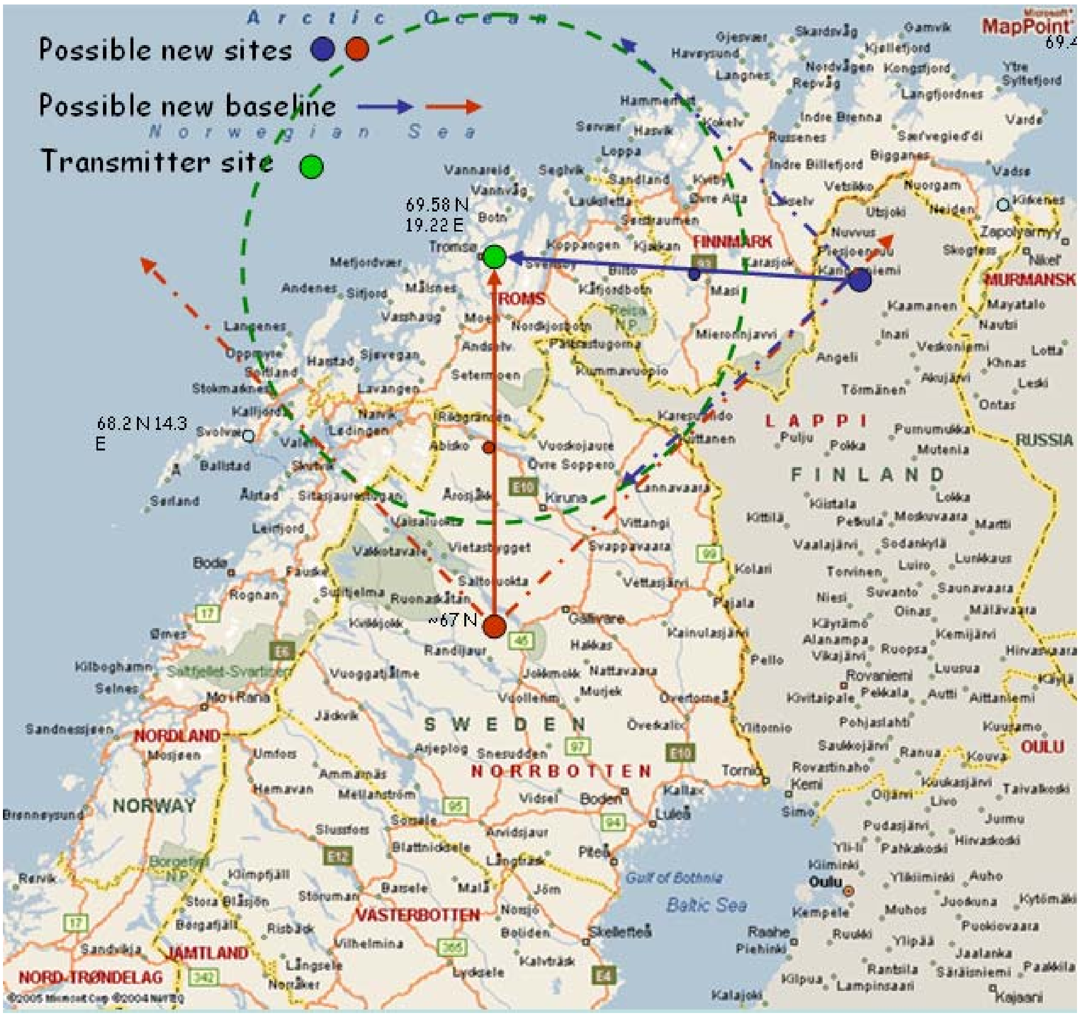
Centre frequency	matching transmitter centre frequency
Instantaneous bandwidth	±15 MHz
Overall noise temperature	better than 50 K, referenced to input terminals
Spurious-free dynamic range	better than 70 dB

Sensor performance in incoherent scatter mode

The parameters of the different subsystems will be chosen such that, for each of the measurement scenarios tabulated below, the radar will generate estimates of incoherently scattered signal power (or equivalently, uncorrected electron density) with statistical accuracies of better than 10 % in the specified integration times:

Altitude [km]	Electron density [m^{-3}]	T_e/T_i	Ion composition	Height resolution [m]	Integration time [seconds]
80	1×10^8	1.0		≤100	30
100	3×10^9	1.0		100	1
150	1×10^{10}	1.0	50% NO^+, 50% O^+	100	1
300	3×10^{10}	2.0	100% O^+	300	1
800	3×10^{10}	3.0	5% H^+, 95% O^+	1000	10
1500	1×10^{10}	4.0	10% H^+, 90% O^+		60

Potential distribution in Northern Scandinavia



The EISCAT_3D Test Array ("Demonstrator")

A 200 m^2 filled array has being erected at the EISCAT Kiruna site to provide facilities for validating several critical aspects of the full-scale 3D "remote" (receive-only) array in practice under realistic climatic conditions.

The array is oriented in the Tromsø-Kiruna plane and consists of 48 short, 6+6 element crossed-Yagis at 55° elevation providing coverage between ~200 and 800 km above Tromsø. A centre frequency of 224 ± 3 MHz allows reception of transmissions from existing the Tromsø VHF system and the achievable SNR is estimated to be sufficient for useful bistatic incoherent scatter observations (> 6% @ 300 km, for electron densities of $10^{11}m^{-3}$.

The test array will be used to investigate:

- Receiver front ends, A/D conversion
- SERDES, copper/optical/copper conversion,
- Time-delay beam-steering,
- Simultaneous forming of multiple beams,
- Adaptive pointing and (self-) calibration,
- Adaptive polarisation matching,
- Interferometry trigger processor,
- Digital back-end/correlator for standard incoherent scatter
- Time-keeping

Test array at Kiruna