WHY do we need EISCAT_3D?

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 the "What is EISCAT?" section below. 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.

WHAT is EISCAT_3D?

EISCAT_3D is a new kind of international research radar, for studies of the Earth's upper atmosphere and the region of interplanetary space surrounding the Earth, known as "Geospace". The new radar system, to be located in northern Scandinavia, will comprise several large fields of antennas, known as phased arrays, some of which will have both transmitting and receiving capabilities, while others will be passive receivers. According to the current design, there will be at least five radar sites, of which at least one, known as the "central site" will include a transmitter. Because the arrays are designed to be modular, it will be easily possible to enlarge the sites, or to add additional transmitting capabilities, as funding allows.

EISCAT_3D is designed to use several different measurement techniques which, although they have each been used elsewhere, have never been combined together in a single radar system:

Volumetric Imaging – The design of EISCAT_3D allows large numbers of antennas to be combined together to make either a single radar beam, or a number of simultaneous beams, via a process known as beam-forming. In phased array radars, the properties of the beam-forming can be changed very rapidly, so that the direction of the radar beams can change every few milliseconds. These capabilities, possible because there are no moving parts, are a huge advantage compared to the traditional kinds of radar using large dishes. They 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. While radar systems with a single, slow-moving, beam can only show us what is happening in a single profile of the upper atmosphere, volumetric imaging allows us to see geophysical events in their full spatial context, and to distinguish between processes which vary spatially and those which vary in time.

Holographic Imaging – Several of the EISCAT_3D sites will be 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, and this will enable the transmitter beam from the central site to be imaged simultaneously over a large range of altitudes from a variety of different observing directions. This will make it possible to construct continuous 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.

Aperture Synthesis Imaging – Most radars suffer from the limitation of not resolving any structure smaller than the width of their narrowest (transmitter or receiver) beam, typically of order a kilometre for ionospheric radars. In EISCAT_3D, this limitation is overcome by dividing the core site into a number of sub-arrays, the signals from which will be continuously cross-correlated in a technique similar to the Very Long Baseline Interferometry approach used by radio astronomers, except that the baselines here are only a few hundred metres. The result of inverting the cross-correlations is a "brightness function" showing the distribution of backscatter within the receiver beam, distinguishing between situations where the beam is evenly filled with electrons, and those where the scatter comes from a few discrete intense structures, the study of which could produce exciting new science.

Scanning, Tracking and Adaptive Experiments – Because EISCAT_3D is so flexible compared to traditional ionospheric radars, it will allow several new operating modes including the capability to track moving objects such as meteors and space debris, or to respond intelligently to changing conditions, for instance by changing the parameters of a scanning experiment. Other novel techniques, including passive radar measurements and active control of the beam shape, for instance to control the shape of phase fronts in the near field, should also be possible with EISCAT_3D.

WHERE will EISCAT_3D be located ?

EISCAT_3D will be distributed across the northern regions of the three mainland Nordic countries (Norway, Sweden and Finland) located under the auroral oval. This location is doubly appropriate, since these latitudes also coincide with the equatorward edge of the polar vortex in the circulation of the high-latitude middle atmosphere. This region is unique in offering such a rich combination of geophysical conditions, together with all the well-developed infrastructure of an advanced society. This part of northern Fennoscandia already hosts a superb range of supporting instrumentation, including a variety of imaging systems, magnetometers, riometers, satellite receivers and other types of radar, plus the two rocket ranges at ESRANGE and on Andoya, all of which will provide a superb complement to the capabilities of the new radar system.

A number of potential EISCAT_3D sites have already been surveyed, to establish the availability of suitable flat land with a good horizon profile, potential access to infrastructure and freedom from radio interference in the nominal EISCAT_3D band. While a number of suitable locations were identified, no definite site selections have been made so far, and further testing and surveying work is planned for the Preparatory Phase. The final selection will depend on a variety of factors, including support from the relevant local and regional authorities, planning restrictions and good relations with the local community, as well as the technical factors summarised above.

The most significant requirements apply to the central site, which will comprise a circular array of around 120m diameter, filled by around 16,000 antenna elements. The antennas themselves will be elevated by about 2.5m above ground level and divided into small groups, each centred on a container housing the initial signal processing hardware. The central site will contain more than 2,000 such containers, each around 5m apart. In addition, the central site will also have a few tens of extra “outlier” antennas, distributed in a spiral configuration extending for about a kilometre around the circular core array. These additional receivers are needed to provide the long baselines required for aperture synthesis imaging. The receiver sites will be similar in design, but each site will contain only half the number of antennas, and no outlier arrays.

WHEN will EISCAT_3D be operational ?

The EISCAT_3D project is divided into four phases:

The Design Phase (2005-2009) took the form of a four-year study funded by the EU 6th Framework. During this period, the basic EISCAT_3D concept was developed into a detailed design, with many aspects of the system being specified at the hardware level. The study also covered some aspects of software development, for example to make possible the aperture synthesis imaging technique. Discussions about frequency allocations were initiated with the relevant regulatory authorities, and some prospective radar sites were identified and surveyed. Contacts were established with the funding bodies in many of the prospective member countries which led, among other things, to the project being proposed for addition to the ESFRI roadmap (see Section ??). The Design Phase completed on time and within budget, and all of the published outputs can be found at www.eiscat3d.se.

The project is now entering the **Preparatory Phase** (2010-2014) which will address all those issues for which resolution is needed before construction can begin. The main activity is the assembly of the consortia which will actually provide the funding for, and undertake the construction of, the new infrastructure. In addition, the site selections and frequency allocations must be finalised, so that the required land can be purchased once funding is assured. The remaining design issues must be closed, suppliers will be identified and prototypes of key system elements will be assembled so that their reliability and cost effectiveness can be assessed. The legal and financial implications of the new organisations will be considered, and the science case will be further developed in consultation not only with established EISCAT users, but also with allied communities such as middle atmosphere scientists, meteorologists and modellers.

Once these activities are completed, we will begin the **Construction Phase** (2014-2016) in which the EISCAT_3D radar sites will be prepared and the new hardware assembled. The required computing, storage and networking facilities will be deployed and integrated into the wider system of regional e-infrastructure, and all aspects of the system will be subjected to rigorous acceptance testing to verify that the new radar is functioning correctly.

Once this is done, the **Operational Phase** can begin, in which the radar will run continuously and largely autonomously. EISCAT_3D is designed for a 30-year lifetime, ensuring that it provides its users with a world-leading facility throughout the first half of the twenty-first century.

WHO is involved in EISCAT_3D ?

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, Germany, Japan, Norway, Sweden and the UK. EISCAT also has associates from 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 programme, 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, 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 (Vetenskapradet)
- The University of Oulu, Finland
- The University of Tromso, Norway
- The Technical University of Lulea, 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) and the US National Science Foundation, based on shared science interests and the possibilities for use of similar hardware and techniques across multiple projects –

see the section below on the international context of EISCAT_3D. 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.

HOW MUCH will EISCAT_3D cost?

Because EISCAT_3D is designed to be modular and expandable, it does not make sense to discuss a total cost for the whole system. A more appropriate discussion would be about the kind of system that could be realised for various amounts of available funding. A range of different system configurations are possible, and the discussions on funding and site selection, which will take place during the Preparatory Phase, will determine which one is finally selected. It is likely that the initially constructed system may not be the one which fully reflects the most ambitious design, but rather the one that provides the best basis for expansion, as further funding is received incrementally.

During the Design Phase, an attempt was made to quantify the costs of EISCAT_3D, based on a central array of 16,000 elements and four passive remote arrays of 8,000 elements each. The estimates, made at 2007 prices, were drawn partly from the experience of building a small "demonstrator" array to provide proof of concept for the design study ideas, partly from approaches to potential vendors requesting cost estimates and partly from the experience of the EISCAT staff, gained from operating a modern IS radar system over several decades.

According to these estimates, the hardware cost of the central site, after tax, was estimated to be in the order of 120M Euros, of which the largest elements were the cost of the transmitter (40M Euros), the signal processing system (25M Euros) and the antennas themselves (15M Euros). The cost of each remote site was calculated to be around 40M Euros, of which the largest elements were the signal processing system (12M Euros) and the antennas (9M Euros). Extrapolating these costs to an EISCAT_3D system with one central site and four remotes, would give a total cost of 280M Euros. These estimates exclude the staff effort and ancillary costs associated with the construction work.

It is anticipated, however, that it should be possible to realise the system much more cheaply in practice. Firstly, there might be significant scope for sharing hardware solutions with other projects. LOFAR, for example, has already developed a High Band Antenna array for radio astronomy applications, including the required signal processing hardware, which is available "off the shelf" for less than 1M Euros. An important early target of the Preparatory Phase will be to assess whether these LOFAR antennas can be used as receivers for EISCAT_3D, allowing the possibility to deploy additional remote sites very cheaply, or even to base the active sites on separate transmitting and receiving arrays. Another factor not included in the above cost calculations is the potential saving from dedicated mass production, as compared to buying components at the market price. We estimate that this could save anything between 30% and 50%, depending on the type of component.

The EISCAT_3D Preparatory Phase will be very important in quantifying the exact costs involved, based on detailed discussions with vendors and the production and testing of various prototype designs for mass production. At the same time, discussions with funding agencies, and our degree of success in applications for construction funding, will give us a good idea of the resources available and the system configuration which can be realised for the available budget.

The INTERNATIONAL CONTEXT of EISCAT_3D

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 50m 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 Andoya 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 "Antarctic ISRs" will be a major global project, requiring a wide range of international partners, and EISCAT has been involved from an early stage. Discussions have included the possible use of EISCAT_3D imaging techniques in the Antarctic Radars and the possibility of situating an Antarctic Radar in a location magnetically conjugate to EISCAT_3D. Decisions on funding for the McMurdo radar are expected soon, with the possibility that it could come into operation around the same time as EISCAT_3D.

These new developments in ground-based observation will complement an impressive programme of planned STP and solar spacecraft missions, including SWARM (launching 2011), Radiation Belt Storm Probes and KuaFu (launches 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.

About EISCAT

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

Radar operations of some 3,000 – 4,000 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), Deutsche Forschungs Gemeinschaft (Germany), National Institute for Polar Research (Japan), Solar-Terrestrial Environment Laboratory (Japan), Norges Forskningsrad, (Norway), Vetenskapsradet (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, 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 Tromso, 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.

About ESFRI

The European Strategy Forum on Research Infrastructures (ESFRI) is a strategic instrument, designed to develop the scientific integration of Europe, and strengthen its international outreach. Its aim is to keep Europe at the rapidly evolving forefront of science and technology, through the provision of internationally leading research infrastructures to meet the needs of the European and global scientific community. In order to achieve this aim, ESFRI's mission is to put in place a coherent and strategy-led approach to policy-making on European research infrastructure, and to facilitate multilateral initiatives leading to the better use and development of research infrastructures, at both European and international level.

ESFRI was formed in 2002 at the request of the European Council, and has already made significant advances in rationalising the development of new European programmes and increasing their international impact. The first "ESFRI Roadmap" of future pan-European research infrastructures was issued in 2006, and identified 35 projects, covering all areas of science, which were likely to be realised in the coming 10 to 20 years. In 2008, the roadmap was updated with the addition of a further nine projects, including EISCAT_3D, meaning that 44 projects are now being developed within the ESFRI framework. A further update to the roadmap, focusing on the areas of energy, food and biology, is now in preparation and will be published in December 2010.

ESFRI roadmap projects need to demonstrate potential impact on science and technology at an international level, supporting new ways of doing science in Europe and thereby contributing to the enhancement of the European Research Area. In addition, they require the support of European governments or inter-governmental research organisations. Since the establishment of ESFRI, an increasing number of European countries have prepared national roadmaps setting out their prioritisation of national and European research infrastructures, using the ESFRI Roadmap as a basis. This process is helping to define national budgets, facilitate political support for the ESFRI projects, and establish the long-term financial commitments which will be needed for their realisation.

The ESFRI projects are organised into four "clusters", in the areas of physical sciences, life sciences, environmental sciences and social sciences/humanities. The idea of such clustering is that infrastructures within each cluster should collaborate together on issues of common concern, such as the development of underpinning technology and e-infrastructure.

The European Commission is providing considerable support to the ESFRI process through funding calls targeted at specific projects, or clusters of projects, on the ESFRI roadmap. In this way, the Commission is able to fund the development of the ESFRI projects up to the point at which they are ready to enter the implementation phase. This enables the Commission to facilitate the formation of the organisations which will operate the new infrastructures, including the establishment of new legal entities, the formation of funding consortia, and securing the resolution of the other legal and logistical issues which arise before construction/implementation can begin. Much of the funding for EISCAT_3D Preparatory Phase, beginning in October 2010, has been provided by the European Commission through a targeted call under the 7th Framework, so that EISCAT_3D exemplifies the practical approach to implementing a new infrastructure via the ESFRI process.