PROJECT FINAL REPORT

PUBLISHABLE SUMMARY

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Executive Summary

Since 2000, the European Commission has supported a successful RadioNet cooperation network of European radio astronomy infrastructures. During the years 2012-2015, RadioNet3 succeeded in pulling together all of Europe's leading radio astronomy facilities in an integrated cooperation to achieve transformational improvement in the quality and quantity of scientific research by European astronomers. A vibrant programme of technical developments in hardware and software kept European radio astronomy at the scientific and technical forefront. Moreover, the RadioNet3 developments are of significant importance to ensure a strong European role in upcoming challenges such as Atacama Large Millimetre/submillimetre Array (ALMA) and Square Kilometre Array (SKA). RadioNet3 involved 27 partners out of 13 countries including Australia, the Republic of Korea and South Africa, operating world-class radio telescopes and performing cutting-edge R&D.

RadioNet3 achieved all goals. In particular:

- The Networking Activities promoted timely and effective communication of results and continuous exchange between astronomers in Europe. These activities transformed the way science is conducted in Europe; they provided a natural forum for the development of European collaborations, making possible the sharing of ideas and results, and the mobilisation of researchers. RadioNet3 made possible the organisation of 111 scientific events, which were attended by more than 7600 young and experienced scientists and engineers. On average 26% of the participants were women. The events were attended by scientists and engineers coming from all over the world. The RadioNet3 consortium laid the foundations for future sustainability and defined a scenario of a self-standing collaboration.
- The Joint Research Activities integrated and optimised the use and development of European radio astronomy infrastructures by increasing the observing bandwidth and the field of view of the telescopes. The RadioNet3 technical developments are already in use by radio telescopes worldwide and are relevant for the newest (ALMA) and future (SKA) telescopes. The EC investment of 4.5 million Euro yielded a development of (i) a generic high-performance computing platform (UniBoard[2]) built on the newest FPGA (Field Programmable Gate Array) technology and pin-compatible with devices (14nm) becoming available towards the end of 2016; (ii) miniaturized receiver modules capable together to cover the full mm/sub-mm spectrum visible from the ground; (iii) a low-noise wide-band integrated amplifier for VLBI antennas with the frequency range of 1.5 GHz to 5 GHz (compatible with SKA), and (iv) a VLBI digital backend with 4 GHz bandwidth, single FPGA processor unit and 40 Gbps Ethernet output data highway (DBBC3), and (v) in software: the CASAcore (Common Astronomy Software Application) library for the area of enhancements to measurement set access, table queries, and multi threading support.
- The Trans-National Access Activities suited radio astronomical facilities offering unique capabilities over an unprecedented range of wavelengths, from the largely uncharted territory of decametric astronomy to the sub-millimetre emission. Thus an access to the complete range of Europe's world-leading radio astronomical infrastructures was provided to produce top-class science. RadioNet3 enabled European users access to 19 state-of-the-art radio telescope facilities launching 416 observing programmes for about 9400 observing hours. The provided access exceeded the plan by 220%. Scientific discoveries were disseminated in more than 100 articles, published in well-respected astronomical journals such as Nature and Science.

RadioNet3 is recognised by funding agencies and international consortia as the European entity representing radio astronomy and facilitating the access to excellent facilities and their scientific exploitation. This is of paramount importance, as a formal European radio astronomy organisation to coordinate and serve the needs of this scientific community does not yet exist.

A summary description of project context and objectives

Since 2000, the European Commission has supported an infrastructure cooperation network in radio astronomy. It started under the 5th Framework Programme as cooperation of 11 partners from Europe, Australia and Canada and with the EU contribution of 800,000 Euro. This collaboration successfully continued over FP6 (RadioNet) and FP7 (RadioNet-FP7), increasing the scope and the number of partners. RadioNet3 was funded under FP7 for the period 2012-2015 with the project cost of 11.6 million Euro and 27 partners from Europe, Australia, Republic of Korea and South Africa; the EC contributed 9.5 million Euro.

The ambition of RadioNet3 was to foster European radio astronomy, and to shape the radio astronomical scene in Europe into a complete, innovative and accessible set of research facilities. RadioNet3 specifically provided a sustainable and broad-based platform for the continuation of an organised European radio astronomy community, essential for securing a lasting European leadership in all aspects of radio astronomy.

The RadioNet3 Transnational Access programme (TNA) was designed to stimulate the full exploitation of the open skies policy that had been at the core of the operations philosophy of most radio astronomical facilities for decades. In the era of new facilities like LOFAR and ALMA becoming operational, new scientific fields were introduced as research topics.

The RadioNet3 Networking Activities (NA) transformed the way the science is conducted in Europe; they provided a natural forum for developing European collaborations, for the sharing of ideas and results and for mobilizing the researchers themselves. This gained importance due to the emergence of new research opportunities through SKA and its pathfinders.

The RadioNet3 Joint Research Activities (JRA) supported targeted developments to be used by facilities where an upgrade was to be done. The main focus was in the areas of new digital techniques that allow radio astronomers to make a more efficient use of telescope hardware by increasing the observing bandwidth or the field of view of the telescopes. Some of the developments are specifically relevant towards reaching the ambitious goals that are set for the SKA.

RadioNet3 struck a balance between the needs of the users and the needs of the infrastructures in terms of expanding the scientific and technical horizons. The mission of RadioNet3 was to optimise use and development of European radio astronomy infrastructures. The general goals were:

- To provide and facilitate for a growing community of European researchers access to the complete range of Europe’s outstanding radio-astronomical facilities, including the ALMA telescope, in order to address a wide range of topics in astronomy;
- To secure a long term perspective on scientific and technical developments in radio astronomy, pooling the skills, resources and expertise that exists within the RadioNet3 partnership;
- To stimulate new R&D activities for the already existing radio infrastructures in synergy with ALMA and with the SKA, as the radio telescope of the future, ensuring that a healthy scientific and technical community will be ready and prepared for the SKA;
- To contribute to the implementation of the vision developed in the ASTRONET Strategic Plan for European Astronomy by building a sustainable radio astronomical research community with world leading questions;

All RadioNet3 objectives were met within the project duration time.

TRANSNATIONAL ACCESS ACTIVITIES – ENSURING SCIENTIFIC EXCELLENCE

Under the Transnational Access programme RadioNet3 offered access to the complete range of radio astronomical world-class facilities: EVN, e-MERLIN, Effelsberg, LOFAR, WSRT, APEX, IRAM-NOEMA, and IRAM-PV. Unfortunately, the consortium had to amend the contract twice due to the withdrawal of the TNA infrastructures JCMT and SRT. The James Clerk Maxwell Telescope – JCMT withdrew from the project because the owner of the telescope, STFC, had decided to terminate operation funding. The Sardinia Radio Telescope – SRT did not become operational and was not available as a single dish to the community under RadioNet3 due to unexpected problems during the manufacturing and commissioning periods. The obligations of JCMT and SRT were distributed among the remaining TNA infrastructures.

At each TNA infrastructure, the calls for proposals were open to all astronomers, not only to experts. The allocation of the observing time was granted basing only on scientific merit. Financial support for TNA users to visit the facilities for observations or data reduction was offered. The TNA users received extensive help from local experts at all stages from the preparation of the observing proposal, through the preparation and execution of the observation until the data reduction. Special attention was given to new users. The intensive support procedure resulted in an increased number of new users and a considerable number of scientific publications. The TNA programme had a great impact; the oversubscription rate of observing time was for almost all TNA infrastructures a factor of 3.

The TNA programme was designed to offer access to European users to the best, world-class research infrastructures. Almost all RadioNet3 infrastructures operate under ‘open sky policy’. The participation in TNA programmes led to an indirect return of the EC contribution into the support of the operational cost of research infrastructures. Some of the TNA infrastructures support the so-called friends of telescopes, scientists who intensively support especially inexperienced users; other TNA infrastructures invested the EC contribution in the upgrade. In all cases the EC funding was of great impact. This funding is vital for the long-term support of the instrument as a whole.

NETWORKING ACTIVITIES – WEAVING THE FABRIC OF SCIENCE

To secure a long-term perspective on scientific and technical development in radio astronomy, RadioNet3 designed and ran a complementary aspect of the Networking Activities addressing the audience and its demands. Making possible more than 100 conferences and workshops, RadioNet3 properly disseminated the scientific results obtained in the last 4 years; this reinforced its relevance during a time when new radio astronomical facilities were becoming fully operational. Overbooked schools (a total of 30) hosted world-leading experts in radio astronomy as tutors and lecturers furnishing inexperienced participants with basics of radio astronomy, instrumental techniques, extending to specific advanced skills. Engineering events succeeded in attracting besides engineers also astronomers interested in instrumentation. This provides a solid and formal ground for mutual growth of technical experience at the various groups and institutes and facilitated using synergies between them. RadioNet3 assured the visibility of the radio astronomical community at national and international spectrum meetings. Thus the frequency bands allocated to the radio astronomy and crucial for high quality observations were effectively protected from the manmade interference.

About 25% of all supported scientific and engineering events were ALMA and SKA orientated. This ensured that the European radio astronomical community will be ready and prepared for the SKA. Access to the ALMA telescope was offered indirectly, since ALMA was not offered as a TNA facility. RadioNet3 supported a large fraction of the European ALMA users by enabling the data reduction at the European ALMA Regional Centre - ARC nodes. The RadioNet3 contribution was of big importance as almost 50% of the entire ARC visits were possible thanks to MARCUs´ support.

JOINT RESEARCH ACTIVITIES – TECHNICAL DEVELOPMENT FOR FUTURE DISCOVERIES

RadioNet3 stimulated new R&D activities for the existing radio infrastructures in form of Joint Research Activities involving 70% of the project partners. The JRAs developments focused on the existing radio infrastructures; however, they are also of interest for ALMA and SKA – the radio telescopes of the future.

UniBoard[2] was to create a computing board aimed at applications that deal with large computations on large streams of data. As radio astronomical instruments become larger and more complex, with everlarger numbers of beams and greater fields of view, they produce more and more data, most of which has to be dealt with in real time. UniBoard2 is perfectly suited for this kind of operation.

UniBoard^2 will be used by JIVE as a VLBI correlator for the EVN. UniBoard2 could have an application for the next generation ALMA digitizers and it has been considered as a possibility for the SKA Low Frequency Aperture Array correlator.

AETHER responded to the critical demand on novel broad-band millimetre and sub-millimetre (terahertz) detector development, which is essential for improving the performance and fully exploiting the capabilities of the leading facilities in this range of wavelength, most notably the European mm/sub-mm telescopes, such as and ALMA. The programme addressed specific prototype needs for the next generation ALMA instrumentation, as well for planned new instruments that will boost the sensitivity of other major European facilities such as the IRAM 30-m telescope, NOEMA, and APEX.

To address the dramatic increase of the quality and volume of astronomical data at present and in the future, a new development model for astronomical processing software has been explored. RadioNet3 Hilado results achieved improvements to the CASAcore (Common Astronomy Software Application) library in the area of enhancements to measurement set access, table queries, and multi threading support. The latest version of CASA is based on the new CASAcore. A fast transient imager developed and deployed to search for transients, was incorporated into the LOFAR Transient Pipeline. A new, fast calibration algorithm was developed and was deployed in the LOFAR data processing pipeline and will in the near future be incorporated in the CASAcore library. Also the developed software reducing the amount of re-computations to the minimum after a change in a data reduction pipeline, based on the SWIFT scripting language, is being incorporated in a CASA-based data reduction environment.

DIVA focused on developments mostly for Very Long Baseline Interferometry (VLBI): a prototype of a wide-band receiver for the low frequency range from 1.5 GHz to 5.5 GHz, which is also usable for SKA, and a VLBI backend with a very large input bandwidth and a very high output data-rate (DBBC3), which allows to make full use of the aforementioned receiver for VLBI. The performance of the coherent and integrated development programme provided RadioNet3 facilities leadership towards future developments and helped to determine the global developments towards the SKA.

RADIONET - LONG-TERM PERSPECTIVES

RadioNet3 provided a sustainable and broad-based platform for the continued organisation of the European radio astronomy community, which is essential for securing a lasting European leadership in all aspects of radio astronomy. RadioNet3 provided a significant input to the report made by the European Radio Telescope Review Committee (ERTRC) - appointed by ASTRONET. From the viewpoint of all astronomy as a whole, this report took a broader look at the current situation of radio astronomy in Europe and its contributions to the scientific goals set out in the ASTRONET Science Vision. The following recommendation for the long-term sustainability was stated by ERTRC:

[7.] "We recommend that local and national radio institutes remain independent, as local support and expertise centres for radio astronomy, but that their joint activities, such as EVN and RadioNet, become more robustly and permanently organised and funded (but not through the same body that organises the European participation in the SKA)."

This is complementary to the vision presented in the RadioNet White Paper, which describes the future organisation and coordination of radio astronomy in Europe. The White Paper recommends an option for the establishment of "RadioNet-work" as an entity that persists between EC contracts, and takes responsibility for preparing or coordinating responses to EC opportunities specific to the field of radio astronomy research infrastructures. RadioNet-work should provide a safety net that ensures that cooperation and collaboration between the various radio astronomy partners in Europe is maintained with or without EC funding.

A description of the main S&T results

NETWORKING ACTIVITIES

The efforts in **WP2-QueSERA** aimed primarily at interaction with policy makers, astronomers, who are not radio astronomy specialists, and the general public. The main result was to formulate a long-term strategy for a vibrant European radio astronomy community. This effort resulted in a policy document – White Paper - that is publicly available and lists the options for continuing the RadioNet interactions. This document, but certainly also the process to establish it, is important for the continuity of the research in the field of radio astronomy. The outreach activity produced a number of books and other material to be used at the various telescope outreach centres. Moreover, a web site was produced to provide a central overview of the joint capabilities of the RadioNet facilities for the general public and astronomers respectively.

The **WP3-SWG** addressed needs within the radio astronomical community as a whole. In particular, RadioNet3 supported and co-organised a total of 62 astronomical events. All together, 12 large conferences, each with an attendance well above 100 participants, 6 small meetings, and 44 topic-oriented meetings could take place. Thematically the events focussed on LOFAR, ALMA, SKA, e-MERLIN, EPTA (European Pulsar Timing Array) and VLBI science results. The RadioNet3 project gained visibility, in particular because the supported meetings were part of EWASS and of COSPAR events. The scientific presentations of the events are available on the respective conference web page and on the RadioNet3 web page, and in four cases also as online proceedings. RadioNet3 enabled young students and expert scientists, as well as participants from emerging countries to attend the events. Roughly 10% of the participants received support. The fraction of women is around 20%, mostly from countries in the Mediterranean area. Most of the attendees (~60%) came from EU and associated countries. Participants from the United States and Canada are the most numerous among non-EU countries (15%).

The **WP4-New Skills** equipped astronomers with the tools to exploit current and future radio astronomy facilities. The new instruments are making great efforts to be 'user friendly' but the huge expansion in wavelength coverage and sensitivity presents a major challenge for the current generation of radio astronomers to update their techniques. Various events aimed at different audiences, from mainly new students across radio astronomy, to specialists seeking to improve and exchange advanced skills. Highlights were the European Radio Interferometry Schools (ERIS) covering techniques from metre to sub-mm wavelengths attended by more than 130 participants and including about 20 tutors, the IRAM 30-m schools offering the increasingly rare chance to perform hands-on observing and analysis with the IRAM-PV dish, and the summer schools of CESRA (Community of European Solar Astronomers) covering solar radio physics theory and hands-on practice of modelling and analysis techniques as well as observations and imaging. Additionally, the continuation of the Young European Radio Astronomers Conference (YERAC) was assured. The YERAC sessions are entirely devoted to early-career participants so that they can gain practice, receive feedback and network. The YERAC in 2012 in Pushchino/RU featured one of the founders Prof. Harry van der Laan.

The **WP5-MARCUs** enabled approximately 40 researchers the visit of one of the European ALMA Regional Centre nodes, where they received expert face-to-face support from the local staff. The majority of these visits concentrated on ALMA data reduction, where users were assisted in maximising the scientific output from their ALMA projects. In the most recent global ALMA users satisfaction survey, this face-to-face support was rated highest of all services provided by ALMA, with 100% of the users judging the help they received as ‘above average’ or better. Of all 165 European peer-reviewed ALMA-based papers to date, at least 30 have benefitted directly from face-to-face support provided by MARCUs. In addition, MARCUs provided financial support to seven meetings and conferences related to ALMA community development and training.

The **WP6-ERATec** improved the communication and scientific interaction between engineers and scientists involved in the development and operation of radio-astronomical instruments. Four Technical Workshops brought together the two groups, engineers and technicians and managed to involve a significant number of scientists interested in instrumentation. The gap of information between the scientific and technical communities decreased. In order to bring the engineering results and expertise of the European radio astronomical engineers to the attention of the broader engineering communities special sessions were organized within the framework of large international conferences (e.g. IEEE, SKA).

Under **WP7-Spectrum Management** RadioNet3 supported participants of CRAF to coordinate the activities for keeping the radio astronomy frequency bands free of man-made interference in order to safeguard this environment for fundamental astronomical research. The organization of five CRAF-meetings was supported; meetings important for the dissemination of information about international developments that may have an effect on radio astronomy and for the discussion in a common policy on these issues. A very important issue was the preparation for the World Radio Conference (WRC-15), 2-27 November 2015 in Geneva/CH; it was attended by more than 3000 representatives, among them four CRAF members. Several agenda items had impact on radio astronomy, but CRAF, together with IUCAF (Scientific committee on frequency allocations for radio astronomy and space science), managed to minimize the impact for most of the agenda items. Furthermore, during the project duration CRAF wrote and contributed to a number of technical or regulatory input documents to the spectrum management process.

JOINT RESEARCH ACTIVITIES

The aim of **WP8-UniBoard^2** was to continue where UniBoard, a JRA of the previous RadioNet (No 227290), had left off. The first UniBoard project created a very powerful and versatile computing platform, that has since been produced in the hundreds and is in actual use in several major astronomical instruments. A lot of valuable experience in digital engineering and firmware programming was built up during this project. Making use of this experience, UniBoard^2 set off to create a next generation board, based on the newest technology, ready for the large radio astronomical instruments of the future, notably the SKA.

In the course of the project one prototype board was produced. After extensive tests and some design modifications, a production run of seven boards was done. The boards are equipped with four 20nm Altera Arria10 FPGAs each, but are pin-compatible with the 14nm Stratix10 devices, which will become available in 2017. Because of the very high number of multipliers on Stratix10, the type of Arria10 with the most transceivers was chosen, as many multipliers need many transceivers to ensure a continuous flow of data.

The PCB has 16 layers. The front side of the board has QSFP+[1] cages; the backside has backplane connectors. The FPGAs have connections to front and backside, the inter-FPGA mesh is implemented on an extension board. This architecture makes the main board highly suitable for a beamformer architecture. Two DDR4[2] modules per FPGA can be mounted on the reverse side of the board. Seven test extension boards were designed and produced, connecting to the backplane connectors and providing some test traces to the FPGAs and the fan control. The form factor of this board is identical to the Hybrid Memory Cube Extension Board, the HEM, of which only one will be produced, after the formal end of the project. Hybrid Memory Cubes (HMCs) are a completely new type of memory devices that are accessed via transceivers, making the memory a part of the mesh between the FPGAs. These HMCs can also be accessed by more than one FPGA at the time, making them ideal for, for example, corner turning operations. The HEM also has QSFP+ cages for additional connectivity. As these HEM boards become available in the future, it will be possible to exchange the test boards for HEMs without any modifications to the enclosure of the UniBoard^2.

The produced UniBoard^{2}s are standard equipped with water cooling. With Arria10 devices one UniBoard^2 provides about 5 TMAC/s, with Stratix10 this will go up to a whopping 21 TMAC/s, comparable to the combined computing power of some 40 of the fastest currently available multi-core PCs. It should be possible to sustain more than 2 Tb/s into the front nodes, and in fact, during tests of

[1] Quad Small Form-factor Pluggable
[2] Double Data Rate fourth-generation

the prototype, the 1 Tb/s barrier was already broken. For comparison, the aggregated traffic on all AMS-IX (Amsterdam Internet Exchange) connected network ports has a peak of 3.7 Tb/s.

Firmware development was spread out throughout the course of the project, with work on pulsar binning and RFI mitigation taking place during the first years. As this firmware is device-independent, the delay in the choice of FPGA and board architecture had no effect on the timing of this effort. After the board design had been decided upon, work on the other applications picked up, with several design documents produced and later revised. A great deal of firmware was ported and re-written and placed in the common repository, and an extensive suite of hardware-independent test firmware modules completed. This test firmware will be delivered with the finished hardware. A number of documents were produced exploring the ways firmware designs can be made to be more power efficient. All these documents are publicly available on the project wiki.

The JRA **AETHER-WP9** addressed technical questions related to the millimetre and sub-millimetre-wave receivers operating in the atmospheric windows accessible from the ground, i.e. from 67 GHz (ALMA band 2) to 1.5 THz (ALMA band 11). Special attention was given to the development of lumped components (mixers, amplifiers, couplers) suited for focal plane arrays of heterodyne receivers (FPAs). Such components are designed for integration into receiver modules that may eventually be installed on existing radio telescopes. The first challenge was to understand the physics of the most critical devices (HEMT[3]s, SIS[4] tunnel junctions, HEB[5]s) and to design miniaturized, albeit performing receiver components. The second challenge was to fabricate in a reliable way such devices and components, some of which have micro-metre or nano-metre sizes. Different technologies had to be investigated, in view of the very wide range of wavelengths considered (7 mm-0.2 mm). The bulk of the effort went on development of (i) wideband C+X-band and W-band semi-conducting MMIC[6] cryogenic amplifiers (LNAs), (ii) miniaturized 2SB SIS receivers fit for mm-wave 2-dimensional FPAs, (iii) DSB and 2SB SIS mixers operating through ALMA Band 10, and (iv) Supra-THz SIS and HEB mixers covering ALMA Band 11. Marking achievements were reached.

A compact LNAs based on GaAS mHEMT MMICs, covering the 4-12 GHz band were developed. A set of 16 units were fabricated and tested at cryogenic temperature. The 16 amplifiers show very similar properties: noise temperature between 4K and 8 K across the 4-12 GHz band and gain ≈ 20 dB. The units have a low power dissipation and are small enough to be packed by two in a 1 square inch footprint, hence are fit to serve as first IF amplifiers in 2-dimensional focal plane arrays of receivers. The 16 units were used for the prototype receiver modules.

A single-pixel 2-polarization receiver module, based on MMIC amplifier operating at cryogenic temperature, was developed and fabricated. It covers the band 67–116 GHz that corresponds to ALMA Bands 2+3. Its mechanical design is compact enough to allow arraying of several such modules into large FPA of heterodyne receivers. Special challenge for the development of all components, besides the requirement of extremely low noise, was the extremely large bandwidth targeted, which is considerably more than the standard W-Band (75-110GHz). The MMIC are based on the GaAs 50 nm gate length mHEMT technology developed at IAF Fraunhofer, which allows large size wafers and relatively low fabrication costs and is well suited for the fabrication of large series.

The first step was to build a 2SB SIS mixer operating at 1-mm wavelength. Apart from requirements of low noise temperature and large RF and IF operating ranges (200-280 GHz and 4-12 GHz, respectively), the mixer module must have a small footprint (≈ 2.5 cm). This implied integrating all components of the 2SB mixer module into one single E-plane split-block. The 2SB mixer module was successfully designed and several units fabricated and characterized. The next step was to design a 7-pixel linear array of receivers, based on the 2SB mixer. The array module consists of 7 horn antennas, an LO signal distribution coupler, 7 2SB mixer E-plane split-blocks and 14 cryogenic IF amplifiers. All

[3] *High-Electron-Mobility Transistor*
[4] *Silicon Integrated Systems*
[5] *Hot Electron Bolometer*
[6] *Monolithic Microwave Integrated Circuit*

the parts were designed and have been or are being fabricated and tested. The horn antennas have an original smooth-walled design, which makes them both inexpensive and easy to fabricate. The 7 2SB mixers show similar performance and are the state-of-the-art for such a wide RF band. Several 7-pixel array modules may be stacked together to form a large 2-D FPA. It is planned that a 49 pixel 1-mm FPA will be built for the IRAM 30-m Pico Veleta telescope.

DSB SIS mixers, covering the frequency band 790-950 GHz have been designed, built and tested in the laboratory. Nb, the standard material used for the junction barrier at lower frequencies becomes inadequate at such high frequencies and was replaced by the AlN alloy, which has a higher energy gap. The mixers are based on Nb/AlN/NbN tunnel junctions of small area that meet both conditions of high gap voltage and high current density. The tested mixers have the required 160 GHz-wide RF bandwidth, but the latter is shifted to slightly lower frequencies. A new iteration should correct the shift. In parallel, a RF hybrid block has been developed, which, combined with 2 DSB mixers and an IF hybrid will allow to separate the signal and image sideband and form a 2SB mixer. It is planned that the developed 2SB mixer will replace the DSB mixers presently installed on APEX/CHAMP+.

AETHER aimed at developing supra-THz mixers that could open to high sensitivity astronomical observations the highest atmospheric windows accessible from the ground or balloons. Two solutions were explored, namely SIS junction and HEB mixers. The fabrication of SIS tunnel junctions operating above 1 THz is a difficult challenge, as it requires barrier alloys with very high gap energies. Nb/AlN/NbN and NbN/AlOx/Nb junctions were designed and fabricated in two parallel developments. The junctions showed the proper high gap voltage, albeit marginally low current densities, which make them improper for low noise mixers. The alternative to SIS junction mixers are HEB mixers, a technology that has the advantage of being readily adaptable to very high frequencies. Two HEB mixer developments with different optics were carried out within AETHER. Both yielded HEB mixers with record noise temperatures of TDSB=400-500 K at 1.3 THz. One of the design has been retained for a balloon experiment.

The scientific and technical goal for **WP10-HILADO** was to create optimized prototype software and demonstrator processing pipelines that improve the capabilities of planned software packages for existing and emerging radio telescopes, characterised by huge datasets (hundreds of terabytes).

CASACore is a C++ library with essential functions for the CASA and other data reduction packages such as those for LOFAR. In the past, the library was maintained in an informal consortium, which severely limited further optimisation. HILADO made substantial improvements “under the hood”, leading to significant efficiency improvements and making processing of very large datasets possible: an interface between data in several formats from different instruments and the CASACore internal data format was implemented, other parts have been made thread-safe, allowing CASACore to be used in multithreaded programs, exploiting available parallelism and potentially reducing processing time. The CASACore table system was improved to support state of the art file systems, and the functionality of its table querying language was extended, resulting in enhanced usability. The CASACore image library has been enhanced to support instrument-specific meta data. Besides such functional extensions, CASACore’s implementation was brought in line with the C++ 2011 standard, improving maintainability. By moving the CASACore repository to github, access and availability for the larger radio astronomical community was improved.

The growing size of data streams prohibits interactive processing, moving data reduction into the domain of streaming processing. Through the development of a Fast Transient Imaging Pipeline (FTIP), HILADO both built a specific application (boosting LOFAR Transient Processing) and developed insights and components to ease further development in this area. The FTIP deals with a number of challenges in the area of (near-) real time data processing with state of the art radio astronomical instruments: handling the data communication between instrument and processing facilities, detection and removal of non-astronomical interference, removing the effects of very strong sources outside the field of view (demixing), data calibration, and imaging. A demonstrator pipeline was implemented and tested, showing encouraging results. The imaging library in CASACore was enhanced to make it possible to stream the resulting images to the TraP pipeline, which searches for transients in the images.

The calibration of observations obtained by modern radio astronomy interferometers such as LOFAR is a very intensive computational task. HILADO studied the mathematical foundation and implementation of Fast Solvers for this type of radio astronomy applications. Current mainstream methods, such as the widely used Levenberg-Marquardt algorithm, scale unfavourably with the large number of antennas in modern and future instruments. In HILADO a new iterative approach was therefore studied, implemented and applied, commonly referred to as StEFCal, with far better performance and scalability properties: StEFCal's number of operations depends on the square of the number of antennas, with particularly favourable memory access patterns. A rigorous mathematical assessment of its properties was also provided. Both non-polarized and polarized versions of StEFCal have been developed, as well as a number of variants to study the reduction of noisy data. StEFCal has been applied successfully in a number of real applications: for the calibration of LOFAR antennas; in the MeqTrees package. StEFCal is being considered and studied as the likely calibration algorithm for the SKA. Preliminary work towards the incorporation of StEFCal in CASACore was carried out and it was ported experimentally to GPUs.

Processing datasets from radio interferometry observations, often with tools such as CASA or AIPS, is an experimental endeavour. Data reduction pipelines consist of a sequence of data processing tasks, where each task must be tuned for optimal results. Data reduction pipelines are often implemented as scripts in e.g. Python, detailing the order and operational details of each step. In the simplest case, the tasks in such a script are run from first to last. Changing the setting of a downstream task results in redoing all computational steps, even unchanged steps upstream from the changed one. As data reduction is often compute-intensive (time consuming), automatically skipping such unchanged computational operations and reusing the results from earlier pipeline runs can save a lot of time and energy.

To this end, a set of tools was reworked to perform a minimum re-evaluation of results from a modified data reduction script. It targets the parallel Swift scripting language, popular in MRI applications, which face similar challenges. Interfacing Swift with AIPS is done through ParselTongue support in Swift. (ParselTongue provides an interface between AIPS and the Python programming language.) Also, a tool was developed that captures the dataflow of a CASA data processing script, producing a graph showing the data dependencies between each of the CASA tasks together with a companion tool which takes the data dependency graph and generates a Python script, which can then be run through CASA. A prototype ParselTongue/AIPS-based imaging pipeline for Very Long Baseline Interferometry (VLBI) that uses the Swift parallel scripting language was developed as well, together with tooling to generate data flow graphs for ParselTongue pipeline runs. Even though the re-computation-elimination engine has not been adapted to handle this Swift/ParselTongue combination, this does show that even a legacy environment like AIPS can benefit from modern functional programming techniques.

JRA **DIVA-WP11** focused on two development tasks, both mostly for VLBI: a prototype of a wide-band receiver for the low frequency range from 1.5 GHz to 5.5 GHz, which is also usable for SKA, and a VLBI backend with a very large input bandwidth and a very high output data-rate (Digital Base-band Converter – DBBC3), which allows to make full use of the aforementioned receiver for VLBI.

DIVA evaluated the performance of commercially available Silicon Germanium (SiGe) heterojunction bipolar transistors (HBT) as Low Noise Amplifiers (LNA) for radio astronomy. Recent advancements in SiGe BiCMOS technology have created an interest from RF designers for the use in LNA, in particular for phased array radio telescopes, like the SKA, because of their high volume tape-out capability and the low power consumption of the devices. The LNAs were designed with packaged SiGe HBTs from the 7th generation QUBiC4 process of NXP Semiconductors.

Additionally wide-band MMICs (Monolithic Microwave Integrated Circuit) were developed and packaged. The resulting two LNAs (one per polarisation) were connected with a feed horn and tested. The initially proposed range of 1 GHz to 4 GHz was changed early in the project to 1.5 GHz - 5.5 GHz to match the new frequency range decided by the SKA wide-band single pixel feed consortium and make the new LNA/feed combination suitable for the SKA.

A design based on a Quad Ridge flare horn (QRFH) feed was realised. The particular QRFH was newly developed as part of the SKA program. The RF chain consists of two DIVA LNAs directly connected to the corresponding ports of the feed. The test showed receiver noise of about 15 K between 3 GHz and 5.5 GHz, which is a very good result. The receiver noise varies between 1.4 and 3 GHz due to impedance mismatch.

In the course of the project a backend DBBC3 was designed, based on the know-how gained from the previous work on the DBBC2, which is now used as the standard backend in the EVN and the geodetic network. The aim of DIVA was to extend the usable bandwidth to 4 GHz per polarisation with an output data-rate of 16 Gbps per polarisation.

For the DBBC3 a sampler board was designed and produced (ADB3L), which uses four 1GHz-wide samplers to sample a 4GHz-wide band at base-band. Directly connected to the ADB3 board is a single FPGA (Xilinx Virtex 7) processing board (CORE3) which outputs several high speed data streams to the FiLA-40G. The FILA-40G post-processing unit is realised by means of a high-end computer in a RAID chassis with four 10GE and one 40GE ports and a large number of fast disks connected via a high-end RAID card. The FILA-40G was designed for the functions needed for further processing of the data of the four 8 Gb outputs of the CORE3 including the capability to record at 32 Gbps for short periods of time.

The DBBC3 was tested in laboratory and in field. The laboratory tests showed that the system works as expected. The field test was an observation at 22 GHz between the two antennas in Onsala and Effelsberg using a bandwidth of 4 GHz. Both DBBC3s reproduced the input band as expected, and real interference fringes were found. The DBBC3 system is modular and can be extended up to 128 Gbps by using eight 4 GHz wide inputs, for which additional stacks of sampler board plus processing board have to be added.

TRANS-NATIONAL ACCESS ACTIVITIES

The **WP12-EVN** TNA programme strengthened the European radio astronomy community by lowering thresholds for accessing the EVN through funding of support capabilities at JIVE and participating EVN institutes as well as visits by individual team members. There were a total of 336 different observations arising from 158 TNA proposals. These TNA projects were conducted by teams that included 434 individual researchers of whom 68% were affiliated with institutes in 17 EU members and associated countries (BE, DE, DK, ES, FI, FR, GR, HU, IE, IL, IT, NL, PL, PT, RO, SE, UK). The future generation of radio astronomers benefited from the TNA programme. There were 48 individual students involved in EVN TNA projects, of which 85% were affiliated with institutes in EU member and associated states. Sixteen of these students were team leaders of a project. The use of TNA support to help broaden the user base of the EVN also paid dividends: of the 84 individual team leaders of eligible projects, 46% had never previously been team leader of an EVN project. The amount of provided access over RadioNet3 was 2918 hrs, exceeding by 4.5 times that contracted. The EVN-TNA enabled European and international researchers to attack a wide variety of cutting-edge astronomical questions: e.g. the evolution of galaxy and star formation, supernova, active galactic nuclei, transient events, blazars, gamma-ray bursts and X-ray binaries, the interstellar medium, and Planets.

Interest in using the EVN remains high. The oversubscription ratio, defined as the network hours proposed within a year divided by the actually observed network hours, stands at 2.4. Support subsequent to observing has proven to be a critical aspect of expanding the EVN user base, in terms of bringing in both students as well as more experienced astronomers from outside of the traditional radio astronomy community. Thirty-six visits to JIVE or other EVN institutes (OSO/SE, ASTRON/NL, MPIfR/DE, UMAN/UK, INAF/IT) received travel support; ten of these were made by students and five by more established researchers new to radio interferometry. A total of 23% of the EVN-TNA projects had a female team leader, and 29% of the 84 distinct team leaders of the TNA-eligible projects were women. A higher percentage, 39%, of EVN-TNA supported visits was made by women.

The biennial EVN symposia provided a forum to highlight recent EVN results, receive feedback during the Users' Meeting, and discuss more extended global collaborations. The symposia during the RadioNet3 period drew more than 120 participants, of which average of 17% from non-EVN institutes.

The **WP9-e-MERLIN** TNA programme offered the European radio astronomy community access to the e-MERLIN facility and a full range of remote and face-to-face support to individual user teams. Individual users benefited significantly from travel funding opportunities to access the facility directly and be trained as new radio astronomers. In total, e-MERLIN provided over 1500 hours of observations for 35 TNA eligible programmes over the RadioNet3 period, exceeding the contracted hours by a factor of 2.3. These projects involved 205 individual researchers of which 77% were affiliated with institutes allocated in EU (excluding UK) and associated states.

At the beginning of the period of RadioNet3 the e-MERLIN facility undertook its first initial open science observations, following significant facility upgrades prior to 2012. As a new instrument, e-MERLIN, required enhanced support and specialist training from facility staff for the users. The European radio community benefited significantly from the additional support by the TNA programme, which facilitated science and enhanced the growing user community. The scientific interest in e-MERLIN through this period was exceptionally strong, with typical proposal rounds oversubscribed by a factor of 5 (defined as the ratio of requested science observations and available observing time). Through this period, the overall user base for the facility continued growing with a number of new user groups emerging from within Europe.

The **WP15-Effelsberg** TNA programme helped European radio astronomers to get easier access to the 100-m telescope of the Max Planck Institute for Radio Astronomy, one of the world's biggest fully steerable radio telescopes. The telescope has an oversubscription factor of about two (ratio of requested observing time to the time granted). During the reporting period, 29 projects could be supported within the framework of this programme, corresponding to 1036 hours of observing time, some 5% more than contracted. Included in these projects, there were 66 individual researchers coming from AT, FR, FI, GR, HU, IT, PL, PT, ES, NL and UK. Out of these 66 scientists, 31 persons were early stage researchers (students and postdocs) and one third were women. A substantial fraction of the PIs (60%) were new users of the Effelsberg 100-m telescope, female scientists led one third of the teams. Travel support was granted to more than a half of the projects, facilitating the visit of the observatory for the concerned scientists.

The **WP16-LOFAR** TNA programme significantly contributed to the European radio astronomy community. Access to the transformational new facility LOFAR was given as well as funding support capabilities at LOFAR's operations centre, and funding for research visits to the facility. The first regular observation started in December 2012. LOFAR offered 3200 hours per year. Demand for LOFAR time was significant, 200 proposals were accepted and observed during the RadioNet3 period. 48% of all projects were offered under the TNA programme. On average this translates to 40 accepted proposals per semester with an oversubscription rate of 1.6. In each semester this involved about 228 individual researchers, of whom 68% have affiliation outside the Netherlands. A study of the demographics of LOFAR users shows that most proposals involve several graduate students or young researchers (representing a ratio of 50% or more in each proposal).

The gamut of LOFAR science covers from cosmology and extragalactic research to Galactic, planetary, and solar system topics, and was presented by LOFAR users at large conferences: the 2nd LOFAR Collaboration Science Workshop (March 19-20, 2013; attended by 105 participants), the LOFAR Community Science Workshops (8-9 April 2014, attended by 117 participants and 1-2 June 2015, bringing together 90 researchers).

In view of its upgrade with the APERTIF phased-array system, the **WP17-WSRT** TNA operated for only part of the period covered by RadioNet3. Nevertheless, the interest remained high. LOFAR received a total of 174 proposals by 380 individual authors with an over-subscription factor of around 2. The vast majority of the authors (73%) were affiliated to an institute not based in the Netherlands, demonstrating the strong appeal of WSRT to the international community. The group leaders for almost half of the proposals (49%) were also affiliated to an international institute. The demand for transnational access was also noticeable (19% projects). The TNA programme was also contributing to the development of young researchers; 55% of the group were graduate students, the remaining were young researchers. More than half of all group leaders were also first time users of the WSRT instrument. Females led half of all TNA projects. Most of the projects received an extensive support in the remote use of the infrastructure.

The European community's interest in using the **WP18-IRAM** TNA facilities kept growing during RadioNet3. In the years 2012-2015, IRAM observatories received more than 1900 observing proposals from more than 1400 unique users originating from 45 countries. In the same period, IRAM counted over 250 TNA proposals submitted by researchers affiliated to scientific institutions from 18 European countries (AT, BE, CH, CZ, DK, FI, GR, HR, HU, IE, IL, IS, IT, NL, PL, PT, SE, UK) and from 2 independent international organizations (ESO, ESA). TNA observing time at the IRAM facilities was granted to 167 TNA eligible proposals for observations with the NOEMA interferometer (68) and the 30m-telescope (99). The observing capabilities offered by the two facilities to TNA groups benefitted to more than 200 researchers with a well-balanced distribution between senior scientists and younger PhD students. IRAM provided a total of 4032 hrs to TNA projects (1143 hrs granted for NOEMA interferometer and 2889 hrs for the 30m-telescope). This amount exceeding the contracted obligation by a factor of 8 (NOEMA) and 7 (30m-telescope), testifying to the overall success. A total of 67 astronomers received financial support to visit IRAM facilities. Guidance and support was provided to all visitors to ensure the highest quality results on every project.

The synergy of IRAM with ALMA and the HERSCHEL heritage showed to be of the utmost importance for the European scientists. They were the key to EU astronomers to prepare, complete and complement observations from these major astronomical facilities, a fact which can be traced by the large number of successful EU proposals for ALMA. IRAM runs regular training schools to promote astronomical research at (sub)millimetre-wavelengths with state-of-the-art facilities. The IRAM schools are open to qualified researchers from all branches of astronomy, and concentrate on interferometry and single dish observing. During RadioNet3, an interferometry school was held in Grenoble/FR (15-19 October 2012) and two single-dish schools in Pradollano/ES (13-20 September 2013 and 11-18 September 2015). All schools were oversubscribed.

The **WP19-APEX** TNA programme enabled a large number of European scientists to use this world-class submillimetre telescope. During the 4-years period of RadioNet3, a total of 66 TNA eligible user-projects were observed with the APEX telescope, for a total of 825 hours (2.5 times the contracted hours). These projects were led by 45 different individual scientists from 10 different European countries (AT, BE, DE, DK, ES, FI, FR, IT, NL, and UK). About half of the team leaders were post-docs, the rest approximately equally distributed between post-graduate students and experienced researchers. There were typically 4 or 5 TNA eligible users in each user-group. The interest in using APEX was high throughout the period. In total, TNA eligible user-groups applied for 2240 hours of observing time, distributed among 114 different projects. Thus, 58 % of the proposed TNA eligible projects were observed, and about 37 % of the requested TNA time was allocated.

The TNA eligible projects carried out at APEX covers a large range of astrophysical topics, including star and planet formation, evolved stars, the interstellar medium (in the Galaxy, the Magellanic Clouds and in more distant galaxies), and active galactic nuclei. The conference Science with the Atacama Pathfinder Experiment (APEX) took place 19–22 February 2014 at Ringberg Castle/DE and hosted about 70 registered participants including several TNA users.

The potential impact and the main dissemination activities and exploitation of results

The primary aim of RadioNet3 was to integrate the key European research facilities in radio astronomy and their resources with a long-term perspective. The RadioNet3 project was accordingly structured to maximise the integrating effect.

IMPACTS OF THE NA PROGRAMME

Timely and effective communication of results and uninterrupted interchange of ideas are important for advancing cutting edge research programmes and constantly progressing science and technology. The networking activities of RadioNet3 promoted these vital aspects. The main impacts of the NA programme were:

- preparation of a long-term strategy for structuring radio astronomy in Europe in the periods without EC funding,
- enabling the dialogue on future research directions,
- representation and advertisement of radio astronomy facilities and ambitions within the three major stakeholder communities: the European policy makers, the broader, European and worldwide astronomical community, and the general public,
- assuring of the availability of the results to the outside world in a comprehensible and coherent form,
- establishing interaction between the scientific and engineering fronts,
- ensuring that the next generation of scientists and engineers are exposed to, and become familiar with, the capabilities of the RadioNet facilities,
- strengthening the European astronomy community by offering access to the European ARC nodes and boosting their effectiveness by establishing an efficient exchange mechanism for best practices,
- training of students and new users in the techniques of radio astronomy,
- protecting the European and global radio frequency environment in which the RadioNet facilities and future telescopes operate.

IMPACTS OF THE JRA PROGRAMME

The RadioNet3 JRAs stimulated new R&D activities for the already existing radio infrastructures in synergy with ALMA and with the SKA, as the radio telescope of the future. This ensures that Europe has the scientists and engineers that are ready for the next period, when the possibilities for radio astronomy research will be revolutionized by the advent of the SKA. The JRA developments keep the existing facilities state-of-the-art and competitive with other world-class facilities.

The UniBoard^2 project aimed at the creation of a computing platform to address the needs of the large radio-astronomical instruments of the future, specifically the SKA. UniBoard^2 was the de facto board of choice for the construction of the SKA LFAA correlator, and a large amount of firmware was written to this purpose. In the end the LFAA consortium was re-arranged and the decision was made to design new hardware for the correlator. As this new board will also be FPGA-based, the experience gained in the UniBoard^2 project will certainly feed into this effort.

The board is currently equipped with Arria10 FPGAs. With Stratix10 devices it will turn into a veritable computing powerhouse. Several instruments may benefit from this:

- The Apertif Radio Transient System, which will be used to do pulsar timing, VLBI and fast-transient searching with the upgraded WSRT will definitely use UniBoard2.
- The large number of transceivers and multipliers will make UniBoard2 an ideal platform for a next version of the JIVE UniBoard Correlator, easily overcoming the computational limitations that the current UniBoard imposes.
- Optimization of FPGA resources and of the transceivers on UniBoard2 offer new possibilities for ALMA digital signal processing in two polarizations.
- The Nancay Radio Observatory in France plans to move the RFI mitigation firmware, now implemented on UniBoard, onto a UniBoard2 when it becomes available.
- UniBoard2 with Stratix10 will offer so much connectivity and computing resources that it will be an ideal platform to experiment with a high-level programming language such as OpenCL. This language potentially offers an enormous simplification and speed-up of the programming effort, compared to traditional VHDL, but at a cost of lower computing efficiency. Considering the effort and time that is spent on firmware programming nowadays, moving to high-level programming languages could be a game-changer in FPGA computing.
- Finally, many applications have ever-increasing needs for computing power at the lowest possibly energy consumption. The availability of this board, from 2017 on equipped with 14nm FPGAs, will certainly influence future upgrades of existing applications.

AETHER responded to the critical demand on novel broad-band millimetre and sub-millimetre (terahertz) detector development, which is essential for improving the performance and fully exploiting the capabilities of the leading facilities in this range of wavelength. This apply most notably to the major European mm/sub-mm telescopes, such as the IRAM 30-m telescope, NOEMA, APEX and ALMA, for which next generation instrumentation is planned for the short or medium term. The progress made in AETHER with respect to previous state of the art for the performance of key receiver components:

- Extremely wideband mm/sub-mm MMIC LNAs and SIS mixers has already an application in the current upgrade of the IRAM 30-m and NOEMA receivers. Several components were designed for integration into heterodyne focal plane arrays. They are a first step toward the realization of large arrays. Plans exist to build in the near future such arrays for the 30-m and the APEX telescopes.
- Similarly, the developments made in AETHER for supra-THz HEB mixers were applied for the construction of the dual-pixel dual-polarization receivers for the Stratospheric Terahertz Observatory STO2.

Hilado developed computing approaches to address the dramatic increase of quality and volume of astronomical data with the advent of new facilities and advanced observational techniques. Thus pushed the capabilities of the RadioNet interferometer telescopes by enabling observing modes that otherwise cannot be supported. These developments are essential to increase the potential of the RadioNet3 user community in opening up those facilities for the more demanding scientific applications:

- NRAO started using CASACore as the base for the CASA radio astronomical reduction package. This resulted in October 2015 in the first CASA release based on the new CASACore library. The releases of CASA and CASACore are expected to be synchronised in the near future.
- The software group at ICRAR (http://www.icrar.org, not part of HILADO) in Australia is developing a storage manager, based on the HILADO work on table storage, to improve IO performance for some often used cases. The goal is to see if it can be used in the SKA software development.
- The ‘Transients team’ at the University of Amsterdam built the TraP (Transient Pipeline) software based on HILADO developments, to extract transients from images produced by offline DPPP/awimager software. First results were published (see DOI 10.1016/j.ascom.2015.03.002).

DIVA developed key technology building blocks for centimetre radio astronomy that will increase the bandwidth and therefore sensitivity of European facilities including the European VLBI network. The successfully tested integrated receiver opens the possibility for using the development concept in projects like:

- future geodetic VLBI (VGOS): The application of both QRFH and LNAs or either of them in VGOS is quite straightforward, in terms of system design, and only some further design optimisation in terms of bandwidth must be performed.
- EVN: The system can be used on the EVN telescopes with primary feeding, re-design of the optics is necessary for using the system on Cassegrain systems.
- SKA: The frequency band of the receiver covers Bands 3 and 4 from the SKA baseline design and Band A of SKA Wide Band Single Pixel Feed Advanced Instrumentation Program. The experience gained in the development of both LNA and QRFH designs will be applied for further SKA progress.

The DBBC3 is widely regarded as the next version of a very flexible and powerful VLBI backend of the next generation. It competes with US-American, Chinese, Russian, and Japanese backends. It is expected that the DBBC3 will win over the competing backends for wide-band geodesy, and mm-VLBI. The first DBBC3 was delivered to the Hobart VGOS antenna of Auscope/AU (the national provider of integrated research infrastructure to realise the collective potential of Australian Earth and Geospatial Science researchers). It is planned to upgrade the IRAM-PV/ES and APEX/CL telescopes in the beginning of 2016. Both will then be able support observing with the EHT. Additionally, DBBC3 backend has already been ordered by several EVN stations.

IMPACTS OF THE TNA PROGRAMME

The TNA programme of RadioNet3 offered access to world-class research infrastructures in Europe. Although these facilities operate (at least partly) on the principle of "open skies" access, the TNA programme is absolutely essential in assuring that this principle can be maintained and that a level of support that really allows non-expert users from all over Europe to access these facilities can complement the policy.

The impacts from the RadioNet3 TNA programme were:

- remove technical, financial and logistical barriers which prevent European astronomers from taking full advantage of these world leading facilities,
- encourage external European use of the full range of nationally funded radio astronomy facilities,
- contribute towards the provision of a high level of professional support given to European users of nationally funded facilities covering all aspects of their use, from proposal preparation, through scheduling and execution of observations, to data analysis and interpretation,
- provide external European users with the opportunity to visit world-leading radio astronomy facilities, to participate in the observing process, and to interact with other expert engineers and scientists at these institutes,
- maintain the global competitiveness of the TNA facilities In Europe by continued technical development and substantial investments.

The anticipated outcome of this broader European use of radio astronomy facilities was an increase of the scientific output of European research groups. The results of RadioNet3´s TNA programme were published in front ranking astronomical and multi-disciplinary science journals (e.g. Science, Nature), and often also posted on open-access pre-print servers. Additionally, many of these results were presented at high impact international conferences and seminars. Furthermore, all observations and data obtained by the RadioNet3 infrastructures will become publicly available to all users after an initial embargo period defined by the individual observatories. These data become available to be used by all for further exploitation – for resulting in many future outputs.

The project public website

http://www.radionet-eu.org/

Promoting the work of the project.

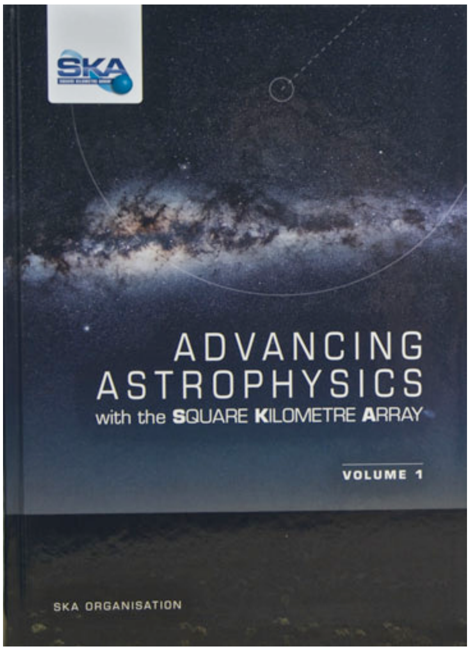
RadioNet3 logo

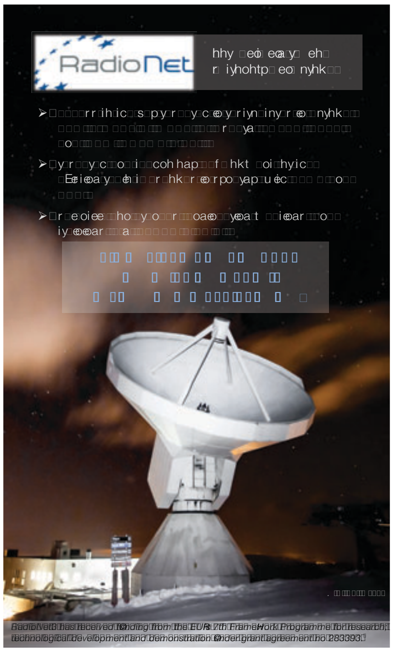
RadioNet3 flyers

RadioNet3 roll-up displays placed at the supported events.

Left: RadioNet3 roll-up displays at the EWASS 2013 (Turku/FI 2014). Right: the booklet "The Invisible Universe" realized together with the UNAWE project (FP7-263325).

Left: New SKA science book, Advancing Astrophysics with the Square Kilometre Array, published in two volumes in 2015, sponsored by RadioNet3. Right: The advertisement inserted in the EWASS2015 programme (Tenerife/ES).

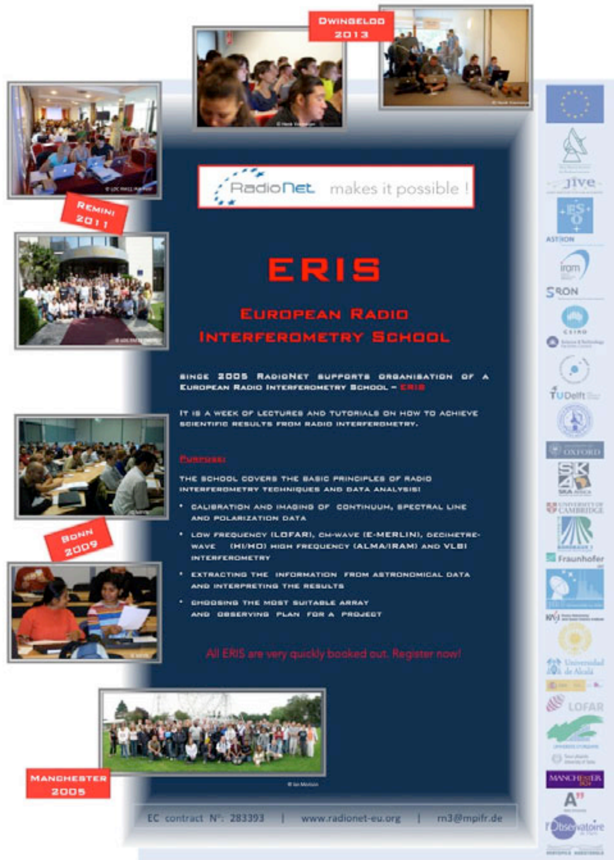




Interactive map of the RadioNet facilities (http://www.radionet-eu.org/mapview).

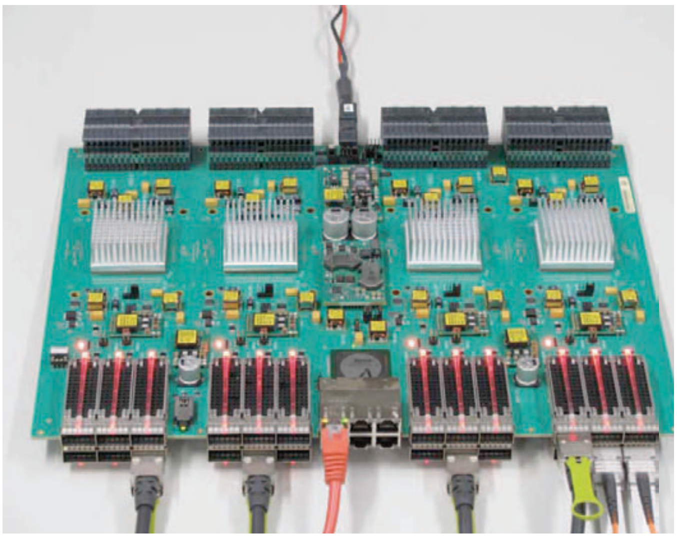
YERAC poster created for the RadioNet3 booth at EWASS2014 (Geneva/CH).

ERIS poster created for the RadioNet3 booth at EWASS2014 (Geneva/CH).



Front view of the DBBC3 – a VLBI backend developed in JRA DIVA.

First production UniBoard[2] powered up and connected, development of the JRA UniBoard[2]



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