EISCAT_3D

Final Report

EISCAT_3D: A European three-dimensional imaging radar for atmospheric and geospace research (Preparatory Phase)

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1 Executive summary

The EISCAT_3D Preparatory Phase project has identified a consortium to build EISCAT_3D, determined the overall design, location, e-infrastructure and costs of the system, and prepared a plan to implement EISCAT_3D in four stages with each stage having advanced measurement capabilities that are cutting-edge on an international level. Funding applications were submitted or prepared in all present EISCAT member countries. These combined are expected to cover the 76 M€ investment needed for EISCAT_3D stage 1. The ministries and research councils of these countries negotiate their investments in round table discussions with the goal to facilitate the transition into the implementation phase after the end of this Preparatory Phase project. A support project was started to negotiate the e-infrastructure solutions for the implementation. Special hardware components were identified for developing production readiness in collaboration with industry and EISCAT will address those in a dedicated project proposal to the European Commission.

The six EISCAT Associate Members, who invest and own the system, will cover the operation costs at a basic level. Other contributions to the EISCAT operation budget, estimated to amount 6.2 M€/yr after implementation of stage 1, will be covered by annual payments from Affiliate members and through projects for space weather and space debris observations. Institutions in Russia, Ukraine and France are already Affiliate members and institutions in Germany, South Korea, Belgium and Poland have indicated their interest. EISCAT is engaged already in space weather and space debris projects. The conditions for using EISCAT_3D to track space debris are at present evaluated in an expert group nominated by EISCAT Council.

The high-latitude atmosphere and ionosphere are critically important for the study of solar-terrestrial relations and space weather, physical processes in the Earth atmosphere and coupling between different atmospheric layers. Northern Europe, where EISCAT_3D will be installed, provides a unique opportunity to observe this Arctic region with instruments placed within a well-developed infrastructure of observational facilities and research institutions.

The EISCAT_3D multi-static phased array radar system will be an integral part of EISCAT Scientific Association, an international organisation with headquarters in Kiruna, Sweden and observation sites in Norway, Finland and Sweden. EISCAT has successfully operated incoherent scatter radars for more than thirty years and has constantly developed its science case. EISCAT measurements were used for research leading to more than 2000 journal articles authored by researchers from more than 30 countries.

EISCAT_3D will be the first system of its kind that offers 3D vector imaging capability and it will improve temporal and spatial resolution of this type of ionospheric observations by more than an order of magnitude. It will be a key atmospheric monitoring instrument for climate and space weather studies and an essential element in international global multi-instrument campaigns for studies of the Earth's environment.

2 Context and objectives

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 and a key atmospheric monitoring instrument for ionospheric and space weather studies. It is an essential element in international global multi-instrument campaigns for studying the geospace environment above Northern Fenno-Scandinavia, a unique location for research into the polar atmosphere. Within the global network of geospace observatories it will will be a key element for covering the auroral zone. This Preparatory Phase project aimed to establish a consortium to finance and implement EISCAT_3D and to reach a mature project plan so that the implementation can begin at the end of the project.

EISCAT_3D is a system of distributed phased array radars that enable comprehensive three-dimensional vector observations of the atmosphere and ionosphere. 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 beam-forming. While traditional radar systems with a single slow-moving antenna, and thus a single beam, can only show us what is happening along a single line in 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 over time. The use of new radar technology, combined with the latest digital signal processing, will achieve ten times higher temporal and spatial resolution than obtained by present radars while simultaneously offering, for the first time, continuous measurement capabilities. EISCAT_3D is designed to use several different measurement techniques which, although they have individually been used elsewhere, have never been combined together in a single radar system. The Preparatory Phase aimed to finalise the design, estimate the costs and prepare a plan for construction of this advanced system.

The flexibility of the EISCAT_3D system will allow the study of atmospheric phenomena at both large and small scales unreachable by the present systems. EISCAT_3D will use the incoherent scatter technique which measures the spectra of radio-waves that are back-scattered from free electrons, whose motions are controlled by inherent ion-acoustic and electron plasma waves in the ionosphere. The measured spectra reveal high-resolution information on the ionospheric plasma parameters. The instrument can also be used for obtaining atmospheric data and for observing other objects that scatter radio waves such as meteors, near-Earth objects and space debris. EISCAT_3D is devoted to the overall theme to study how Earth atmosphere is coupled to space, but as a versatile instrument it will be used for a number of specific different studies. The Preparatory Phase aimed to develop a common Science Case, in close collaboration with a broad community of present and potential future users, providing a basis for the instrument performance specifications and project decisions.

The EISCAT_3D system will consist of five phased-array antenna fields located in the northernmost areas of Finland, Norway and Sweden, each with around 10,000 crossed dipole antenna elements. One of these sites (the core site) will transmit radio waves at 233 MHz, and all five sites will have sensitive receivers to measure the returned radio signals. Digital control of the transmission and low-level digitisation of the received signal will permit instantaneous electronic steering of the transmitted beam and measurements using multiple simultaneous beams. The central antenna array at each site will be surrounded by smaller outlying arrays which will facilitate aperture synthesis imaging to acquire sub-beam transverse spatial resolution. The central array of each site will be of a size of about 70 m from side to side, and the receive-only sites will be located at a distance of 90 km to 250 km from the core site in order to be able to maximise the coverage by the system. The Preparatory Phase aimed to identify a site configuration that provides the maximum scientific return, to survey suitable sites in the areas suggested by this configuration and prepare for land acquisitions and infrastructure provision. EISCAT will also need permissions to use the radio frequency range of EISCAT_3D at the sites.

With scientists in more than 30 countries being recently involved in research based on EISCAT data, EISCAT is already today a truly international research infrastructure. The advanced measurement capabilities of the new system will expand the area of research, and hence also the user community. 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. The advanced radar facilities should also act as “magnets” to attract a variety of complementary instruments, some of which will be deployed for a long duration, and some for specific shorter-term observations. The Preparatory Phase aimed to establish a consortium to fund the investment for the construction of EISCAT_3D and a consortium agreement to develop a flexible research infrastructure that offers cutting edge measurement capabilities and the environment for researchers and their students to carry out and participate in excellent research.

The EISCAT_3D observations will both be organised through common observation modes and through requests from individual groups. In both active and passive mode, the receivers will provide high-quality scientific and monitoring data from the ionosphere as well as from space within its designed frequency spectrum. Since EISCAT_3D is very flexible compared to traditional ionospheric radars, it will allow several new operating modes, including the capabilities to determine vector velocities of moving objects and to respond intelligently to changing conditions, for instance by changing the parameters of a scanning experiment. EISCAT_3D will also allow remote continuous operations, limited only by power consumption and data storage. This is important for monitoring the state of the atmosphere, especially as a function of solar variability, as well as for capturing events that appear suddenly and are hard to predict. Radio astronomy observations will be performed when the transmitters are inactive. The Preparatory Phase aimed to establish an organisational structure to facilitate optimal observation planning and to provide the e-infrastructure needed to make best use of the data. The Preparatory Phase aimed to develop a strategy for sustainable funding of the EISCAT operation and for facilitating open access to the EISCAT data.

The timing of EISCAT_3D is ideal. It is now feasible to construct and operate the system and to handle the data volume that the system will provide; this was not the case a few years ago. An increasingly technology-dependent society needs to understand the ionospheric processes caused by space weather in order to minimise their effects on sensitive systems. EISCAT_3D will offer state-of-the-art instruments to the scientific community for dedicated observation campaigns to study processes important for the understanding of our environment and climate, such as the energy coupling between the upper and lower atmosphere, the linkages between the different layers of the upper atmosphere and to interplanetary space, small-scale structures and phenomena as well as micro-meteoroids that enter the atmosphere and participate in atmospheric processes. The Preparatory Phase aimed to expand the existing user community to include more space weather and atmospheric researchers.

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. It is an explicit goal of ESFRI to support international research infrastructures located in Europe and EISCAT_3D is a leading example.

The plans for this project were developed within EISCAT and its user community and have been underpinned by discussions and consultations with the international EISCAT user community, with scientists in the region and with potential new users locally, regionally and globally. The EISCAT_3D project is based on the results from design studies incorporating the latest ideas and advances in radio array technology, software radar techniques, and advances in available components and technology. EISCAT Scientific Association has successfully been running incoherent scatter radars in the Arctic for more than thirty years. EISCAT is currently funded and operated by research councils and research institutes in Norway, Sweden, Finland, Japan, China and the United Kingdom and has its headquarters in Kiruna, Sweden.

3 Main results

The EISCAT_3D Preparatory Phase was concerned with building a consortium, procuring the financing, selecting the sites, identifying the scientific requirements, designing the system, planning for the construction and operation, planning the transition to implementation and preparing for the data handling.

3.1 Building of a consortium

EISCAT_3D will be implemented, owned and operated by EISCAT Scientific Association, an international research organisation with a working governance structure. The consortium agreement for EISCAT_3D will be that of the current EISCAT Scientific Association

(EISCAT Bluebook) with some modifications in the governance that are specifically intended to be better prepared for the implementation of EISCAT_3D. The new version of the Bluebook foresees two different forms of membership, Associates and Affiliates. The EISCAT Associate Members have joint ownership of the Association; they provide investment funding and the minimum conditions for running the Association by paying an annual contribution to the operation costs. The Affiliate members solely pay an annual fee. Both, the Associates and Affiliates are expected to contribute with their scientific expertise to the work and governance of the association. As a result, EISCAT is now open also for institutional members with a smaller financial commitment. At present EISCAT has six Associate Members, which are the present members of the association, and three institutes are paying already Affiliate membership contributions.

EISCAT will in the future have a more stringent work-flow of reporting and strategic planning in order to better support the implementation of EISCAT_3D. The Bluebook also provides guidelines for the assessment of in-kind contributions. Procedures are implemented to safeguard good scientific practice and to ensure the commitment to excellent research. A newly developed "Code of Conduct" encourages atmosphere of tolerance and mutual respect within the EISCAT community. It also suggests a path to solve conflicts potentially arising within the community and to form an Ethics Board on ad-hoc basis, when needed. EISCAT has made progress in the revision work of its data policy to prepare for the new system. Because of the cutting-edge detection capabilities that EISCAT_3D will have, the Council decided to explicitly state that EISCAT shall be used "for non-military purposes" and that "users shall not use the facilities for collecting data on military sensitive objects".

3.2 Financial procurement

To procure the finances, major investments will be needed from several countries. The current estimate of the investment required for EISCAT_3D is 1,127,459 kSEK (132,642 k€). This estimate is based on figures given by individual manufacturers, and reductions may still be possible on individual parts depending on the exact specification as well as bidding from several competitors. The total investment budget was made for the installation of the core radar site and four receiving sites, assuming this is carried out within 8 years. It covers all investments needed and the staff directly assigned to the EISCAT_3D implementation, such as project office, management, commissioning and development work, site preparation, radar hardware, core signal processing, and radar software infrastructure needed to deliver calibrated and validated measurements to the scientific end users.

The project prepared a plan to implement EISCAT_3D in four stages with each stage having advanced measurement capabilities that are cutting-edge on an international level. EISCAT_3D stage 1 will consist of a reduced core array and two remote sites. The total construction cost of stage 1 is 596,964 kSEK. Submitted and/or prepared proposals in Finland, Japan, Norway, Sweden and the United Kingdom are expected to cover the investment needed for EISCAT_3D stage 1. The ministries and Research Councils of the countries with EISCAT ownership started round table discussions to directly negotiate their investments. While the time-lines for some proposals are still unknown, the first decisions are expected in early 2015. The transition from the Preparatory Phase to the Implementation Phase still needs to be managed, possibly with support from the European Commission within the INFRADEV-3 call for supporting the transition toward implementation with submission deadline in January 2015.

When Stage 1 is fully operational the needed annual operation budget for the full EISCAT will be 51,785 kSEK compared to 30,442 kSEK in 2014. The EISCAT members will provide the major funding for operating EISCAT_3D through annual contributions. Several institutions have indicated their interest in joining EISCAT as Affiliates; the most concrete discussion are made with institutions in France, Germany, Poland, Russia, Ukraine, and South Korea. The project also explored additional funding sources for the operation through space weather and space debris observation projects including, but not limited to the ESA SSA programme. In this context EISCAT Council nominated an expert group to evaluate under which conditions EISCAT_3D shall be used for tracking space debris.

3.3 Site selection

During the preparatory phase a configuration of the site locations of the radar system was developed on the basis of extensive discussions within the EISCAT community. The EISCAT_3D system will consist of five phased-array antenna fields, one of these sites (the core site) will transmit radio waves at 233 MHz, and all five sites will have sensitive receivers to measure the returned radio signals. The receiver sites will be located roughly between 90 km and 250 km from the core site. Near distance sites are optimal for studying the atmospheres at low altitude, long distance sites for studying higher altitudes. Observations from different directions contain vector information about the direction of motion of the charged particles. All sites require a quiet radio environment in the vicinity of the central observation frequency around 233 MHz, an open area that is relatively flat and dry and an unobstructed view toward the transmitter site respectively for the core site in other directions with the maximum horizon elevation angle not exceeding 30°.

Based on extensive discussions with the user community the location of the core site was chosen to be roughly 100 km of a point at 69° North and 20.5° East. This location offers an observation geometry that is suitable for studying the atmospheric phenomena that appear east of the Scandinavian mountain range at low altitude. It is relatively close to the existing site near Tromsø, so that EISCAT_3D can be operated together with the EISCAT Heating facility that is located there. The configuration also accounts for the two permanent launch facilities for sounding rockets and balloons that are located in Northern Scandinavia. It permits measurements along the geomagnetic field lines that are followed by the down leg path of sounding rockets launched from Esrange, a facility of Swedish Space Corporation. One of the remote sites will be located near the Andøya Space Center in Norway. Cloud cover statistics was taken into account for selecting the core site in order to have the best conditions for complementary optical observations, for auroral studies for instance.

A list of preferred sites was finalised. In the first stage of the construction of the EISCAT_3D system, the core site near Skibotn, Norway and receiver sites near Bergfors in Sweden and Karesuvanto in Finland will be built. For the later stages of the construction, areas near Andøya (Norway) and Jokkmokk (Sweden) were identified as locations for receiver sites.

3.4 Science requirements and system design

The scientific requirements have a major influence on the system design and for this a Science Case has been continuously revised in collaboration with the present EISCAT user community and with prospective future users. Communication with the scientific user community was facilitated through outreach activities, conference presentations and a series of dedicated meetings organised by the project. The website for EISCAT_3D has been online since March 2009 and is regularly maintained and updated.

The planning of the construction and operation of the new system requires a detailed instrument design. The project made use of innovative theoretical studies in signal processing, radar coding, data handling and data analysis that was summarised in a handbook of measurement principles. The EISCAT_3D will carry out signal processing using software-defined radio receiver systems. The design of the hardware elements needed for the final system and the work on the technical integration of these subsystems were the focus of several of the Work Packages in the project.

A radar system of the level of complexity of EISCAT_3D requires specialised software both for the system control and for the signal processing and beam-forming. The EISCAT system control software EROS was updated to be able to be used in the context of EISCAT_3D. A parallelised tool for signal processing and data analysis, RLIPS, to be used in the EISCAT_3D radar system was developed, and signal processing and beam-forming software were prepared and tested.

3.5 Plans for construction and operation

The project office prepared a first overall description of EISCAT_3D in April 2012 and in October 2012 it prepared a first construction plan including baseline design, cost estimate, construction and commissioning plan. The plan was further refined during the progress of the preparatory phase and adjusted to an implementation of the system based on stage-wise investments. In response to the discussions with research councils where funding applications are pending, the project office prepared a Cost Book. It lists the cost values of all the project items and specifies which components are amenable to in-kind contributions.

The operation of EISCAT_3D will be fully integrated into the operation of the overall EISCAT research infrastructure. It is expected that the present EISCAT radar systems located on the Scandinavian mainland will be phased out when EISCAT_3D becomes operational. A plan describing the EISCAT operation cost during and at the end of implementing EISCAT_3D was prepared in March 2013. The EISCAT operation will then comprise the new EISCAT_3D, the EISCAT Svalbard radar and the EISCAT Heating facility. The first test measurements, including also scientific operation, will be carried out as soon as the first parts of the system become operational. The science operation during the implementation phase will be discussed in the EISCAT_3D user meetings which were established during the Preparatory Phase project and will continue on an annual basis. The overall science operation will be decided in the relevant committees of EISCAT Council. In preparation for operating EISCAT_3D the revised Bluebook also includes a document describing the different observation programmes and the access to those programmes as well as a revised data policy.

3.6 Plans for transition to implementation

A plan was prepared within the project to implement EISCAT_3D in four stages with each stage having advanced measurement capabilities that are cutting-edge on an international level. This requires mass-production of highly reliable components, since the instrument is made of tens of thousands of individual antennas that will be placed in remote locations in a harsh Arctic environment. To facilitate the implementation this plan foresees in the next step the advancement from prototypes and blueprint designs to the mass production through close collaboration with industrial partners.

Some of the e-infrastructure needs of EISCAT_3D, such as the network connections between the sites and the computing and data storage near the instruments, require local solutions. Hence a plan was developed with e-infrastructure providers in the host countries for their involvement in the local planning. A dedicated project was defined to support EISCAT in the preparation for, and during the implementation of, EISCAT_3D. The solutions to some other e-science and e-infrastructure requirements will be developed through collaboration within European projects, and EISCAT joined several consortia to prepare proposals within the Horizon 2020 Programme.

3.7 Plans for data handling

The project plans to distribute the required computational tasks on an operation centre, a data centre and on-site computing at each of the radar sites. The operation centre will conduct the measurements, monitor the production of the standard data products from the different sites, generate non standard products as well as the products resulting from combining the measurements from the different sites (multi-static data products) and transfer them to the data centre. On each radar site, the raw data will be collected and stored for a limited amount of time (ring buffer), the data products will be generated and subsequently shipped through the network. The data centre will have scalable storage and sufficient computing capacity for standard operations, image processing and search engines. It will serve as an interface to the users who access the data centre through a portal. The location of the operation centre and the archive within one (or several) of the national infrastructures for computing will possibly be a cost-efficient solution and this issue will be negotiated with the stakeholders.

3.8 Results from the Work Packages

A short summary of each of the fourteen Work Packages in the EISCAT_3D Preparatory Phase project, and their main results, follows.

3.8.1 Work Package 1: Project management and reporting

Work Package 1 (Project management and reporting) contained activities ensuring a smooth and efficient approach towards the objectives of the EISCAT_3D Preparatory Phase, with respect to both financial management and the general project administration.

The daily work within the project was overseen by the EISCAT_3D Executive Board, which discussed project-related issues on a regular basis, normally every week or every second week. The Preparatory Phase Executive Board initially contained five representatives including two from EISCAT. Since beginning of 2013 it was extended to seven members, three of which from EISCAT. The Executive Board had regular teleconferences (more than 100) and ten physical meetings to discuss the progress of the project.

The overall governing body for the project was the EISCAT_3D General Assembly which included representatives from all project partners. The General Assembly had eight meetings during the project.

The main project meetings for all project participants were held annually, with a kick-off meeting in Stockholm, Sweden, 21 – 22 October 2010, all-hands meetings in Kiruna, Sweden, 11 – 13 October 2011 and 12 – 13 November 2012, a technical meeting in Kiruna 5 November 2013 and the end-of-project summary meeting 10 – 12 September 2014.

3.8.2 Work Package 2: Legal and logistical issues

Work Package 2 (Legal and logistical issues) contained support activities needed in order to clarify the site selection and to identify infrastructural issues needed to be resolved before the implementation of the EISCAT_3D system. The original plan for Work Package 2 included some concluding discussions about the frequency allocations in Norway, Sweden and Finland. However, it turned out at an early stage in the Preparatory Phase that a change in the strategy for obtaining frequency allocations was needed because of the uncertainties in their time-line and because of their connection to decisions to be taken at a level beyond the scope of the Preparatory Phase project. These discussions are thus performed outside this project. Some other planned activities in Work Package 2, such as the negotiations with the stakeholders in the areas of interest in order to be able to purchase and use the land, could not be fully concluded since they require a firm decision from funding agencies on the financing of the EISCAT_3D system.

Already during the EISCAT_3D FP6 Design Study, surveys of potential sites for the construction of EISCAT_3D were performed. These surveys were revisited and some additional sites were surveyed during the Preparatory Phase and Radio Frequency Interference (RFI) measurements were carried out. The list of potential sites for EISCAT_3D was finalised during the summer of 2013. An area near Skibotn in Norway was identified as the best suited location for the core site from the scientific point of view. Areas near Bergfors in Sweden and Karesuvanto in in Finland were identified as suitable for the first receiver sites. Additional Radio Frequency Interference (RFI) measurements were conducted in these three areas during the summers of 2013 and 2014. For the later stages of the construction, areas near Jokkmokk (Sweden) and Andøya (Norway) were identified as locations for receiver sites. Following feedback from Norwegian and Swedish funding proposals, four levels of budget and implementation of the EISCAT_3D system were defined. Thus, a plan for a stage-wise implementation of EISCAT_3D was prepared. Stage 1 in this plan consists of the sites in Skibotn, Bergfors, and Karesuvanto.

The discussions with the local stakeholders at Skibotn and Bergfors have started regarding topics such as land rights, terms, conditions and environmental impacts. These discussions also include access to infrastructure such as roads, power and data networks. Tromsø University participated in the site discussion and established local contacts through a local consultant. The official negotiations cannot truly begin before there are firm decisions on the site locations, and these depend on the time-line of the project funding. The discussions during the Preparatory Phase were made with the goal to prepare for and facilitate smooth and efficient negotiations once the funding decisions are made.

3.8.3 Work Package 3: Science planning and user engagement

The key objective of Work Package 3 (Science planning and user engagement) was to engage with the new and experienced users whose activities will come within the scope of the enhanced EISCAT_3D facility, and to gather their requirements for the science topics that they will address, to be included in the EISCAT_3D Science Case.

The leaders of Work Package 3 formed three Science Working Groups (SWG) by inviting scientists from different research fields and from different countries, including many non-EISCAT countries. The members of SWG worked on the EISCAT_3D Science Case during joint meetings and electronically between the meetings. In addition, the SWG members together with other invited speakers gave talks in the yearly EISCAT_3D User Meetings. The Science Case document received input also from various other active members of the EISCAT user community.

The members of the first SWG in 2010 – 2011 (in addition to the Work Package leaders) were: Asta Pellinen-Wannberg (IRF Kiruna, Sweden), Kjellmar Oksavik (UNIS, Norway), Mark Clilverd (British Antarctic Survey, UK), Markus Rapp (IAP Kühlungsborn, Germany) and Yasunobu Ogawa (National Institute of Polar Research, Japan). The special topic covered by this group was atmospheric science.

The members of the second SWG in 2011 – 2012 were Lucilla Alfonsi (Istituto Nazionale di Geofisica e Vulcanologia, INGV, Rome, Italy), Hervé Lamy (Belgian Institute for Space Aeronomy, Brussels, Belgium), Frederic Pitout (L'Observatoire Midi Pyrénées, OMP, Toulouse, France), Iwona Stanisławska (Space Research Centre, Warsaw, Poland) and Juha

Vierinen (SGO, Sodankylä, Finland). The special topic covered by this group was space weather and modelling.

The members of SWG for 2012 – 2013 were Craig Heinselman (EISCAT Scientific Association), Björn Gustavsson (EISCAT Scientific Association), Mike Kosch (University of Lancaster, UK) and Johan Kero (IRF, Kiruna, Sweden). The objectives for this group were slightly different from the two previous groups, since the main aim was to collect experts able to further refine and condense the requirements for the radar based on the scientific needs (as originally defined in the Science Case document), and to enhance the interaction with the technical work packages, in particular with Work Package 6 (Performance Specification). The SWG discussed different measurement modes and complementary instruments and the results of the work are included in appendix A of the Science Case.

Two one-day workshops were organised through Work Package 3, in association with the annual EISCAT_3D User Meetings in Uppsala, Sweden, in May: "Atmospheric Science and EISCAT_3D" in 2011 and "Space Weather and Modelling" in 2012. Since these workshops appeared to be a very effective way to interact with the user community, the special topics at these workshops were continued as follows: "Data analysis and management" in 2013 and "Complementary measurements and EISCAT_3D" in 2014.

The main outcome of Work Package 3 is the final version of the EISCAT_3D Science Case. It has been presented in several international meetings and it has recently been submitted for publication in the peer-reviewed open access journal Progress in Earth and Planetary Science.

3.8.4 Work Package 4: Outreach activities

For a successful implementation of EISCAT_3D it is imperative for the project to establish and maintain a strong outreach activity. The goals are to extend the present user base by aiming at the students and young people who will form the next generation of EISCAT users, but also to keep the stakeholders on all levels (local, regional, national and international) informed on the development of EISCAT_3D and to keep the communication active with the general public as well as within the extended EISCAT_3D community. Those were the aims for Work Package 4 (Outreach activities).

An outreach plan was made at an early stage of the project including which material to produce, the priority order of the production and the definition of the target audiences. In practice, a more ad-hoc approach to the production of material was found to be better suited, so that material was produced when it was required. A list of contacts in funding and policy organisations was also produced early in the project to be used in finding funding and publicity opportunities. The lists turned out to be almost identical to the official information and publicity outlets of these organisations.

The outreach material during the Preparatory Phase was in the form of website texts, handouts, brochures, advertisements and material for posters and presentations, and it was produced when required by the project. Similarly, material covering project descriptions, strategy documents and EISCAT_3D system details was updated following requests at each large funding application that the project was involved in.

Work Package 4 also contained activities to ensure that the EISCAT_3D project was made visible by participating at conferences, meetings, interaction with regional authorities and at special events. Other project participants were also assisted with material for similar activities. The progress of EISCAT_3D Preparatory Phase was reported both within the project as well as to the different stakeholders including the European Commission.

The main point of contact to the project is the project website (www.eiscat3d.se). This website is hosted and maintained by EISCAT Scientific Association and has been online since March 2009 and in its present form since November 2010. The website is accessed from around 3000 unique IP-addresses each month. The website is prepared using the content management system Drupal, which is an open source system written in PHP. Using a content management system simplifies the maintenance of the website significantly. Most of the website is accessible for all visitors, but some of the areas require login for reasons related to privacy and confidentiality. Users may contact EISCAT if they wish to gain access to the restricted areas of the website. The website contains all materials related to the project such as background, documents, Deliverables from the FP6 Design Study and the FP7 Preparatory Phase (some with restricted access) and presentations from project meetings. Other web presence by EISCAT_3D is made through a couple of mailing lists and RSS feeds. A dedicated blog site, a Facebook group and a Twitter account were maintained by Sodankylä Geophysical Observatory independently from the Preparatory Phase project.

3.8.5 Work Package 5: Consortium building

The objective of the Work Package 5 (Consortium building) activities was to prepare for EISCAT_3D in terms of identifying a supporting consortium of funding bodies, a funding scenario and an organisational structure that permits the implementation of the EISCAT_3D system. The tasks in the Work Package were concerned with discussing the project with existing and potential future partners, clarifying the project costs, identifying funding opportunities, and completing the building of a consortium for funding the construction and operation of the EISCAT_3D system.

The progress of the consortium building showed that the best way forward is to fund from investments of the present EISCAT membership the construction of the EISCAT_3D stage 1 system and make use of the world-leading measurement capabilities of the system to attract new members to invest into the research infrastructure. The operation of stage 1 will be financed through a combination of annual fees from the EISCAT owners (EISCAT Associates), funding from projects, primarily to carry out space debris and space weather observations, and annual fees from institutions that join EISCAT on a smaller level of commitment. For this purpose a new membership (EISCAT Affiliates) will be introduced. The consortium agreement for EISCAT_3D will be that of the present EISCAT, the Bluebook, with some modifications in view of the new investment.

The incentives for joining EISCAT and the distribution of observation time in return to the investment and annual contribution from the member countries were discussed in detail. A model was developed that was found appropriate for the transition from the present system to EISCAT_3D. Council expects, however, that the distribution of observation time based on payments from the members needs to be updated from time to time as the national funding schemes change and operational conditions of EISCAT_3D develop. The discussion concerning space debris observations is already mentioned elsewhere in this report. Other modifications of the Bluebook are related for instance to the work-flow within the Association and to introducing the new type of membership.

Since EISCAT Scientific Association published a new Membership Policy in June 2013 that includes a new Affiliate membership, several institutions have indicated their interest in joining EISCAT as Affiliates: the French Institute de Recherche en Astrophysique et Planétologie (IRAP-CNRS), the Russian Arctic and Antarctic Research Institute (AARI) and the Institute of Radio Astronomy of the National Academy of Sciences of Ukraine (IRA-NASU) are planning to change funding from time-buying schemes to Affiliate memberships. Discussions on potential future affiliate memberships took place with the German Aerospace Center (DLR) and with the German Leibniz-Institute for Atmospheric Research (IAP) in April 2014 and with the Korea Polar Research Institute (KOPRI) and the Korea Astronomy and Space Science Institute (KASI) in August 2014. A closer collaboration on a specific research topic to raise funding for an Affiliate membership will be discussed with the Space Research Centre (PSC) of the Polish Academy of Science in December 2014.

Other potential partners of EISCAT_3D are the European Space Agency with its scientific programme and its Space Situational Awareness Programme (SSA) and newly emerging space weather consortia. The project also reached out to potential e-infrastructure partners in the Nordic host countries. This dialogue was initiated in collaboration with Work Package 13 (Data handling and distribution), and it will continue after the end of the Preparatory Phase project. Discussions were also held with several e-science projects both on a European level and beyond. EISCAT will follow up on those discussions and also participate in some related proposals in the near future.

Cost-estimates were prepared for the investment into EISCAT_3D and an operation budget was prepared that included the operation costs for the entire EISCAT, including the Heating facility and the Svalbard radar, that will continue operation when EISCAT_3D is built. In response to discussions with ministries and research councils in the host countries, a revised project plan was prepared for a stage-wise construction of the new system and a Cost Book was prepared.

3.8.6 Work Package 6: Performance specification

The preparation of an initial specification of the performance expected from EISCAT_3D was undertaken already at the start of the EISCAT_3D FP6 Design Study. This was revisited in the Preparatory Phase as part of Work Package 6 (Performance specification) and the trade-off between the desired system performance and the level of resources likely to be available for EISCAT_3D implementation was mapped.

System performance requirements for EISCAT_3D are driven by a combination of influences. The basic motivation for these requirements is the scientific goals of the system described in the EISCAT_3D Science Case prepared in Work Package 3 (Science planning and user engagement). In particular, it specifies the required spatial and temporal resolution as well as indicating the number of 'simultaneous' beams that the system should support for each science topic. These measurement goals could, of course, be met in a number of different ways and various work packages of the Preparatory Phase project explored the technical trade-offs involved in meeting them.

A summary of the most important details of the EISCAT_3D system is as follows: The EISCAT_3D facilities will comprise one core site and four distant remote sites equipped with antenna arrays, supporting instruments, and high data rate internet connections. The core site with full transmitting and receiving capability will be located within roughly 100 km of 69°N 20.5°E, preferably in the valley near Skibotn, Norway. Stage 1 of the overall EISCAT_3D implementation will include the core site (with 50% of the eventual peak transmitter power) and two remote sites. Each site will comprise a phased-array antenna with 9919 crossed-dipole elements. The transmitter centre frequency will be 233 MHz, and the peak output power per crossed dipole will be 1 kW.

EISCAT_3D will also incorporate a range of new measurement principles made possible not only by the innovative phased array design, but also by the innovative types of signal processing, coding, data handling and data analysis. A handbook of measurement principles was thus prepared as part of Work Package 6, in order to outline the optimum strategies for the use of the new facility. The final version of this handbook was published 29 September 2014 and it is available at the EISCAT_3D project website, with the final title "EISCAT_3D measurement methods handbook".

The main purpose for writing the handbook was to incorporate the results of extensive work of the Finnish EISCAT community and the Centre of Excellence in Inverse problems in the plans of EISCAT_3D signal processing, data analysis and antenna geometries. While mainly based on published results of optimal incoherent scatter experiment design for desired range resolutions, new theory on phased array antenna geometries for transmitter/receiver antenna pairs needed to be developed. Additionally, much of the mathematical work published needed to be developed towards practical recipes in signal sampling and filtering.

The handbook shows that the EISCAT_3D radar digital signal processing can be implemented using building blocks from at least three different vendors either as finished products or as plans close to completion. It also shows that the original goals set at the FP6 Design Study can be met by this design. A specification of controlling parameters for the signal processing firmware and software is also suggested in the handbook, using a simple approach minimising the need of metadata by avoiding base band conversion. The results of the handbook will be published in open scientific literature.

3.8.7 Work Package 7: Digital signal processing

Modern design methodologies for incoherent scatter radar systems advocate a phased array approach for EISCAT_3D, which in turn puts heavy demands on signal processing techniques and technologies. In Work Package 7 (Digital signal processing), the techniques of signal processing using Software-Defined Radio (SDR) receiver systems were developed as a suitable method for parallel processing of signals from a phased array radar. The development was initially done via laboratory set-ups of hardware and software, followed by a field trial of the developed units, to establish their reliability and performance.

An implementation of the digital signal processing for the EISCAT_3D system was proposed in Work Package 7. The field work to test this proposed implementation was carried out with three demonstration projects: KAIRA – Kilpisjärvi Atmospheric Imaging Receiver Array, Kiruna Demonstrator Array and Kilpisjärvi Test System.

KAIRA is a large multi-purpose facility, capable of carrying out multiple receive-type experiments, and its deployment garnered useful experience in practical matters regarding the development of a new site and the utilisation and integration of commercially available components within the context of Arctic location and cross-disciplinary application. However, specific for EISCAT_3D is the application of new signal processing techniques, allowing for lag-profile inversion and thus accomplishing multi-beam, remote-location reception of the signal from the present EISCAT VHF transmitter. This is a critically important step in the construction and operation of EISCAT_3D for multi-beam, multi-static incoherent scatter radar measurements.

The Kiruna Demonstrator Array was developed for the FP6 EISCAT_3D Design Study and was thus an existing facility in terms of infrastructure. However, what remained untested was the deployment of an alternative SDR implementation that was proposed. In order to test this, the Kiruna Demonstrator Array was converted to make use of commercially available USRP units.

The third prototype system was introduced to study the feasibility of the chained beam forming concept and having an operational implementation field-tested before the end of the EISCAT_3D Preparatory Phase. This is the third critical area covered by the proposed system. Specifically, it demonstrated the analogue front-end and A/D conversion, SDR implemented at the chip level within an FPGA, timing signal generation and distribution capable of supporting a distributed system, data transmission line and server software.

The scale of EISCAT_3D means that industrialisation of designs and prototypes is mandatory and Work Package 7 undertook the assessment of the suitability of existing products and the application of these to the specific task. Additionally, the feasibility of the implementation of new designs was considered, and whether these can be realistically tendered. A conclusions from this endeavour undertaken with industry partners, in particular that pertaining to the Kilpsjärvi Test System, is that with this demonstration system the set goals can be achieved using modern FPGA chips.

Critical to these results is to have excellent timing, which is needed to provide a stable enough clock for under sampling scheme, and a properly designed RF front end is essential for good signal reception. It was also demonstrated that the required data transmission speeds of 10 Gbit/s can be achieved using optical links and off-the-shelf Ethernet components.

In concluding, it was noted that although innovative, none of the proposed technologies lie beyond the scope of the technical resources available to the project and that the solutions envisaged can be realised within the scope of the complete EISCAT_3D vision.

3.8.8 Work Package 8: Antenna, front end and time synchronisation

The antenna design, the array layout, the receiver front end and calibration system all play important roles in determining the achievable performance of EISCAT_3D system. The objective of Work Package 8 (Antenna, front end and time synchronisation) was to produce designs of these hardware elements which will be suitable for industrial consideration, and to identify potential manufacturers.

A study on the feasibility of various principal antenna designs was conducted in an early stage of the EISCAT_3D Preparatory Phase. From this study, a crossed dipole antenna was selected for an initial antenna design. In order to verify the electrical performance estimated from simulations, a full scale electric prototype of the antenna element was built. The major purpose of the prototype at this stage was to use it for verification that the simulations matched the measured data for a single element antenna. The verification was successful. However, an important conclusion from these initial activities was that further antenna work must be based on the performance achieved on array level, and not on the performance of a single antenna element.

Following the initial prototype, a major effort was made to develop a simulation and optimisation environment that could evaluate various antenna options in a setting where array performance is the critical outcome. For this purpose, electromagnetic simulations were performed using the FEKO software package. In order to enable automatic optimisation and an exhaustive search over design parameters, as well as performance parameter evaluation, a set of antenna array design tools were implemented using Matlab. These tools were used to perform a comprehensive investigation over a number of design parameters including rectangular/hexagonal array layout, antenna spacing, element (tip) angle relative to the horizontal, and the antenna impedance. The resulting antenna design and array layout were prototyped and verified as scale models, with performance matching the simulations very well. Finally, studies on the manufacturing tolerance influence as well as the array near field strengths were performed. Even though the successful design of an antenna element and an array layout are important, the usefulness of the method in itself needs to be emphasised. The method used here, and the tools developed for it, can be of great value for the upcoming implementation of EISCAT_3D.

The activities on the electric and mechanical front end design were initiated with a thorough characterisation and selection of the transistors suitable for Low Noise Amplifier (LNA) design at VHF frequencies, albeit not characterised therefore. Based on the selected devices, an optimisation technique was developed in order to find an optimal amplifier design. In addition to the noise performance, effort was made on the overload recovery, the electronic tuning, and the calibration signal injection. The front end design has a strong focus on repeatable and stable performance as well as on low cost and rapid pulse overload recovery. The design was measured and verified to adhere to the set specifications. As a step towards mass production, the design was complemented with supply voltage regulators and required switches for signal calibration. This front end design was subsequently further refined and verified in Work Package 14 (Technical integration and production issues).

An in-depth evaluation was performed of a number of different calibration options that could be applicable to the daily operation of the EISCAT_3D system. It was concluded that it would be entirely feasible to achieve excellent calibration accuracy using a suitable combination of methods. For example, radar reflections from objects in Earth orbit allow rapid receiver calibration over the transmitter bandwidth while enabling accurate transmitter calibration on a longer time scale. As a complement, the reception of signals from celestial sources can be used to calibrate the receiver outside the transmitter bandwidth. In addition, a solution for distributed phase-aligned clock signals has been evaluated and found to be a feasible choice for EISCAT_3D.

3.8.9 Work Package 9: Transmitter development

In Work Package 9 (Transmitter development), important parts of the EISCAT_3D radar transmitter subsystem were designed and evaluated. These particular areas of the transmitter design were planned to be addressed already during the EISCAT_3D FP6 Design Study but were left unfinished due to a lack of manpower and time.

An import aspect of the transmitter system is that it should be made future-proof, i.e. it should allow the seamless introduction of new modulations, including arbitrary combinations of amplitude and phase modulation, without any modifications in the hardware. The three blocks in the transmitter design are the exciter, the solid state power amplifier and the power supply.

The exciter generates radio frequency signals for amplification and distribution to the antenna elements. These signals include all information about the frequency, phase and polarisation. Separate signals can be sent to each antenna (within limits) to facilitate beam steering/forming as well as polarisation encoding. The exciter will be fully time synchronised and will be distributed.

The AD9957 by Analog Devices was found to offer all the functionality required to meet the basic requirements specified in the EISCAT_3D FP6 Design Study. It also meets the phase noise and spurious requirements with one minor exception, which can be corrected by adding some external bandpass filtering. The AD9957 contains a built-in sync generator / sync receiver system which can be used to synchronise the internal state machines of multiple chips to make them to run in phase and time coherence. A synchronisation detector system is also provided. These features make the AD9957 particularly well suited to the EISCAT_3D application, where each element in the array will be provided with its own exciter unit, all of which must remain phase-locked at all times in order for the beam-forming and beam-steering to work as intended.

A prototype Transmit/Receive (T/R) switch is built on two printed circuit boards, the radio frequency board and the diode bias board. In the transmit state, all PIN diodes are forward biased. In the receive state, all PIN diodes are reverse biased and appear as high-impedance capacitive shunts across the 50 Ω micro-strip transmission lines. As designed, the prototype T/R switch thus meets the power handling and switching time design targets. It also approaches the isolation and loss targets to within acceptable tolerances, considering the intended application.

The Solid State RF Power Amplifier (SSPA) will be a building block containing also the T/R switch. This unit should be built in such a way that the complexity for installation and removal of the unit is minimised. The centre frequency for the transmitter will be 233 MHz with an instantaneous bandwidth of 5 MHz, but could be moved anywhere in the range 210 MHz to 256 MHz if necessary. The SSPA should have a linear operating interval of 50 W to 500 W output power, at a maximum RF duty cycle of 25% for pulses up to 3 ms in duration. The SSPA should also contain supervisor functions for output power, excess reflected power, excess temperature and other critical system parameters, and these functions should be readable from the central control system. The transmitted signal should be available from a directional coupler, and the methods to control the SSPA through remote commands should be available.

The T/R switch will preferably be put on the same circuit board as the power amplifier itself. This will minimise the number of RF cables and connectors inside the unit and allow for a minimum insertion loss for the receiver chain. The SSPA unit, including T/R switch and necessary support electronics for power distribution and control, should be fitted in one physical unit, preferably using passive cooling. If possible, self-mating connectors for RF in and out, power and system control should be used. The SSPA unit should be RF screened to keep the RF leakage to a minimum.

3.8.10 Work Package 10: Aperture synthesis imaging radar

Work Package 10 (Aperture synthesis imaging radar) contained activities related to the use of EISCAT_3D applying the Aperture Synthesis Imaging Radar(ASIR) technique.

Software for the simulation of incoherent scatter signals was developed, so that imaging algorithms could be tested using different configurations of the antenna arrays. The basis of the software was the simulation of ionospheric electron density structures and the incoherent scatter signals they produce.

Different algorithms for image inversion to be used in the aperture synthesis data analysis were evaluated. The relevance and usefulness of the image inversion algorithm based on the Maximum Entropy Method (MEM) principle was already shown, and a prototype software package was developed, within the FP6 Design Study project. Here other existing algorithms was evaluated using simulated data. It was found that the MEM method is preferred for EISCAT_3D purposes since it is the most mathematically developed method and it works well with broad, smooth brightness distributions. In case there is a presence of point-like sources the MEM and CLEAN methods should be combined. The Capon algorithm should be used in case of fast moving targets like satellites or space debris.

The optimum number of outlying passive phased array antennas was determined, and their optimum localisation (antenna configuration) in order to fulfil the imaging (across-beam) spatial resolutions of the ASIR technique. It was found that a greater number of outliers provide better angular resolution, in particular taking into account the fact that the passive outlying modules must be considerably cheaper than the modules comprising the core antenna. A simple double triangle configuration appeared to be favourable, often demonstrating higher resolution than other layouts. Nominal horizontal resolutions of 50 m and 100 m at an altitude of 100 km imply a longest baseline of 2.7 km and 1.3 km, respectively.

Operational software for interferometric image inversion was developed employed in the evaluation of candidate antenna configurations. It was distributed as a runnable jar (Java archive) file containing the source code. This allows the software to be modified and upgraded in order to, for instance, add the capabilities to view partial image frames during/after data processing, to decode raw data in case of complex transmission codes or to improve GUI functionality.

Beam matching of the transmitting and receiving phased array antennas was evaluated. Depending on the target of interest and the system capabilities, it is possible to apply binary phase coding or parabolic phase fronts. Some specific recommendations were prepared. If the target of interest has long correlation times, then complementary binary phase coding could be used, with practical implementation depending on the actual antenna geometry used. Parabolic phase fronts are the most recommended procedure if the system allows phase changes with good precision. On the other hand, if a very smooth wide beam is needed then amplitude modulation with good precision is needed on transmission.

3.8.11 Work Package 11: Software theory and implementation

The main activity of Work Package 11 (Software theory and implementation) was the development of a radar data analysis software package. This development consisted of two tasks. The first task was the parallelisation and productification of FLIPS (Fortran Linear Inverse Problem Solver), a Fortran95 module for solving statistical linear inverse problems.

FLIPS was rewritten as an R package and it was parallelised using OpenCL language utilising GPUs (Graphical Processing Units). Although this new package (renamed RLIPS) can be used as a general linear problem solver, it is mainly using as the solver in the LPI (Lag Profile Inversion) analysis package.

The second task was the development of DSP (Digital Signal Processing) and beam-forming software and algorithms to be used by the EISCAT_3D radars. This was done using the principles described in the EISCAT_3D measurement methods handbook developed as part of Work Package 6 (Preformance specification). Both the necessary pass-band filtering and the delaying of the sampled signals are done using optimised FIR filters which can be implemented in one or several stages for both FPGA hardware and computer software.

An additional task was to develop new multi-purpose codes and radar experiments for the EISCAT_3D radar, using the principles presented EISCAT_3D measurement method handbook (Work Package 6). The multi-purpose codes use three levels of coding. The first level is an aperiodic pulse coding that provides a pulse-to-pulse spacing sufficient for measuring the lower ionosphere without affecting height coverage of the measurement. In the second level, the pulses are phase-coded with numerically optimised near perfect codes to provide sufficient resolution in range, although bit lengths shorter than the required lag resolution will not be used at this level. In the third level, range resolution better than the lag resolution is achieved by means of sub-coding individual bits of the second-level phase codes with codes decoded at voltage level, e.g. Barker codes or near perfect codes. In special experiments designed for specific targets, also poly-phase alternating codes, amplitude coding, and dual polarisation coding can be used. The poly-phase codes were tested also in practice and found to perform as theoretically predicted.

The radar data analysis software was developed as an R package called LPI (Lag Profile Inversion). The original Fortran code was completely rewritten in R and C and numerous improvements were implemented. The new R package contains options for example for parallel analysis in clusters of several computing nodes and cross-correlation analysis that is needed in radar interferometry and dual-polarisation analysis. The package is maintained and further developed at University of Oulu, where it is routinely used for analysis of special radar experiments recorded as voltage level signal samples, including radar measurements obtained by KAIRA.

The final task involved the integration of hardware and software. The Kilpisjärvi Test System constructed in Work Package 7 used the FIR filters developed in this Work Package. They were embedded in the FPGA of its sampler units, and was successfully tested at KAIRA site in June 2014.

3.8.12 Work Package 12: System control

Work Package 12 (System control) determined the changes needed to be implemented in the existing EISCAT system control software (Eros) in order to control a system on the scale envisaged for EISCAT_3D with sufficient flexibility and programmability. The work plan for

Work Package 12 was significantly changed compared to the original work plan, since the development of an operating system for a specific hardware cannot be made within the scope of the Preparatory Phase project. Instead the focus was turned towards general considerations needed for a system of the scale of EISCAT_3D.

The basic premise of the activities in Work Package 12 was that the EISCAT_3D system should, from the point of view of the users, be controlled via software that is not too dissimilar to how the present-day EISCAT systems are controlled. Therefore, an implementation was made of an update of the existing Eros needed to meet the needs of a baseline EISCAT_3D system. The focus of this update was in two main areas. First, in adding more flexibility into the control system; second, in improving the internal structure of the system.

The added flexibility means particularly new possibilities of user-level multitasking. From a single Unix process, visible to the user as a terminal window, it is possible to start any number of jobs that run in parallel. How these facilities will be best used with EISCAT_3D remains to be seen. With the present system, one job could run the main experiment script, another job could run an antenna pointing loop, while a few other jobs could maintain a few automatically updating status windows for monitoring. The process-level multitasking facilities have been implemented with two different means. First, using threads; second, using coroutines. Coroutines are a multitasking facility implemented within a single Unix thread, and therefore avoids to lot of the problems related to resource sharing that are normally associated with threads programming. It is also possible to run multiple experiment scripts from within a single process, although it probably makes more sense to use separate (esh-) processes for entirely separate experiments; this is now also possible.

Coroutines have also allowed a new implementation of the main context-switching command (goto) in Eros, and also allow one to suspend and resume a running job. These facilities should help in implementing context switching by external events. However, the analysis performed within the work package about the possibilities to halt running experiments temporarily because a higher-priority special event requires another program to be run, and then return to execution of the original programs, indicates that this will be exceedingly difficult to achieve in the general case. The main problem is how to force the hardware state to be identical to the state where the system was when it was interrupted by the high-priority task. Within an Eros-like system, the only remotely realistic possibility seems to be, in effect, to re-run the suspended program(s) from their beginning in some kind of skipping-on mode, as is done in a limited form already in the present Eros.

The enhanced Eros internal structure comes in two fronts. First, a new, clearer, division of labour between the various system components. This is achieved by breaking Eros into two main blocks, the E-OS and the e-shell (esh). The E-OS is the long-living, all-time-on radar operating system proper. Its task is to implement the various hardware-access system commands that are needed to control the various radar subsystems (which may have their own subsystem manager blocks, which hide the hardware details from the top level of E-OS). The

E-OS side of Eros is not directly concerned about how those system commands are generated; E-OS just serves a stream of them.

The actual experiment programming is done outside the E-OS. It can be implemented via user scripts, written by any programming system that allows Unix command line commands to be executed; to that purpose, the ECO (e-commander) interface is available. But in addition, this work package has provided a program, the e-shell, which has built-in facilities that make it easy to run all the existing experiment scripts as-is within the new Eros structure, and which in addition supports the user-level multitasking features.

The other, significant, internal enhancement to Eros is an improved handling of long-living commands, which in the present Eros can freeze the system for the full length of the execution of a command. In a multi-user, multitasking environment, that kind of freezing of service cannot be tolerated. The implementation uses both threads and coroutines, together with advanced object-oriented entities, so called future objects, of the comm interprocess communication package that underlies Eros IPC.

3.8.13 Work Package 13: Data handling and distribution

The aim of Work Package 13 (Data handling and distribution) was to determine how the EISCAT_3D data system will be implemented on the e-infrastructure which currently exists in northern Scandinavia (or is planned for the near future). This was achieved through engagement with the national providers of networking, storage and high performance computing in order to ensure that the requirements of the project can be optimally satisfied.

The EISCAT_3D data handling will be distributed over on-site computing, operation centre and data centre. A plan was developed for the on-site data processing and for reducing the data volume in a way that is economical affordable and technical feasible, while at the same time having a maximum of scientific information. This is facilitated by on-site data storage in a ring buffer and long-time storage of well defined data products. A smaller part of the data that is archived includes selected parts of the data products from each site as well as centrally processed data, such as three-dimensional data products for instance. All data will be replicated at two sites; this provides a high level of data security as well as better accessibility of the data. The initial level of data archiving is planned to be 2 PB/year, which permits storing the basic ionospheric parameters with full 3D resolution and an altitude resolution reduced by a factor of 4, as well as storing selected raw data streams and integrated profiles. The detailed archiving strategy for additional data products is up to further negotiations within the community during the commissioning of the system.

This plan is well in line with the EISCAT_3D budget and it is expected that the volume of stored data per year will increase as data storage becomes more affordable. Nonetheless, network capacity and storage costs are likely to be a limiting factor during the entire operational period of EISCAT_3D. Networking requirements and provision to the identified sites are an important step for the construction of EISCAT_3D and the project informed the network providers at an early stage. When plans became more concrete, the network, computing and storage for EISCAT_3D were discussed with a consortium including national research network providers and national infrastructures for high performance computing as well as relevant Nordic organisations. The discussions will continue as mentioned elsewhere in the report.

3.8.14 Work Package 14: Technical integration and production issues

Work Package 14 (Technical integration and production issues) focused on technical integration between the various sub-systems and the overall manufacturing, reliability and quality assurance.

As the EISCAT_3D system will consist of multiple phased array sites (three sites already in stage 1), each comprising nearly 10,000 antenna elements with associated electronics, there is a need for industrial scale production. Phased array technology has been in use since the mid 1960s in military, civil and academic hardware meaning that a large amount of experience with development and construction is available in many parts of the society. During the Preparatory Phase project much focus has been on finding ways to utilise this knowledge in the development and construction of EISCAT_3D. The functionality, specifications and first blueprints of the integrated system have been developed by academic and industrial partners in the Preparatory Phase, but leaving open the issues of taking these deliveries into production ready designs. The reasons for this are:

Cost efficiency: By not settling for a defined production-ready blueprint of a component at the beginning of the EISCAT_3D, but rather its overall design, its interface with other components in the system and its operational specifications, it is possible for EISCAT to utilise the latest available technology and/or to cut costs since the price of electronics and computer hardware generally decrease over time.

Functionality: EISCAT will contract radar electronics manufacturers not only for the production of components but also for the production engineering design and testing. EISCAT will be involved in the process to ensure the system functionality, find cost efficient solutions and optimise potential technological trade-offs. However, it is in the interest of EISCAT that the manufacturer provides guarantees that the components meet the agreed specifications and long-term reliability needed for the EISCAT_3D system as well as long-term availability for spare parts and future extension of the system. Furthermore, EISCAT must have shared rights to the design enabling complementary purchase in case the initial manufacturer is not able to deliver due to changing circumstances.

Knowledge transfer: The final design and construction of EISCAT_3D will be a joint venture between academia, industry, the local society and EISCAT. Involving several aspects of the civil society in the project will allow for knowledge transfer between them. The interest from local society stems primary from the already established space research, education and industry platforms in the Nordkalotten region (Northernmost Norway, Finland and Sweden).

In-kind contributions: During the Preparatory Phase it has become evident that there is a will from the partners to provide parts of their contribution as in-kind. This enables the partners to access alternative funding sources as well as letting EISCAT utilising the partners' technological strengths in areas relevant for the construction. To enable this, EISCAT has now produced an itemised Cost Book with details on costs for production engineering and testing, software development as well as production of the actual hardware. Partners have already started to suggest items which they can deliver as in-kind. It is also a clear understanding from all partners that not all contributions to EISCAT can be made as in-kind and that there is a need for some key items to be developed by EISCAT itself.

There is an agreement between all parts involved in the project that EISCAT will lead the technical integration and testing of all sub-systems in EISCAT_3D as well as the overall system integration. This is somewhat challenging as some items will be delivered in-kind. The work and costs of technical integration and system testing are defined in the Cost Book as items that have to be covered with cash contribution from the partners.

An important first step in the technical integration and system testing is to set up a test-bed transmitter/receiver array consisting of a 91-element sub-array. It will enable EISCAT to test all components, software and the system integration prior to launching full scale production of the 10,000 antenna units in the transmitter/receiver array as well as the 20,000 antenna units for the two receiver arrays. This is possible since the technical design of both the transmitter and receiver arrays are the same, with the sole difference that the transmitter array will be fitted with transmitter electronics.

A document was prepared to give background technical information about the EISCAT_3D system in the initial discussions with potential in-kind contributors. This document is also a starting point for as technical input for future requests for quotations.

Part of the activities in this work package included work on prototyping and verification aiming at achieving production ready designs. A number of external influences, including direction from EISCAT funding agencies, resulted in a more limited scope for this work, since some sub-systems of EISCAT_3D, for instance, will likely be provided as in-kind contributions. As a result, these efforts were concentrated on prototypes for the antenna and the low noise amplifier, which are least affected by these influences.

4 Potential impact

The overall theme of EISCAT 3D is to explore the multiple facets of the question how the Earth's atmosphere is coupled to space. Is science encompasses climate change, space weather, space debris and near-Earth object studies; all of which are directly of wider societal interest. The project has also established links to other Arctic research initiatives and to the overall space weather community and has strengthened the links to space institutions in Northernmost Scandinavia. Major areas of impact are outlined below.

4.1 Regional impact

When in operation, EISCAT_3D will be at a central position in the international, and trans-regional, space cluster of Northernmost Scandinavia, which includes large space research centres in Kiruna (Sweden), Sodankylä (Finland) and Tromsø (Norway), two rocket launch facilities in Andøya (Norway) and Esrange (Sweden), and several other instruments and instrument networks for geospace observation such as magnetometers and auroral cameras.

The cooperation between the EISCAT_3D community and other space research and space technology actors in Northernmost Scandinavia, including regional and local authorities, has contributed to high-lighting the regions competitive advantages in space activities. This has led to the inclusion of space activities in the regional agendas of e.g. smart specialisation. There are now efforts by the actors to integrate their activities in research, education, technology development as well as to integrate space activities based on current and future platforms, such as rockets and balloons, research infrastructures (including EISCAT and EISCAT_3D) and research and training institutes.

4.2 Industry connection and technical development

The construction of EISCAT_3D requires close interaction with industry in order to ensure the production of components of the high quality and in large numbers needed by the research infrastructure. This includes the manufacturing of the antenna elements and the corresponding electronics. Engineering solutions could be a development driver for large-scale distributed systems in harsh environments. Enterprises, both regional and national, within the EISCAT member countries are expected to respond to invitations to tender for e.g. radio and the digital signal processing instruments, antenna front end and timing systems, and other advanced subsystems. EISCAT and its users are working together with industry to develop technology and applications for EISCAT_3D.

Already the Preparatory Phase project had an economic impact since it made use of consultancies, procured prototyping hardware components and made use of services ranging from travel agency support to antenna design work. Several small and medium-sized enterprises were involved on different levels in the work on the technical tasks. In addition, students were involved in technical design work for the antenna and the array configuration and could acquire knowledge and skills from this cooperation. The radar development also bears synergies with the radio astronomy community in terms of research as well as technical development. In some initial discussion with astronomy projects (JIVE, LOFAR, VLBI, CTA) real time data transfer, timing and time synchronisation were some of the areas that were identified as potential topics for future collaborations. The project was invited to participate in the next International VLBI Technology Workshop, organised by JIVE in Groningen, Netherlands in November 2014.

4.3 Space debris observations

Space debris is considered one of the major threats to space communication satellites and to space exploration. EISCAT_3D will also be able to contribute to the Space Situational Awareness (SSA) programme by tracking known space debris and assisting communication and navigation services like the Galileo navigational system. Discussions have just been initiated between EISCAT, agencies and institutes in the Nordic countries and the European Space Agency (ESA) on the prospect of including EISCAT 3D in ESA's SSA programme. EISCAT will continue to be an active participant in global observation campaigns and international and European research projects. From its foundation EISCAT has been a purely scientific organisation. Since radar technologies to be used with EISCAT_3D allow the detection and tracking of small objects in space, the new Bluebook has stipulations that ensures that the EISCAT facilities will be used strictly for scientific and civilian purposes.

4.4 Space weather, space climate and Arctic research

EISCAT_3D will provide an unprecedented resource for observations of the near-Earth space. It will provide long-term time-series data of the ionospheric conditions enabling studies of variations on a time-scale over several solar cycles. The scientific data from EISCAT_3D will be an invaluable asset for models and near real-time forecasts of space weather effects on modern technology, including power grids and other important infrastructures. EISCAT Scientific Association already participates in several collaborative projects in these areas and was also asked to join an initiative to prepare for a new European consortium to support space weather research, with the prospective to form a collaboration in the future with EISCAT_3D as a participant. The first discussions on this initiative will take place in November 2014 during the European Space Weather Week.

It is notable that the possibilities of the present EISCAT and the future EISCAT_3D systems bring together the polar atmosphere and the Space Situational Awareness (SSA) research communities. In the interaction with these communities, the possibilities to make continuous high-resolution observations of the dynamics across the Arctic/sub-Arctic atmosphere at the location of the Polar vortex and the ability to obtain 3D vector data have been of particular interest.

Several regional observational networks will complement and be complemented by EISCAT_3D. Some of these are SuperDARN measuring large-scale plasma convection, the MIRACLE/Image magnetometer/all-sky camera network measuring the aurora and related ionospheric currents, the ESRAD and MAARSY radars measuring winds, waves and turbulence. Lidars are also operated in the region as well as other aurora cameras and collaborations exist already between individual user groups.

As a result of this Preparatory Phase project the discussions on site selection with researchers that carry our optical observations led to closer links to Arctic researchers that use optical observations. Indeed EISCAT_3D is seen as an incentive for transnational projects to carry out optical atmospheric observations. A closer collaboration with this community is envisioned to use for instance the same observation sites. As a first step toward such a collaboration, the two communities decided to run their next international meetings in September 2015 in parallel, with some shared sessions and activities. These meetings are the 17th EISCAT Symposium and the 42nd Atmospheric Studies by Optical Methods Symposium. These symposia will be hosted by the South African National Space Agency, a potential new partner of the EISCAT_3D project. It is also expected that the future EISCAT membership of the Korea Polar Research Institute (KOPRI) will further strengthen the link of the project to other Arctic research.

4.5 Atmospheric research

Since EISCAT_3D is a research infrastructure for the environment it is important to understand its contribution to the development of climate models and the investigation of human effects on the atmosphere. The climate models discussed in this context typically refer to the lower atmosphere below the range of the observations of the present EISCAT radars (starting at roughly 80 km). EISCAT_3D is expected to offer standard data products from 60 km to 1200 km altitude. Hence the data will cover altitudes also included in standard climate models. In addition, the project and the EISCAT community has emphasised the importance of the upper atmospheric layers and of the coupling of the layers as well as auroral phenomena for the Earth's atmosphere and climate as a whole.

The relevance of EISCAT measurements for studying the effects from greenhouse gases was documented in a recent analysis of more than 30 years of EISCAT incoherent scatter observations. This was published by an EISCAT user group from Japan and it was highlighted in the weekly journal of the American Geophysical Union. *Ogawa et al.* present on the basis of the EISCAT observations a quantitative description of the cooling of the upper atmosphere between 200 km and 400 km altitude as predicted due to anthropogenic carbon emission. (The original publication is in *Geophys. Res. Let.* doi:10.1002/2014GL060591, 2014.) While this first result is important for the planning of satellite missions, it also shows the importance of high altitude observations and the importance of long time series data for atmospheric research and climate models. Even though this long-term trend study started many years before the EISCAT_3D project, it demonstrates the importance of having long-term continuous incoherent scatter radar observations available, hence providing one strong motivation to realise the EISCAT_3D system.

4.6 E-science and e-infrastructure

The technical challenges to handle large data volumes will employ tools from the newly emerging field of e-science, spur collaboration with local computing centres and contribute to developing e-science competence in environmental and space research. Contacts were established with national, Nordic and European e-infrastructures and e-science projects during the Preparatory Phase. To prepare for EISCAT_3D, EISCAT Scientific Association and other partners participate in proposals for new projects within Horizon 2020. With the already existing 30-year data set, EISCAT has made important contributions to the joint e-infrastructure planning of the ESFRI projects for the environment. The EISCAT data provided a use case for the ENVRI reference model.

4.7 Collaboration between research infrastructures

EISCAT Scientific Association has not only acted as Coordinator of the EISCAT_3D Preparatory Phase but has also participated in other projects funded by the European Union through Framework Programme 7. These include ENVRI and COOPEUS, in which EISCAT could participate due to being included on the ESFRI roadmap.

The ENVRI project on "Common Operations of Environmental Research Infrastructures" had the goal to develop common e-science components and services for European environmental research facilities in order to allow scientists to use data and software from each facility to enable multidisciplinary science. In addition, ENVRI worked for harmonised solutions and guidelines for the common needs of the environmental ESFRI projects (MSO, EURO-ARGO, ICOS, Lifewatch, EISCAT_3D, EPOS and SIOS) with a special focus on data architectures, metadata frameworks, data discovery in scattered repositories, visualisation and data curation. This project started in October 2011 and continued until September 2014.

The COOPEUS project aims to strengthen the cooperation between the United States and the European Union in the field of environmental research through enhancement of their interaction on common data policies and standards relevant to global research infrastructures in the environment field. The project started in October 2012.

4.8 Dissemination activities

In order to attract new users and funding organisations, and also to whet the interest of the general public, EISCAT_3D was presented at conferences and expos in areas where the system can be made of good use. These included not only scientific conferences containing topics such as geophysics, environmental monitoring, radio physics, atmospheric physics and advanced data analysis, but also conferences about radar hardware, research infrastructures and e-science.

Aside from the outreach activities of the project, the national user communities follow their own outreach programmes related to the EISCAT_3D funding applications and related to their research carried out in view of the new system. Scientists of the EISCAT user community described and advertised the project in their research presentations at conferences and in seminars presented at academic institutions.

Through the support by the European Commission, the EISCAT_3D partners have been able to significantly raise the awareness of incoherent scattering radar capabilities in fields outside aurora and plasma research. Several invited presentations were given directly on the topic of the Preparatory Phase Project. These were made at the National Instruments "Big Physics" Symposium in Paris, France (February 2011); the "Imaging the Inner Heliosphere" Workshop in Aberystwyth, UK on (June 2011); the GEANT Innovation Workshop in Copenhagen, Denmark (October 2011); the Nordic e-Science Meeting in Trondheim, Norway (May 2013), the IEEE Conference on Phased Arrays in Boston, USA (October 2013); Japanese Geophysical Union Annual Meeting in Yokohama, Japan (April 2014), two invited presentations, related to the science case of the project and related to the e-science solutions, were given during the COSPAR 2014 General Assembly Moscow, Russia (August 2014) and finally an invited presentation on EISCAT 3D was given during the 41st Annual European Meeting on Atmospheric Studies by Optical Methods in Stockholm (Sweden) (August 2014). Moreover, as Directors of the EISCAT Scientific Association Esa Turunen and Craig Heinselman were invited to present EISCAT at several international meetings. These ranged from scientific conferences to dedicated events on Research Infrastructures, like the Conference on the joint "Nordic Focus on Research Infrastructure – Looking to the Future" in Stockholm (November 2013). In July 2013 a short article about EISCAT 3D was published in Physics Today. The project office provided the information for this article, which cites the EISCAT Director and the project leader for EISCAT_3D in Norway.

The annual EISCAT_3D Users Meetings, held in Uppsala Sweden in May, have been important not only for the present EISCAT user community to get information about the status of the EISCAT_3D project, but also as a way of expanding the potential EISCAT_3D users to groups in new areas of research. This has been obtained by having a theme at each meeting targeting a specific area of research that could exploit the capabilities of EISCAT_3D. Similarly, the progress of EISCAT_3D has been an important topic at the biennial EISCAT international workshops, informing the international EISCAT users of future possibilities. Presence at the regularly occurring incoherent scattering radar schools, arranged by EISCAT and the US counterparts, has been fruitful in teaching the next generation of scientists the possibilities of EISCAT_3D. Different aspects of EISCAT_3D have been presented at the annual European Space Weather Weeks in Belgium to a broad audience of people interested in the different aspects of space weather, such as scientists, engineers and applications developers as well as space weather service providers and end users.

EISCAT_3D has been presented also for the general public on a number of occasions, for example at the Norwegian national event in Tromsø, Norway, in connection to the Venus solar transit 5 – 6 June 2012. That event was visited by thousands of people, many flying in specifically to experience the rare astronomical occurrence, providing a superb possibility to inform about the EISCAT_3D plans to many interested people, both locally in Tromsø and internationally. This event was also televised globally. Contributions to a couple of BBC productions have also been made by EISCAT_3D. The radio shows "Thin air" and "Science in action" and episodes of the TV shows "Sky at night" and "Stargazing live" all contained material related to EISCAT_3D. The EISCAT_3D Preparatory Phase end-of-project meeting in Kiruna, Sweden, 12 September 2014 was a public meeting announced in local media.

5 Other

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www.eiscat3d.se

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