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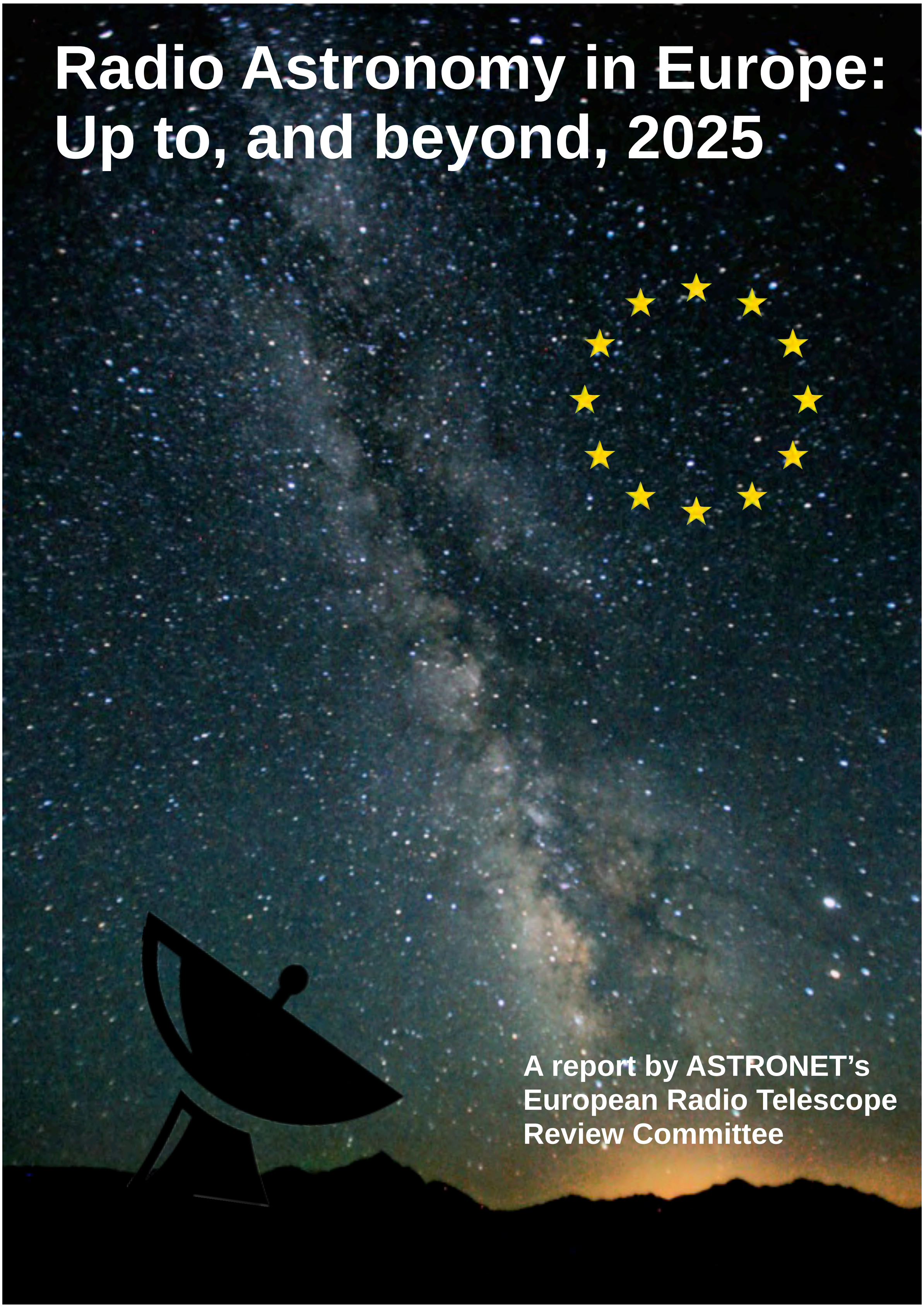

Radio Astronomy in Europe: Up to, and beyond, 2025

A report by ASTRONET's
European Radio Telescope
Review Committee

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Chapter 1: Executive Summary

Radio astronomy in Europe has played a predominant role for more than 5 decades, both in terms of outstanding scientific achievements, and cutting edge technical work. To mention only a few major achievements: the discovery of the 21cm line of neutral hydrogen and its use in the study of the structure of the Milky Way, the role in discovering radio recombination lines from ionized hydrogen (H II) regions, the discovery of pulsars and their use in the fundamental study of gravity and space-time, the survey work that led, e.g., to the identification of the first quasar (3C 273), structural studies of radio sources from arcminute to sub-milliarcsecond scales, the many-faceted work on masers, the study of cosmic magnetism, etcetera. Given this outstanding record, European radio astronomers naturally strive to continue this success story into the future.

The present report was initiated by the ASTRONET Board to take a broader look, from the viewpoint of all of astronomy, at the present situation of radio astronomy in Europe and the contributions this field can make to the scientific goals set out in the ASTRONET Science Vision. The review that the ERTRC was tasked to carry out in concert with RadioNet, complements the ASTRONET Roadmap exercise which highlighted, by design, only some of the future needs of radio astronomy.

The timing of this review is motivated not only by the current Science Vision, which has recently been updated since it was first published in 2007, but *a fortiori* by the ongoing efforts to prepare the Square Kilometre Array (SKA) project, which will constitute a giant leap forward for radio astronomy in many respects (sensitivity, survey speed, etc.). The unprecedented size of this project clearly requires global collaboration of the radio astronomical community.

We have examined in detail how radio astronomy contributes to the goals of the Science Vision, and find that its contribution is very significant in many areas, and absolutely crucial in some, such as those mentioned above. Many of the existing facilities contribute to this, and will continue to do so well into the future, even after Phase1 of the Square Kilometre Array is fully operational. At the same time, the Square Kilometre Array will be crucial in achieving some of the most ambitious goals of the Science Vision, and thus Europe must continue to play a strong role in its development and exploitation.

Besides the facilities themselves, the human capital of European radio astronomy is also a crucial factor to its success. This means that thorough training of new radio astronomers is needed at all levels, from the occasional non-expert using only standard data analysis to black-belt experts who drive innovation. Increasingly, radio astronomy is being revolutionised by large-scale computing, and so the expertise that is needed includes such skills as software engineering and supercomputing. As observatories become more and more complex, thorough systems engineering is also essential. This human capital is vested in the radio institutes and observatories and university groups, whose continued existence is therefore key to a strong future for European radio astronomy.

Increasingly, astronomy is done in an object- or problem-centred way, and not segregated by observing method. As such, there will be fewer `pure radio' astronomers in the future, and much of the use of radio data will come from people who are not black belt experts. In order that the science return of radio observations is maximised in this new mode of working, better access to data via public archives and more standardisation of data reduction techniques is required.

The existing large single-dish observatories will remain important for a long time still, but we do note an increasing importance in linking those observatories together in pan-European efforts such as Very Long Baseline Interferometry, and concerted campaigns for the most accurate pulsar timing ("LEAP"). Such international collaboration is a strong and old tradition in radio astronomy, of course, and we think that this trend will continue even more strongly as the Square Kilometre Array becomes the world's premier facility.

In summary, radio astronomy is changing rapidly and considerably, and we must adapt to those changes to remain at the forefront. We see a need for closer collaboration between the existing radio observatories (but not their assimilation into a large conglomerate: their local and independent role remains crucial to provide support to observers, and technical innovation to the field). The current pan-European structures may well not be robust enough in their organisational structure and funding stability to last long into the future; the ERIC structure that has just started for JIVE holds some promise as a sufficient structure, provided the partners in such an ERIC can commit to long-term funding. This trend is entirely in line with what other fields, such as optical and submillimetre astronomy and particle physics have gone through before: as the complexity and size of the facilities needed to make progress grows, so does the need for stronger and more durable international collaboration. A particular problem for radio astronomy that also requires a well-organised European effort is the continuing encroachment of commercial use on the protected radio frequency bands.

For the biggest facility foreseen now, the Square Kilometre Array, none of the existing transnational structures in radio astronomy are durable and robust enough to undertake its building and operation. We agree with the Square Kilometre Array organisation that an international treaty organisation should be constructed to build and operate it. Furthermore, based on the examples of ESO, ESA, and CERN, we also feel that the impact of Europe in the Square Kilometre Array will be much greater and more effective if the European countries organise themselves first into a local European organisation, and join the Square Kilometre Array through it. The ERTRC considers ESO to be a prime candidate to be that organisation.

In short, our report describes a field that is vibrant and ambitious, but also rapidly changing. We expect it to continue its crucial contribution to the Science Vision well into the future, and to require even stronger international collaboration than at present to achieve that. Finally, we list the short summary recommendations of our committee from Ch.12:

1. Radio astronomy, with existing and upcoming facilities, including the SKA, will make unique and essential contributions to our knowledge of the Universe in key areas described in the ASTRONET Science Vision.

2. Continued and coordinated efforts in technical development and in attraction and training of talent are required to keep radio astronomy vital and relevant.

3. Protecting radio frequencies for scientific use continues to be essential.

4. Key capabilities and excellent science are delivered by old and new pan-European collaboration and coordination of facilities.

5. Key science is delivered by coordination of radio observations with observations at other wavelengths; such coordination should therefore be facilitated.

6. Wide and easy access to radio astronomical observatories and data significantly increases the amount of excellent science delivered. This should be promoted through "open skies" policies (i.e., merit-based access to telescopes by all astronomers) and the use of archives and standardized data reduction techniques.

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).

8. We recommend that the European involvement in the SKA be organised through a treaty organisation that is robustly mandated and funded, to ensure the strongest impact of and participation in SKA by Europe. The ERTRC considers ESO to be a prime candidate to be that organisation..

Chapter 2: Introduction

2.1 – Background and method

The review of European radio telescopes presented here results from the activities of ASTRONET, the EU-FP7 ERANet for astronomy, to chart the future of European astronomy. The initial effort was reported on in two documents, a Science Vision outlining the opportunities and priorities for European astronomy (2007), and a Roadmap translating that vision into a plan for building the required large-scale facilities (2008). These updates have been finalized at the time of writing of this report, and will appear in Spring 2015. One outcome of the roadmapping exercise was a realization that some specific areas of astronomy required a closer look by a specialized panel. Among these were astronomy with 2-4m class optical telescopes and radio astronomy. The *Report by the European Telescope Strategic Review Committee on Europe's 2-4m Telescopes over the Decade to 2020* has appeared, and the present report concerns radio astronomy.

In order to review European Radio astronomy facilities, the ASTRONET board instituted the European Radio Telescope Review Committee (ERTRC) in 2011. It was constituted to contain a range of expertises and backgrounds and – given that no reasonably sized panel could cover all required expertise – the assignment to consult extensively with the community. The terms of reference for the ERTRC were set by the ASTRONET board and are given in Appendix A, and the membership of the committee in Appendix B. It is important to note that, while the ERTRC consulted extensively with the astronomical community, and in particular with the many radio observatories and their organising bodies, the consulted parties share no responsibility for this report. It is important to emphasize that the ERTRC draws expertise and advice from the *entire European astronomical community,* and thus our report is not an internal view by the radio community of itself, but the view of the full European astronomical community.

2.2 – New horizons in radio astronomy

Radio astronomy in Europe is in a phase where several new facilities have recently been constructed, commissioned and are now into scientific operations (e.g. LOFAR and the Sardinia Radio Telescope). Other facilities have recently undergone, or are undergoing, significant technical enhancements (e.g., e-MERLIN and e-EVN), or major extensions (e.g., PdB-NOEMA and the APERTIF focal plane array on WSRT). In parallel, European radio astronomy groups are heavily engaged in the scientific case, conceptual design and technical development of a very large, next generation facility: the Square Kilometre Array (SKA). As is well demonstrated by the SKA project, a clear trend in the radio astronomy community, as in other areas of astronomy, has been towards increasing scale and complexity of observatories, prompting the need for more international collaboration. This will undoubtedly also affect the current organizational structure of the radio-astronomical community in Europe.

While the current activities are primarily carried forward by existing, and often long-established radio astronomy groups in Europe, it is clear that in the future use of radio-astronomical facilities will be (and must be) made by a very much broader scientific community. This will probably organize itself in groups of astronomers who share the same scientific interests and combine their complementary observational experience in order to collect and analyse data obtained throughout the entire range of the electro-magnetic spectrum. This cultural shift is already being demonstrated by the international science teams preparing to exploit (and in some cases already exploiting) the three official SKA "Precursor" telescopes[1] (i.e. MeerKAT,

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[1] See https://www.skatelescope.org/precursors-pathfinders-design-studies/

ASKAP and MWA), and the expert teams forming the SKA Science Working Groups. Europe also proudly hosts more than half of the official SKA "Pathfinders", which, like the Precursors, serve as critical stepping-stones towards the SKA (LOFAR, EMBRACE, APERTIF, NenuFAR, e-EVN, and e-MERLIN). The discussions of the scientific topics that have been identified as the key science questions for the period up to 2025 in the ASTRONET "Science Vision" document, and that have guided the preparation of the "Roadmap" towards future facilities, have clearly highlighted the increasing role of multi-wavelength studies and large international teams.

2.3 – Approach and mode of operation

The ERTRC activities began with the preparation of a questionnaire (see Appendix C), which was sent out to all major radio-astronomical facilities in Europe. The aim was to establish an inventory of the hardware (and software) that exists today in radio astronomy in Europe. The observatories could also define their contributions to the realisation of the ASTRONET Science Vision goals. From the answers it has furthermore been possible to compile a list of on-going and planned upgrades to these facilities, which will continue the effort to significantly enhance their capabilities. While many of the ASTRONET Science Vision goals are currently being addressed with existing European radio telescopes, others will have to wait, or will only be fully realized, with the advent of major new facilities like the SKA.

After defining, in a first face-to-face meeting, the topics to be addressed in this review, the ERTRC defined for itself a schedule with a number of milestones, and a list of tasks distributed amongst its members. It was decided to only address medium-sized (> 10 m dishes) and major facilities. In order to monitor progress, telephone conferences were held at regular intervals (weekly towards the end of the process), in addition to a half dozen face-to-face meetings in France, Germany and the Netherlands. Further information was requested from some of the observatories, specifically on the issue of which elements of the Science Vision radio astronomy contributes to, and to what extent. On topics where more input was needed than the questionnaire or other written material could provide, special face-to-face discussions were organized with representatives from the respective projects. This applied to the EVN, LOFAR, and the SKA. Other meetings were organized with other institutions like ESO and CRAF.

One of the ERTRC's major concerns was how to involve the European radio astronomy community during the review process, and how to distil the feedback for inclusion in the final report. It was decided to open an Internet Forum at http://ertrc.strw.leidenuniv.nl. A significant number of thoughtful community responses were received via this discussion forum, and even more were communicated in person. Given the fact that RadioNet exists as an EC-supported networking activity amongst a number of radio astronomy institutes in Europe (27 institutes in 13 countries), and that one of the work-packages for the FP7 funding period is also concerned with the future perspectives of radio astronomy in Europe, a contact was established in order to coordinate activities with RadioNet. The ERTRC also discussed its progress with the community at the 2012 and 2013 EWASS meetings in St. Petersburg and Turku, respectively. Additionally, ERTRC members presented the on-going work and invited feedback during a number of other relevant conferences at which many members of the radio community were present (e.g. the Modern Radio Universe conference in Bonn, 2013). Specifically, a first draft of our conclusions and recommendations was discussed with RadioNet, and then with the full community via the ERTRC internet forum and the 2013 EWASS, in early Summer 2013. ERTRC progress reports were given at the RadioNet Board meetings in Bonn (Feb 2012), Bologna (Mar 2013), and Bordeaux (Feb 2015). In the Spring of 2015, we discussed our near-final draft report with the RadioNet Board and the ASTRONET Executive. The RadioNet Board thus played an advisory role in the construction of our report, but the contents of the report are solely the responsibility of the ERTRC. Finally, a draft was made available for comments by the entire European astronomy community through the ERTRC website, and requests for comments were publicised widely in all national communities that belong to ASTRONET and RadioNet. After taking account of the comments received, the final report was published in early June 2015.

2.4 – Organization of this report

This report is structured in the following way:

- In Chapter 3 we describe the current landscape of European radio facilities, as well as planned technical developments, upgrades, and extensions.
- In Chapter 4 we map the capabilities of the existing facilities and their planned enhancements onto all the key science topics listed in the ASTRONET Science Vision.
- Next, we discuss factors that affect the scientific output of these facilities (Chapters 5, 6 and 7).
- In Chapter 8 we discuss the importance of multi-wavelength approaches and the way this affects strategies and practicalities at radio observatories.
- We then briefly comment on some aspects of education in Chapter 9.
- We summarize and briefly comment on organizational and funding aspects affecting the future of radio astronomy in Chapter 10.
- Future requirements and possible scenarios are discussed in Chapter 11.
- Finally, we summarize our conclusions and recommendations in Chapter 12.

Some factual materials and summaries of responses and inputs to our committee have been taken out of the main body of the report, and included in the Appendices.

In line with the remit given to the ERTRC by the ASTRONET Board, millimetre and sub-millimetre wavelength facilities are not included in this report, with the exception of their participation in the global mm-VLBI arrays. As our report is part of the ASTRONET effort and based on its Science Vision, we only deal with astronomical use of the facilities we describe, though we are well aware that some also make important contributions to other fields, such as geodesy. Also in keeping with the ASTRONET remit, we discuss here only facilities that are relatively large, and require transnational effort for their science and operation. This applies that small, local facilities and their science are not discussed. The combination of these ASTRONET choices of remit imply that some types of work and observatories are omitted from this report, e.g., most of solar radio monitoring.

Chapter 3: Review of major European radio telescopes

3.1 – Introduction

This chapter aims to present a mostly factual overview of the radio telescopes in Europe: their characteristics, primary functions, and future prospects for technical development. As such, this chapter serves to give the overall landscape of major radio astronomy facilities and instruments in Europe. In keeping with the general ASTRONET policy we only discuss facilities above a threshold size and impact, for which the international context is of practical relevance and which participate in activities of which the support goes beyond the means of individual European countries. Due to this, some facilities and types of science are not well represented in this report. A notable example is solar radio monitoring.

The basic technical parameters of these instruments – e.g. frequency range, collecting area, and angular resolution – are summarized in the Appendix of this chapter. A summary of the primary science drivers for each telescope can be found in Table 2 of Chapter 4 (and a more detailed version is available in Appendix E). Graphical overviews comparing these facilities are provided in Figures 1 to 6.

The various radio facilities have been grouped into four different types:

- Regional interferometers (Section 3.2).
- Pan-European interferometers (Section 3.3).
- Large single dishes (Section 3.4).
- Medium-sized single dishes (Section 3.5).

When appropriate, we place these telescopes in a broader context by also briefly describing major telescopes outside of Europe.

3.2 – Regional interferometers: e-MERLIN, WSRT, and AMI

We define "regional interferometers" as arrays that are located (primarily) within a single country, and that provide spatial resolution intermediate between the single-dish telescopes and the pan-European interferometers – i.e. resolutions of approximately 0.3 – 30 arcseconds. Three European arrays can be included in this category: e-MERLIN in the UK, the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands, and the Arcminute Micro-kelvin Imager (AMI) in the UK. These three arrays are highly complementary in terms of the frequency range and angular resolutions they provide.

3.2.1 – e-MERLIN

e-MERLIN is operated by the University of Manchester, as a national facility, through a contract with the Science and Technology Facilities Council (STFC). e-MERLIN consists of 7 telescopes: 2 antennas located at Jodrell Bank and 5 remote stations distributed across the UK with a maximum baseline of 217 km. This configuration allows sub-arcsecond imaging with very high (microJy) sensitivity. The telescopes are all connected by high-throughput optical fibre to the central correlator at Jodrell Bank Observatory (JBO), allowing fast processing of the data. The construction dates of the various elements range from 1957 (the 76-m Lovell) to 1991 (Cambridge).

The array has undergone a major upgrade during the last few years. This involved the construction of new receivers with bandwidths of up to 4 GHz, a redesign of the telescope optics, a new fibre network, a new correlator, as well as many updates of various observing systems. The most common frequency bands range from 1.3 – 1.8 GHz, 4 – 8 GHz and 22 – 24 GHz.

e-MERLIN is a uniquely sensitive instrument for imaging on milliarcsecond to arcsecond scales at centimetre wavelength; it bridges the gap between the capabilities of the very-long-baseline Interferometers (VLBI) and smaller interferometers such as the Jansky Very Large Array (JVLA; USA), the Westerbork Synthesis Radio Telescope (WSRT; Netherlands) and the Australia Telescope Compact Array (ATCA; Australia). Furthermore, its new correlator is highly flexible, meaning that continuum, polarimetric and spectroscopic observations can be undertaken simultaneously. Potential further upgrades could include the addition of new telescopes in order to extend its sampling of the u-v plane, as well as a possible new observing window in the 8 – 12 GHz range. E-MERLIN will address a broad range of astrophysical topics, e.g. from the formation of stars and galaxies to the energetic processes in jets from compact objects. A set of legacy programs has been defined for the first few years of operation after the recent upgrades.

For the first few semesters, 50% of the observing time will be dedicated to the legacy programs. The rest of the observing time is open to the international community with the selection of proposals purely based on scientific merit. There have already been a few open calls for proposals since its reopening. With the recent upgrade, it is expected that the e-MERLIN user base will likely grow to be even more international than the previous MERLIN community. e-MERLIN now also participates in VLBI observing sessions (e.g. e-EVN).

e-MERLIN

3.2.2 – WSRT – The Westerbork Synthesis Radio Telescope

The WSRT is located in the Netherlands and is run by ASTRON – Netherlands Institute for Radio Astronomy. It consists of fourteen 25-m dishes located along a 2.7-km east-west track designed to provide good u-v coverage through Earth-rotation aperture synthesis. Producing data since the early 1970s, it has since been upgraded several times. It is currently equipped with a multi-frequency frontend system, allowing observations with receivers that together span the 0.3 – 8.6 GHz range.

The complex spectral channel back-end implies that all observations are done in spectral line mode. Very high spectral resolution, as well as high dynamic range imaging, constitute the main and unique characteristics of the WSRT. The WSRT is open to the international community, with 60% of the proposals received from outside the Netherlands. The WSRT participates in all EVN and centimetre global VLBI sessions (as a tied-array, equivalent to a 94-m single dish), which represents a 25% fraction of its observing time. Also using the tied-array mode, the WSRT performs regular pulsar timing observations and has provided the bulk of the low-frequency (350 MHz) pulsar monitoring needed for the European Pulsar Timing Array (EPTA). These low frequencies complement the L-band pulsar data obtained at the WSRT and the other EPTA telescopes; it is crucial for correcting the data for variable dispersion measure delays in the interstellar medium.

The WSRT is currently undergoing a major refurbishment (called APERTIF – Aperture Tile in Focus) with the installation of 56-pixel phased-array feeds on 12 of the 14 telescopes. Designed with wide-area, 1.15 – 1.75 GHz surveys in mind, it enlarges the current WSRT field-of-view by a factor 30, and with an increase in total bandwidth of a factor 2, its overall survey speed will be boosted by a factor of about 20 (this takes into account the unavoidable increase in receiver temperature that comes with an uncooled aperture array system). This unique capability for the Northern Hemisphere will nicely complement the Australia Square Kilometre Array Pathfinder (ASKAP) and MeerKAT arrays in the Southern Hemisphere (see section 3.3.3). Furthermore, APERTIF constitutes an operational demonstrator for the focal plane array technology to be developed for the SKA. With APERTIF, the WSRT science will be driven full-time by large all-sky surveys, but two remaining individual WSRT dishes will continue to be used for complementary scientific objectives: VLBI, high-cadence monitoring of bright pulsars, and perhaps also spacecraft tracking.

WSRT

3.2.3 – AMI – Arcminute Micro-kelvin Imager

Operated by the University of Cambridge, AMI is located in the UK. AMI consists of two arrays: ten 3.7-m “small” antennas (SA) and eight 12.8-m “large” antennas (LA). The AMI dishes are those that used to make up the Ryle Telescope. AMI was last upgraded in 2008 with the installation of 4.5-GHz bandwidth receivers in the 13.5 – 18 GHz observing range. AMI is about to have an upgrade to a digital correlator, which will significantly increase its sensitivity. The baselines of each array are correlated individually, with no correlation done between the arrays. The LA array achieves a typical sensitivity of 50 microJy for an hour-long integration and spatial resolution on the order of 30 arcseconds.

The University of Cambridge privately operates AMI with additional support from the STFC. AMI is optimized for observations of structure with low surface brightness, with a main focus on the Sunyaev–Zel’dovich (SZ) effect. An official collaboration is also in place with the Planck consortium. New powerful SZ telescopes for operation at higher frequencies have entered the competition like the Atacama Pathfinder Experiment (APEX), the South Pole Telescope (SPT), and the Atacama Cosmology Telescope (ACT). The AMI arrays have also been used to carry out observations of supernova remnants and variable transient sources. Also, it is the only continuously operating radio array in the world, which has a robotic response mode (50% of time on AMI is devoted to follow up transients).

AMI

3.2.4 – Major regional interferometers outside Europe: ATCA, JVLA and GMRT

With its six 22-m antennas, the Australia Telescope Compact Array (ATCA), located in Australia, is currently the only full-time radio interferometer located in the Southern Hemisphere (in addition to ALMA in the millimetre range, and KAT-7 in the early stages of operation). ATCA is managed as a national facility by CSIRO and welcomes proposals from all over the world. With a major upgrade in 2009 (Compact Array Broadband Backend), the maximum bandwidth of the ATCA has been increased from 128 MHz to 2 GHz, resulting in a factor of four improvements in its continuum sensitivity. Observations can now also be conducted over the larger 1 – 105 GHz frequency window. With its exclusive location in the south, and until the advent of full MeerKAT and the SKA, the ATCA has the unique capacity to perform sensitive radio observations with good angular resolution over a large frequency range.

The Jansky Very Large Array (JVLA), located in New Mexico (USA), is composed of 27 antennas of 25-m diameter along a reconfigurable "Y" array providing a wide range of angular resolutions. It operates with eight receivers at frequencies from 1 – 50 GHz. The JVLA has just completed a very major upgrade with a large, 8-GHz broadband backend, making it the most sensitive radio telescope in the world. The JVLA is primarily funded by the American National Science Foundation, but proposals are received from all over the world and are selected on the basis of scientific merit.

The Giant Metre wave Radio Telescope (GMRT) consists of thirty antennas with a diameter of 45 m spread over distances of up to 25 km. The GMRT is located near Pune (India) and is managed by the National Centre for Radio Astrophysics (NCRA) of the Tata Institute of Fundamental Research (TIFR). The GMRT is a versatile telescope, with unique capabilities (high sensitivity and high resolution) in the metre wavelength range. The telescope is open for all users and selection is based on scientific merit.

3.3 – Pan-European interferometers: EVN & LOFAR

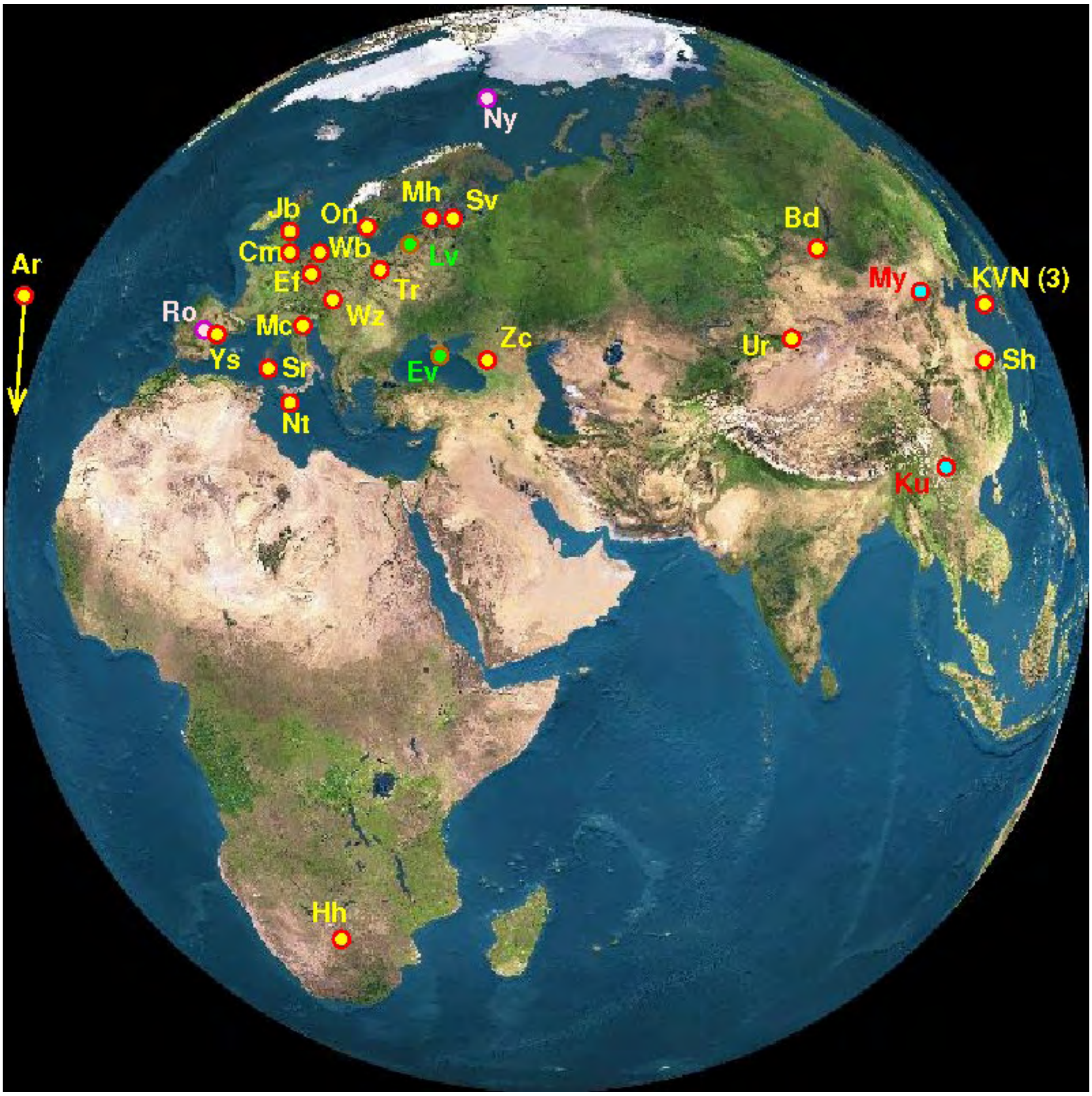
We define "pan-European interferometers" as any long-baseline interferometer with European leadership; this includes the EVN and LOFAR. Due to their vastly different frequency coverage and array technology, very different and complementary scientific goals are pursued using these two arrays.

3.3.1 – EVN – European VLBI Network

The European VLBI Network (EVN) is a collaboration of radio telescopes in Europe that operates regularly with telescopes in China, Russia, South Africa, and other single dishes in the world. Up to 20 telescopes, including almost all the single-dish telescopes described in sections 3.4 and 3.5, participate in the array. These instruments are run by 12 different organizations. With various observing bands between 327 MHz to 43 GHz, the EVN provides a unique resolving power: from a few milliarcseconds to sub-milliarcsecond scales. Moreover, since some of the largest dishes of the world are part of the consortium, it provides unique sensitivity (tens of microJy). Additionally, VLBI and Space-VLBI (VLBI with an orbital radio telescope like RadioAstron) are providing the most precise spatial resolution achieved at any wavelength.

The Joint Institute for VLBI in Europe (JIVE) provides many of the central services, including the correlator as well as the interface between the EVN and the user community. It is funded from the science councils of the participating countries, while the European Community (EC) sponsors some of the upgrades (e.g. the recent NEXPReS project for real-time VLBI). During recent years, the EVN has undergone a major upgrade. Most EVN telescopes have now been equipped with a digital backend. In addition, connecting the EVN telescopes to the central correlator via fibre connections (called the e-EVN) is providing rapid-response science capabilities: users get much faster access to the data, which is critical for responding to transient events and for coordinating observations at other wavelengths. The availability of the new SFXC software correlator has furthermore provided new capabilities for spectral line observing, wide-field imaging and pulsar binning.

Due to its high angular resolution, high sensitivity and superb astrometric precision, the EVN had become a unique astronomical facility. These unique capabilities allowed the EVN to cover a vast range of astrophysical phenomena, establishing itself as a general-purpose observatory. The EVN is accessible through a regular call for proposals, where open access and selection are based on scientific merit (roughly 33% of the selected proposals come from outside Europe).



EVN

3.3.2 – LOFAR – Low-Frequency Array

The Low-Frequency Array (LOFAR) is a telescope based on phased-array technology, in which thousands of low-cost, stationary collecting elements are digitally combined in a central processor. Innovative software then reconstructs the radio maps for a given region of the sky, making LOFAR an IT-telescope. The International LOFAR telescope (ILT) acts as a single radio interferometer consisting of all the 48 LOFAR stations distributed within Europe (38 in The Netherlands; 6 in Germany; and 1 in France, Sweden and the United Kingdom, respectively). Additional international stations are also planned (in fact 3 more stations are now under construction in Poland), in order to improve the long-baseline u-v coverage. The 24-station core of the array can be coherently combined in order to make the world's most sensitive low-frequency telescope for observing pulsars and other high-time-resolution science. Individual stations are also sensitive enough to be used in parallel to observe bright sources.

The frequency range covered by the existing receivers is 10 – 90 MHz (low band) and 110 – 240 MHz (high band). The gap between 90 – 110 MHz is due to the FM band. In practice, the 10 – 30

MHz range is particularly challenging because of RFI and lower sensitivity (the low-band dipoles have a strong resonance peak near 60 MHz), but has been used for science in some cases. Each LOFAR station has 96 low-band antennas and 48 (for NL) or 96 (for other countries) high-band antenna tiles (each containing 16 bowtie dipoles) spread over an area of 50 x 100 m. The switching between any frequency and any spatial direction is fully electronic and selectable at intervals of a few seconds, with up to hundreds of independent beams formed simultaneously at each station (or hundreds of tied-array beams formed by the correlator). More than half of the Dutch stations are situated in the 2 x 3-km core located close to Exloo, Drenthe. The maximum baseline between LOFAR stations is approximately 1500 km.

The running costs of the ILT are contributed in-cash and in-kind by the international station owners in proportion to the number of stations owned, meaning that ASTRON contributes a significant fraction (80%) of the LOFAR cost. Their individual owners cover the local costs associated with stations. LOFAR is a transformational facility, facing new challenges in different technical areas: the calibration of low-frequency data; the removal of ionospheric effects in the visibilities; the ability to deal with huge fields-of-view and massive data sets. LOFAR is a major SKA pathfinder instrument, exploring new techniques and opening new areas of research that will be taken to the next level by SKA-Low.

The design of LOFAR was driven by “Key Science Projects”: i) Epoch of Reionization:; ii) Extragalactic Surveys; iii) Transients and Pulsars; iv) Cosmic Rays; v) Solar Physics; and vi) Cosmic Magnetism. While other low-frequency, digital aperture arrays have been built outside of Europe (e.g., LWA, MWA, and PAPER), LOFAR provides many times more collecting area, much longer baselines, and a full view of the 10 – 240 MHz spectral range. It also has a broader scientific scope, and corresponding standard observing modes, than these other technologically similar instruments.

LOFAR

3.3.3 – Other major, non-European facilities: VLBA, MeerKAT and ASKAP

The Very Long Baseline Array (VLBA) consists of an array of ten identical 25-m antennas spread across the USA with a maximum baseline of 8000 km. All antennas are controlled and scheduled dynamically from the NRAO centre in Soccorro, New Mexico (USA). Its construction began in 1986 and it was completed in 1993. It is currently the only fully dedicated, full-time VLBI observatory available.

The VLBA can observe from 312 MHz to 90 GHz in several discrete bands, including a few narrow bands centred on some very important maser spectral transitions. The VLBA has recently finished an important sensitivity upgrade. Its continuum sensitivity can furthermore be improved by a factor of 5 or more by adding the GBT and the phased JVLA to the VLBA. It also offers Global VLBI with a single proposal.

MeerKAT is a planned array comprised of 64 dishes of 13.5-m diameter each, and is currently under construction in South Africa (with a completion planned for 2016). Located on the radio-quiet, future SKA South-Africa site, MeerKAT will have a dense inner core (baselines from 29 m to 1 km) with 70% of the dishes and an outer component (30% of the dishes) with baselines ranging from 2.5 km to 8 km (with a possibility of an extension up to 20 km with 7 additional antennas). The antennas have been designed to achieve high sensitivity, a large 4-GHz bandwidth, and high imaging dynamic range in several observing windows ranging from 0.6 – 15 GHz. The construction of the KAT-7 science prototype array was successfully completed in 2012, and several refereed scientific publications have resulted from the data it has produced.

The first few years of MeerKAT will mainly be reserved for large projects (70% of the available observing time) following an international call for proposals in 2009. Ten large proposals have been selected[2], each with a total observing time ranging from 1900 – 8000 hours. European PIs lead (or co-lead) a significant fraction (55%) of these large programs, whereas 27% of the proposals are led by South African PIs (18% are lead by the rest of the world).

ASKAP is the Australian SKA precursor. It comprises 36 antennas of 12-m diameter each. It is located in Western Australia in a radio quiet zone that will later host part of the SKA. One of the novel features of the ASKAP array is its use of phased-array feeds, which allow a 30-square-degree field-of-view. Phased-array feeds, as pioneered by ASKAP and the WSRT/APERTIF, greatly increase the instantaneous field of view of the telescope, which has distinct advantages, e.g., for certain types of line surveys and searches for rare transients. Typically this is achieved at the cost of narrower total bandwidth and higher antenna temperature, especially with respect to new, very broadband feeds that have been developed. How they compete with single-pixel feeds is therefore quite application-dependent, and both technologies are being pursued for cutting-edge observatories. It is envisioned that MeerKAT will eventually morph into the SKA-Mid telescopes,.

For ASKAP, the maximum resolution is on the order of 8 arcseconds and it will operate over the 0.7 – 1.8 GHz frequency range. A 6-antenna test array (BETA) was completed in 2013 and is being used to test the phased-array feed (PAF) technology. ASKAP is primarily a survey instrument and after its completion, at least 75% of its first five years of observations will be devoted to large survey science projects. For that purpose, ten projects[3] (needing more than 1500 hours each, but some of them are fully commensal) have been selected based on their scientific merit. None of these projects are lead by a European PI. However, these programs

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[2] http://public.ska.ac.za/meerkat/meerkat-large-survey-projects

[3] http://www.atnf.csiro.au/projects/askap/ssps.html

comprise 363 investigators from 131 institutions with 28% of the Co-Is from Europe (33% from Australia, 30% from North America and 9% from the rest of the world).

3.4 – Large single dishes: Effelsberg, Lovell, Yevpatoria, Nançay and Sardinia

We define "large" single-dish radio telescopes as those with a diameter greater than 50 m and which are often used in isolation, i.e. not connected with other radio telescopes. These dishes provide very high sensitivity but limited angular resolution when used in isolation (typically 10 – 15 arcminutes at 1.4 GHz) compared with regional and long-baseline interferometers. Such telescopes are well suited to observations where sensitivity is more important than angular resolution (or where the lower angular resolution matches well the size of structures to be mapped on the sky, i.e. "short baselines"). The science drivers include for example high-time-resolution observations of pulsars, HI mapping, polarimetric mapping and spectral lines.

With the recent addition of the Sardinia Radio Telescope (SRT), Europe is now fortunate to host 5 of the world's 10 largest single-dish radio telescopes. These telescopes are not used exclusively in isolation, however; they also play key roles in the European VLBI Network (EVN) by greatly boosting the overall sensitivity. They are also combined to form the Large European Array for Pulsars (LEAP), which includes the Lovell, Effelsberg, Nançay, Sardinia, and WSRT(as a tied-array) telescopes.

3.4.1 – Effelsberg

The 100-m Effelsberg telescope was built in 1968 – 71 and it is still the largest fully steerable (with active optics) single-dish radio telescope in Europe (second only to the Green Bank Telescope on the world stage). The telescope is run by the Max Planck Gesellschaft and largely used by the MPIfR in Bonn, though it is also open to outside users. Effelsberg offers a very large available frequency range, reaching from about 300 MHz up to 96 GHz. Effelsberg offers high polarization purity and high frequency agility, as well as the possibility to observe large bandwidths with high spectral resolution. The new "Ultra Broad Band" (UBB) receiver has recently been commissioned and it provides instantaneous 600 – 3000 MHz coverage (though some of this range must be excised because of RFI). Pulsar survey/timing observations (including LEAP) as well as maser line work, as well as sensitive polarization observations, feature prominently in the telescope's activities. Effelsberg is a key element for the high-sensitivity observations of the European VLBI Network (EVN). Effelsberg is also officially part of the VLBA and the HSA. Effelsberg has an active, continuous upgrade programme, with switchable feeds introducing flexibility between high- and low-frequency work, and foresees the installation of a phased-array feed in 2016 for greater field of view.

Effelsberg

3.4.2 – Lovell

The 76-m Lovell telescope was the largest single dish radio telescope in the world at the time of its construction in the 1950s. It allows observations in six frequency bands from 151 MHz to 8 GHz, but is most commonly used at 1.4GHz. The telescope is currently run by the STFC and observing time must be paid for (i.e. the telescope is not offered openly to outside users, though in practice the data is often used in broad collaboration). A large fraction of the observing is used to time radio pulsars. This effort has produced an unparalleled database of pulsar "times of arrival" spanning 40 years. The Lovell is also used as part of the EVN, the largest dish in the e-MERLIN interferometer and, along with Effelsberg, the WSRT, Nançay, and Sardinia, is participating in LEAP. The Lovell telescope also takes part in the e-MERLIN array.

Lovell

3.4.3 – Yevpatoria

This 70-m radio telescope (RT-70) was constructed in 1980. RT-70 is operated by the Institute of Radio Astronomy of the National Academy of Sciences of the Ukraine. With a mostly European user base (50% from the Ukraine, 40% from Europe and 10% from the rest of the world), the RT-70 telescope is mainly used for single-dish observations. It has a broad frequency coverage (six different receivers in the 327 MHz to 22 GHz range), but the 3 low frequency bands are strongly affected by RFI. RT-70 takes part in VLBI observations, including a project to provide ground support of the VLBI RadioAstron space antenna. RT-70 is currently being upgraded aiming to be included in the EVN array.

Yevpatoria

3.4.4 – Nançay

The Observatory of Paris currently runs the Nançay Radio Telescope (NRT), which was constructed in 1965. It operates in the 1.0 – 1.8 and 1.7 – 3.5 GHz frequency range. As a transit telescope, only about 1 hour of visibility per source is available for a given day, but this is compensated by the telescope's large collecting area. The user base is mostly European (50% from France, 30% from Europe and 20% from the rest of the world). Half of the available observing time is devoted to pulsar timing, with the rest being dominated by spectroscopy (e.g. extragalactic HI, comets). In recent years, efforts have been successful to include the NRT in a network of international collaborations (e.g. Fermi, EPTA, LEAP).

Nançay

3.4.5 – Sardinia

The Sardinia Radio Telescope (SRT) is a new 64-m telescope that is currently being commissioned in Italy and which is run by INAF. The high-precision and active surface of the SRT is designed to achieve high efficiency at high frequencies (in theory up to 110 GHz). To start, the SRT will be able to observe from 300 MHz to 26 GHz, but upgrades are already planned and funded for a multi-pixel wide-band 43-GHz receiver. The SRT is designed to be used as a single-dish telescope, but a significant fraction of its time (3 months a year) will also be devoted to long baseline interferometry (EVN/VLBI), resulting in significant improvement of the EVN u-v coverage due to its location in the south of Europe. With a 64-m diameter, it is the smallest of the large European radio telescopes, but its advanced instrumentation make it a very competitive facility. It is also capable of reaching to more southernly declinations than the other large European dishes.

SRT

3.4.6 – Other major, non-European facilities: Arecibo, Parkes, GBT and FAST

The 305-m Arecibo radio telescope remains the largest single-dish in the world. Though it is significantly larger than any other existing radio telescope, the main reflecting dish is immobile and the sky coverage is limited to declinations between –2 to 38 degrees. Furthermore, usually not the full 300-m aperture is illuminated during observations, and in general the telescope is more like a 200-m dish. Operating since the 1950s, its unique sensitivity has enabled many important discoveries in, e.g., the areas of HI mapping, radar observations of Solar System bodies, and pulsars. Arecibo is a member of the EVN to provide both a long western baseline and a huge boost in sensitivity. The Arecibo telescope is part of the National Astronomy and Ionosphere Center (NAIC), which is operated by Universidad Metropolitana de Puerto Rico and SRI International under a cooperative agreement with (mainly) the National Science Foundation in the USA. It is an open facility with many international proposals, including European PIs.

The 64-m Parkes radio telescope is one of the largest single-dish radio telescope in the Southern Hemisphere and has long benefitted from its geographical location, which enables a clear view of the Galactic centre and southern skies. Operating since the 1960s, the telescope was upgraded in the mid 1990s with a 13-beam receiver system operating around 1.4 GHz. This system gives the telescope an excellent survey speed, which has been exploited, e.g., to make it the most successful pulsar survey machine in history. It is an open facility operated by CSIRO with many international proposals, including ones from European PIs.

The 100 x 110-m Green Bank Telescope (GBT) is the largest steerable, single-dish radio telescope ever constructed. Its novel offset feed system gives it an unblocked aperture and its active surface offers the possibility of high-frequency observations up to 100 GHz. Though smaller than Arecibo, it has access to roughly three quarters of the sky. It is an open facility operated by NRAO with many international proposals, including ones from European PIs.

Construction of the Five-hundred-meter Aperture Spherical Telescope (FAST) is well underway in China. Using an Arecibo-like design, FAST will provide a significantly larger dish (500 m diameter), with also a large sky coverage enabled by a deformable dish. Furthermore, using a focal plane array, it may be possible to combine the telescope's enormous sensitivity with a reasonable field-of-view. FAST will be an excellent telescope for all of the traditional single-dish science cases, and can, e.g., contribute significantly to HI studies, pulsar timing, searches, etc. A new 65-m meter (Tianma) single dish telescope is also being built in China.

3.5 – Medium-sized single dishes: Medicina, Noto, Metsähovi, Onsala, Toruń and Yebes

We define "medium-sized" single-dish radio telescopes as those with diameters of 10 – 50 m. Though such dishes are significantly less sensitive than their larger brethren, they play important roles in the EVN (by filling out the u-v coverage), are often test beds for developing new technologies and/or training students, and can be used for high-cadence monitoring of bright sources.

3.5.1 – Medicina and Noto

The Medicina and Noto radio telescopes are located near Bologna and in Sicily (Italy), respectively, and are both 32 m in diameter. They are both run by the Istituto di Radioastronomia of the Istituto Nazionale di Astrofisica in Bologna. Medicina was built in 1983 and Noto in 1988.

Medicina features frequency agility – i.e., the capability to change frequency very quickly. The frequency range is 1.3 – 26.5 GHz. For single-dish use, about 50% of the projects are spectroscopic and 50% in the radio continuum. The Noto antenna is currently the only one in Europe (besides the SRT) where the primary mirror is equipped with an active surface, i.e. 256 computer-controlled panels that can be adjusted to compensate for surface deformations. The frequency range is 0.3 – 43 GHz. For single-dish use, about 60% of the projects are spectroscopic and 40% in the radio continuum.

Both Medicina and Noto are part of the EVN and the International VLBI Service (IVS; geodesy). Their commitments to VLBI networks are about 4 months/year. A series of meetings have been performed to develop a long-term collaboration between Italy (Medicina and Noto dishes), Japan, and Korea in the field of VLBI. Currently, their main long-term projects are monitoring of Galactic maser sources and of flux density variability of blazars. Also, the telescopes perform monitoring projects in coordination with space missions.

Medicina & Noto

3.5.2 – Metsähovi

The Metsähovi Radio Observatory (MRO) in Finland operates a 13.7-m radome-enclosed telescope, built in 1974 and upgraded during the 1990s. The surface accuracy of 100 microns allows operation from 2 GHz up to 100 GHz. The Aalto University runs the Observatory. Most of the observing time is spent on continuum observations in the 20-GHz and 30-GHz ranges. Metsähovi, as a member of EVN, participates in VLBI campaigns for a limited fraction (10%) of its total observing time. Quasar monitoring is a scientific priority for the telescope, along with the maintenance and continuous updating of a large database with total flux density variability measurements of AGN – usually to support high-energy follow-up observatories (e.g. VERITAS, MAGIC, and Fermi).

Metsähovi

3.5.3 – Onsala

The Onsala Space Observatory is organized around a 25-m diameter cm-wave telescope and a 20-m diameter radome-enclosed millimetre telescope, located 50 km south of Göteborg in Sweden. They were constructed in 1963 and 1975, respectively, and they are both operated by Chalmers University of Technology. Their receivers cover different frequency ranges from 800 MHz up to 116 GHz.

Both single-dish facilities participate in EVN-organized VLBI-sessions (the 25-m participates in all EVN sessions). The 20-m telescope is also used as a single dish for cm (20% of time) and mm (80% of time) observations. The majority of time is spent on observations of spectral lines from molecules in comets, circumstellar envelopes and the interstellar medium in our Galaxy and in extragalactic objects. A new radome has been installed at the 20-m telescope, with the goal to move most of the VLBI observations to this telescope (with the development of new receivers when needed).

Onsala

3.5.4 – Toruń

This 32-m radio telescope, built in 1994, is located near Toruń, Poland, and it is run by the Center for Astronomy, Nicolaus Copernicus University, in Toruń. It covers the frequency range from 0.75 – 34 GHz. About 20 – 25% of the observing time is allocated by the EVN. The main scientific projects are related to the physics of AGN, the S-Z effect, surveys of extragalactic radio sources, novae and micro-quasar outbursts, magnetic fields in the Galaxy, and the physics of star-forming regions.

Toruń

3.5.5 – Yebes

Yebes is a 40-m telescope located in Yebes, Spain. It is run by the Instituto Geográfico Nacional in Madrid. It was constructed during 2000 – 2009, and the frequency band covers 2 – 115 GHz. It operates as part of the EVN, and the time allocation is via the EVN Programme Committee. Its astronomical scientific goals range from star-forming regions to distant galaxies. It also performs geodetic observations within IVS. It participates in the campaigns of the Global Millimetre VLBI Array (GMVA).

Yebes

3.5.6. – Other medium-sized facilities

Three Russian fully steerable 32m radio telescopess -"Svetloe" (Sv), "Zelenchukskaya" (Zc) and "Badary" (Bd)- make up the three-element VLBI Network "Quasar" with baselines of about 2015×4282×4404 km. The three telescopes are linked to Control and Processing Center in St. Petersburg by optical fiber lines. The QUASAR Russian stations have participated regularly in the EVN observing sessions since 2011. They have a frequency coverage from 1.4 GHz to 22 GHz.

The Korean VLBI Network (KVN) consists of three 21 m radio telescopes, which are distributed along Korea and produce an effective spatial resolution equivalent to that of a 500 km radio telescope. The KVN co-observe with the EVN at 22 and 43 GHz.

The Irbene radio telescopes near Ventspils (Latvia) are former Soviet military instruments that are being refurbished and are expected to come online by the end of 2015. The 16-m and 32-m dishes will operate in the EVN in C band (5 GHz).

3.6 – Conclusions

In conclusion, Europe is undoubtedly world leading in the radio astronomical facilities that it is hosting. Five of the ten largest single-dish radio telescopes in the world are located in Europe. Together, these facilities provide sensitive measurements over the full range of MHz-GHz radio frequencies with high spectral and time resolution, as required. When combined with Europe's medium-sized single dishes, these telescopes form the EVN – the world's premier VLBI instrument. Though some of the single-dish telescopes might at first appear redundant in terms of their frequency coverage and aperture size, it is precisely this overlap along with their wide geographic distribution, which allows them to form the world's most sensitive VLBI array. Furthermore, they perform complementary high-cadence monitoring experiments when not part of the EVN. With LOFAR, Europe is leading the renaissance in low-frequency, wide-field radio astronomy, which has an even brighter future with SKA-Low. These instruments also serve an important role in developing technologies that both expand the science that they can do and pave the way towards the SKA. This also includes training the next generation of radio astronomers.

A.1 – Graphical comparison of telescope parameters

In this section, we present a graphical overview of some of the overall parameters of the radio telescopes in various European observatories, in comparison with each other and with the premier facilities in the rest of the world, followed by a table with the detailed numerical values of the frequency ranges available at each telescope. We use a uniform colour code for all the graphs, namely blue for the smaller single dishes and yellow for the larger ones; green for the pan-European interferometers and red for the regional ones; and black for the non-European facilities. Some points to note are:

- The frequency coverages of the telescopes are very similar, both because they are dictated by which radio bands are protected and by astrophysical considerations, and because when collaborating in the EVN, all telescopes must use the same frequency. A notable exception is LOFAR, which was built especially to explore the long-neglected lowest frequencies (Fig.1).
- In angular resolution (Fig.2), the single dishes of course clearly stand out for poorer resolution relative to the interferometers (though note that sometimes this low resolution is a scientific ncessity), and the unique role of the EVN for providing very high resolution stands out.
- The fields of view are again largely determined by the dish size, and thus similar, except for the phased-array telescopes (LOFAR and SKA1-Low), which have much larger FoV.
- The sensitivities show an obvious improvement with collecting area of the telescope, but not a completely strict relation, since other factors such a receiver quality also influence it significantly (Figs. 5 and 6).

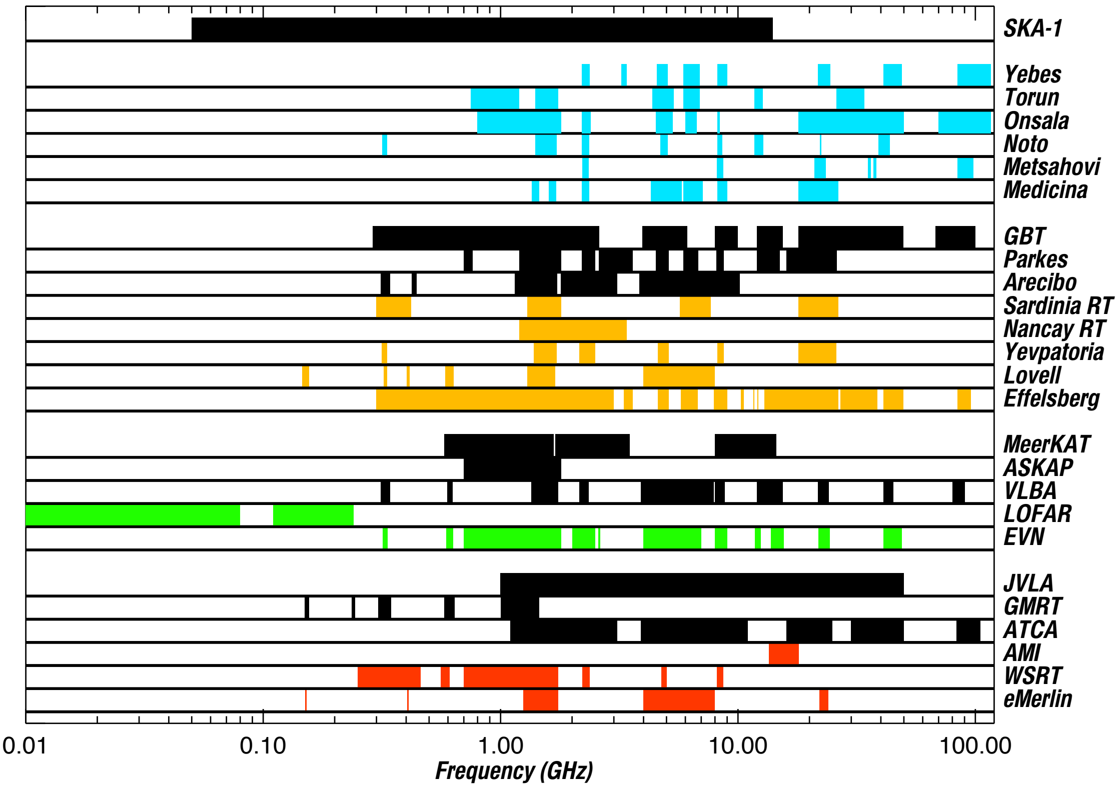


Figure 1: The frequency coverage of the European radio telescopes. For comparison, major non-EU facilities are shown in black, as are SKA Phase I and its precursors MeerKAT and ASKAP. Together, the European facilities provide full coverage from 10MHz to roughly 100GHz at a large variety of angular scales (see Figure 2) and with different available fields-of-view (see Figure 3). The telescopes are grouped by category as discussed in this chapter (Red: Regional interferometers, Green: Pan-European interferometers, Orange: Large single dishes and Blue: Medium-sized single dishes). The ability of the medium-sized (Blue) and large (Orange) single dishes to cover many of the same frequency bands is a prerequisite for their use in the EVN.

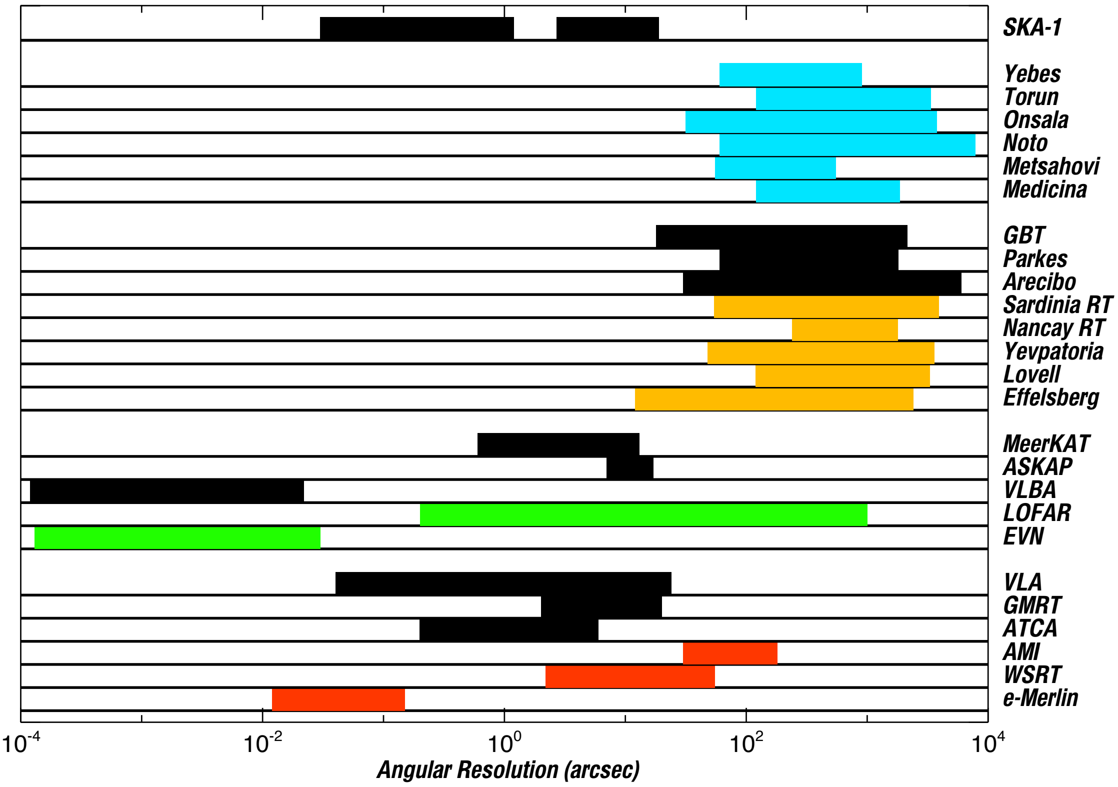


Figure 2: The range of angular resolutions provided by the European radio telescopes. For comparison, major non-EU facilities are shown in black, as are SKA Phase I and its precursors MeerKAT and ASKAP. Together these provide sub-milliarcsecond (when operating together in the EVN) to arcminute resolution at a large range of frequencies (see Figure 1). The telescopes are grouped by category as discussed in this chapter (Red: Regional interferometers, Green: Pan-European interferometers, Orange: Large single dishes and Blue: Medium-sized single dishes).

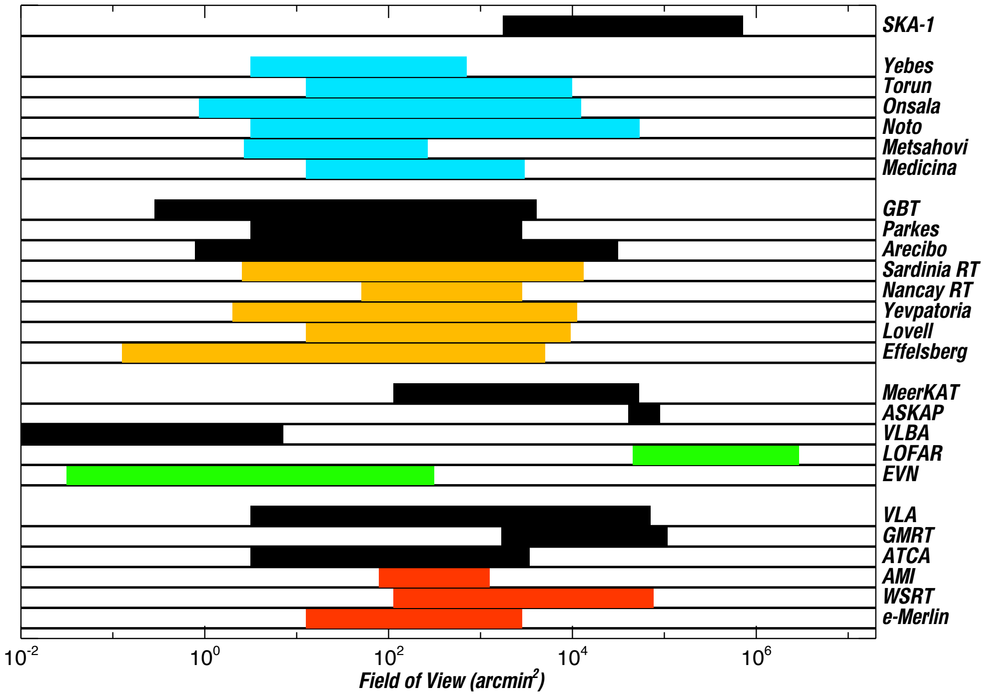
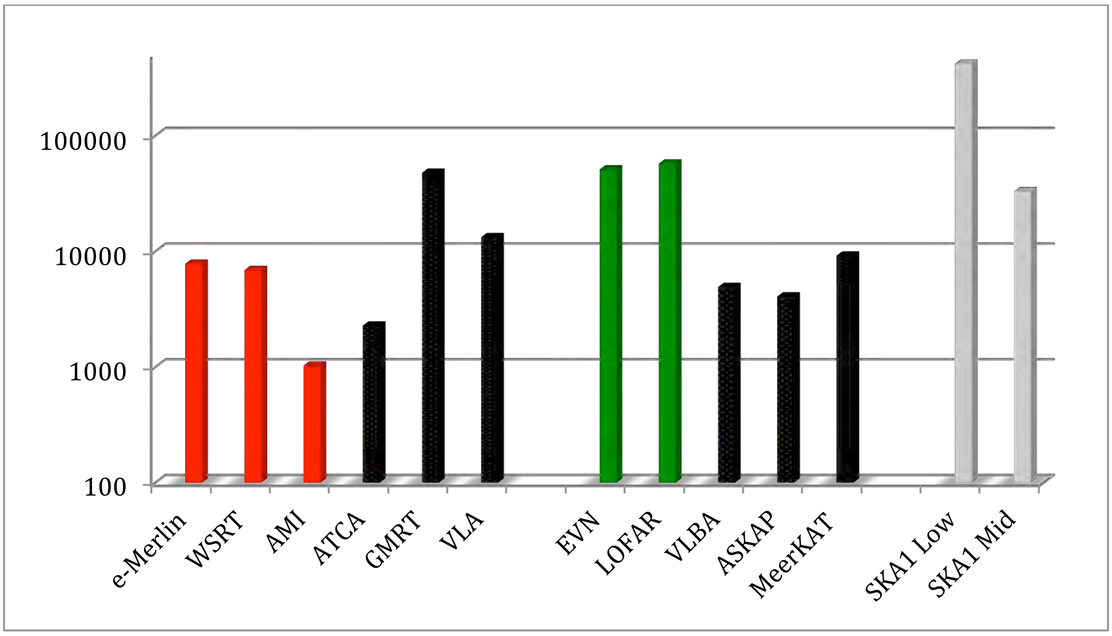


Figure 3: The range of fields-of-view provided by the European radio telescopes. For comparison, major non-EU facilities are shown in black, as are SKA Phase I and its precursors MeerKAT and ASKAP. The complementary frequency ranges and achievable angular resolutions are shown in Figures 1 and 2, respectively. The telescopes are grouped by category as discussed in this chapter (Red: Regional interferometers, Green: Pan-European interferometers, Orange: Large single dishes and Blue: Medium-sized single dishes). Thanks to the new correlators, the EVN provides a FoV more comparable to the primary beam of the participating telescopes.



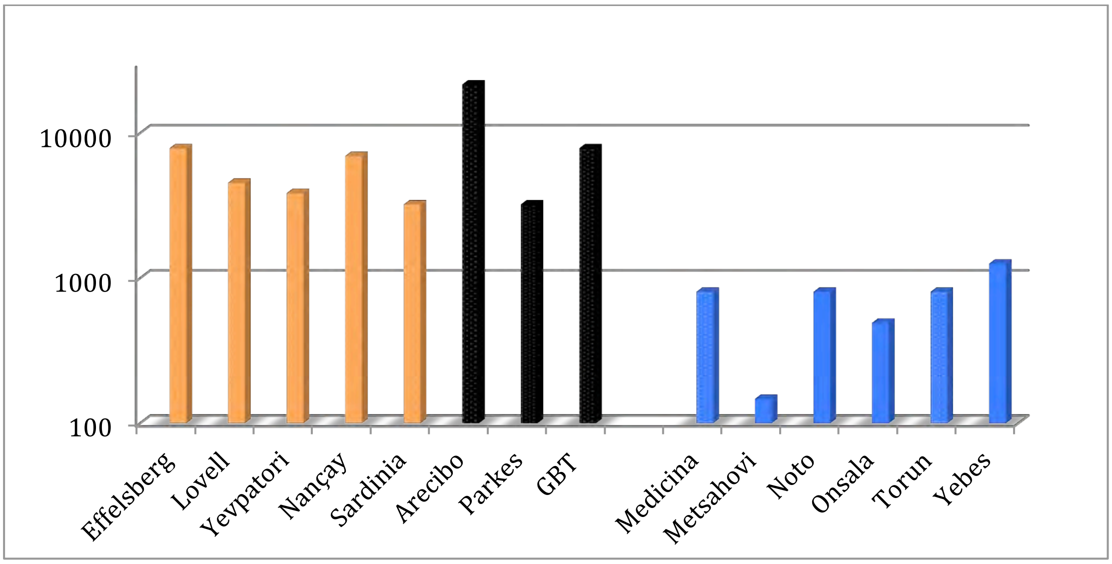


Figure 4: The range of geometrical surface areas (in square metres) provided by the European radio telescopes (top panel: the interferometers, bottom panel: the single dishes). For Arecebo, we used the full geometric size, even if the full aperture is not illuminated during observations (it is more like a 200-m dish, e.g. twice the diameter of Effelsberg or GBT).

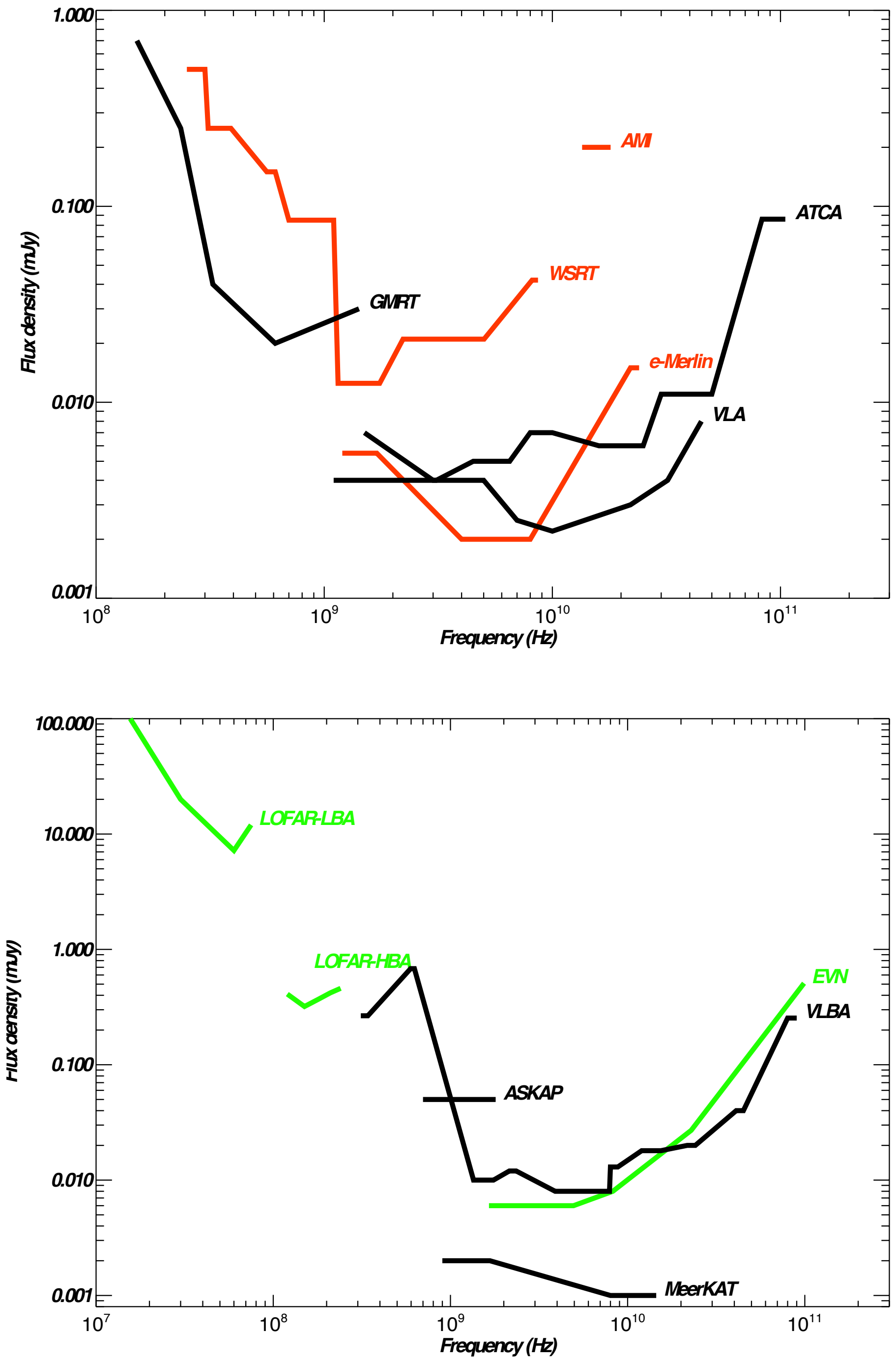


Figure 5: Sensitivity (expressed in achievable rms noise level) for standard observing conditions and typical observing time[4] of the regional interferometers (*top panel*) and the pan-European interferometers (*bottom panel*). Existing and planned non-European telescopes are shown in black for comparison.

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[4] Based on an approximately 12-hour run in the case of the ATCA, the GMRT, e-Merlin, the WSRT; approximately 8 hours for AMI and the VLBA; and 6 hours for the EVN; 1 hour for ASKAP, the JVLA, MeerKAT and LOFAR.

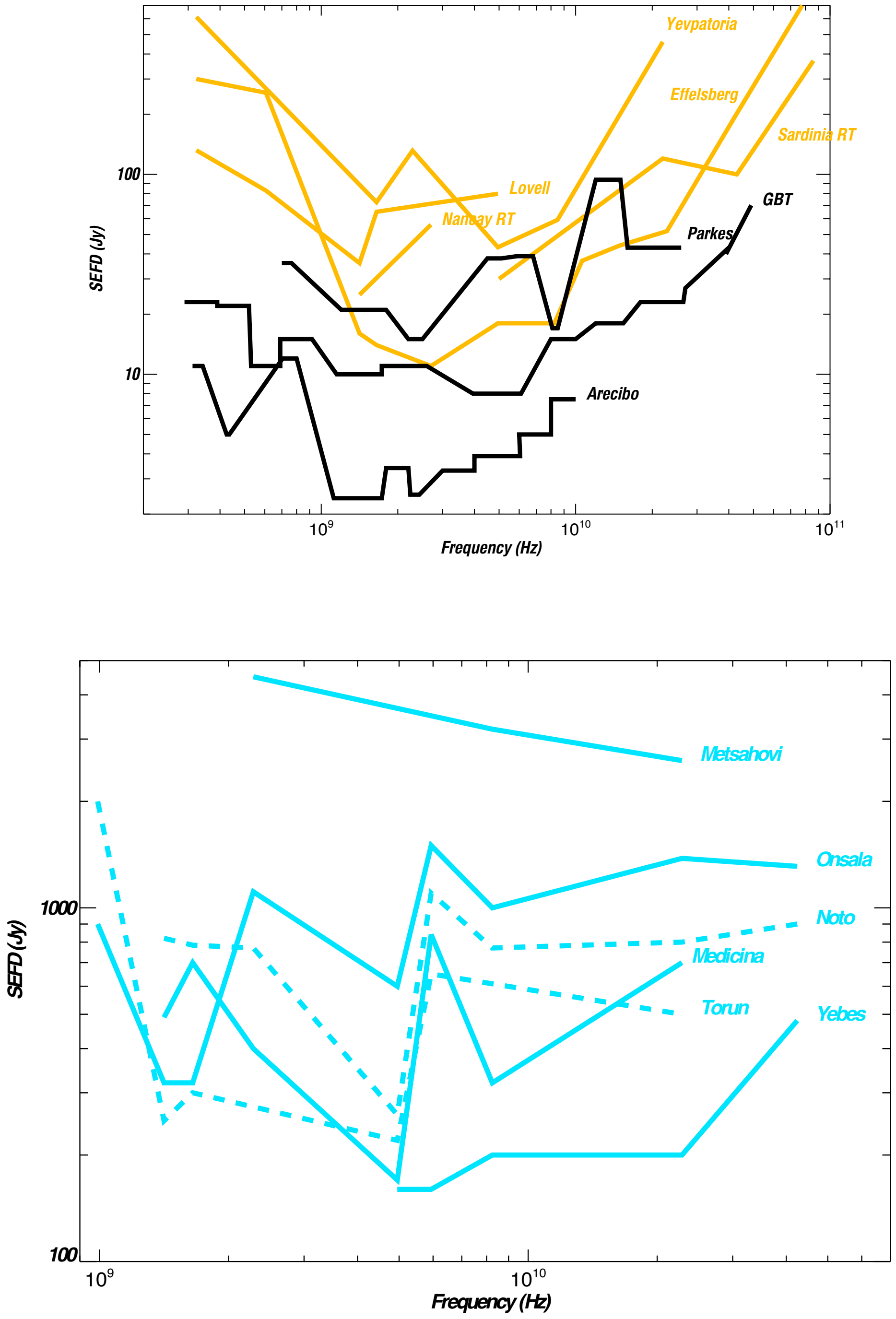

Figure 6: Sensitivity for typical observing conditions of the large single dishes (*top panel*) and the medium-sized single dishes (*bottom panel*) expressed in SEFD (System equivalent flux density. Existing non-European facilities are shown for comparison in black. Different line styles are used for visualisation purpose.

Telescope / Facility	Available frequencies (GHz)
Regional interferometers:	
e-MERLIN	0.150-0.152; 0.406-0.410; 1.25-1.75; 4-8; 22-24
AMI	13.5-18
The WSRT	0.250-0.460; 0.310-0.390; 0.560-0.610; 0.7-1.2; 1.15-1.75; 2.22-2.38; 4.77-5.02; 8.15-8.65
ATCA	1.1-3.1; 3.9-11; 16-25; 30-50; 83.5-105
VLA	1-50
GMRT	0.150-0.156; 0.236-0.244; 0.305-0.346; 0.580-0.640; 1.00-1.45
Pan-European interferometers:	
EVN	0.325-0.329; 0.608-0.612; 0.7-1.8; 2.2-2.5; 4-7; 8-9;11.8-12.5; 13.8-15.6; 21.8-24.3; 41-49
LOFAR	0.010-0.080; 0.110-0.240
VLBA	0.312-0.342; 0.596-0.626; 1.35-1.75; 2.15-2.35; 3.9-7.9; 8-8.8; 12-15.4; 21.7-24.1; 41-45; 80-90
ASKAP	0.7-1.8
MeerKAT	0.58-1.015; 0.9-1.67; 1.7-3.5; 8-14.5
Large single dishes:	
Effelsberg	0.3-3.0; 3.3-3.6; 4.5-5.1; 5.75-6.75; 7.9-9.0; 4.0-9.3 (in commission); 10.3-10.6; 11.6-11.7; 12.1-12.2; 12.9-26.5; 27-38.5; 41-49.7; 84-95.5
Lovell	0.150-0.152; 0.326-0.328; 0.407-0.409; 0.608-0.612; 1.3-1.7; 4-8
Yevpatoria	0.316-0.332; 1.38-1.72; 2.15-2.5; 4.5-5.1; 8.18-8.68; 18-26
Nançay	1.2-3.4
Sardinia	0.3-0.42; 1.3-1.8; 5.7-7.7; 18-26.5
Arecibo	0.312-0.342; 0.422-0.442; 1.15-1.73; 1.8-3.1; 3.85-10.2; 1.3-1.7; 4-8
Parkes	0.700-0.764; 1.2-1.8; 2.2-2.5; 4.5-5.1; 8.1-8.7; 12-15; 16-26
GBT	0.29-2.6; 3.95-6.1; 8-10; 12-15.4; 18-49.8; 68-100
Medium-sized single dishes:	
Onsala (20 or 25 m)	0.8-1.8; 2.2-2.4; 4.5-5.3; 6.0-6.7; 8.2-8.4; 18-50; 70-86; 85-116
Metsähovi	2.21-2.35; 8.15-8.65; 21-23.4; 35.3-36.3; 37.3-38.3; 84-98
Medicina	1.35-1.45; 1.6-1.7; 2.2-2.36; 4.3-5.8; 5.9-7.1; 8.18-8.98; 18-26.5
Noto	0.317-0.332; 1.4-1.72; 2.2-2.36; 4.7-5.05; 8.18-8.58; 11.7-12.75; 22.18-22.46; 39-43.5
Torun	0.75-1.2; 1.4-1.75; 4.35-5.35; 5.9-6.9; 11.7-12.7; 26-34
Yebes	2.2-2.37; 3.22-3.39; 4.56-5.06; 5.9-6.9; 8.18-8.98; 21.75-24.45; 41-49; 84-116

Table 1: List of potentially available observing frequencies at the various facilities. Some frequency ranges may correspond to several frequency-adjacent, independent receivers.

Chapter 4: Addressing the ASTRONET Science Vision goals with existing European radio telescopes

4.1 – Introduction

European radio astronomy is in a very healthy and vibrant state. It provides strong contributions to many of the ASTRONET Science Vision goals (http://www.astronet-eu.org/spip.php?article149&lang=en), as well as some unique views of the Universe through, for example, HI observations at cosmological redshifts, pulsar timing measurements, synchrotron emission of relativistic matter and thermal emission of cosmic dust.

The purpose of this chapter is to map the on-going scientific activities of the European radio telescopes to the themes of the ASTRONET Science Vision. First, we discuss qualitatively, per Science Vision topic, how radio astronomy contributes. Then we present a tabulated summary of the importance of contributions from European radio observatories to the Science Vision. We note that the Proceedings of Advancing Astrophysics with the Square Kilometre Array (8 – 13 June, 2014, Giardini Naxos, Italy, in press) also serves as a detailed description of the scientific capabilities of the SKA and its pathfinder/precursor radio telescopes.

4.2 – Contributions of radio astronomy to the ASTRONET Science Vision

In this section we discuss each Science Vision question in turn, and comment on how various radio astronomical techniques contribute to answering them, without as yet paying much attention to the relative importance of the contribution of radio astronomy between topics, and the relative importance of radio astronomy versus other wavelengths in addressing each question.

A. Do we understand the extremes of the Universe?

A1. How did the Universe begin?

The key experiments in this area involve: i) the measurement of the Galactic continuum emission and extragalactic sources in total intensity and polarisation, which enable the foreground subtraction that is critical for the correct interpretation of the Cosmic Microwave Background (CMB) experiments (for details, see, e.g., the papers from the Planck Collaboration); and ii) the detection of the stochastic gravitational wave background (nano-Hertz gravitational waves) through the high-precision timing of milliseconds pulsars (e.g., van Haasteren et al. 2011, MNRAS, 414, 3117). For the latter, radio telescopes, including VLBI, provide an accurate determination of pulsar positions and proper motions, which are critical for maximizing the use of these sources as precision clocks. On the other hand, Effelsberg is making various experiments to probe the constancy of the fundamental constants. VLBI could also provide a direct and independent way of detecting the gravitational wave background by observing its subtle effect on the apparent positions of quasars (e.g. Jaffe 2004, New Astron. Rev. 48, 1482).

A2. What is dark matter and energy?

Interferometers can be used to carry out cosmological tests via the redshift-apparent size relation of AGN (Gurvits et al. 2003, ASP Conference Proceedings, Vol. 300, 285). A direct way of probing the dark energy is to measure the distance-redshift relation in gravitational lenses with milli-arcsecond resolution (the effect of Dark Matter fluctuations on lensed images should be observable). On the other hand, high-precision pulsar timing with the EPTA will provide stringent tests for the existence of additional scalar fields that are often invoked to explain Dark Energy (e.g., Antoniadis et al. 2013, Science, 340, 448). These results need to be combined with astrometry.

Gravitational-wave detectors, (Advanced LIGO and VIRGO) could soon detect gravitational waves from binary neutron-star coalescence at distances up to a few hundred mega-parsecs (redshift $z \leq 0.1$). The detection of an accompanying electromagnetic signal (radio counterpart) would strongly complement these efforts, providing an independent confirmation of the discovery. The search for such an electromagnetic signal would be of high scientific interest (Nakar & Piran 2011, Nature 478, 829), but requires very wide-field radio observations. In the particular case of a neutron star – neutron star inspiral, the electromagnetic counterpart can lead to two independent distance measurements on cosmological scales, which could test the gravitational leakage into extra dimensions in "braneworld" models (i.e., higher-dimensional theories of fundamental physics).

e-MERLIN will measure cosmic shear from weak lensing radio surveys – complementing optical observations with high-resolution radio observations that offer advantages in terms of the stability of the primary beam response over wide fields of view. A new technique will be added using radio polarization position angle data.

The use of galaxies as tracers of the distribution of matter on large scales and the details of the large-scale structure and its evolution are at the heart of contemporary cosmology, especially since effects of a possible dark energy show mainly at redshifts of a few and below. Huge past and present efforts have concentrated mainly in optical and NIR bands in both detecting galaxies and measuring redshifts via spectra or, more coarsely, using photometric redshifts, especially for the faint population. Weak gravitational lensing in the optical band has flourished as well. The advent of the new generation of radio telescopes with sub-GHz capabilities now opens up the exciting opportunity of measuring HI in galaxies up to cosmological distances and for huge volumes, complementing and extending the present approach based mainly on optical data. Therefore the full arsenal of observables and techniques for measuring galaxy correlations, the power spectrum of density fluctuations, features such as the Baryonic Acoustic Oscillations (BAO) and redshift distortions will be applied to HI selected samples of galaxies. Shapes can be measured too and therefore weak gravitational lensing can be studied in radio as well. Moreover, when interested in particular scales such as the one of BAO, one can trade off angular and spectral resolution for sensitivity and measure a smoothed version of the HI belonging to single galaxies, thereby getting a 3D intensity map. Scientific collaborations in which European researchers have a significant contribution have proposed such experiments for ASKAP, MeerKAT and especially SKA (Proceedings of Advancing Astrophysics with the Square Kilometre Array, 8 – 13 June, 2014, Giardini Naxos, Italy (in press)).

In addition to cosmological HI surveys, low-frequency radio surveys will also provide essential complementary data for studies of the growth and evolution of large-scale structure. Deep, low-frequency radio surveys with instruments like LOFAR and ultimately the SKA can constrain the energy input into the galactic and intra-cluster medium (ICM) by AGN and star-forming galaxies out to redshifts of $z \sim 2$. Similarly, low-frequency observations of diffuse emission in the forms of radio haloes and relics can be used to constrain the energetic effect of both mergers and the growth of turbulence in the ICM during the formation of large-scale structure. Understanding these terms in the total formation energy budget will be essential for studies that wish to exploit the observed mass and spatial distributions of galaxies and clusters of galaxies to study the primordial power spectrum as well as the growth of large-scale structure in the present epoch.

To date the most accurate and unbiased determinations of the Hubble constant have been derived from mega-masers (Humphreys et al., 2013 ApJ 775 13). The determination of the

Hubble constant is getting closer to the precision required to improve or constrain the equation of state parameters for Dark Energy.

A3. Can we observe strong gravity in action?

There are two premier contributions from radio astronomy in terms of understanding strong gravity: i) Using VLBI it is possible to probe nearby supermassive black holes down to a few tens of Schwarzschild radii, contributing to studies of the launching of relativistic jets (Doeleman et al. 2012, Science 338, 355). In the future, at mm-wavelengths, it will be possible to detect the light bending effect in the accretion flow at the last stable orbit. This is the so-called "Event Horizon Telescope (EHT)" (Krichbaum et al. 2013, arXiv1305.2811K). VLBI also contributes to the understanding of the accretion state changes in micro-quasars, coupled with new ejections in the collimated relativistic jets (Fender & Belloni 2012, Science 337, 540); ii) There are also unique contributions coming from pulsar timing: such data have unparalleled precision for measuring the orbital elements, including post-Keplerian parameters, in binary pulsars. Pulsar data have been used for the most stringent tests of general relativity and alternative gravitational theories (e.g., Kramer et al. 2006, Science, 314, 97). Exotic neutron-star systems, like the recently discovered pulsar triple stellar system also hold the promise of uniquely sensitive tests of the "strong equivalence principle" (Ransom et al. 2014, Nature 505, 520), a central tenet of general relativity. The non-detection of spin precession of solitary pulsars from pulse profile analysis has been used to constrain the strong-field parametrized post-Newtonian (PPN) model parameters (Shao et al. Class. Quantum Grav 2013, 30).

Exploiting pulsar timing measurements to constrain these strong gravity signatures requires extreme time precision. An important element of achieving the required precision is the ability to accurately determine the effects of dispersion and scintillation caused by the intervening ISM. Since these effects are stronger at lower radio frequencies, low-frequency radio observations from facilities like LOFAR (as well as the large European single dishes) are ideally suited to constraining these processes and provide important complimentary data to the EPTA observations at higher frequency (Archibald et al. 2014, ApJL, 790, L22).

A4. How do supernovae and gamma-ray bursts work?

Expansion speeds of the radio-shell structure of young nearby core-collapse radio supernovae have been determined with VLBI observations (e.g. Martí-Vidal et al. 2011, A&A 526, A142). For some of the most extreme type Ib/c systems (hypernovae) the supernova explosion is driven by a `central engine' – i.e., an accreting black hole that produces collimated, relativistic jets. VLBI provides the only direct way to resolve these jets, but so far it has been done only for a single, nearby GRB. It will be possible in the near future for nearby supernovae as well. LOFAR, with its unrivalled all-sky transient detection and monitoring capability, will permit to monitor the evolution of supernova and GRB blast waves shortly after the explosion (even in the optically thick phase) for those cases in which they are detected; this will require LOFAR to achieve its ultimate, milliJansky sensitivity and thus optimal calibration. VLBI provides the resolution and sensitivity to study the detailed physics of nearby supernova factories (starburst galaxies; e.g. M82, Fenech et al. 2008, MNRAS 391, 1384). Moreover, a radio sky survey would be ideal to uncover large supernova populations, undetected in the traditional optical searches (Perez-Torres et al. 2014, arXiv:1409.1827). WSRT and Nançay will measure radio-SEDs of GRBs via monitoring of the radio afterglows.

Pulsar velocities can be measured via pulsar timing. These measurements, e.g. those obtained with the Lovell telescope's large database of pulsar arrival times, constrain the kick mechanism that is produced in supernova explosions. Moreover, it has been revealed a "pulsar spin" / "pulsar proper motion" alignement via polarization observations (Noutsos et al. 2012, MNRAS 423, 2736):

A large number of Supernova Remnants (SNRs) have been discovered through single-dish radio multi-frequency continuum polarization surveys of the Galactic plane.

The APERTIF system on the WSRT will provide a field-of-view of 8 square degrees, which will allow it to survey the entire sky at 1.4 GHz at high time resolution, enabling powerful searches for millisecond transients, which could be localized by sending triggers to LOFAR.

A5. How do black hole accretion, jets and outflows operate?

By combining high-angular-resolution polarimetric/interferometric observations and single-dish flux density monitoring (high sensitivity, quasi-simultaneous multi-frequency observations thanks to the frequency-agile receivers) with a high cadence of observations, it is possible to study the relativistic jets of AGN and microquasars – including processes from accretion to jet formation, acceleration, and feedback mechanisms (see Proceedings of the Workshop "The innermost regions of Relativistic Jets and their Magnetic Fields", 2013). The role of high-sensitivity antennas such as the 100-m radio telescope in Effelsberg, in the range from 3 to 30 GHz with its polarization properties, is fundamental – as is shown by the studies of the F-GAMMA Program (Angelakis, E. et al. 2010, J.Phys. Conf. Ser., Vol. 327, ID 012007; Beuchert, T. et al. 2013, EPJ Web. Conf., Vol. 61, ID 06006). It will be possible to study in a unique way the launching, collimation and acceleration of the relativistic jets. Real-time e-VLBI greatly enhances such studies (Paragi et al. 2013, MNRAS 432, 1319). The increased sensitivity of the instruments will provide the ability to carry out rotation measure and spectral index measurements within a single, wide-band observation. Such studies will also be very important in the growing field of radio transients, including Tidal Disruption Events (TDEs). We should note that these studies will only be fully realized when they are made in concert with other wavelengths. For example, this is already the case in X-ray binaries (XRBs), where the basic physical description comes from simultaneous radio, optical/IR and X-Ray observations (e.g. Deller et al. 2015, ApJ, in press).

Studies of XRBs provide an opportunity to study the evolution of the accretion process on both short and long timescales, and by mass scaling provide insight into higher-mass black hole (BH) systems. Simultaneous, multi-wavelength monitoring campaigns are essential to these studies to detect and track both the steady temporal changes in the output of the system but also the strong outbursts and flares that occur sporadically. VLBI permits to obtain images of the XRBs during the flares, tracing structural changes. With its ability to provide all-sky monitoring and detection at low frequencies, LOFAR can provide an additional source of complimentary data to these campaigns. Along with broad-band, simultaneous coverage of the 10 – 240 MHz window, its ability to both generate and to respond rapidly to triggers associated with flares or outbursts will be extremely useful for catching these sporadic events and either initiating or joining coordinated multi-wavelength campaigns.

At larger scales, e-MERLIN has the ideal resolution and polarimetric capabilities to study the radio outflows and radio galaxy lobes, obtaining information on the magnetic field configuration and the spectral behaviour.

A6. What do we learn from energetic radiation and particles?

Radio polarization measurements of galaxies and clusters will extend our understanding of the Galactic and intergalactic magnetic fields, which govern the propagation and interaction of cosmic rays, and perhaps even their origin, and help identify their sources (e.g., microquasars, gamma-ray binary systems, pulsar wind nebulae, supernovae, and AGN). Effelsberg has been fundamental in imaging the polarized large-scale structure of galaxies with its unique continuum polarization capabilities at cm-wavelengths. LOFAR's broad bandwidth at low frequencies, coupled with high sensitivity and arcsecond angular resolution, provide unique capability to measure Faraday rotation measures at extraordinarily high precision and measure weak magnetic fields. It should be mentioned that the LOFAR transient buffer board observations of synchrotron radiation from cosmic-ray shower debris, when used together with air shower detectors, will pin down the energy of the initial event (Schellart et al. 2013, A&A, 560, 98). The detection of radio emission resulting from the impact of neutrinos on the Moon is also an area of active effort (ter Veen et al. 2010, PhRvD, 82, 3014). Lastly, radio facilities are contributing to clarifying the nature of unidentified TeV/GeV sources (e.g., Hessels et al. 2008, ApJL, 682, 41). Centimetre radio observations with sub-arcsecond resolution are perfectly suited to relate gamma-ray and radio emission generation in AGN (e.g. J. Aleksić, et al. Science, 2014). The Effelsberg program F-GAMMA relates the time radio variability and spectral index evolution of Fermi-selected blazars.

High-resolution radio imaging on scales from milli-arcseconds to arcseconds are particularly useful to image outflows and identify shocks in gamma-ray novae, as was recently demonstrated for V959Mon (Chomiuk et al. 2014, Nature, 514, 339).

Gamma-ray binaries are extreme systems that produce non-thermal emission from radio to very-high-energy gamma rays, emission that is modulated by the orbital motion of the system. Interferometers trace the radio synchrotron outflows of relativistic particles on AU scales. They are excellent laboratories where the high-energy particle acceleration, diffusion, absorption and radiation mechanisms can be explored via multi-wavelength observations.

B. How do galaxies form and evolve?

B1. How did the Universe emerge from the Dark Ages?

Low-frequency studies (especially with LOFAR and later with SKA-Low) will contribute to the study of the Dark Ages via the detection (with LOFAR) and imaging (SKA-Low) of the redshifted HI 21-cm brightness temperature fluctuations of several independent patches on the sky. A good understanding of the various foregrounds along the way to detecting the HI spectral signal of the "Epoch of Reionization" is possible with LOFAR thanks to its combination of short and long baselines, full polarization operation, broad frequency coverage, excellent spectral resolution, and the capabilities for continuous wide-field calibration and high dynamic range imaging (van Haarlem et al. 2013, A&A, 556, 2). On the other hand, LOFAR, e-MERLIN and the EVN will contribute to distinguishing between AGN and star formation as the dominant source of radio emission in galaxies throughout cosmic time, taking advantage of the natural magnification provided by gravitational lensing (it would be possible to probe sources which would otherwise be at the nano-Jy level). Important constraints on galaxy evolution and the role of massive black holes can also be expected. The removal of Galactic foreground fluctuations is essential for calibrating the CMB observations and, for this, the surveys carried out by Effelsberg are very important (La Porta et al. 2008, A&A 478, 641).

B2. How did the structure of the cosmic web evolve?

Radio astronomical facilities, such as LOFAR, the other SKA pathfinders/precursors and SKA1, will favour the study of the large-scale structure via radio continuum surveys with an unprecedented combination of depth, resolution and frequency coverage. SKA1 will cause a breakthrough for HI intensity mapping of the large-scale structure at high redshift. LOFAR will carry out all-sky surveys in the 10 – 90 MHz and 110 – 240 MHz low-frequency bands, which are well adapted to finding (through their spectral morphologies) the first objects to emerge from the Dark Ages. This will establish the nature of the objects that reionized the Universe and discern the first seeds of galaxies. The role of the environment on the evolution of galaxies will be studied through observations of polarized radio continuum and HI emission, providing a consistent view of the inter-relationship between star-formation (resolved starbursts), black-hole growth (AGN), magnetic field generation, galaxy interactions (HI imaging) and the intra-cluster environment. Telescopes like Effelsberg and WSRT complement ongoing studies at other wavelengths, but provide polarization and hydrogendata uniquely available at radio frequencies.

Medium-sized dishes equipped with L-band, phased-array receivers have the right combination of field-of-view and sensitivity to carry out large radio surveys to study the objects populating the entire radio Universe.

B3. Where are most of the metals throughout cosmic time?

Large-area surveys are key to measuring the metal enrichment of the inter-galactic medium (IGM) at early epochs, by combining HI 21-cm absorption in their spectra with metal absorption in the near-infrared spectra of these objects. The molecular absorption (of lines like OH or formaldehyde) against ubiquitous radio emission can be used to measure atomic abundances. Some of the absorption studies can be accurately done with VLBI. These studies can be used to measure the cosmological evolution of fundamental constants.

B4. How were galaxies assembled?

The contributions of radio observations to the field of galaxy formation are multiple and of high scientific relevance. Radio offers the possibility to study dusty star-forming galaxies, providing extinction-free measurements of synchrotron emission, thermal free-free and dust emission, and provides unique tracers of galaxy dynamics through spectroscopy. With radio, in particular exploiting the wide-frequency coverage offered by LOFAR, SKA1 and its pathfinders/precursors (and also ALMA), it will be possible to tackle the gaseous evolution of galaxies in great detail. Radio astronomy offers some key diagnostics to understand the formation of galaxies.

What are the first phases of galaxy formation? Wide-field-of-view facilities, including LOFAR in concert with higher frequency facilities leading up to the SKA, will provide both all-sky catalogues and deeper imaging of selected areas over a large frequency range, favouring the observation of highly redshifted (luminous) radio galaxies and tracing their evolution over cosmic time.

Radio observations provide a unique window onto the physics of AGN and their influence on the formation and evolution of galaxies. They can chart the jets emerging from them, and the impact they have on the environment of a galaxy. Radio interferometers, in particular L-band instruments (including VLBI) and mm telescopes such as ALMA, offer the possibility to trace – at very high angular resolution – the distribution and kinematics of the fast outflowing cold gas component, witnessing the interaction between the radio jet and dense clouds in the ISM (e.g., Morganti et al., 2013, Science, 341, 1082). The large-area HI absorption surveys planned with SKA1 and its pathfinders/precursors, will dramatically increase the number of known cases of such outflows. At the lowest frequencies, radio data elucidate the oldest ejecta from the AGN, tracing back the history of feedback for 100 – 300 Myr into the past, as demonstrated by recent LOFAR observations. What fraction of radio emission is originating from an AGN and how much from star formation in the faint radio source population (including high redshift galaxies)? These issues will be addressed directly by studies of radio source counts (dN/dS) and spectral index distributions based on large-scale surveys at low frequencies. It should be noted that high sensitivity VLBI will be particularly important to separate AGN (compact) from nuclear starburst (more extended) emission at high redshifts (Pérez-Torres et al. 2010, A&A 519, L5).

Another key issue that radio observations are uniquely able to address is the formation of magnetic fields, and the feedback of magnetic fields on the formation and structure of galaxies.

Rotation-measure imaging will be a major contributor to answering this question. First hydrodynamical cosmological simulations of a present-day disc galaxy, in which the dynamics of magnetic fields have been included, came even to the conclusion that the large-scale magnetic field can be understood as a result of structure growth alone (Pakmor et al., ApJ 783, L20, 2014). Quasi-cosmological simulations of isolated disc galaxies with and without magnetic fields by Pakmor & Springel (MNRAS 432, 176, 2013) indeed show effects of magnetic fields on the star formation rate and the spiral arm structure, and may even cause outflows of gas and magnetic fields from the disc. This also leads to the question whether, and to what extent, do galaxies magnetize the intergalactic medium? Effelsberg has made fundamental contributions to the study of magnetic fields in galaxies and clusters, thanks to its high sensitivity, high polarization purity, large frequency range, high frequency agility and the possibility to observe large bandwidths with high spectral resolution. Low-frequency radio interferometer observations, e.g., with WSRT and LOFAR, have revealed extended structures in galaxy clusters, suggesting the presence of large-scale shocks with magnetic fields, elucidating further the origin and importance of such fields and their role in particle acceleration, and the physical conditions and energetics of the intra-cluster medium. In addition, one of the most powerful tools for studying magnetic fields in clusters of galaxies is to measure Faraday rotation in background and embedded radio sources (e.g., Bonafede et al., A&A 513, A30, 2010). The exquisite rotation measure sensitivity of LOFAR will make its contribution to this area quite significant.

Megamasers, due to their high luminosity and the high resolution with which they can be observed with VLBI, provide a unique view into the molecular gas distribution within the inner 100 parsecs of a galaxy, and their motion allows precision measurement of the masses of the nuclear black holes The role of the large dishes, equipped with wide band spectrometers is essential for the detection of the water masers that can be later studied with VLBI. . It has also been possible to measure the magnetic field through maser Zeeman measurements (e.g. Vlemmings et al., 2007, ApJ 656, 198).

A number of large HI surveys are planned with SKA1 and its pathfinders/precursors. Because of their high sensitivity, survey speed and resolution, these new instruments will allow us to make the important step from knowing the relationship between global gas properties (from ALFALFA and HIPASS) and other galaxy properties, to giving the definitive inventory of the *resolved* HI properties (morphology and kinematics) of galaxies over the complete range of galaxy mass, type and environment at low redshift. They can thus reveal the cause of the high HI-deficiencies found in high-density environments (Verdes-Montenegro et al. 2001, A&A 377,812), which is suspected to be in the form of low-column density intra-group material extending to large relative velocities. They will also help, through deep, high-redshift surveys, to uncover the role of gas accretion and gas loss through interactions (between galaxies and with the intra-cluster medium) in galaxy evolution, and elucidate the apparent shortage of observed accreting gas compared with what is needed to sustain the observed star formation rates.

B5. How did our galaxy form?

Wide-area radio surveys provide the unique capability to map out, in fine detail, the large-scale structure of the Milky Way and its interactions with companions, providing direct insight to the continuing build-up of the structure of our Galaxy. Multifrequency continuum surveys of the Galactic plane are conducted both in total and polarized flux to reveal the physical properties of the individual objects and the diffuse emission. Faraday tomography (or rotation measure synthesis) measurements of the local ISM with LOFAR have revealed very complex magnetic structures.

VLBI Astrometry will enable distance and proper motion measurements of astronomical objects across the Milky Way and within the Local Group. It will be possible directly to map the spiral structure and dynamics of the Milky Way via maser observations of the star-forming regions through the Galaxy. (the Bessel survey, http://www3.mpifr-bonn.mpg.de/staff/abrunthaler/BeSSeL/index.shtml, determines distances and proper motions to star forming regions in the Galaxy by observing water and methanol masers). Moreover, VLBI offers a unique possibility to address the Local Group dynamics by estimating local group proper motions. Interferometric observations, with micro-arcsecond astrometric capabilities, can provide accurate distances to different tracers such as star-forming regions, OH/IR stars and/or planetary nebulae, combining spectroscopic line-of-sight expansion velocities with proper motion measurements in the plane of the sky. For the case of OH/IR stars, in order to transfer the highly accurate radio position to infrared images, a grid of stars visible at both radio and infrared wavelengths is needed. Stars such as Mira-like variables are strong infrared sources and have circumstellar SiO masers that are strong radio sources. This approach has already been used for the case of the Galactic Center (Menten et al. 1997, ApJ 475, L111). These measurements are complementary to Gaia, which cannot probe the inner regions of the Galaxy.

C. What is the origin and evolution of stars and planets?

C1. How do stars form?

Radio telescopes permit to determine the initial physical conditions of star formation, including i) the evolution of molecular clouds under the influence of gravity and magnetic fields, ii) the subsequent development of structures, and iii) the formation and mass distributions of single/binary/multiple stellar systems and stellar clusters (Cesaroni 2005, IAU Symp 227; Zinnecker & Yorke 2007, ARA&A 45, 481, and references therein).

Single-dish surveys of Galactic masers (OH, methanol, water, SiO) provide unique insights into the late stages of stellar evolution. The determination and time monitoring of the stellar SEDs qive unique information about the emission mechanism. Radio interferometry (especially VLBI) has the unique power to resolve the physical processes of star formation with milli-arcsecond resolution, probing 10 – 1000 AU scales for objects at kpc distances. Since such observations require bright, non-thermally emitting regions, this is especially relevant for high-mass star formation in which maser emission is ubiquitous. Masers reveal the differentiation of the wind into clumps. VLBI observations of these maser spots uniquely probe the dynamics of massive stars with enough accuracy that proper motions, and thus 3D velocity fields, can be studied. The infall and outflow mechanisms can be discerned and the presence of binary or multiple stellar systems can be inferred. Moreover, such studies take advantage of the astrometric capabilities of the interferometers and often yield direct parallax distances, setting the mass and luminosity scales for multi-wavelength studies (these active star-formation sites can be identified with Spitzer and Herschel sources). In addition, bright maser emission can be used to measure magnetic fields, both in magnitude and orientation, through the Zeeman effect and linear polarization. This latter field has been pioneered in the EVN for the widespread 6.7 GHz methanol line (e.g. Surcis et al., 2013, A&A 556, 73), but also water masers are accessible.

C2. Do we understand stellar structure and evolution?

Single dishes will monitor the strong radio bursts shown by some classes of star, like dMe stars and active binaries. With interferometry, it will be possible to resolve and characterise the more violent stellar winds from hot, massive stars, revealing shock interactions from colliding winds in binaries, resolving the clumping and asymmetries of these winds and pinpointing the location of synchrotron radiation. High-precision studies are accessible for stars with coronal activity: i) through astrometric measurements we can directly measure their parallax distances and determine their multiplicity; ii) through polarimetric imaging it is possible to determine the emission mechanisms (gyro-synchrotron, synchrotron, thermal). High-resolution radio observations (EVN and e-MERLIN) can trace the ejected matter out through the SiO, water and OH maser zones, complemented by ALMA images of dust and thermal lines. Monitoring the transitions between the different layers delimited by the physical formation/disruption and the excitation conditions for these species will reveal how much of the mass loss is concentrated in clumps, whether these clumps remain confined all the way from the stellar surface into the circumstellar envelope and if they survive into the ISM.

C3. What is the life cycle of the interstellar medium and stars?

Radio telescopes enable a deeper understanding of the life cycle of matter, from the ISM, to its processing in stars, and back into the diffuse medium during the last stages of stellar evolution (e.g. Proceedings of the IAU Symposium 227: "Massive star birth: A crossroads of Astrophysics" 2005). The interplay between the ISM and the processing in stars in various stages of their life cycle is traced through the study of circumstellar envelopes in hundreds of stars of all ranges of mass-loss rate, age, variability and chemistry. Pulsar observations contribute to the study of the Galactic ISM through high-precision observations of propagation effects like dispersion, scintillation, scattering, and Faraday rotation (e.g. Noutsos et al. 2015, A&A, 576, A62). These studies benefit both from the low frequencies provided by LOFAR as well as the high sensitivity at higher-frequencies given by Europe's large single dishes.

Effelsberg is a leading facility in the study of the life cycle of molecular clouds, dark clouds, dust clouds, young stellar objects and other related aspects of star formation. Through wide-field surveys of the Galactic plane, a census of intense star formation in the Milky Way will be provided. Multi-transition molecular observations of the ISM in galaxies will trace, in a unique way, the ISM temperature and density.

Moreover, VLBI offers some unique capabilities to measure the dynamics and magnetic field strengths of the ISM. Relevant projects are: i) Mapping the spiral arm structure of the Galaxy through the study of the distribution and 3D kinematics of star-forming regions (masers); ii) Measuring the small-scale structure of the ISM through (HI or molecular) absorption studies against sources with milli-arcsecond structure; iii) Mapping of the ionized ISM turbulence through the signature of angular broadening and scintillation, observable with VLBI. Moreover, in AGB stars and (proto-)planetary nebulae with maser emission, VLBI can be used to study the mass-loss mechanism and the magnetic field. Such observations test our understanding of stellar wind flow models and stellar evolution. In particular, the LOFAR Transients Key Science Project will study the variable radio emission associated with different types of stars in various stages of their life cycle making use of its full polarization imaging capabilities.

C4. How do planetary systems form and evolve?

e-MERLIN will address which types of circumstellar disc proceed to the pebble-forming phase (cm-sized, which then leads to km-sized planetesimals), where this growth occurs in discs and what mass reservoir is involved. This will test the competing planet-formation models of core-accretion and gravitational collapse. For the brightest objects, they will be able to provide direct images of the rocky as well as icy zones within a disc with a resolution of less than 2 AU at the distance of the Taurus star-forming region. These observations will be complementary to ALMA programs at sub-mm wavelengths.

C5. What is the diversity of planetary systems in the Galaxy?

The sensitivity and accuracy of VLBI is bringing the possibility to detect planets within reach; by doing accurate astrometry of active stars one can hope to detect the small motions imposed by orbiting planets (Guirado & Ros 2007, ecf.book.257). In a completely different way, pulsar systems can also sometimes host and/or form exotic planetary mass objects, which are detectable through pulsar timing experiments (e.g. Wolszczan & Frail 1992, Nature, 355, 145; Bailes et al. 2011, Science, 333, 1717).

C6. Determine the frequency of Earth-like planets and push towards direct imaging.

Nothing applicable.

D. How do we fit in?

D1. What can the Solar System teach us about astrophysical processes?

With single-dish radio telescopes, images and dynamic spectra of the giant planets can be obtained at high cadence. Ground-based observations of Jupiter are an essential support for planetary space missions (e.g. Juno, JUICE, and Cassini). Jupiter is a magnetized planet archetype and a laboratory for plasma physics that provides as much information as similar Earth-based experiments. It allows us to address mechanisms of radio generation such as the cyclotron maser, the relation to aurora, the magnetosphere dynamics, the satellite-magnetosphere interaction and magnetosphere-solar wind. It will be possible to extrapolate these results to exoplanets, with the ultimate objective of opening the new field of comparative exo-magnetospheric physics.

Low-frequency radio observations can detect both the planetary magnetic field structure in nearby planets such as Jupiter as well as radio bursts associated with these objects. LOFAR has already shown itself to be an effective tool for monitoring these systems. The ability to provide simultaneous imaging and high time resolution data on these events at the lowest frequencies, where their emission peaks, is a unique observing capability. There exists the possibility (although very remote) of detecting radio bursts from extrasolar planets with LOFAR (Hess & Zarka, A&A 531, A29 (2011)). In the case they are detected, this will probe the combination of stellar winds with the influence of the magnetic field, providing a measure of the planetary rotation period. This latter determination could allow us to test whether the discovered extrasolar planets (“hot Jupiters”) are tidally locked to their host star and would provide clues on how the planets got to their positions.

D2. Develop a unified picture of the Sun and the Heliosphere.

LOFAR uses the vicinity of Solar System plasmas, in (i) the Sun, (ii) the heliosphere and (iii) planetary environments, to develop a detailed understanding of physical processes which apply to astrophysical phenomena. LOFAR provides a wide suite of capabilities that make it a powerful tool for studies of the Sun and heliosphere. High-cadence, low-frequency imaging can detect, map, and follow the propagation of solar bursts out through the solar corona. These images in turn can be used to constrain the density of the coronal medium. Simultaneously, it can provide millisecond or even microsecond-scale dynamic spectra for solar bursts (Morosan et al. 2014, A&A, 568, 67) as well as burst-triggered imaging campaigns.

MERLIN has been used to measure the structure of the solar wind using scintillation observations of compact background sources (Jones et al. 2009, JGR 112, A8). e-MERLIN can extend the spatial and temporal resolution of these observations. In the same way that they provide powerful diagnostic of the ISM, pulsar propagation effects are also of interest for studying plasma in the Solar System, as this has a subtle but non-negligible effect on pulsar timing. Pulsar timing observations are an effective tool to track the solar wind evolution. With polarimetric observations, it will be possible to detect the impact of the solar wind on the ionosphere.

There are VLBI scintillation observations of spacecraft that allow a study of the physics of the interplanetary medium (Molera Calvés 2014, A&A 564, 4). The low-frequency response and high spectral and temporal resolution of LOFAR also make it well suited for interplanetary scintillation (IPS) experiments to study the interplanetary medium.

Solar radio imaging and spectrometry by the Nançay Radio Heliograph (NRH) and other solar radio observatories provide information on solar weather activity, heliospheric or geophysical conditions forecast.

D3. What drives solar variability on all scales and transient activity?

The LOFAR Solar System and Space Weather Key Science Project is designed specifically for producing both images and dynamic spectra of the Sun at high cadence. Because of its excellent sensitivity, the wide range of baselines, and the high spatial, frequency, and temporal resolution, LOFAR represents a leap forward with respect to previous radio instruments. It will advance the study of the radio emission mechanism, magnetic reconnection and particle acceleration. These solar observations, with a spatial resolution comparable to that of optical telescopes, are crucial to understand solar magnetic activity and solar variability.

NRH provides images and dynamic spectra of the Sun at high cadence, giving information on the radio emission mechanism, magnetic reconnection and particle acceleration. These observations will be complementary to LOFAR and to optical ones, in terms of understanding solar magnetic activity and variability.

D4. Understand the role of turbulence and magnetic fields in the evolution of the primordial nebula

Radio methods probe the interplanetary plasma via scintillation measurements, as noted above, and directly measure turbulence in the interstellar medium via rotation measure data, especially at low frequencies.

D5. Determine the dynamical history of TNOs and the composition of comets

Some single-dishes (Nançay, Effelsberg) measure the production rate and kinematics of water in comets: the observation of the 18-cm lines of the OH radical in comets traces the production rate and the kinematics of water. They also probe the cometary magnetic field through observations of the Zeeman effect.

D6. Constrain the models of internal structure of planets: What can we learn from Solar System exploration?

Although at first these themes may not seem relevant for VLBI, it should be noted that the EVN and JIVE provide VLBI support to planetary science missions led by the European Space Agency (ESA) and other space agencies (Duev et al. 2012, A&A 541, A43). VLBI tracking of deep-space probes proved to enable state-of-the-art estimates of the spacecraft state-vectors with record-breaking accuracy (for the case of Mars Express (MEX), EVN observations provide estimates of the spacecraft state-vectors with an accuracy of tens of metres; this level of accuracy is sufficient to directly investigate the interiors of gravitating bodies). The EVN tracking of the Huygens probe as it descended through Titan's atmosphere is a great example on that. In general, ultra-precise VLBI tracking of interplanetary spacecraft and planetary probes provides accurate data for an extremely broad range of scientific applications ranging from gravimetry and studies of planetary interiors to the structure and dynamics of extra-terrestrial atmospheres, to fundamental physics. The planetary science applications of VLBI techniques developed within

EVN are highly synergistic with other major technological developments of VLBI: broadband data transport and processing (including real-time), development of high-sensitivity radio astronomy devices (including correlators).

Some EVN members participate in geodetic VLBI activities, organized through an European VLBI group for Geodesy and Astrometry. VLBI can accurately measure the geodetic parameters associated with the shape of the Earth and its orientation (UT1-UTC, polar motion, nutation, site location). VLBI measurements of the relative positions and velocities of the antennas on the surface of the Earth determine accurately the scale of the Earth-fixed reference frame. The changes in position are due to the motion of the tectonic plates, to deformation of the crust near faults, and/or to volcanic activity among others. These studies of plate tectonics on Earth give hints to the circumstances on other planets.

These geodetic observations provide the fundamental International Celestial Reference Frame (ICRF) defined by quasars and contribute radio source absolute positions down to 50 micro-arcsecond precision. This in turn enables measurements of the Galactocentric acceleration to be made (e.g. Titov et al. 2011, A&A 529, A91) and to put limits on the strength of cosmic gravitational waves (e.g. Gwinn et al, 1997, ApJ 485, 87). Additionally, comparison of AGN positions measured with Gaia and VLBI will enhance studies of the AGN jet formation, collimation and acceleration processes.

D7. Where should we look for life in the Solar System?

Radio astronomy does not obviously directly contribute in this area, though ideas have been proposed to use radar or occultation techniques to probe the thickness of ice on Europa and the presence of a possible sub-surface ocean.

4.3 – Observatory grades with respect to Science Vision

In Table 2 we link the capabilities of the existing European radio telescopes and the Science Vision (SV) topics according to three categories: i) “Scientific Coverage”: do the radio-astronomical observations imply an almost complete coverage of a particular SV topic (grade 3), a significant contribution (grade 2), or a minor one (grade 1)?; ii) “Uniqueness”: are the radio-astronomical observations unique in being able to answer a particular SV topic (grade 3: unique; grade 1: one of few; grade 0; one of many)?; iii) “Decisiveness”: are the radio-astronomical observations decisive in answering the SV topic (grade 3), somewhat decisive (grade 1), or not decisive (grade 0)? We have deliberately omitted the grade 2 for Uniqueness and Decisiveness in order to identify more clearly for which areas radio observations are really key to progress. Details of the grades can be found in appendix C. In order to arrive at this assessment, we started from the answers of the various observatories to our questionnaire (Appendix C), in which we explicitly asked them to indicate their contribution to the Science Vision, and from our survey of the literature and feedback from the community. Preliminary grades for each observatory were communicated to the observatory for comment, and the comments we received back were taken into account in the final grades.

This matrix of scores identifies in a clear way the Science Vision topics in which radio astronomy contributes in a major way. A few points deserve to be noted. First and foremost, the table clearly illustrates the fact that present and future radio astronomy contributes crucially to addressing the questions of the ASTRONET Science Vision, most prominently in areas A and B. It should also be noted that the lower grades for the smaller dishes should be interpreted with caution: indeed, their contributions to the Science Vision as standalone facilities are minor, but they are all part of the e-EVN, which receives some of the highest grades, and thus in the end they do contribute in a very important way to the Science Vision, collectively. It should be mentioned that single dishes fill the zero spacing flux of the EVN array.

	EVN	LOF	eMR	Eff	Wes	Lov	SRT	Med	Not	Tor	Nan	Met	Yeb	Ons
A1	4	3	3	4	3	3	3	2	2	3				
A2	3	3	4	3	3	3					2			
A3	8	7	5	6	3	4	4				6		3	3
A4	4	3	4	4	4	3	3	2	2		2			
A5	7	5	5	5	4	3	3	4	4		2	3	3	2
A6	4	6	3	4	3	2		2	2		2			
A+	4	4	4	9	9	9	4				9			
B1	4	9	4	3	2									
B2	4	4	4	3	3		2	2	2	4	3		2	
B3		2			2									
B4	7	8	5	7	5		3	4	4		3		3	3
B5	6	4	4	6	6									
C1	6		6	6	4		3	3	3	3	5		3	3
C2	4		4	3	3	3	3	3	3		3		3	3
C3	6	4	6	6	4	3	4	4	4		3		3	3
C4	5		7								3			
C5	5		3			2								
C6														
D1		3		3				3	3		4			
D2	3	4	3	2							4	3		
D3		6		3							3			
D4														
D5		3		3			3	3	3		5			
D6	2		2	3				3	3				3	3
D7														

Table 2: Summary of observatory grades with respect to the ASTRONET Science Vision. Darker colours represent a greater contribution by that observatory in that area. 'A+' is a specific category we created in addition to the known Science Vision ones for pulsar astronomy, which is specifically important in radio astronomy and not captured clearly enough by the other categories.

4.4 - Conclusions

In summary, we have examined in detail the contribution of European radio telescopes to the ASTRONET Science Vision, and have concluded that this contribution in crucial in a number of very significant areas. The EVN and LOFAR, as well as the larger single dishes, stand out as more prominent, and will deliver key science even into the SKA1 era. The SKA will deliver a very significant leap in capabilities in a number of key areas.

Chapter 5: Technical parameters impacting science output

5.1 – Introduction

This and the following two chapters aim to evaluate the existing European radio astronomy infrastructures in order to identify both positive and negative factors affecting their science output. This chapter builds on the mostly factual description of these facilities presented in Chapter 3 ("European Radio Telescopes") and the primary science drivers associated with these, as detailed in Chapter 4 ("Science Drivers"). Significant input from the community – via the ERTRC online discussion forum and during live discussion sessions at conferences – has been incorporated. An overarching question that this chapter addresses is: what are Europe's greatest strengths in radio astronomy and how can we expand on these?

The scientific capabilities of Europe's radio facilities are driven by i) the front-end hardware – i.e. the antennas and receivers, ii) the back-end data recorders – i.e. the correlators, spectrometers and beam-formers, iii) the offline data reduction and calibration software pipelines, and iv) the long-term archives of data products. This chapter covers all of these aspects in turn. We make an overview of the current technical capabilities in terms of important performance parameters like, e.g., spectral coverage, field-of-view, polarimetric purity, and u-v coverage. We continue in Chapter 6 with a discussion of how telescope operations affect science output. Data processing and archiving are also discussed. Near-horizon technical developments as well as the path to SKA are discussed in Chapter 7, where we also provide conclusions.

5.2 – Current technical capabilities

Like many areas of science, big discoveries in radio astronomy are often enabled by cutting-edge technology and instruments that provide a major leap forward in capability over their predecessors. Key features that are required for front-line radio astronomy instrumentation include raw sensitivity, spectral coverage, wide bandwidths, high spectral resolution, polarization purity, time resolution, field-of-view, and angular resolution.

European radio astronomers have access to front-line instrumentation that pushes the envelope in terms of, e.g., sensitivity, time resolution, field-of-view, spectral coverage, and observing cadence. There are good examples in which the combination of multi-frequency coverage, angular resolution, high sensitivity and access to "Target of Opportunity" observing time provides excellent science; for example, the study of stellar black hole outbursts with their associated ejection of plasmons in relativistic jets, which can be imaged and studied with exquisite detail using the EVN and e-MERLIN, or the study of relativistic jets with the EVN after a Gamma flare, providing unique information on the radio-gamma ray connection in these sources. To give another example, high-cadence monitoring of the Galactic Center using the Effelsberg single-dish radio telescope discovered the nearest radio pulsar to Sag A*. Similarly, high-cadence timing observations using WSRT's tied-array mode (where the dishes are coherently combined to mimic a single dish) are leading to gravity tests using the first pulsar in a stellar triple system.

We now discuss these important observational parameters and their impact on science, in turn.

5.2.1 – Sensitivity

Europe hosts the world's largest VLBI network (EVN), 5 of the world's top 10 largest single dishes (Effelsberg, Lovell, Nançay, Sardinia, and Yevpatoria), and the world's largest low-frequency radio interferometer (LOFAR), among others.

The European VLBI Network (EVN) is a pan-European interferometer that has grown into the most sensitive VLBI array in the world thanks to the large telescopes in Europe (notably the Effelsberg 100-m dish) and the agreements with other arrays in Asia, Africa and America. It routinely provides angular resolution on the order of milli-arcseconds, with a progressively improving sensitivity through the upgrade of data recorders and the central correlator. The EVN may also soon grow even larger and more powerful with the addition of dishes in the new African VLBI network. In this regard, the future inclusion of the 500-m Chinese FAST telescope would also provide a major sensitivity boost. Importantly, the EVN will *remain* the premier VLBI instrument even during the first phase of the SKA (SKA1) because no similarly long baselines are included in the design until SKA phase 2 (SKA2, which is likely at least 15 years away) (though some groups are pushing for this; see Paragi et al., ApJ 791, 2, 2014). As such, the EVN (benefitted from its extension to the Southern Hemisphere, and possible combination with the SKA1 core) will remain a critical instrument for following up SKA survey discoveries at the smallest angular scales – including for precision astrometry. Moreover, the EVN will remain as the key instrument for investigations in the Northern Hemisphere. Maintaining the maximum array sensitivity will be critical to ensuring this role. For a typical EVN observing run at 5 GHz, with 150 minutes on-source integration time and a data rate of 1 Gbps, the image thermal noise is around 10 microJy/beam (1 sigma) using natural weighting. At 1.7 GHz, for the same observing parameters, the image thermal noise is of 9.25 microJy/beam (1 sigma) using natural weighting. Increasing the bandwidths, these numbers will improve. It may be possible to use the EVN and the SKA1 core at frequencies less than 3 GHz (no higher frequencies are currently envisioned in SKA1, though this issue is still under discussion).

LOFAR will remain the largest low-frequency radio interferometer in the world until the construction of SKA1-Low (a major component of the first phase of the SKA that will be hosted in Australia), and even then, LOFAR will still have more than ten times greater linear imaging resolution thanks to its pan-European baselines (quite apart from being the only sizeable low-frequency array in the Northern Hemisphere). Due to its early technical success and scientific potential, LOFAR will continue to play a lead role in informing the design and scientific approach to SKA1-Low for many years to come.

Until the advent of SKA1 and/or FAST, many applications of high-time-resolution radio astronomy – currently a major area for Europe's large, single dishes – will remain sensitivity limited. With major upgrades to receivers and backends, Effelsberg, Lovell, Nançay, and Sardinia are now making near-optimal use of the available collecting area. Novel projects like the Large European Array for Pulsars (LEAP) are pushing the envelope beyond Arecibo-like sensitivity by coherently combining these dishes, as well as WSRT, into a tied-array. This gives a taste of SKA1 sensitivity and science – in fact, LEAP sessions currently provide a sensitivity that is close to what SKA1 will offer for pulsar timing.

However, despite these world-class instruments and the continuing upgrades, many of the radio-astronomy-related goals of the Science Vision remain strongly sensitivity limited, and Europe's major involvement in the SKA is thus critical to continue these fruitful research lines into the next decade.

5.2.2 – Spectral coverage and wide-bandwidth observing

As described in Chapter 3, Europe's radio facilities cover the full frequency range from the very lowest to the highest frequencies observable from the ground in the radio window of the Earth's atmosphere. With this wide spectral view comes a rich variety of science topics based on, e.g., synchrotron emission, free-free emission, maser emission, the 21-cm line, and radio recombination lines.

At the lowest frequencies, Europe hosts LOFAR, the world's premier radio telescope in the 10 – 240 MHz range (the lowest 4 octaves of the radio window). LOFAR promises breakthroughs in the low-frequency range because of its excellent u-v coverage, pan-European baselines, wide field-of-view, flexible multi-beaming, and its large number of science-specific data processing pipelines (see below).

Europe's large radio dishes pick-up where LOFAR leaves off. Several of these instruments are capable of observing as low as 300 MHz or up to as high as 100 GHz. The advent of the new Sardinia Radio Telescope reinforces Europe's strengths across the entire range of the radio window. Effelsberg also remains, next to the GBT, one of the world's most powerful instruments at high frequency. Again here it is critical to realize that SKA1 will possibly only provide coverage up to a frequency of about 3 GHz[5], and thus important components of the Science Vision portfolio depend on maintaining these European capabilities well into the next decade.

Many of Europe's radio telescopes also provide large instantaneous bandwidth. For instance, LOFAR is capable of providing 80 MHz of instantaneous bandwidth, which is a huge fractional bandwidth at such low frequencies and is critical, e.g., to enable the search for the Epoch of Reionization signal (likely existing somewhere in the 110 – 190 MHz range). At Effelsberg, the Ultra-Broadband (UBB) receiver is opening a simultaneous 300 MHz – 3 GHz window for high-precision pulsar timing. Such broadband coverage is important for mapping the dynamic space-weather that affects the pulsar's clock-like signal. The EVN is already extending the IF bandwidth of the EVN stations to 1 GHz at L-band and to 2 – 4 GHz at C-band, with simultaneous developments for wide bandwidths and high-bitrate VLBI backends, favouring the use of the full potential of the wide-band receivers.

5.2.3 – Spectral resolution

High spectral resolution for spectral line observing is one of the main goals of the European radio telescopes, both as single dishes (e.g. for HI surveys or monitoring projects of water and methanol masers) and as part of interferometric observations.

Understanding the process by which galaxies convert gas into stars is one of the important issues in galaxy evolution. It is very relevant to map the gas in nearby and high redshift galaxies with high angular and high spectral resolution in order to determine the spatial extent of the galaxies, to measure their kinematics and determine the velocity profiles to distinguish between regular and turbulent motions, and compute the dynamical mass to test theories of galaxy assembly. This high spectral resolution is also very important for cosmology: it is possible to get redshifts for individual galaxies permitting the study of clustering evolution and, gaining intensity through lowering resolution, obtain HI intensity maps. The search for high spectral resolution, particularly in the HI work, has pushed new technical developments: a new digital FFT spectrometer with 64K spectral channels is available at the Effelsberg telescope; in WSRT, depending on the number of IF bands and polarizations, up to 8K channels are available, providing velocity resolutions better than 1 km/s at 21 cm.

High spectral resolution is also required for observations of masers. It has become an essential astrophysical tool for different astrophysical scenarios, from the study of the circumstellar envelopes of evolved stars, to the precise determination of BH masses in AGN and the determination of the Hubble constant through the Megamaser Cosmology Project. It is also

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[5] Though there is a substantial effort by different SKA Science Working Groups supporting the availability of Band 4 (2.8 – 5.2 GHz) and Band 5 (4.6 – 13.8 GHz) already for SKA1.

worth noting that the EVN's SFXC correlator can provide arbitrarily high spectral resolution, which is used for spacecraft tracking and studies of the Zeeman effect.

At the lowest frequencies, LOFAR provides kHz spectral resolution for observations of radio recombination lines (RRLs). Even higher frequency resolution (on the order of Hz) is needed for on-going SETI experiments and studies of the interstellar medium using cyclic spectroscopy (an advanced technique that gives both high frequency resolution and high time resolution across the pulsar rotational phase) on pulsars. This can be achieved through a baseband recording mode and offline channelization.

5.2.4 – Polarimetry

Polarization purity is very important for interferometric observations. The polarization leakage should not exceed a few percent in order to correct for the instrumental values in the determination of the degree of polarization and polarization-angle. The combination of frequency agile receivers and polarization purity is also very valuable for Faraday rotation measure imaging (rotation measure synthesis), which has added new possibilities to the 3D-study of complex magnetized regions.

Also for pulsar timing, the required precision for gravitational wave detection necessitates accurate polarization calibration, without which the measured pulse profile can deviate from its true shape in a dynamic way that introduces noise into the timing residuals. For instance, large European dishes like Effelsberg provide superb polarization purity (due in this case to its symmetric design), which is being exploited to provide high-precision and high-*accuracy* pulsar timing data as part of the European Pulsar Timing Array.

5.2.5 – Time resolution

High time resolution is an obvious concern for studies of known pulsars as well as pulsar surveys. Europe's large single-dish instruments now provide near-optimal time resolution for such studies, because they employ broadband coherent dedispersion backends, which are capable of completely correcting for the deleterious effects of interstellar dispersion. This has greatly increased the precision and value of pulsar timing data coming from these instruments. Such precision is critical for tests of gravity, and will be essential for using an ensemble of millisecond pulsars to directly detect the stochastic gravitational wave background of the Universe.

Beyond the realm of so-called beam-formed observing techniques, several groups are implementing fast imaging algorithms in order to find transients. This involves either running the correlator with a much smaller (sub-second) integration time and/or using novel, visibility-based detection algorithms for triggering high-time-resolution data dumps (e.g., Law & Bower 2012, ApJ 749, 143L). These techniques are being implemented and tested on telescopes like LOFAR (e.g., the AARTFAAC and DRAGNET projects).

The JIVE correlator now includes a pulsar-binning mode. Both incoherent and coherent dedispersion is also possible. Coherent dedispersion is needed for shorter period pulsars with high dispersion measures.

5.2.6 – Field-of-view

Wide-field radio astronomy is a major growth area because it affords exploration of transients and efficient, deep, all-sky surveys. Field-of view is being driven by i) new front-end technologies (aperture arrays and focal plane arrays) and ii) larger correlators and computing power, which enable processing of these data. Compared with high-energy X-ray and gamma-ray satellites, which routinely monitor the whole sky, the technology of radio astronomy currently affords only a limited field-of-view at the required sensitivity.

LOFAR is the world's largest, sparse digital aperture array. Though the antennas themselves are stationary, they can be pointed to any region within the field-of-view by applying analogue and digital delays in a number of steps, including in software on the correlator/beam-former. This enables flexible multi-beaming – i.e. pointing the telescope in multiple, sometimes independent, directions at once. This enables both more efficient use of the telescope time, by observing multiple science targets at once, as well as a naturally larger field-of-view for surveys and transient detection experiments. Very similar technology is the basis for SKA1-Low. Through commensal observing, these new facilities can provide a more efficient way to conduct some science cases.

At higher observing frequencies, telescopes like the Lovell and Effelsberg have cryogenically cooled multi-beam receivers, which are used to conduct efficient pulsar surveys. Dense aperture arrays are also being developed – e.g. the EMBRACE demonstrator at WSRT and Nançay. These two demonstrator arrays each feature close to 100 1x1m tiles of Vivaldi elements (a particular type of antenna design), which are first combined at tile level and then across the array. They operate around 1.4 GHz frequencies and have the promise of providing large, cheap collecting area as well as wide, flexible field-of-view. Though the collecting area of the EMBRACE demonstrators is too small to do new science, radio astronomical demonstration observations have successfully been completed, including the simultaneous detection of a pulsar and the mapping of HI using two independently steered beams. This technological development is part of the SKA's advanced instrumentation plan, with possible inclusion in SKA2. Europe is leading this effort.

Europe's dish-based antennas are also expanding their fields-of-view using multi-pixel cameras (so-called focal plane arrays). For example, developments are underway to equip Effelsberg with an L-band focal plane array by early 2016; this will substantially expand its pulsar surveying capabilities compared to what is possible with the current multi-pixel feed mentioned above. As a next step, a *cooled* focal plane array is being considered for Effelsberg. Similar efforts are also underway with the GBT and Arecibo telescopes in North America. Also notably, the WSRT is being fitted with the Aperture Tile in Focus (APERTIF) system, which will increase its field-of-view by more than an order-of-magnitude through the use of 56-element focal plane arrays. This will effectively turn WSRT into a northern hemisphere survey interferometer similar to ASKAP in the south (though each telescope will also have its own unique specific strengths).

Lastly, the naturally large fields-of-view of Europe's 25-m class telescopes are now being better used when they are combined as part of the EVN. With the SFXC software correlator, the EVN has implemented the possibility of correlating at multiple phase centres, increasing the processed field-of-view of the EVN observations (up to now, for EVN observations at 1.6 GHz, with a bandwidth resolution of 0.5 MHz and a basic integration time of 2 seconds, the FoV was only around 10 arcsec wide). The new generic, scalable, FPGA-based correlator (the UniBoard) will also include this feature. With the new correlators it possible to image a few to very many targets across the entire primary beam (the effective primary beam is roughly equivalent to that of a 32-m dish for the non-homogeneous EVN array). A number of scientific fields would benefit from the full imaging of the effective primary beam (still a very expensive and challenging endeavour), and faint targets would also benefit from the availability of nearby in-beam calibration sources.

Software correlation has become feasible in recent years. It has several advantages: it is very flexible in the way to allocate the processing resources of varying numbers of stations, frequency and time resolution; it favors also special processing modes, with no fundamental fixed limits other than the finite performance of the processing cluster. In MPIfR, VLBI observations are processed using the DiFX software correlator.

5.2.7 – Angular resolution

With the European radio telescopes, we can probe astrophysical scenarios with angular resolutions from degrees (with single dishes at the longer wavelengths), to tens/hundreds of milli-arcseconds (with regional interferometers), to milli-arcseconds (with the EVN), down to micro-arcsecond scales (via VLBI astrometry).

The WSRT provides an angular resolution of 15 arcseconds at 21 cm. With the advent of APERTIF and its associated increased field-of-view, it is possible to survey large areas on the sky much faster. APERTIF will be an excellent instrument for the study of the evolution of the HI content of galaxies, the evolution of star formation and the population of active galaxies with cosmic time (as well as searches for transients).

e-MERLIN achieves 50 – 150 milli-arcsecond resolution, with sub-microJy sensitivity in deep observations, across relatively large fields-of-view. With this angular resolution, we can probe uniquely astrophysical scenarios such as the pebble-sized material in planet formation, the disc-jet zone (linear sizes of tens of AUs) in newly forming stars, the powerful jets of AGN and X-ray transients and the star-forming regions in distant galaxies.

The EVN has a unique resolving power, down to sub-milliarcsecond scales. This enables the study of a wide range of objects and topics, which was outlined in the document "EVN2015: the future of the EVN" (http://www.evlbi.org/publications/EVN2015FinalV2.pdf). Besides the classical VLBI topics like the study of the inner regions of AGN, blazars and radio galaxies, we could mention other astronomical fields – many of them taking advantage of the fact that radio emission is free from dust emission – like i) the study of young radio supernovae, GRBs, pulsars and transients in general, ii) the study of circumstellar rings and the process of high-mass star formation, considering the gas dynamics, molecular excitation and the magnetic fields very close to the forming star, iii) the study of distant star-forming systems and the central regions of nearby galaxies, iv) the astrometric capabilities of the VLBI arrays, providing very accurate determinations of the proper motions, parallaxes and distances to the star-forming regions within the Milky Way, and absolute positions of transients or v) the extremely precise determination of state vectors of planetary probes.

Radio observations are also a unique probe for the diffuse synchrotron radio emission in the ISM of galaxies and the ICM of galaxy clusters. In this last case, the diffuse structure is observed in the form of giant radio halos at the cluster centre or in the form of radio relics at the cluster outskirts. The radio emission traces shocks and magnetic field structures in the cluster gas. Radio halos, relics and filaments are related to the particle acceleration produced via shocks and/or turbulences. These structures are visible at low and mid radio frequencies. LOFAR and, in the future, SKA1 are the key instruments for these kinds of studies thanks to their large instantaneous fields-of-view and good angular resolution.

5.3 – Conclusions

In summary, we see that instrumental improvements that significantly affect the science capabilities of Europe's radio observatories continue to be made. The European facilities are equipped with front-line radio astronomy instrumentation including a number of key features such as multi-frequency capability, frequency agility, large bandwidth/high sensitivity, polarization sensitivity and good polarisation purity, wide-field capability and good spectroscopic capability. The broad bandwidths can simultaneously provide high sensitivity and some multi-frequency observing capability, permitting to observe large bandwidths with high spectral resolution. Meanwhile, vigorous technical development of further capabilities continues to be a major activity at radio institutes, both with a view towards improving current facilities, and providing the best possible technology for the SKA.

Chapter 6: Scientific operations

6.1 – Introduction

The technical capabilities of Europe's radio telescopes are paramount to achieving the goals of the Science Vision, but well-coordinated and well thought out science operations can also significantly increase their scientific impact.

Single dishes play very important roles in specific, well-targeted scientific areas such as surveying, monitoring and transient searches, provided that they are outfitted with modern equipment and exhibit a coherent and coordinated approach to their observing programs. Moreover, the science case for single dishes is greatly enhanced by their use in larger arrays and collaborations, such as EVN/JIVE and EPTA/LEAP. In fact, the EVN, JIVE (Joint Institute for VLBI in Europe) and LOFAR are excellent examples of well-coordinated, pan-European scientific operations.

Does the way in which these telescopes are offered to users match the requirements they have to do the best science? Do astronomers have suitable tools for an efficient access to the data, to the distributed computing infrastructures necessary to process them, and for extracting scientifically relevant information from the data deluge that Astronomy is suffering? Is the scheduling of observations flexible enough in terms of optimizing science? Is there enough support for observers? How accessible are Europe's radio telescopes to scientists both within and outside Europe? We should mention that European radio astronomers have full access to non-European facilities (e.g. VLBA, JVLA, ATCA) based on scientific merit. We address such questions in the following sections.

6.2 – Major observing modes

All the basic observing modes are available through the European radio telescopes: continuum imaging, spectral line, polarimetry, pulsar timing, pulsar searching, raw voltage dumps. Furthermore, advanced and commensal observing modes are now also available at a number of facilities. In fact, many of Europe's telescopes are multi-faceted facilities, offering a wide range of observing modes (either in their own right or combined with other telescopes), and hence also a great diversity of science, as shown in Chapter 4.

As more of the signal processing chain becomes digital, and limited only by the available computing power, great opportunities present themselves for increasing the value and effectiveness of each hour of observing time. In part this is due to the possibility of commensal observing – i.e. multiple observing modes running in parallel to each other on the same stream of raw data. On the other hand, completely new observing possibilities are also arising. Among the former, an example is multi-beam observing: a phased-array telescope like LOFAR points electronically, and can therefore run multiple pointings simultaneously. LOFAR has demonstrated observing up to a half dozen pulsars simultaneously with independent beams spread over the entire sky. It has also demonstrated performing a low-sensitivity time-domain imaging survey of the North Celestial Pole region by always pointing one subband at that region while doing its first low-band (30 – 80 MHz) survey of the northern sky. Simultaneous beam-formed and imaging observations of the same field provide an imaging survey of that field and simultaneous high-time-resolution monitoring of a pulsar in the same field. For example, such a mode is being developed for the APERTIF phased array feeds at WSRT. The backends on large single dishes can also simultaneously provide high-spectral resolution data for spectral line work while at the same time providing high-time-resolution data for pulsar searches and timing. Real-time searches for fast radio transients are now also being conducted at several large

European single-dish telescopes (e.g. Lovell and Effelsberg, and likely soon also Nançay), commensally with other observing programs.

Completely new possibilities are for example the real-time processing of data, again enabled by vastly increased computing power. An example of this is real-time, high-time-resolution imaging of the sky. This is as yet experimental, and is being tried out with the so-called AARTFAAC experiment on LOFAR. Another example is the use of hardware or software buffers to store very high volumes of raw data for later analysis. This can be done only for short periods of time, which are chosen based on triggers of the telescope by independent data circuits or external instruments. An example of this is the observation of cosmic rays with LOFAR. Completely automatic re-scheduling and re-pointing of a telescope based on triggers from other telescopes is also a novel strategy, which has been used with the AMI array to do rapid follow-up of GRB alerts generated by the Swift satellite. Again we also underscore the great scientific benefit provided by real-time VLBI with the e-EVN.

6.3 – Scheduling of observations

6.3.1 – Open skies policy

The European radio telescopes should achieve the right balance between good bread-and-butter science, evaluated through the usual refereeing process, and more exciting high-risk/high-gain projects, which should be supported and even encouraged by the observatories. To this end, the European radio telescopes have a policy of "open skies". For some of them (EVN, e-MERLIN, Effelsberg, LOFAR, WSRT, APEX, IRAM), RadioNet3 offers Transnational Access (TNA) travel support. (Note that APEX, IRAM and LOFAR do not have completely open sky policies) The observing time on these facilities is awarded based on scientific merit and feasibility. They have well defined observing proposal deadlines (http://www.radionet-eu.org/observing-proposals), with their own TACs. Some of the telescopes not included in the TNA access also offer observing time, although due to budget restrictions, they are unable to guarantee full technical support during the whole observing runs. For most of them, there is observing time reserved for Director's Discretionary Time (DDT) access.

Rigorous and well-considered approaches to time allocation are in place at the European radio observatories, including those mentioned above. To give one specific example, observing time for the EVN is allocated by the EVN Programme Committee (EVNPC), which distributes three "Call for Proposals" per year, and discusses the scientific merit of the proposals in three meetings per year. The EVNPC comprises 8 observatory members and 4 at-large members chosen from non-EVN institutions to complement the astronomical expertise of the committee. There is a well-defined policy for Target of Opportunity (ToO) access (http://www.evlbi.org/proposals/too.2011.pdf).

6.3.2 – Rapid response to targets of opportunity

With the upcoming availability of facilities like the Large Synoptic Survey Telescope (LSST), the astronomical community (including the radio community) needs to define how to handle follow-up observations that will be required to identify, classify and characterize those events reported by the synoptic facilities, some of which may represent exciting new (astro-)physics. A clear definition of how to combine the scientific programs of the existing major facilities with time-critical alerts is needed. In that sense, clear protocols should be established to set up information flows between the synoptic telescopes and the radio facilities, and develop the trigger mechanisms and the basic standards for the observations. It is obvious that the SKA and the largest facilities will not be the instrument to follow-up most of the transients, but many of the European radio telescopes (including the EVN or a sub-array of it) can play an important role in the source characterization. A successful example of triggering has been implemented on the AMI array, which receives GRB alerts and then quickly slews to achieve very early radio flux measurements, in some cases only minutes after the alert.

Thanks to the project (N-)EXPRES, the EVN is leading the VLBI arrays in obtaining (near) real-time, high-resolution images. The development of e-VLBI has been possible by transferring the data directly from the telescopes to the central processor through high-speed optical fibre networks, obtaining interferometric images in real time. The e-EVN offers the opportunity to react to transient alerts, once the TAC has approved the DDT proposal, and contribute to the source identification/classification, giving new insights on the physics of the transient radio emitters.

6.3.3 – Coordination with other wavelengths

Our understanding of the physics of most astronomical objects is based on multi-wavelength observations. In the radio regime, there is often a close link with high energy X-rays and gamma-rays because of the non-thermal emission that is common to these bands. Many objects common to the radio and higher-energy bands are transient in their nature, e.g., various manifestations of pulsars, low-mass X-ray binaries, and AGN. Responding to rare, or in some cases unique transient behaviour at multiple wavelengths is often critical for this science. This is described in more detail in Chapter 8. Coordination between radio and high-energy facilities is sometimes difficult, however, requiring many separate proposals. The ability to make a single request for simultaneous radio observations with a number of X-ray and gamma-ray facilities would thus lower the threshold for such projects greatly. Increased flexibility of scheduling can increase the possibility for multi-wavelength synergies (i.e. simultaneous observing campaigns between high-energy observatories and radio), as can reserving some explicit fraction of observing time for multi-telescope proposals.

6.4 – Science support

RadioNet3 offers access to world-class facilities included in the current RN3- Transnational Access program (EVN, e-MERLIN, Effelsberg, LOFAR, WSRT, APEX, IRAM-NOEMA, IRAM-PV). The calls for proposals are open to all astronomers, i.e. not only to the experts. Time is granted on a scientific merit basis. RadioNet3 also offers a limited amount of financial support for astronomers travelling to the TNA facilities and/or to data reduction centers. The visitors receive help from local experts, both with the observations and with the data reduction. The goal is to increase the user-base of the TNA facilities and to optimize their scientific output.

In case of EVN observations, a support scientist is assigned to each observing programme, who assists the PI and his team during every step from scheduling, the observations, the correlation of the data obtained, the data reduction and scientific analysis. Similar help is provided at e-MERLIN, WSRT, and Effelsberg. LOFAR aims to implement a similar support scheme, some parts of which are still under development – owing in large part to the complexity of the instrument and the broad range of observing modes that gradually become available. Annual LOFAR data schools help users to get acquainted with the unique capabilities of the instrument, and an online version of the LOFAR data analysis cookbook is continuously updated.

An effort is still necessary to provide the user community with advanced tools – e. g. scientific workflows, visualization tools- for the access to the data and their analysis. Likewise, an increasing amount of resources are needed to store the data and high capacity computing infrastructures for processing them. Astronomy could benefit from the use of the web environments known as Science Gateways (SGs), from which other disciplines suffering their own data deluge (e.g. the solid-Earth science [http://www.verce.eu/) are benefiting. The SGs ease the access to data and tools distributed among different computing resources, promoting the sharing of methods and data among the user community. In astronomy, the prime effort to construct common platforms for data visualization and handling is made through the so-called Virtual Observatory efforts, e.g., the European Virtual Observatory (http://www.euro-vo.org) and the International Virtual Observatory (http://www.ivoa.net).

6.5 – The future role of data reduction pipelines

New developments to increase the capabilities of currently available/planned software packages are required to optimize the scientific use of the facilities and open them to new users.

Within the framework of RadioNet3, a Joint Research Activity called Hilado has nearly been completed. Hilado aimed at creating optimized prototype software and demonstrator processing pipelines, combining both automated pipelines and user-adaptable scripts, allowing a flexible interaction with the applications. Hilado addresses the specific topics related to large datasets (imaging the full field-of-view of the telescopes, providing large numbers of spectral channels, and/or using short integration times). It is based on publicly available software, like the CASACore library (which is maintained by NRAO, ASTRON and CSIRO) and the Python scripting environment. This prototype software constitutes a strong scientific base for the SKA construction phase. Initiatives like Hilado should be strongly promoted.

For VLBI, JIVE provides pipelined-datasets, which have been investigated to check whether they require any reprocessing, which can be fully analysed within AIPS. The products of the automatic pipeline program include preliminary images and (importantly) calibration information for the target sources. The EVN data become public after a 12-month proprietary period. When the data are distributed to the PI, the investigators have the option to visit JIVE in order to analyse the data. JIVE is also supporting the ParselTongue package, which is a Python interface to the AIPS package.

The e-MERLIN team provides full support to all users, from proposal preparation assistance to data reduction support. The e-MERLIN data reduction is done within AIPS. The e-MERLIN team provides access to a fully automated pipeline for the e-MERLIN data reduction, which is written in Python and uses the ParselTongue interface to AIPS. Automated RFI flagging tools are also provided (SERPent software).

The definition of a robust and automated LOFAR calibration strategy is very challenging but is continuously improving, and reaching closer to thermal-noise-limited images. LOFAR requires a two-stage calibration: first a calibration of each station, and then a calibration across the array. The main difference in the LOFAR calibration with respect to other interferometers is that the gains are position-dependent. Moreover, the ionospheric delay depends strongly, for a given station, on the position within the field-of-view. Therefore, a generalized self-calibration system would require an independent complex gain for each point on the sky for every station and each time interval. From a conceptual point of view it is similar to conventional self-calibration, but with the difference that the number of gains will depend on the number of independent locations within the field-of-view, making the number of parameters to be solved excessive for any algorithm. New developments are required, and are continuing to be developed and implemented by the LOFAR Imaging Tiger Team. These developments will be essential to set the stage for the SKA in the future. The task of providing robust, nearly automatic data analysis for LOFAR and enabling non-expert users doing science with the telescopes has proven much more challenging than anticipated; this should inform work estimates for future large radio telescopes.

Generalising from these specific examples, it is clear that modern radio telescopes are as much software as hardware instruments, and thus good software is critical to optimising the scientific harvest. Areas were significant improvements are being tested are:

The general use of real-time data pipelines. These are critical for doing time domain astronomy. Examples include creating automated pipelines that are fast enough to find sources and monitor them with very short latency times (seconds to minutes). These will allow discovery and analysis of new phenomena in near real time, and dynamical changes to observing modes or alerting of other instruments while a short-duration phenomenon is ongoing.

The use of robust, automated pipelines. It may seem that real-time data pipelines introduce vastly greater capability requests than are otherwise needed, but this may not be so. A radio telescope collects vast amounts of raw data and of course we want it to be operational all the time. This implies that the data have to be processed at the same rate as they are collected. While a significant latency might still be allowed, such latency implies increased data storage requirements. Another advantage of such pipelines is that automated, high-quality data processing will make radio astronomy accessible to a greater user community, which we have highlighted previously as a requirement for future radio astronomy. Thus, near real time automated data processing in standard modes appears required for new large radio telescopes even in the absence of the desire for rapid, time-domain applications.

The Hilado effort was mentioned before as one concerted community effort to achieve some of these goals. Other experimental efforts that are on-going are the AARTFAAC experiment, which is creating a near real time, wide-field radio sky monitor out of the 12 innermost LOFAR stations, and the ARTEMIS experiment, which searches the data stream of international LOFAR stations (in particular at Chilbolton) for pulsars and fast radio bursts (FRBs).

Most of the above refers specifically to radio imaging studies, but also in the domain of pulsar-like data, i,e,, the study of high time resolution beam-formed data, the development of new software methods and data analysis strategies has been extensive. Searching such data streams for period and single-pulse signals implies searching large parameter spaces and without fail involves supercomputing strategies to search large amounts of stored data, and GPU and FPGA signal processing immediately after the receivers.

6.6 – Archiving and data access

In several fields, raw sensitivity or other data quality metrics are not the only limitation for doing science. The limitation is more one of access to reduced data products, especially in cases where the science requires mining large volumes of data. As such, easy access to archival data is critical. This is an area where European radio astronomy facilities have traditionally lagged behind other wavelengths, and can make big strides in terms of more efficiently using data that have already been acquired. We should mention here that the EVN archive, and a few other notable exceptions, has been fruitful instruments for science. This issue takes on a new dimension when one considers the enormous data volumes that are now being produced and the need for users to manipulate data sets that are much too large to move to a local processing site.

A number of European radio astronomy facilities routinely archive their data and make them freely available after an initial proprietary period. We recommend that individual observatories likewise make their own data accessible through public archives after an appropriate proprietary period. This should be implemented using standardized formats and software, and should ideally be centrally coordinated. It would also be worthwhile to explore the possibility of making more radio data available through multi-wavelength databases, such as CDS or IVOA. It is also desirable for the individual observatories to provide pipeline processing of their data, to maximize the ease with which these data can be used, particularly by non-specialists. Investments in these post-processing systems, user-oriented software pipelines and easily reachable online public archives will be necessary. This will necessitate the development of standards for much more complex data sets, such as data cubes and higher-dimensional entities, as well as commensurate high-performance computing systems to process such data is reasonable time.

Over the last decade, the access to astronomical data over the internet has seen a tremendous expansion, and the usage of data accessible in various archives has become a vital resource. Many national and international observatories have started to provide data archives and frequently the dissemination of original observing data is also accomplished via these archives. The Multi-mission Archive at the Space Telescope Science Institute (MAST) or the ESO Science Archive Facility define a “gold standard”, providing raw data as well as many “pipeline” processed products. The total number of astronomical data centres is estimated to be ~50 with typical data volumes from a few to several 100TB. The growth rate is enormous and the annual increment is already significantly larger than 1PB/yr – i.e. similar to the total volume archived to date. The use of broadband receivers and higher time resolutions at most radio facilities will significantly contribute to this growth rate. To give a few examples, the LOFAR archive already contains 12PB of data and the ALMA archive is expected to grow by 5PB/yr. Major radio astronomical facilities such as JVLA, ATCA, or WSRT provide data archives that give access mainly to raw data.

For some of the well-maintained “gold standard” data archives the data retrievals already exceed the growth rate by several factors, and refereed papers based on archival data represent 2/3 of the total publications (MAST). This general trend also holds true for archival data from radio facilities: in 2012 slightly more than 1/2 of the refereed JVLA publications were based on archival data and roughly 1/2 of the archival papers made use of large surveys such as NVSS or FIRST.

The importance of archival survey data in contemporary research can be documented by access rates at archive sites such as CDS or the VISTA science archive in Europe (or at NRAO in the US, more specifically with regard to radio surveys). Since about 2010, radio surveys such as FIRST, the Texas Survey of Radio Sources, WENSS, VLSS, and SUMSS have more than two million hits. NVSS is accessed upwards of five times more frequently. To demonstrate the potential of archival survey data, it is worthwhile to mention that the (re-)analysis of the data can lead to high-impact results as shown, e.g., by the all-sky RM distribution obtained from NVSS (Taylor et al. 2009, ApJ 702, 1230) which is, among other applications, of importance for the interpretation of data obtained with cosmology satellites. The five most cited radio surveys have thus contributed to more than 300 high-impact publications (those with more than 100 citations).

While the European Virtual Observatory has made an attempt to establish more data centres besides CDS, e.g., in Germany, Italy, and Spain these centres are not yet well known in the broader community. With the upcoming survey instruments in Europe (e.g., LOFAR, WSRT with APERTIF) adequate archiving needs to be given higher priority, in order to guarantee the highest possible scientific return from the current investments.

6.7 – Preserving the radio spectrum for astronomy

In order to enable radio-astronomical observations that are sensitive enough to contribute significantly to relevant science goals, access to protected frequency bands of the electromagnetic spectrum is required. In times of an increasing demand by several commercial applications, from mobile and satellite telecommunication to automotive short-range radar systems, this has to be negotiated with other users of telecommunication frequencies in the framework of the International Telecommunication Union (ITU), a United Nations agency. For Europe the use of the radio spectrum is organized by the European Conference of Postal and Telecommunications Administrations (CEPT). The Committee on Radio Astronomy Frequencies (CRAF) represents the interests of radio astronomers and observatories in relevant national and international committees and organizations for the management of radio frequencies. CRAF is thus a recognized member of the ITU and has an observer status in CEPT. In this capacity, CRAF has been actively involved in negotiations between all interested parties concerning the use and protection of important frequency bands for radio astronomy – e.g., the interference problems introduced by the IRIDIUM satellites or the extension of spectrum allocations for International Mobile Telecommunications (IMT).

With the increasing demand on the electromagnetic frequency spectrum by commercial applications, the need for a powerful representation of radio-astronomical interests in Europe is absolutely crucial. CRAF is currently managed as an expert committee of the European Science Foundation (ESF). However, there is a worry in that the ESF is being disbanded or transferred to other organizations. Therefore, a new organizational structure has to be found in the near future in order to guarantee the future standing of CRAF as a serious partner in discussions on international frequency management. As a very specific example, an issue of major concern on the agenda of the World Radio Conference 2015 is the desire to allocate an extra 600 MHz of bandwidth below 6 GHz to broadband mobile phone traffic. A major threat is to the L-band frequencies: 1100 – 1700 MHz The core 1400 – 1427 MHz appears safe, but the 1330 – 1400 MHz band is not. Since this corresponds to HI in the redshift range up to 0.07, this could severely impact the study of the nearby gaseous Universe and dynamics of somewhat more distant galaxies. As such, it will have a major impact on the key science of current efforts such as WSRT/APERTIF and potentially also future efforts using the SKA.

Currently, CRAF operates as an expert committee under the umbrella of the European Science Foundation (ESF). The budget is provided by the CRAF members, which are mostly radio observatories and similar organizations. Together they fund the costs of one radio frequency manager. However, in practice the members of CRAF also contribute through the additional time of their own staff. As the ESF will cease to exist by the end of 2015, a stable formal hosting and funding scheme for CRAF is urgently needed.

6.8 – Conclusions

Some observatories/data are seen as "difficult to use" and this means that outsiders are generally shy about applying for data that would otherwise be useful for their science. Many archival data sets are simply not easily accessible. Some science requires (simultaneous) data from multiple telescopes. Having the proposal deadlines between European telescopes better coordinated would lower the threshold for making such projects happen. Responding to high-energy triggers is important for many science cases. There needs to be a way to make this easier with the e-EVN and other observatories.

In order to keep European radio astronomy at the forefront worldwide, we give the following suggestions referring to telescope operations (while also noting that many European radio observatories have such structures in place and are continually improving in these areas):

- Radio Observatories should make a significant fraction of their observing time available through open skies access, based on a peer-reviewed proposal process. This should include some support to the observers in every step of the research project, ensuring that excellent science will be delivered.

- In order to increase the scientific outcome of the European radio observatories, wide and easy access to radio data via archives, using standardized data products and software, should be promoted.

- The synergies between radio observations and observations at other wavelengths should be facilitated, increasing the scheduling flexibility and the coordinated calls for multi-telescope proposals.

- The protection of key radio frequency bands is essential for current and future facilities.

Chapter 7: Technical developments

A continuous and vibrant programme of technical development (both in hardware and software) is necessary to keep European radio astronomy at the forefront on the world stage and to ensure a strong role for Europe in the new global radio astronomy well into the SKA era. Here we discuss what transformative technologies are currently being developed, tested and implemented. This includes wide-band/wide-field VLBI, a pan-European tied-array mode , denser aperture arrays, focal plane arrays, and ultra-wideband, single-pixel feeds.

Given the associated costs, such programmes need to be well coordinated across Europe, in order to reap the maximum impact. Fortunately, RadioNet3 is already providing important coordination of this type. Some already available technologies could be used to provide European radio telescopes with more uniform sets of equipment, providing more uniformly excellent capability and data quality. Newly developing technologies such as focal plane arrays, flexible aperture arrays, and multi-beam capabilities will play important roles. Another example is the LEAP-developed backends based on CASPAR Roach-board technology, which have been installed at Effelsberg, Lovell and the SRT. They provide the backbone of the local pulsar instrumentation at those telescopes.

Coordinated efforts between institutes and technical universities with specialized expertises, on the one hand, and observing facilities, on the other hand, offer an enormous potential for developing and installing state-of-the-art equipment in an efficient and centrally coordinated way. Both large and small facilities can contribute substantially to key technical and software developments. Some technical developments will require specialized institutions with a critical mass of technical expertise, but smaller groups in a variety of institutions can also make appreciable contributions, particularly in the early phases of development. Sharing the technical knowledge across Europe can only serve to strengthen the community.

There are excellent examples of such fruitful collaboration as the establishment of the European VLBI Network (EVN) in 1980, the infrastructure cooperation network RadioNet since 1980 or, from a technical point of view, the Joint Research Activities (JRA) within the framework of RadioNet. Among these technical developments, we could mention UniBoard (within the framework of RadioNet-FP7), with the coordination of JIVE and the participation of various different institutes like ASTRON, INAF, the University of Manchester (UMAN), Korean Astronomy and Space Sciences Institute (KASI), University of Oxford, the University of Bordeaux (BORD), the University of Orleans (ORL) and Shanghai Astronomical Observatory (SHAO). Following on, UniBoard^2 (UniBoard squared) is another excellent example, with MPIfR, ASTRON, INAF, UMAN, BORD and ORL, coordinated by JIVE. As mentioned previously, EMBRACE, which is testing the phased-array technology with two stations, one in Nançay and the other at the WSRT site, is a further great example of cooperation and collaboration across European borders. Also, the Large European Array for Pulsars (LEAP) can be mentioned here again.

7.1 – VLBI in Europe

The European VLBI Network (EVN) is the most sensitive VLBI network at centimetre wavelengths. JIVE was created to develop and operate the VLBI correlator. The scientific case for VLBI will continue to benefit greatly from new research and development plans. In the last years, new features have been incorporated into the correlator: ultra-high spectral resolution, pulsar binning, multiple phase centres (first included with the SFXC software correlator), and near-field modes. However, in the immediate future, the EVN's requirements cannot be fulfilled with a software correlator. A new generic, scalable, FPGA-based correlator, usually referred to as the UniBoard, and already initiated through FP7-funding, is a fundamental requirement for the immediate future of the EVN. There are also other software correlator developments. For example, the joint ALMA-EHT (Event Horizon Telescope) telescope will process 64 Gbps with the DiFX software correlator. DiFX correlators have been installed at Swinburne and ATNF (Australia), NRAO (USA), Bonn (MPIfR) for production correlation.

UniBoard is a Joint Research Activity within RadioNet3, which consolidates and builds upon the results of UniBoard to develop a multi-purpose hardware board capable of handling a high data throughput. Its applications at the moment include the VLBI correlator, the correlator as well as the antenna beam former for APERTIF on WSRT, and the filter bank for the AARTFAAC (Amsterdam-ASTRON Radio Transients Facility and Analysis Centre). Available new technologies (such as HardCopy or EasyPath) will be investigated, since power efficiency is one of the crucial issues for future instrumentation. GPU correlators are also under consideration; in fact, the next-generation LOFAR correlator COBALT, which went into operation in mid 2014, is a GPU-based machine.

In order to enhance the scientific case for the VLBI technique, more sensitive VLBI observations and better u-v coverage are required. This implies, in turn, the development of i) wide-band receivers and ii) wide bandwidth/high bitrate VLBI backends. For (i), low-noise amplifier wideband feeds should be developed; for (ii), new generation digital backends based on the next generation samplers and FPGAs will be developed in the coming years. The Joint Research Activity DIVA, under the umbrella of RadioNet3 (coordinated by MPIfR, with Chalmers, INAF, ASTRON and Fraunhofer as partners), is working on these key technologies and aiming at consolidating Europe as a leading worldwide competitor.

A third generation of a digital backend system (DBBC3) for VLBI and other applications is currently under development. It will be able to fully implement digitally all the functionality required of a complete 32 Gbps VLBI backend for the EVN. The DBBC3 can process an instantaneous bandwidth of 4 GHz per polarization as a minimum, with a sampling representation of 10 bits. The resulting output data rate for a dual polarization receiver should be at least 32 Gbps, with the option of 64 Gbps for a 4 IF system. In the future, the DBBC3-H system could can process an instantaneous bandwidth of 14 GHz per polarization as a minimum, resulting in an output data rate of up to 896 Gbps. Tests and experiments performed with the prototypes have already showed that direct data conversion to the digital domain for the full 14 GHz band is possible. The partners of the project are INAF, MPIfR and Onsala Space observatory.

One of the main challenges of the EVN will be to extend the benefits of e-VLBI to all EVN operations. In order to maintain robust, flexible, and near-continuous operations, careful monitoring, warning and feedback mechanisms should be implemented. A more useful setup is on the way with disc buffers at telescopes and an efficient Internet data transfer. Moreover, e-VLBI will require an upgrade of the correlator environment to deal with simultaneous data recording and flexible transport mechanisms, accommodating different types of recording units. Further developments will include an increase in bandwidth, additional available telescopes in the EVN array (including both new telescopes and global coordination with other regional VLBI arrays such as the US, Australian, Japanese and Korean arrays, and in the future the African VLBI Network (AVN)), an improvement in image fidelity and the possibility to move also to higher frequencies (86 GHz).

Over the last years, the EVN has averaged 6 – 9 observing weeks per year, with an oversubscription factor of around 2.9 in the period 2009 – 2011. There is still a great potential further to increase the EVN science output and the user-base by expanding its on-sky availability. Since the largest, most-sensitive dishes cannot be made available more often due to other important scientific commitments (i.e. Europe's large single dishes are powerful scientific instruments in their own right and have their own important observing programs), a modest-sensitivity sub-array of EVN telescopes of medium size (i.e. consisting of Jodrell2, Medicina, Noto, Torun, Onsala, Yebes) could be offered for a much higher fraction of observing time. Although the angular resolution (around 5 milli-arcseconds at 6 cm; see Figures 7 and 8) and the sensitivity[6] will be limited, this interferometric array could be extremely useful for certain kinds of projects: i) monitoring of variable objects (AGN, masers, XRBs); ii) target-of-opportunity observations of transients; iii) radio identifications of high-energy sources (e.g. detected by Fermi or HESS), taking advantage of the large FoV currently provided by the EVN; iv) astrometry aiming to measure parallaxes (optimised observing dates are required that may be readily scheduled on a subset of the EVN); v) surveys that require significant amounts of observing time, but could be performed with a limited sensitivity and resolution (e.g. high-angular-resolution studies of nearby galaxies for the determination of supernova and star-formation rates). In the field of transients, the radio interferometers, and the modest-sensitivity EVN will be an excellent contributor to the field, and are essential to obtain precise positions (better than 1 arcsecond) for variable sources.

VLBI plays also a fundamental role in the maintenance of the global (terrestrial and celestial) reference frames, which are required for precise positioning in many research areas such as the understanding and monitoring of global changes, and for space missions. The International VLBI Service (IVS) for Geodesy and Astrometry coordinates the global VLBI components and resources on an international basis. About 25 % of the yearly scheduled geodetic experiments are correlated in the DiFX correlator in Bonn. In 2015 it is planned to upgrade the current DiFX cluster to a brand-new system.

Parallax measurements of stars with accuracy comparable to that of *Gaia* are possible with VLBI and will constitute an independent method to verify Gaia parallaxes. However, the number of objects detectable with current VLBI arrays is not high enough to verify *Gaia*; herefore SKA-VLBI will be needed to accurately measure parallaxes for a significant number of Galactic *Gaia* targets. Moreover, in the future, SKA-VLBI will significantly improve the connection between the celestial reference frames defined in the optical (from Gaia) and radio bands, based on a selected sample of radio loud AGN, ultimately limited by source physics that may dictate offsets between the radio and optical emission centres (core shift with frequency).

The EVN has developed a world-leading group in Space Science, with a well-recognized expertise in near-field VLBI observations. For these applications, highly precise near-field delay models and near-field processing algorithms will be needed. These developments will be extremely helpful for the orbit determination and science operations of current and future Space-VLBI missions.

7.2 – Large single dishes

The large single dishes (Effelsberg, Lovell, Nançay, SRT) all have a vibrant program of technical development, both to improve the front-end receivers (moving to wider bandwidths and/or wider field-of-view) as well as the backend data recorders. The race to make the first detection of a stochastic gravitional wave background has pushed the limits of precision pulsar timing, and the large European single dishes have come together to collectively collaborate and help push a new generation of pulsar data recorders that are providing high-quality data that is competitive

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[6] 1 sigma = 85 microJy/beam, for 150 minutes on-source integration time and a data rate of 256 Mbps; in case Jodrell2 cannot participate, the sensitivity decreases to 1 sigma = 97 microJy/beam; at 18 cm, the corresponding sensitivity drops at 1 sigma > 175 microJy/beam and the resolution is larger than 15 milli-arcseconds, since the largest baselines are not available because Yebes does not have a 18-cm receiver.

on the world stage. Plans to expand Effelsberg's field-of-view with focal plane array technology is also ensuring that the future is bright for pulsar surveys. As an ensemble, these large dishes are used with WSRT in tied-array mode in order to create LEAP – an Arecibo-sized collecting area for pulsar timing. The calibration of LEAP data (e.g. the extremely stringent requirements on polarimetric calibration of the various observatories) has also lead to a fruitful pan-European technical collaboration.

7.3 – Dense aperture arrays

The EMBRACE demonstrator is collaboration between ASTRON and the Nançay Radio Observatory. As previously described, it is formed by close to 100 1x1 m tiles of Vivaldi elements (a particular type of antenna design) at each of the two sites in Nançay and WSRT. Beam forming happens at both the ~1m^2 tile level (analogue beam-former) as well as between the ~100 tiles, using re-purposed LOFAR station beam-former technology (digital beam forming). It can be conceived as a demonstrator and/or technology developer for a future mid-frequency aperture array on the SKA.

7.4 – The path to the SKA: European radio telescopes as SKA Pathfinders

LOFAR is a world-leading SKA-Low pathfinder. The EVN is a science pathfinder for the SKA, and its long baselines will not be supplanted by SKA Phase 1 (as we discuss below). e-MERLIN and WSRT with APERTIF are also considered SKA pathfinders because of the technology, software, and analytical techniques they are pushing forward. Additionally, some single dishes, especially Effelsberg, are used as test-beds for SKA technologies. At the same time, Europe is contributing to the development of the SKA precursors in South Africa and Australia. For example, the MPIfR is developing S-band receivers for the MeerKAT dishes, which will enable the next major step forward for precision pulsar timing on the road to the SKA.

7.4.1 – EVN

The recognition of the e-EVN as a SKA-precursor is an extra support for the array. In fact, the EVN (and its extension to the Southern Hemisphere by collaborations with existing or emerging arrays such as the future African VLBI Network) can also play an important role during the SKA era. SKA could have some VLBI capabilities, which could be summarized in two main possibilities: (i) in Phase I, the EVN could perform joint observations with the SKA core, phasing up the dishes of the SKA1-mid, and using some of the remote stations in VLBI mode; (ii) in Phase II, a distributed SKA configuration over hundreds to thousands of kilometres, could merge with existing VLBI networks.

For the calibration and wide-field imaging of VLBI observations involving SKA1-Mid, a beam former with the ability to form multiple simultaneous beams is required. A multi-beam former for the central core of SKA1-Mid is the minimum required. It would be ideal to phase the whole SKA1-Mid, but since it is very hard to implement, it would be interesting – as an initial step – to have different sub-arrays, each one with its own multi-beam former. Moreover, the VLBI data streams should be transported to the external VLBI correlator, possibly through fast internet lines for real-time e-VLBI correlation.

7.4.2 – LOFAR

LOFAR is a transformative telescope in terms of the technology and observational techniques it is using; these serve as the largest pathfinder on the road to SKA-Low. The expansion of LOFAR into the International LOFAR Telescope (ILT) has brought in a much broader community, which is deeply involved in the project through their hosting of an international LOFAR station (Germany, United Kingdom, France, Sweden, and Poland soon to join with 3 stations). This has served to spread the technical knowledge about LOFAR beyond just the main host institute, ASTRON, and into the broader European community, including the training of PhDs and postdocs. The LOFAR Key Science Projects (KSPs) have also served to bring like-minded communities together. Many of the KSPs include strong representation from many European countries. Thus, from a technical point of view, LOFAR provides a pathfinder scenario in term of distributed operation, high bandwidth data links, massive correlation and post-processing, among others.

Furthermore, the LOFAR core and its foreign stations are being used for a number of extensions and add-on experiments all intended to test advanced concepts in radio astronomy. The NenuFAR experiment at the Nançay station extends a station to the lowest frequencies at the ionospheric limit, with much greater collecting area. The ARTEMIS experiment at Chilbolton does real-time beam forming and searches for very fast pulses such as Fast Radio Bursts, pulsar giant pulses, and possibly unknown phenomena. The AARTFAAC and DRAGNET experiments on the LOFAR core correlate the innermost sets of dipoles one-by-one, and search for fast transients in all-sky imaging and in beam formed signals, respectively. In that same core, the LORA particle detector array is used to aid the development of techniques for radio detection of cosmic rays.

At the same time, on a more political and collaborative level, the ILT is forging links between national radio astronomy communities and generating broader interest in building, commissioning, and scientifically exploiting SKA-Low. These links complement those forged through the pan-European partnerships of the EVN and LEAP. Building and commissioning the SKA will require a large European base of technically minded radio astronomers. Providing opportunities for young European radio astronomers to learn how to use and develop new SKA-like instrumentation is thus crucial for ensuring Europe's strong role in the SKA project. The ILT serves an important role in this regard.

7.4.3 – e-MERLIN

The SKA Science and Engineering Committee has also recognized e-MERLIN as an SKA pathfinder in terms of high resolution science observations, long-distance data transport and phase transfer over optical fibre links. e-MERLIN is already in the phase of science production and the legacy projects are already being observed. Future upgrades are also already under consideration: adding additional telescopes, including telescopes in England and even some of the EVN telescopes; adding additional receivers, especially in the 8 – 12 GHz band that would be ideal to test models of star formation; increasing the survey speed through the use of focal plane arrays.

7.4.4 – APERTIF

WSRT with APERTIF is a technology and science pathfinder for SKA. It is a demonstrator for the focal plane array technology, with the associated developments of algorithms and software to calibrate and process APERTIF data both in real time and off-line.

7.4.5 – Effelsberg

The Effelsberg Telescope acts as an important test-bed for SKA technology, both in developing ultra-broad-band and software/hardware technologies. A new focal plane array is under development and an ultra-broad-band receiver (from 600 MHz to 3 GHz) for pulsar timing is being used. A similar receiver is planned for the Lovell Telescope. Simultaneously, a coherently dedispersing backend, with the corresponding pulsar processing pipelines, is now operational. Several other broad-band receivers are under construction or are just being installed (4.0 – 9.3 GHz, 18 – 26.5 GHz – together with an array of FFT spectrometers allowing for observations with 8 GHz BW and order millions of spectral channels between 36.0 – 50.0 GHz) and a digital polarimeter.

7.5 – Conclusions

The European radio observatories will provide unique capabilities complementary to SKA, such as the multi-range coverage of the Northern Hemisphere or the observations at long baselines and high frequencies, contributing to the Key Science Vision goals well into the SKA era. A vibrant programme of technical developments (hardware and software) will be needed to maintain a leading role of the European radio astronomy in the global scenario.

The European radio telescopes are already addressing many of the main technical challenges faced by the SKA, including focal plane arrays, flexible aperture arrays, multi-beam capabilities, wide-band receivers, wide bandwidth/high bitrate backends, massive correlation and post-processing, among others. LOFAR, e-EVN, e-MERLIN, WSRT with APERTIF and EMBRACE are unique SKA pathfinders in terms of the SKA-related technology they are pushing forward.

Adding VLBI capabilities to the SKA will broaden the science of SKA. In a first attempt, this can be implemented by forming a phased-array from SKA1-MID and observing together with existing VLBI arrays. The amplitude and polarization calibration will benefit from the combination of the local interferometry and the VLBI data.

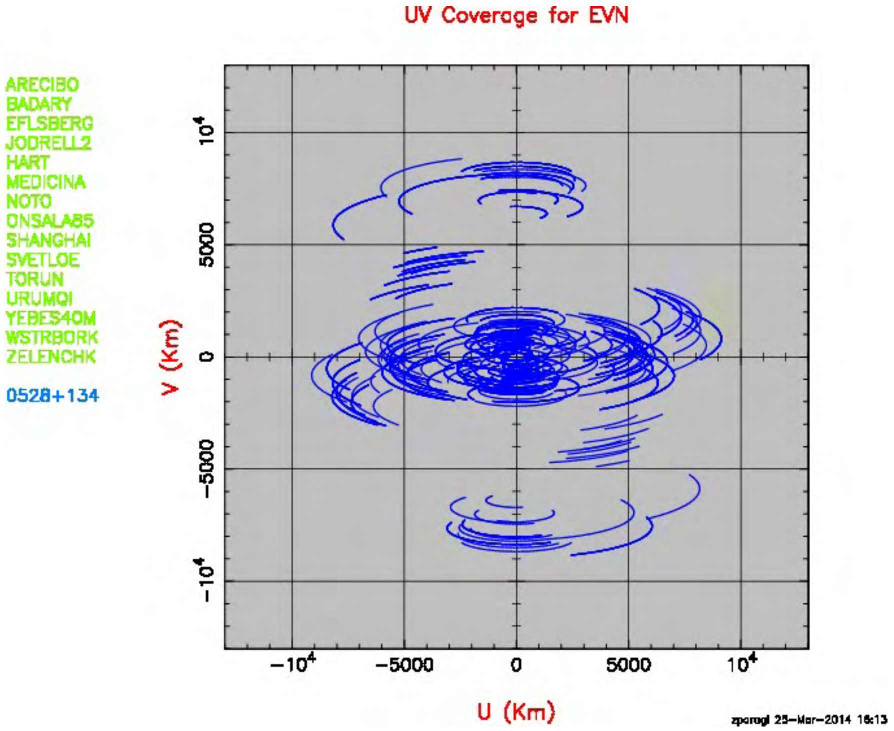

Figure 7: u-v coverage for a 24 hour observing run of the VLBI calibrator 0528+134 with the full EVN.

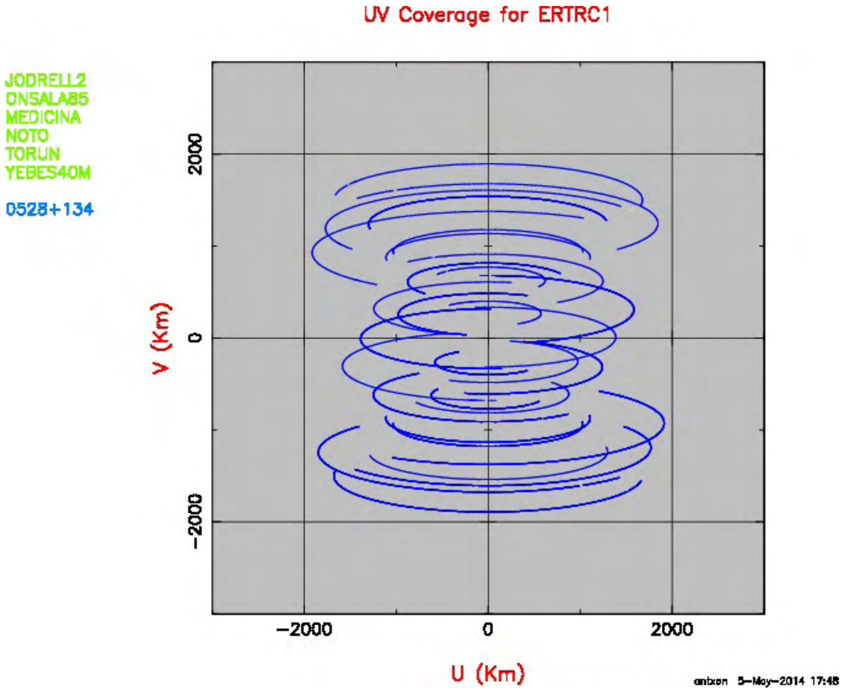

Figure 8: u-v coverage for a 24 hour observing run of the VLBI calibrator 0528+134 with an EVN sub-array of medium-sized telescopes.

Chapter 8: Synergies with other wavelengths and beyond

8.1 – Introduction

Radio observations have in the past provided major breakthroughs independently (e.g. the discovery of pulsars, Hewish et al., Nature 217, 709, 1968, and their subsequent use to test general relativity and to detect gravitational waves indirectly, e.g., Taylor and Stinebring, ARA&A 24, 285, 1986) and will no doubt continue to do so (e.g. the discovery of the `fast radio bursts'; Lorimer et al., Science 318, 777, 2007, Thornton et al., Science 341, 53, 2013). Nevertheless, in most areas their scientific value is multiplied significantly when combined with observations at other wavelengths. In the next 10 – 15 years, in parallel with the new developments in radio astronomy on the road to the SKA, major advances will also be made with facilities at other wavelengths. Indeed, the SKA must be considered in the broader context of next-generation, multi-wavelength facilities that will be available. At the same time, the prospects for truly multi-*messenger* astronomy are ever broadening, e.g., with the commissioning of the Advanced LIGO gravitational wave interferometer, CTA, and Km3Net. It is the aim of this chapter to discuss radio astronomy in the context of multi-wavelength/multi-messenger astronomy, as well as how these facilities may complement and enhance the value of the existing and new radio observatories during this period.

8.2 – Radio in the context of multi-wavelength astronomy

In the following we give some examples of high-impact science that has come from the combination of radio data with observations made at other wavelengths. As the first non-optical astronomy, radio wavelengths have been transformative to astronomy in general because they have provided a powerful window for studying particle acceleration and other non-thermal processes. They have also allowed us to peer deep into regions obscured at shorter wavelengths (e.g., consider the major role that the 21-cm neutral hydrogen line continues to play). Though radio waves constitute the lowest energy photons we can observe, many aspects of radio astronomy also fall under the umbrella of high-energy astrophysics because of the common source classes (e.g., neutron stars and black holes) and radiation processes (e.g., synchrotron, inverse Compton). Sources like neutron stars and AGN emit from the lowest radio frequencies to the highest observable energy gamma rays (TeV). Similarly, gamma-ray bursts, leave radio afterglows and black hole binaries produce relativistic radio jets. It should thus be no surprise that studying these sources depends crucially on a multi-messenger approach.

Indeed, in many areas, the maximum complement of multi-wavelength information is now needed to make major progress in understanding the underlying physics. It is not hard to find examples in the literature where high-impact results are based on the combined knowledge from radio, optical/IR/UV, and high-energy X-ray/gamma-ray data. This has changed the way radio astronomers interact with their colleagues and it can benefit from better coordination and easier access to a host of facilities across the electromagnetic spectrum. For example, it is now sometimes possible jointly to apply for radio data at the same time as high-energy data (e.g. Chandra, Swift, Fermi, etc.). At the same time, making high-quality radio data available and easily accessible (e.g. via the Virtual Observatory) to X-ray/gamma-ray astronomers – who in many cases may not be experts on the analysis of radio data – is a powerful way to maximize the scientific return of current and future radio facilities. We now provide some concrete examples of radio astronomy working together with observations at other wavelengths. This is intended to be an illustrative, though in no way exhaustive, list.

8.2.1 – The radio/gamma-ray link

In the last 5 years, NASA's *Fermi Gamma-ray Space Telescope* has made a major leap in characterizing the sky in 100 MeV to 300 GeV gamma rays. This has resulted in the detection of many known AGN (Nolan et al. 2012, ApJS, 199, 31) and gamma-ray pulsations from over a hundred radio pulsars (Abdo et al. 2013, ApJS208, 17). A big surprise to many is the discovery that radio millisecond pulsars are an important class of Galactic gamma-ray source (Abdo et al. 2009, Science, 325, 848). In almost all cases, gamma-ray pulsations are only detectable using a radio-derived rotational ephemeris, provided by observatories like Lovell, Nançay, WSRT and Effelsberg, each of which have large pulsar timing programmes.

8.2.2 – Unassociated MeV-GeV sources

Excitingly, *Fermi* has also found hundreds of unassociated gamma-ray sources. Targeted radio searches with large single dishes like Effelsberg, GBT, and others have discovered over fifty millisecond pulsars in this way (Figure 9; e.g., Ransom et al. 2011, ApJ, 727, 16). This creates a beautiful synergy between *Fermi* and the large radio telescopes: *Fermi* provides the directions in which to target deep radio searches; later radio discovery and timing observations provide the information needed to detect gamma-ray pulsations.

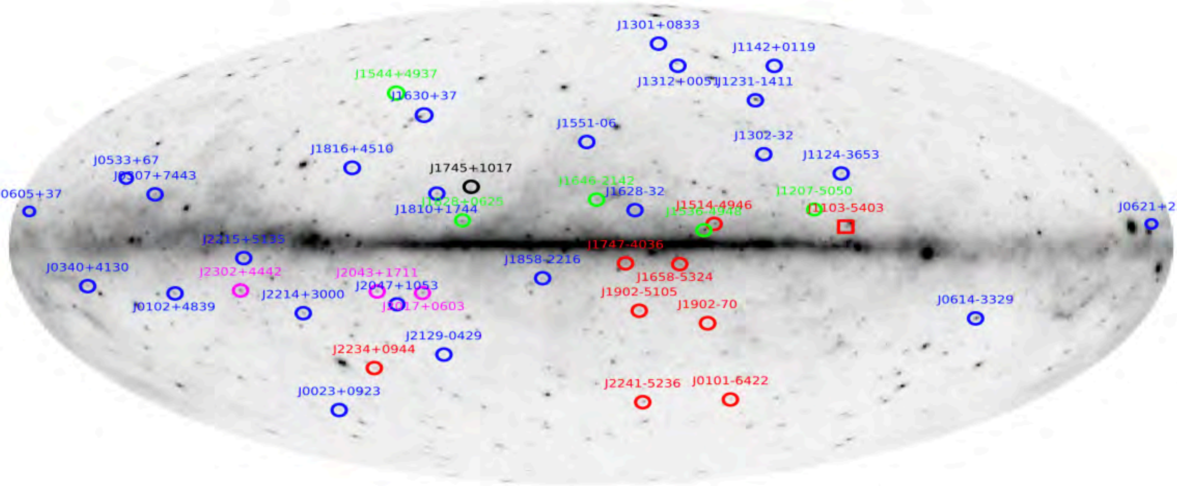

Figure 9: An all-sky map in MeV-GeV gamma rays made with the *Fermi Gamma-ray Space Telescope*. Superimposed are the positions of recently discovered radio millisecond pulsars, found by targeting unidentified *Fermi* gamma-ray sources (Ray et al. 2012).

8.2.3 – AGN across the EM-spectrum

Active galactic nuclei (AGN) are galaxies with extraordinarily luminous cores, which are powered by million, or even billion, solar-mass black holes at their centres. Matter that reaches the galaxy's centre can be attracted by the black hole's gravity, settle into an accretion disc and s.piral down to the horizon. Relativistic jets are launched from the galactic cores in opposite directions, remaining in some cases tightly collimated for hundreds of thousands of light-years. These jets can be studied in great detail using radio (including high-resolution radio interferometers), optical and X-ray telescopes.

The overall shape of the AGN spectral energy distribution (SED) exhibits a broad, double-peaked distribution, where the first peak is attributed to synchrotron radiation and the second one is likely due to one or more components related to Inverse Compton emission. From those spectra, it is possible to estimate some key observational parameters that characterize the SED of a blazar (an AGN with its jet pointing at us): the peak frequency and peak flux of the synchrotron component (related to the particle density and magnetic field), and the peak frequency and flux of the Inverse Compton part of the SED.

Since AGN are extremely variable at all wavelengths, changing both their total and polarized flux densities as well as their spectra on timescales ranging from hours (intra-day variability) to many years, variability has become one of the most important tools for studying the physics of AGN. The relation between the flares at different wavelengths (correlation/anticorrelation, time delay) is a crucial test for models attempting to explain these outbursts and to identify the nature of the jet particles. In fact, there exists strong evidence for a significant correlation between the radio and the high-energy gamma-ray flux for blazars as measured by *Fermi* (e.g. Ackerman 2011, ApJ, 741, 30). On the other hand, the radio-VHE (very high energy emission), as measured by ground-based Cherenkov telescopes like HESS, VERITAS, and MAGIC has proven to be a more elusive correlation to find.

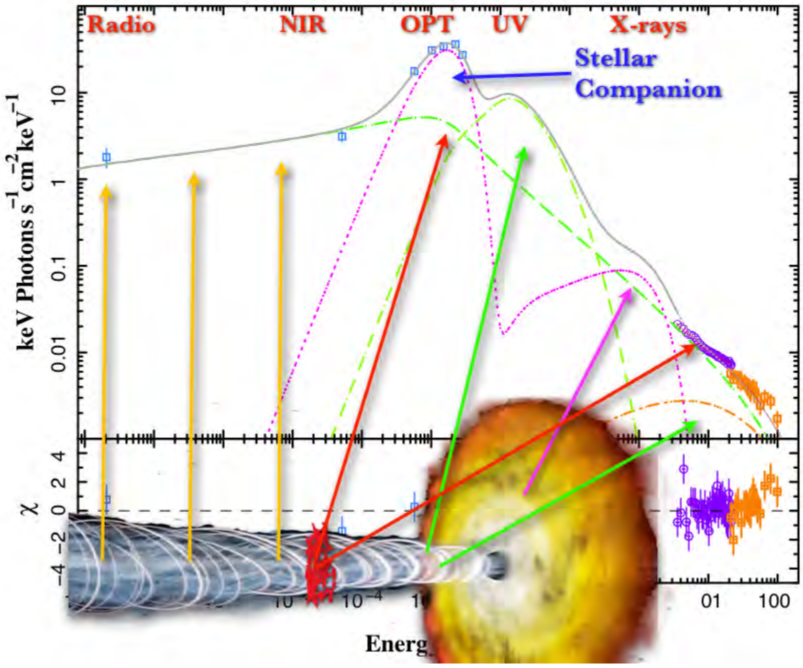

Figure 10: A fit to the broadband spectral data of the microquasar GRO J1655-40, with an artists' depiction of its disc and jet, and arrows indicating which part of the spectral energy distribution is thought to come from where. Data from Migliari et al., ApJ 670, 610, 2007. Figure taken from S. Markoff (www.seramarkoff.com).

8.2.4 – Unidentified TeV sources

Ground-based Cherenkov arrays like HESS, VERITAS, and MAGIC are mapping the sky at much higher energies than reachable with *Fermi*. In only the last few years, surveys of the Galactic plane have identified many unassociated, extended TeV sources. Radio observations have been critical in many cases for identifying the nature of these new sources. For instance, it appears that a significant fraction is so-called pulsar wind nebulae, associated with young, particularly energetic pulsars (e.g., Hessels et al. 2008, ApJL, 682, 41).

8.2.5 – High resolution imaging of transients

High-energy transients, such as accreting black holes or neutron stars in outburst, are associated with strong radio flares from their relativistic jets. Promptly scheduled VLBI observations can provide crucial information on the structure of the jets and their coupling with the accretion process, such as, e.g., the exact time of the ejection event (which cannot be extracted from the radio light curve alone due to opacity effects or possible delay between the onset of the flare and the formation of the shock). In addition, high-precision astrometry plays an important role for measuring accurate parallaxes or proper motions of Galactic sources. This provides constraints on their distance, their natal kicks and henceforth their formation history, or can possibly even help to measure the spin of the black holes (see Miller-Jones et al. 2014, PASA, 31, 16). On a different topic, VLBI observations of AGN may also be crucial to localize the origin of the VHE flaring emission observed, e.g. in M87, as some structural changes at the upstream edge of HST-1 may possibly be related to the VHE events (Giroletti et al. 2012, AA, 538, L10).

In gamma-ray bursts, radio observations have also been crucial in constraining the size and expansion rate of the explosions, both via VLBI measurements and via detection of scintillation variations; the amplitude of these variations has given us the size of the expanding blast waves, and the decreasing amplitude of the variations with time provided the first direct measurement of their relativistic expansion.

8.2.6 – Understanding accretion onto compact objects

It has long been thought that there is an evolutionary link between accreting low-mass X-ray binary systems and the radio millisecond pulsars. In the last few years this link has been demonstrated by, initially, the discovery of a radio pulsar in which past optical data showed the presence of an accretion disc (Archibald et al. 2009, Science, 324, 1411). More recently, this has been demonstrated even more clearly by the discovery of a source that swings between X-ray-bright periods of accretion and a non-accreting state in which a radio pulsar is visible (Papitto et al. 2013, Nature, 501, 517). These systems underline the value of multi-wavelength monitoring. Understanding this accretion process more deeply is also aided by optical observations of the companion star, in which the radio-derived orbital parameters are used to fold the optical light curve (Breton et al. 2013, ApJ, 769, 108).

It has been recognised in the past decade that kinetic and radiative feedback from supermassive black holes in AGN is likely to have strongly affected the growth of galaxies, and therefore has had a strong cosmological role. As well as direct observations of AGN, such as the *Fermi* blazars discussed above, it has been possible to learn a great deal about such processes by observing nearby stellar-mass black holes in binary systems simultaneously at radio and other wavelengths. In such systems, X-ray observations reveal the rate and geometry of the inner accretion flow and the non-thermal radio (and infrared) emission arise in the relativistic jet, which dominates the kinetic feedback in some accretion states (see Fender & Belloni, Science, 2013, 337, 540).

Another example of a multi-wavelength breakthrough is the realization that the non-thermal emission from the jets in X-ray binaries goes much beyond the traditional radio frequency range with observed (anti-) correlations across the whole electromagnetic spectrum. Indeed, the self-absorbed compact jets are observed to emit to at least the optical and near-infrared range, whereas the discrete ejection events in microquasars have been observed, at least in Cyg X-3, up to high-energy gamma-rays thanks to Fermi and Agile (Abdo et al. 2009, Science, 326, 1512; Tavani et al. 2009, Nature, 462, 620).

8.2.7 – The radio/(sub-) mm link

There are recent examples of the fruitful complementarity and collaboration between (sub-) mm and radio observations in different fields like star formation, starburst galaxies, proto-planetary discs, and sub-mm galaxies, among others.

ALMA has shown that supernovae are relevant dust producers. Supernova (SN) 1987A in the Large Magellanic Cloud was the closest supernova explosion to Earth (50 kpc) observed since Kepler's SN1604AD. The emission at radio wavelengths is dominated by synchrotron radiation from shock-accelerated particles. It has been studied with ATCA and it shows a limb-brightened shell morphology, with a non-thermal spectrum, which is the result of the interaction of the shock with the circumstellar medium (Zanardo et al. 2014, ApJ 796, 82). On the other hand, ALMA observations at higher frequencies are tracing dust emission that is concentrated at the centre of the remnant, so the dust has not yet been affected by the shocks. This is showing unambiguously that this dust has formed in the inner ejecta, suggesting that supernovae are important cosmological dust producers (Indebetouw et al. 2014, ApJ 782, L2).

ALMA has also produced important results in the field of young protoplanetary discs. The gravitational collapse of interstellar gas and dust is forming new stars and their planetary systems. Even after the birth of a protostar (a baby star), the gas and dust in the envelope are still "in-falling" onto it. At the same time, the gas disc grows around the baby star, and eventually evolves into a planetary system. Sakai et al. (2014, Nature 507, 78) have observed with ALMA a drastic chemical change associated with the formation of the disc around the young protostar L1527 in the Taurus molecular cloud. Due to the formation of the planetary systems, transitional discs present substantial dust clearing gaps in their inner regions. These can be traced through the thermal emission of large dust grains at radio wavelengths (Osoryo et al. 2014, ApJ 791, L36). In these objects, accretion should be smaller than in classical full discs. Accretion can be traced through outflow activity, detecting the free-free emission radio jets (Rodríguez et al. 2014, ApJ 793, L21).

8.2.8 – The quiet and the active Sun

Observing the electromagnetic radiation emitted by the Sun provides special challenges in a number of respects. The emission occurs across the entire electromagnetic spectrum, from the shortest (gamma-rays) to the longest (radio) wavelengths, making the Sun a prominent target for multi-wavelength observations. This emission is also produced over a wide range of spatial scales, from 1 degree to below 1 arcseconds. The Sun is an extremely bright source, and it can vary by 4 – 5 orders of magnitude within seconds; a variety of emission mechanisms are at work: bremsstrahlung, gyrosynchrotron, plasma emission, and possibly others. Furthermore, the Sun is the nearest cosmic laboratory where particle acceleration mechanisms up to very high energies can be studied in detail. Such mechanisms play an important role throughout the Universe.

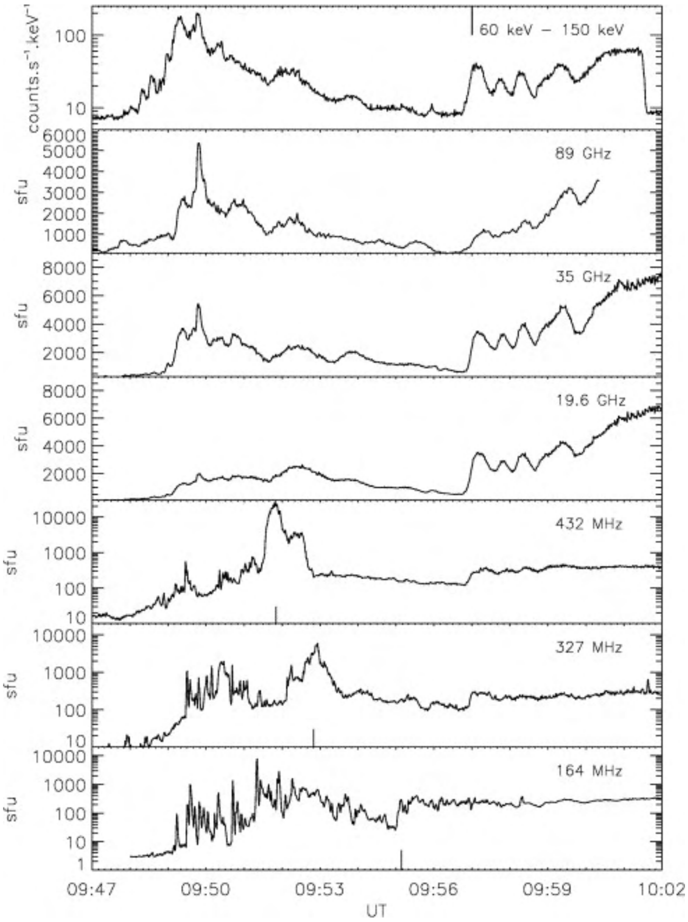

Figure 11: A solar outburst viewed in the hard X-ray flux above 60 keV and in the millimetre, centimetre and metre radio fluxes at 89 GHz, 35 GHz, 19.6 GHz, 432 MHz, 327 MHz and 164 MHz.

Already for decades, radio astronomy has contributed significantly to solar studies, in particular by recording solar radio bursts, which are associated with solar flares, and have an influence on the Earth. The observations have mostly been carried out with relatively small dishes (typically < 10 m diameter), and only in a few cases with interferometers (e.g., at Nançay) or spectrometers. Comparing the results with findings at higher frequencies (optical, UV, X-rays, gamma-rays) has therefore often been hampered by the lack of spatial resolution. While many of these facilities are still in use, operated by relatively small groups and with limited budgets, the situation is changing rapidly. With the advent of LOFAR, ALMA and the SKA in the future, there will be a major improvement in angular resolution, sensitivity, polarisation capabilities, etc. For completeness, we repeat here that small solar radio monitoring observatories and their work fall outside the remit of this report.

Within the LOFAR project, a key program has already been set up that involves more than 30 scientists from 15 different institutes located in 10 European countries. It aims for routine imaging of the Sun, for rapid imaging at a cadence of, e.g., 0.1 sec during solar busts, at coordinated multi-wavelength campaigns (with ALMA, GREGOR, RHESSI, STEREO, Hinode, or SDO), and the use of single LOFAR stations as spectrometers.

8.2.9 – Wide-field, high-energy and multi-messenger transient searches

At high energies, especially in X- and gamma-rays, some or all detectors have always been very wide-field instruments, which deliver detections of often very brief, new events that turn out to be of great astrophysical importance, such as X- and gamma-ray bursts and X-ray novae. The interest in these events is such that their future detection must be ensured. Also, the capability to follow them up at other wavelengths is crucial for understanding them. This means that observatories must have the versatility to respond quickly to ToO alerts, and to deal with the sometimes-large error boxes they deliver. The new multi-messenger observatories also naturally have large fields of view, and sometimes-poor source localisation, creating challenges for the follow-up. At the same time, other wavelengths are also moving towards massive, repeated surveys of large areas of the sky, including radio astronomy. This will give an even larger impulse to time domain astronomy and will make the ability of observatories to give, and respond to, alerts, more important. Since these events are almost always non-thermal in nature, radio radiation is a very common accompanying type of radiation to these outbursts, and therefore it is very important that radio observatories are designed with the versatility to respond quickly to ToO triggers from high-energy observatories. Another, new, type of observatory that is naturally very wide comes from astroparticle physics: detectors for gravity waves, some TeV detectors, and neutrino and cosmic-ray detectors are naturally very wide field instruments. Moreover, they often localise events only with very low precision, and the search for counterparts therefore requires observatories with wide fields of view, such as radio phased arrays. We thus expect many profitable synergies to occur between the lowest and highest ends of the spectrum, provided observatories can handle the quick response and versatility. Figure 13 shows a range of observatories at other wavelengths (and/or messengers) with which one can find synergies in radio astronomy.

8.2.10 More general and generic synergies

The reader should bear in mind that in the above, we have only given some examples of important multi-wavelength synergies. Others could be given, such as the study of the molecular universe in radio and millimetre wavelengths, and everyone will probably have their own favourites depending on their chosen subfield of study. The main point to make here is that many examples exist, and thus that multi-wavelength synergies are tremendously important. They are frequently also somewhat unexpected, and so rather than design for very specific synergies between one telescope and another, astronomers should look to see that in a more broad sense, the push for greater capabilities is coordinated between different wavelength regions. This is precisely the approach advocated by the ASTRONET Science Vision and Roadmap, and we underscore its importance here emphatically. A good example of such a synergy in a very important result is that between optical and radio observations of pulsar PSR J0348+0432, in which a rather massive neutron star is orbited by a low-mass white dwarf (Antoniadis et al. 2013, Science 340, 448). Our strategy should therefore rather be to view the premier facilities worldwide as each being justified in of themselves, for specific reasons, but also for the collection of them to be a sensible match to each other, enabling optimal multi-wavelength studies of astrophysical phenomena. This implies, for example, that in thinking about the angular resolution that the new premier radio observatory, SKA, needs to achieve, one should pay attention to what the premier observatories at other wavelengths will be able to do at the same time. For the SKA, that means, e.g., paying careful attention to the capabilities of VLT and ELT in optical/IR, of ATHENA in X rays, and so on. For comparison, we give below a timeline of the estimated periods of design, construction, and operation of a set of premier facilities across all wavelengths.

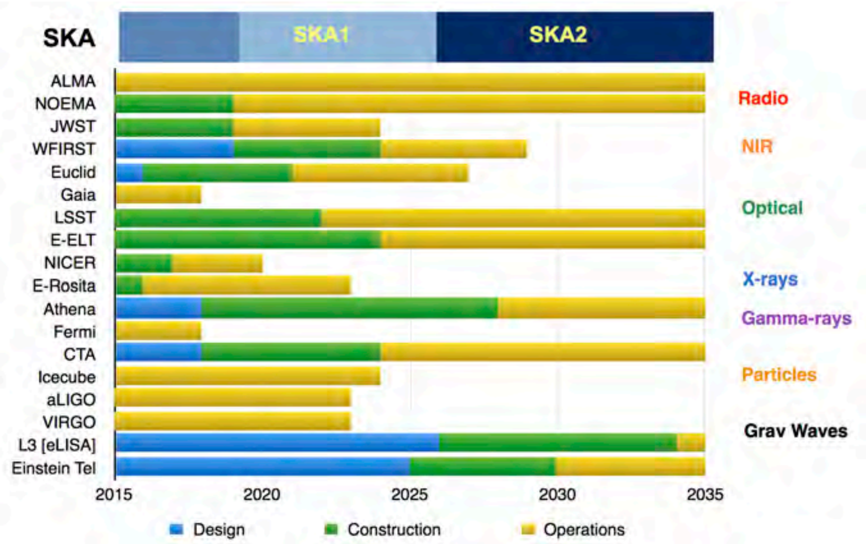

Figure 12: Design, construction, and operation timeline for the Square Kilometre Array and other current and upcoming major multi-wavelength facilities. This is not an exhaustive list, and timelines are continuously in flux.

8.3 – Conclusions

In summary, it is clear that the science of radio astronomy does not exist in isolation from other electromagnetic wavelengths or messengers like gravitational waves. Astronomy has become object- rather than wavelength-oriented, and breakthroughs in our understanding of phenomena more often than not require a multi-wavelength, and thus multi-observatory, multi-technique approach. Radio astronomers and their `shorter-wavelength colleagues' therefore collaborate in many areas to produce some of the most exciting science jointly, and not every project in which radio astronomy plays a role will have a black-belt expert on board. Increasing the ease of access (via well-maintained, easily searchable archive) and the ease of use (providing calibrated, quality images) of radio data to the broadest possible community is therefore crucial to maximizing the harvest from Europe's radio facilities. At the same time, promoting schemes whereby science teams can obtain observing time both on radio and high-energy facilities will streamline the process for certain projects. This requires a high versatility of the observatories: in basic scheduling, so that near-simultaneous observations of the same object by multiple telescopes are feasible. It also needs rapid response to target-of-opportunity triggers: much of radio astronomy is high-energy astrophysics, where a good fraction of the observations need to be in response to unpredictable outbursts of sources such as active galactic nuclei, X-ray binaries, and gamma-ray bursts.

Chapter 9: Education and training in radio astronomy

9.1 – Introduction

In the era of the SKA, radio astronomy cannot just be the domain of black-belt radio astronomers. They will still be key, in order to keep pushing radio observatories to new levels of excellence, but much broader support and use of radio telescopes will be required. Multi-wavelength astronomers need to be able to use SKA data easily for their science.

In this chapter we briefly comment on some aspects of the training of astronomers and engineers that are particularly relevant to radio astronomy, without any intention of giving a complete view on astronomy education in general. We touch upon teaching radio astronomy at the level of awareness of its results and applications at all levels, from public outreach to advanced higher education, as well as upon the technical training required to educate the next generation of users, developers, and builders of radio observatories.

We divide this chapter into various levels of specialization that one can aim for in the teaching of radio astronomy. Obviously, how these levels are mapped onto a specific education system depends greatly on that system, as well as on local tradition: some universities with a long tradition in radio astronomy research may introduce the subject sooner than others, some may be overall more theoretical or observational in emphasis. In general, we believe that because astronomy is a natural science, and thus fundamentally empirical, at some level it is necessary to familiarize students not only with results of radio astronomy, but also with its techniques and pitfalls. In that sense, we should note that teaching radio astronomy has some specific features with respect to other areas of astronomy due to its strong links with interdisciplinary academic matters, such as electrical engineering, signal processing, computer science and the management of large collections of data ("Big Data"). It is necessary to overcome the perception that radio astronomy is harder to learn, although due to the relatively small number of radio astronomers compared with optical astronomers it can be hard to incorporate radio astronomy in the education system.

In order to make the best use of on-going and future facilities, the user community needs to expand. Education and training will be crucial in the effort to include multi-wavelength astronomers in the use of radio data and, incorporate also, new scientific ideas. Such expansion means both increasing the number of places with research and teaching in radio astronomy, but also, as with almost any field in the natural sciences, paying attention to diversity and the inclusion of student groups that traditionally are underrepresented in our field. Moreover, in order to develop and optimize new key observing facilities, a high-level training – both at the scientific and technical level – for the new generation of "black-belt" radio astronomers will be needed.

9.2 – Radio astronomy as a cultural object

At a basic level, one can regard radio astronomy as something that exists as an aspect of our culture and contributes to our view of the Universe. As such, one wishes to convey to the general public, undergraduate and postgraduate students that view of the Universe. Radio astronomy offers a natural framework for the explanation of some basic concepts of astronomy and physics: i) the electromagnetic spectrum and the necessity of multi-wavelength astronomical observations to get a global view of the physics of the emitting objects; ii) the electromagnetic waves and, in particular, the difference between radio waves and sound waves; iii) wave propagation, wave properties, wave polarization, wave interferences, among others.

In order to convey the importance of radio astronomy, one needs to ensure that, where appropriate, the specific contributions of radio astronomy to the progress of astronomy are emphasized. One can do this by specifically highlighting scientific topics or techniques in which radio astronomy excels, such as pulsar timing and all its applications or the study of molecular gas, HI, or ultra-high resolution imaging of relativistic jets with VLBI. Another approach could be adding radio astronomical findings specifically to the multi-wavelength picture of any subjects being discussed.

Several initiatives could be considered at this basic level:

- Outreach activities at the observatories: i) news and press office; ii) involvement in social media networks (Facebook, Twitter); iii) development of an outreach web site, explaining basic concepts and describing the scenarios where radio emission is produced; iv) for those observatories with a long tradition, visitor centres are welcome. It would be possible even to define a "European Tour" around visitor centres, including Effelsberg (http://www.mpifr-bonn.mpg.de/effelsberg/visitors), the Jodrell Bank Discovery Centre (http://www.jodrellbank.net/), Madrid Deep Space network Complex (http://www.mdscc.org/index.php?Section=CEV), Medicina (the "Marcello Ceccarelli" Visitor Centre, http://www.ira.inaf.it/visitMc/index.html); the Nançay "Pôle des étoiles" (http://poledesetoiles.fr) v) development of open and accessible online resources, promoting societal engagement with radio astronomical activities; vi) Open Days, that are already conducted, e.g., by some observatories like Effelsberg, Jodrell Bank, ASTRON or public tours of the LOFAR Core Area. These activities require investment in an outreach officer, equipment, etc., which has been made by several institutes already.
- Development of radio astronomical activities in science museums, including participation in basic astronomy courses, public conferences, online radio astronomical observations, etc.
- Participation in public events, including science festivals, activities at schools, science events in libraries, cultural activities at the radio astronomy locations (e.g. Pop and Rock concerts in Jodrell Bank, http://www.livefromjodrellbank.com/).
- Encourage the development of citizen science projects in radio astronomy topics (e.g. http://radio.galaxyzoo.org/) in which the participation of the citizens in the scientific method is increasingly direct and decisive

One important aspect of improving outreach is to improve the quality and number of people who provide the outreach, by making a measure of public-outreach activity second nature to everyone in the field. Given the enthusiasm of astronomers for their own field, this is not particularly hard to do. It mostly requires imparting a sense of love for, and importance of, outreach to students at least from the PhD level, perhaps even earlier. The natural attractiveness of astronomy to the general public makes this activity very rewarding to those who engage in it with some enthusiasm. However, teaching at this level is also a special skill, so in order to have it done well, it pays to provide training in popular writing and speaking to the majority of PhD students, so that they become ambassadors for their field. For a more select group, training in popular science writing for magazines, web pages of institutes, and the like, should also be considered.

9.3 – Radio astronomy as an academic subject

Here we mean the level of teaching aimed at pre-doctoral students in universities, and we can distinguish at least two aspects of this teaching that are both important. The first is teaching radio astronomy as an observational technique, and the second is teaching the astrophysics that is typically associated with phenomena that are well studied with radio telescopes.

Teaching radio astronomy as an observational technique should begin with teaching the principles underlying it. In the spirit of multi-wavelength astronomy, and also to respect the appropriate level of detail, one expects this to be done at lower undergraduate level in the context of a more general program of teaching basic observational astronomy. With some electromagnetism and quantum mechanics under their belt, students will appreciate the comparison and contrast between the instrumentation for different regions of the electromagnetic spectrum, and recognize the unique aspects. Such a course will then also serve to deepen their knowledge of the underlying physics. At this level, it is of course also great to include hands-on teaching in a lab course. More often, universities will have access to small optical telescopes than to a private radio facility, but where facilities exist it would certainly be great to include them in such lab courses (and in fact, fairly inexpensive kits exist, e.g., to observe Jupiter radio outbursts).

Teaching radio astrophysics again need not be done as a separate standalone course. More naturally, specific aspects thereof should be woven into the curriculum wherever in a course the empirical basis of astrophysical phenomena is taught. Almost certainly, however, a course in radiative transfer and basic radiation physics will be required in addition to the usual electromagnetism, as typically basic physics courses do not treat it adequately for astronomical purposes. After that, one would expect various types of radio observation to come up naturally in a number of courses: e.g., the observation of simple atoms and molecules such as HI and CO in interstellar medium and/or galactic dynamics; maser emission should also find its way into such a course. A course in high-energy astrophysics, pulsars, and AGN, should no doubt include synchrotron emission and coherent high-energy processes, etc. Quite naturally, radio observations arise not in isolation, but in a multi-wavelength context in these examples.

One goal would be to increase the number of undergraduate and master students that have access to radio data (from the archives) and to a radio telescope. By basing such efforts in the observatories (in collaboration with universities) and making them in English, these could immediately have a wide reach, also serving universities in regions without a large existing radio astronomy base. Radio telescopes can serve as tools for university education – both for science and technology. This includes of course the majority of astronomy courses, but also educational programs in geodesy, environment, antenna engineering and receiver technology will benefit. In particular, the R&D activities are of high interest for engineering schools and solid-state physics laboratories, to name a couple examples. Radio astronomy is also an excellent example of some very fundamental signal processing concepts (e.g., Nyquist rate, Fourier transforms, convolution). Some coordination between Master Programmes on Astrophysics at a national level would increase significantly the number of students with access to a radio facility.

This, again, requires a dedicated program at a given observatory for collaborations with universities. We suggest that the observatories could host some of the best undergraduate astronomy students from the universities for a data project in radio astronomy, with durations from some days up to a week. This would be an excellent opportunity to attract young students for bachelor theses, and MSc and PhDs (e.g., ASTRON already offers this kind of project for students in a number of universities). A coordinated European effort to facilitate these collaborations might be helpful. Several options could be considered: dedicated undergraduate observing projects; joint European undergraduate research projects, using different techniques and observatories; a competition between European bachelor projects in radio astronomy. All of this requires that the observatories set aside resources to support these activities, but if the universities (who have the primary responsibility for this teaching) play an active role that investment need not be large. Collaborations of universities and observatories could also consider a `teaching the teachers' programme to provide training to those institutions that do not have radio astronomers.

Some European coordination between the available resources at the different observatories will be valuable. Some of the activities (science, accessibility to databases or outreach telescopes) could be trans-national, but some others (antenna engineering, receiver technology, labs) would be based on local agreements between universities and observatories.

9.4 – Radio astronomy as a tool

At upper undergraduate (and MSc) level specialization increases, and one reaches the point where there is enough to be conveyed to the students that a standalone course definitely becomes necessary. Ideally, such a course will take the student to the level of real radio astronomy by including a practical part, in which the student handles and reduces actual radio data and reports on the results, the observational uncertainties, and the astrophysical implications. This requires a teacher who is familiar with radio data of the type that will be used, but it does not require the use of a radio telescope: there are now enough frontline radio observatories that have an accessible archive, and radio data reduction packages of various sorts are available freely online (and where they are not, it is our strong recommendation that they should be). Also the teacher will have data from previous research projects and the expertise how to handle those. Practical experience with MSc courses in a number of places we are aware of shows that this is an achievable ambition. We also recommend that in fact using data from a frontline research facility is highly preferred at this level, since it exposes the student to realistic research, which is much more stimulating and a better preparation for scientific work. The implication here is that this teaching is now at a level that academic standards require that they be taught by active researchers in radio astronomy. Where those are unavailable, exchange agreements with other universities, or national-level courses can provide access to such courses by a wider student body.

During the research phase of the MSc or during the PhD this level of education should provide sufficient basis for developing expertise up to the level of a competent user of radio data and an independent proposer of new, not-too-complex types of observation – i.e., to the level of a multi-wavelength astronomers who can add radio astronomy productively to their arsenal independently.

Several activities can be considered:

1) The access of students to the facilities should be considered, including a practical part (observations and data reduction). Nowadays, many observatories have an archive and their data are accessible; students can get very real radio astronomy experience provided that the teachers are aware of these databases and train the students in the use of the data. For the cases in which students need to set up new observations for their learning, or they have technological skills/interests at the level where they could start experimenting with the equipment, real access to the observatory should be favoured. Only facilities that are capable of being used for publishable research should be considered. Future generations of observational astronomers need experience with real radio-astronomical data and facilities in order to be trained in radio observational techniques (single dish, interferometry, spectroscopy). This can be facilitated through:

- Organizing training programs and summer schools, supporting and collaborating with university research schools and Marie Curie ITNs. Some of the instruments can be selected for this educational role (many are already doing this). A pan-European radio training network within the frame of RadioNet could be defined.

- Organizing summer student programs (e.g. http://www.astron.nl/astronomy-group/astronjive-summer-student-programme), which will be excellent training opportunities for future users of the radio astronomical facilities.
- Coordination of all the different training schools: Radio interferometry (RadioNet European Interferometry School, http://www.radionet-eu.org/eris-2013; LOFAR Data Analysis School, http://www.astron.nl/lofarschool2014), IRAM (mm-Astronomy and mm-interferometry; http://www.iram-institute.org/EN/content-page-265-7-67-265-0-0.html), and single-dish (e.g., the annual IPTA data school). There is an opportunity to define, within the umbrella of RadioNet, a single school covering all different fields of work (similar to the "Imaging Schools" of NRAO).
- Remote access to telescopes and arrays: it is an opportunity to define some facilities that could be better fitted for this kind of activity.
- Contribute to and encourage multi-disciplinary and multi-wavelength collaborations to broaden the scope of students and to reach a wider community.
- The radio astronomy institutes and the university departments with radio astronomy expertise could support young/inexperienced observers both in writing proposals as well as in supporting data reduction.

2) There should be a policy to promote young researchers: ensure that meetings, workshops and conferences have a significant (perhaps dedicated) fraction of young pre-doc researchers. Dedicated meetings for young researchers (e.g. YERAC) are a good opportunity to acquire experience. European collaborations should be encouraged and supported. YERAC (Young European Radio Astronomers Conference) was the first joint activity that was started (see Section 10.3.1).

9.5 – Radio astronomy as a profession

Finally, radio astronomy needs to train those who will be the next generation of black-belt experts, i.e., the frontline researchers in radio astronomy, and those who will further develop the field. Their training will start with a PhD in radio astronomy or radio instrumentation and software development, where they get to know the techniques of radio astronomy at the deepest level. By definition, therefore, this training is done by the existing experts, and will be concentrated in the institutions where they reside (where appropriate, in collaboration with a PhD-granting university, of course). While we have argued above that in the future the required widening of the community and focus on multi-wavelength expertise implies that these black-belts will not be the majority of radio astronomers, they will nonetheless remain absolutely essential to the vitality and progress of the field. In some ways, there is a paradox here: multi-wavelength astronomy requires that data analysis tools must rise to the level that most practitioners need not be black-belt experts in a given type of instrumentation. However, the development of such powerful tools can only be done by black-belt experts, so even in that multi-wavelength era, mono-wavelength top experts remain a necessary ingredient of front-line astronomy.

Mobility has always been a fundamental ingredient for science, and it is the case also for radio astronomy. In fact, it has been a tradition for the radio astronomical community, especially in the field of radio interferometry with the creation of the European and global VLBI network arrays. A healthy level of exchange between Europe, North America, Australia, South Africa and Asia will keep the black-belt radio astronomers up-to-date on the latest technological developments, while enhancing scientific knowledge worldwide. For instance, we can highlight AERAP (African-European Radio Astronomy Platform; http://www.aerap.org), which is a platform created to define priorities for radio astronomy cooperation between Africa and Europe. It provides a framework, with partners from academia and industry, which will enable major research and technological advances that will drive socio-economic development and competitiveness in both Africa and Europe. Some funding agencies are specifically furthering these efforts, e.g., by a new Dutch/South African exchange program funded by NWO: http://www.nwo.nl/en/funding/our-funding-instruments/ew/cooperation-south-africa---astronomy-and-enabling-technologies-for-astronomya/cooperation-south-africa---astronomy-and-enabling-technologies-for-astronomya.html. Given that international collaboration in radio astronomy is becoming even more important than it already was, an expansion of such efforts is likely needed.

Another form of collaboration that is also increasingly called for is that between subjects, and this also calls for training of people with interdisciplinary skills and interests. There has always been close contact between radio astronomers and engineers, and yet the number of people with significant interests in both areas is still small. In more modern days, the complexity od projects also requires people with a strong background in systems engineering. The modern radio telescopes are, as we have seen, also to a large extent software telescopes, and this results in the need for people with interests spanning the connection between radio astronomy and software engineering.

Lastly, an essential part of acquiring and training talent for (radio) astronomy is proper career management and good understanding of job prospects. We educate far more people in our universities than stay in academia. This is well understood and deliberate, since those talented people are needed throughout society, but we should also make sure that our students understand this throughout their careers. We should also make sure that we make clear what talents are needed for which future careers, and guide students towards the path that suits them and their talents best, regardless of their background. A particular problem in that regard is the career prospects for more technically oriented people, of which radio astronomy needs many. These are often not appreciated in universities as people who do research and write papers, even though that research needs –and often is even driven by—technical innovations in telescopes, receivers, etc. And more recently, it is also by good data analysis software. Setting up proper collaboration between universities, observatories, and technical institutions to train a sufficient number of technically oriented radio astronomers, and offer them similarly rewarding career options, is an urgent concern that our needs to continue to address.

9.6 – Conclusions

In summary, there is a need to convey strong scientific and technical skills and experience with large projects to a new generation of radio astronomers, to help guide the development of the SKA and other frontier observatories; and to train the wider astronomy community in the use of standardized radio data products, ensuring radio data are well utilized by multi-wavelength astronomers and thus useful to a wide community. Excellence in training in science, engineering and computing is crucial to keeping European radio astronomy a key player worldwide, both currently and into the SKA era. For this reason, only facilities that are capable of being used for publishable research or cutting-edge technological development should be used as educational facilities in PhD education. It is clear that the number of top experts will be relatively small. Since not every aspect of radio astronomy expertise will be available at every observatory, significant international collaboration and connection is needed to keep up the full range of radio astronomy expertise. A lively programme of international exchange of (PhD) students and more senior experts will therefore be needed. Furthermore, the challenging nature of new observing facilities and their data reduction also requires training and good career management of interdisciplinary specialists at the interfaces of fields: computer scientists and engineers with a good knowledge of and contact with radio astronomers, and systems engineers with experience in the way astronomers view the specification and operation of their observatories.

Chapter 10: Organisational matters

10.1 – Introduction

Here and in Chapter 11 we summarize our view of the challenges that European radio astronomy is facing now and in the future. The topics addressed are:

- The current mode of operation (Section 10.2).
- Existing organizational structures (Section 10.3).
- The current financial situation (as far as could be determined; Section 10.4).
- European radio astronomy in transition? (Section 10.5)

10.2 – The current mode of operation

As described in detail in Chapter 3, radio-astronomical institutes in Europe operate a large suite of radio telescopes, several amongst the largest and most productive in the world. Some have been in operation for more than 30 years, and several of these have been refurbished and significantly upgraded in recent years; this process will undoubtedly continue, as evidenced, e.g., by recent developments at WSRT and e-MERLIN. During the last 10 years, three new facilities have started operation: the new 40-m Yebes telescope, the LOFAR interferometer, and the 64-m Sardinia telescope..

With the exception of some telescopes, which have been erected as dedicated VLBI antennas, often with the aim to serve both the needs of radio astronomy and geodesy, the facilities are usually equipped with a suite of receivers and backends to tackle a broad range of scientific topics requiring both spectroscopic and continuum observations. This enables them to make significant contributions to key science questions in the coming 5 – 10 years or more, as discussed in greater detail in the previous chapters (particularly Chapter 4).

Observing time on these facilities is in principle granted on the basis of scientific merit, as judged by time allocation committees. These committees normally comprise both local and external scientists, but depending on the ownership, time may be allocated according to some quota, and the community perception of how open facilities are in reality varies somewhat between facilities.

In most wavelength ranges, one finds broad, versatile observatories; these are often the larger, more expensive ones that can push the boundaries in multiple directions. The base cost of these facilities is high and broad, international support is often needed to raise their investment and operating cost. When facilities get older and are no longer the largest ones around, they often can have a very productive second life by optimising their capabilities to tackling specific scientific problems in a focused way. One can foresee this happening for some now existing radio observatories in Europe in the era of the SKA. It would then be good to think carefully about making such facilities complementary to the SKA and to each other, but the issues of access and time allocation then need to be re-thought, and different organisational tools may have to be developed at European level. We shall return to this later.

10.3 – Existing organizational structures in radio astronomy in Europe

Over the last few decades, a number of organisational structures have emerged in Europe in response to common needs and interests of European radio astronomy institutes. These have arisen quite naturally, in the sense that the total radio astronomy activity in Europe is large, but per country it is not. Combining forces therefore often makes sense. At the same time, the different national structures and their histories, to which transnational efforts are often added at a later stage, are not so easily merged. As a result, finding suitable legal and financial structures and agreements for these transnational efforts is complex. The common needs and interests range from the coordinated scheduling of observing programs, to collaborative technical development projects. In addition, groups have started consortia around specific scientific themes – e.g., the European Pulsar Timing Array and the Event Horizon Telescope projects.

In the following we shall briefly summarize the aims, the participants, the legal status, and the financial basis of these different activities. We go by chronological order, starting with the oldest joint activity.

10.3.1 – YERAC

The first joint activity that was started was YERAC, the Young European Radio Astronomers Conference. This series of meetings started in 1968 in Meudon/France, followed by meetings at most of the major radio institutes of Europe; it continues to this day, and the host changes from year to year. The host is responsible for the local logistics and the necessary funding, which may either come from the host institute itself and/or a national funding scheme.

Participation in the YERAC meetings is by invitation. Applications are invited from undergraduates, graduates, and early-career postdocs who have an opportunity to present their on-going research work. In general, the participants are nominated by the directors of the participating institutes. It is particularly noteworthy that the YERAC meetings have been open to participants from eastern European countries since a long time, leading to many fruitful collaborations. The informal way of organising YERAC meetings has worked over a long period of time. Since 2004 RadioNet helped to ensure continuity. It therefore deserves some attention to create a more stable basis for YERAC; helpful measures could be to make a body with a long-term future responsibility for the continuity, and to broaden the basis of participation by including not just the radio observatories, but also universities with radio astronomy groups (as has already been happening somewhat in recent years).

10.3.2 – EVN

The European VLBI Network (EVN) was established in 1980 by a consortium of five major radio astronomy institutes in Europe. Since then the consortium has grown and now comprises as formal partners:

- Joint Institute for VLBI in Europe, Dwingeloo/NL
- Max-Planck-Institut für Radioastronomie, Bonn/DE
- Jodrell Bank Observatory, University of Manchester, Manchester /UK
- ASTRON, Dwingeloo/NL
- Istituto di Radioastronomia, Bologna/IT
- Onsala Space Observatory, Onsala/SE
- Torun Center for Astronomy, Nicolaus Copernicus University, Torun/PL
- Metsähovi Radio Observatory, Aalto University, Helsinki, FI
- Instituto Geografico Nacional, Madrid/ES
- Hartebeesthoek Radio Astronomy Observatory, Gauteng/SA
- Wetzell Geodetic Observatory, Bad Kötzing/DE
- Institute of Applied Astronomy, St.Petersburg/RU
- Shanghai Astronomical Observatory, Shanghai/CN
- Xinjiang Astronomical Observatory, Urumqui/CN
- Arecibo Observatory, Arecibo, Puerto Rico/US
- Korean Astronomy and Space Science Institute/KR

In addition, several initiatives exist to expand the EVN, e.g., with Irbene (Latvia) and Goonhilly (UK) and, potentially, the addition of geodetic dishes as the future Iberoscope and the Azores radio telescope.

The EVN mission is "to enable discovery in radio astronomy through innovative VLBI instrumentation and the management of shared radio astronomy facilities within Europe and with affiliates in other countries."

While European institutes are still in the majority, the VLBI network comprises also telescopes in China, South Korea, South Africa, Russia and other countries. A particular growth potential exists with respect to Africa where a number of telecommunications telescopes exist that may be used as an African VLBI Network (AVN) and also combined with EVN into a bigger network. Typically, up to 20 telescopes participate in an EVN observing campaign, owned and operated by many different organisations (often more than a dozen).

The participating institutes have agreed in an MoU, initially signed in 1984, to make at least 12% of observing time available on a voluntary basis for projects of high scientific value. There is no financial compensation for the telescope owners, neither for the manpower, nor for the operational cost except for a small fraction of projects that fall under the Transnational Access (TNA) program that receives financial support from the EC. As a general rule, the principle of "no exchange of funds" is applied. In other words, EVN is funded to a large extent by in-kind contributions by the participating observatories.

The current EVN organisational setup has successfully worked since 1980. The fraction of total observing time that each observatory devoted to joint VLBI activities has, however, been very limited: about 10 weeks per year. Taking the numbers for 2013, 69 proposals have been submitted in response to the 3 calls, of which 43 were approved. The total amount of time requested was 2283 hours. The total number of hours scheduled was only 1471, and this number is even on the high side because it includes well over 300 hours for joint proposals with the RadioAstron VLBI satellite. The VLBI work leads to 20 – 30 published papers per year. Our recommendation is to substantially increase this fraction of time; this may necessitate a re-thinking of the current support scheme.

Such re-thinking may also be required if full advantage is to be taken of the modern high-speed data links that allow a real-time transmission of the data from each telescope in the array to a central facility that will receive, process and archive the data. This transformation of the EVN into the e-EVN, which started already in the mid-2000s, has the potential of revolutionising VLBI by opening up many new possibilities, including rapid (near real-time) data processing. Also, one would no longer have to buy expensive disc packs and send them to the central correlator, which is sometimes a limiting factor. The EC-supported NEXPres and EXPReS projects (http://www.expres-eu.org) have been designed to prepare this new observing mode.

New types of observation that can be envisaged with an expanded network include rapid response observations in the case of unexpected events (Target of Opportunity observations), and more frequent VLBI contributions to multi-wavelength monitoring campaigns jointly with other observatories. However, the current method of scheduling VLBI observations rather infrequently and in blocks of time fixed almost a year in advance severely limits the practical use of these new types of observation. There may well be a catch-22 here: at the moment, the user base of e-VLBI is relatively small and the amount of observing time not very large, limiting the number of published papers. Yet, the unique capabilities of e-VLBI and the large expansion of those capabilities that is possible with more and more flexible allocation of time and training of a broader user base make us identify e-VLBI as of great value to European radio astronomy, and potentially of even greater, unique value in the future. However, substantial changes to the mode of operation of e-VLBI and a more secure basis of funding those new modes of operation will be required in order to realise that potential. One of the hindrances to the use of e-VLBI is that some observatories, especially in the East, are not yet hooked up with sufficient bandwidth.

Obviously, how a specific observatory puts the balance between single-dish and VLBI work does depend significantly on the standalone capabilities of that observatory, and so may vary quite a bit between them. Therefore, a mode of operation of EVN where the smaller observatories dedicate more time than the larger ones, and where programmes suitable to a variety of configurations can be scheduled flexibly, has great merit. It should also be noted, of course, that EVN nodes also participate in global VLBI, for even greater resolution. This too is of great value, and in that context we note with great concern that some of the larger non-European radio observatories such as Arecibo and Green Bank are under threat. We recommend to our American colleagues to consider carefully also the impact on global VLBI before any funding decisions on these observatories are taken.

10.3.3 – CRAF

A look at any radio frequency allocation table or plot immediately makes it clear that radio astronomy must defend its interests in order to have certain frequency bands, e.g., the 1420 MHz (21cm) band, protected against the interests of parties from the public services sector, commercial services and, in particular, the telecommunications industry. To make the voice of radio astronomy heard in the discussions at the World Radiocommunication Conferences (WRC), where frequency allocations are discussed at governmental level, the Committee on Radio Astronomy Frequencies (CRAF) was created in 1988 as a committee of the European Science Foundation (ESF). A CRAF Frequency Manager was appointed to attend the WRC meetings in Geneva, and many other meetings that prepare the future decisions at Geneva. As European governments pursue their own, often conflicting, interests, CRAF's voice must also be raised in the different countries. This very demanding function requires adequate financial support, which has so far been provided on a voluntary basis by its members. These comprise at present radio observatories and/or their funding organisations in 21 European countries. The EU supported Radionet3 Work package 7 also provides support for matters related to frequency protection.

The biggest challenge in the short term is that CRAF´s current host organisation, the ESF, is expected to close down at the end of 2015. The ESF-follow up organisation, Science Europe (SE), does not want to continue the ESF function. A new legal umbrella is therefore needed for CRAF. Amongst the options under consideration are: (1) a new legal structure at European level called Expert Boards and Committees (EBCs), and (2) a JIVE-based solution, as JIVE operates as a European Research Infrastructure Consortium (ERIC) since January 1st, 2015. It is an urgent matter of attention for the radio community to safeguard the work of CRAF for the long term, as pressures on the existing radio frequency bands are likely to increase even further.

10.3.4 – JIVE

The Joint Institute for VLBI in Europe (JIVE) was founded in 1993 by the European Consortium for VLBI. It is a member of the European VLBI Network (EVN) described above. JIVE operates at Dwingeloo the EVN Data Processor – a special purpose supercomputer for astronomical VLBI data correlation. During the first few years, JIVE's primary task was the design, construction and commissioning of this correlator, and has developed several further ones since. In parallel, JIVE provided support to the users of the European VLBI network through a team of support scientists. In addition, JIVE has built up a strong R&D division, which works on the continuous enhancement of the VLBI technique, in particular the move towards e-VLBI.

JIVE was established as a scientific foundation under Dutch law. Its Director reports to the JIVE Board of Directors. The Board members are nominated by the funding organisations and institutes. These have so far been the NWO and ASTRON in the Netherlands, the CNRS in France, the MPIfR in Germany, INAF in Italy, the OSO in Sweden, the IGN in Spain, the STFC in the UK, and the NAOC in China. Together, they finance an annual budget of 1.9 million Euros. Additional funds come, e.g., from contracts with the EC.

As of 2015, JIVE has become an ERIC. This new legal entity requires financial commitments at governmental and/or funding agency level from the participating countries. This is a step towards longer-term stability. So far a fair fraction of the partners have signed the JIVE-ERIC agreement, and more, who are still awaiting governmental approval, are expected to join soon. It should be noted that the host country is paying a big share of the total cost. The MPIfR, as the German partner, is not able to join the ERIC but is ready to continue its JIVE support as an associate member. The ERIC structure requires a longer-term commitment of funding from the partners (5 years, as opposed to 2 – 3 years in the previous structure), and the commitment seems to come from a higher-level body in the funding structures of the partner countries in some cases.

10.3.5 – RadioNet

Since 2000, the European Commission supports an infrastructure cooperation network in radio astronomy. This started under the 5th Framework Program (FP5). During the first funding period from 2000 to 2004, the EU contributed 800,000 Euros to a total cost of 890,000 Euros. The project was coordinated by JIVE. Participants were the National Research Council of Italy, the Commonwealth Scientific and Industrial Research Organisation in Australia, the Netherlands Foundation for Research in Astronomy (now ASTRON), the Nicolaus Copernicus University in Poland, the Chalmers University of Technology in Sweden, the Helsinki University of Technology in Finland, the Centro Nacional de Informacion Geografica of Spain, the national Research Council of Canada, the Max-Planck-Society in Germany, the University of Bordeaux in France, and the University of Manchester in the UK. The purpose was to enhance the quality of operations and to make more effective use of the existing European VLBI network of radio telescopes (EVN), and to prepare for the next generation of major facilities.

Under FP6, RadioNet was continued with now already 24 participating organisations and institutes. This Integrated Infrastructure Initiative (I3) included a number of networking activities (in total 8), a Transnational Access program with the EVN, MERLIN, WSRT, JCMT, IRAM-PdB, IRAM-PV, Effelsberg, and OSO as participating observing facilities, and three Joint Research Activities called ALBUS (Advanced long baseline user software), AMSTAR (Advanced millimetre and sub-millimetre technology for astronomical research), and PHAROS (Phased arrays for reflector observing systems). For the 5-year period 2004 to 2008, the total cost amounted 15.2 million Euros, of which the European Commission contributed 12.4 million Euros.

RadioNet continued under FP7, with 27 partners. For the period 2009 – 2012, the total cost of the project amounted to 14.9 million Euros, of which the European Commission contributed 10.0 million Euros.

At present, RadioNet3 is funded with a total project cost of 11.6 million Euros, of which the European Commission contributes 9.5 million Euros for the 4-year period 2012 to 2015. 45% of the budget goes into Transnational Access (TNA) activities, 40% into Joint Research Activities (JRAs), and 15% into networking and management activities.

The current TNA program supports the access to 8 facilities (EVN/JIVE, e-MERLIN, Effelsberg, LOFAR, WSRT, APEX, IRAM-NOEMA, IRAM-PV). For some institutes the financial compensation received under the TNA program is vital. JIVE is a prominent example.

The 4 ongoing Joint Research Activities comprise the projects UniBoard2, AETHER, Hilado and DIVA. They all aim at improving the capabilities of existing and future facilities.

The 6 ongoing Networking Activities (NAs) cover a wide range of topics, including support for ARC users to facilitate research with ALMA.

The current RadioNet will come to an end in 2015, and there will not be an immediate follow-up. The institutes that are currently involved seem to be determined to continue their collaboration, e.g. the JRAs, even if there is no EC support for some time. The hope, of course, is that EC support will again become available under a new contract that could start late in 2016, or 2017. This is of paramount importance: not only for RadioNet, but also for other past joint activities. European funding has proven invaluable (e.g., SKADS, PrepSKA, NEXPReS). It appears that even when that funding covers only a small fraction of the total investment into a new project, it can be spent on certain aspects of the joint work that the partners find hard to cover with their own budgets.

10.3.6 – The Square Kilometre Array (SKA) preparatory activities

For more than a decade, European radio astronomy groups have been deeply involved in the preparation of a new project: the world's largest radio telescope, the SKA. At the same time, a number of precursor and pathfinder projects like LOFAR, MeerKAT and ASKAP have been major initiatives. European participation in the latter two projects is by agreement between individual European groups and the lead organisations in South Africa and Australia, respectively. LOFAR, while started in the Netherlands, is now the MoU-based International LOFAR Telescope (ILT) with participation from six European countries. In the preparation of both LOFAR and preparations for the SKA, European funding again played an important role: regional development funding contributed to LOFAR, and the important SKADS and PrepSKA activities by a large number of European institutions were funded through EU FP6 programs.

The international SKA project office located in Europe has for many years coordinated the preparation of the SKA project. Today, the more recently created SKA Organisation, a not-for-profit company established in December 2011, has taken over the coordination. Its headquarters are located at the Jodrell Bank Observatory. The following countries are participating in the current study phase as SKA full members: Australia, Canada, China, Germany, India, Italy, New Zealand, South Africa, Sweden, The Netherlands, and the United Kingdom. About 10 more are also engaged at some level in the detailed design of the telescope (Brazil, France, Japan, Malta, South Korea, Poland, Portugal, Russia, Spain, the USA)

Among the current major tasks of the SKA Organisation is the formalization of the relationships between the international partners and to centralize the leadership of the project. In total, 11 design consortia have started their work with broad international participation. A Science and Engineering Advisory Committee (SEAC) is closely following these development as well as the outcomes of a new science prioritisation process by a Science Review Panel that has been set up to consider recommendations made by international Science Working Groups.

The current science review and the technical design activities will lead to a Critical Design Review currently planned for 2017/18, which should result in the final go-ahead for the first construction phase of the SKA project. The revised baseline design has been given a cost cap of 650 million Euros (in current economic conditions), and several options are under study, together with industry, to reach this goal. These preparatory activities for the SKA have already stimulated, and given a strong focus to many joint technical and scientific activities, as well as intense collaboration with high-tech industries.

10.3.7 – Summary

This compilation shows that there are several very successful on-going activities in European radio astronomy that were started bottom-up between different institutes and that provide observing (and data reduction) capabilities that no single existing institute could provide alone.

The success of these collaborative efforts is owed to a huge number of "in kind" contributions, which are made available by the institutes on a case-by-case basis. This has worked extremely well so far. It still works for the current phase of the preparation of a new project like the SKA, but it is obvious that a project of this calibre is too big to simply extrapolate the current approach. New organisational and financial tools will be needed.

10.4 – The current financial situation

The ERTRC has not been able to establish a comprehensive overall picture of the current funding situation of radio astronomy in Europe. This is due to the fact that the funding schemes differ widely from country to country, and they even differ within some of the countries.

The numbers that we were able to compile are given in Appendix D. They illustrate primarily the current operating costs of the existing facilities (personnel, running costs, current investment costs). They do not include the initial investment costs. Also, departments, institutes, and small science groups working in the field of radio astronomy at various universities are not systematically accounted for. As shown in Appendix D, the annual cost for operating the listed facilities amounts to more than 40 million Euros. To this, the costs for scientific and technical groups not directly involved in running the telescopes considered here must be added. We estimate this amount to be well above 10 million Euros. For comparison, we note that the current annual budget of ESO for building and operating its facilities is about 135 million Euros, and that of the ESA science programme is about 507 million Euros (which also does not include the costs of scientists exploiting those facilities). Given the high profile of radio astronomy and the priority given in the Science Vision and Roadmap to the goals and facilities for radio astronomy, the cost of radio astronomy facilities seems very reasonable. It is also clear, however, that the cost of Europe's participation in the SKA will be of the same order as the current cost of European radio facilities.

10.5 – European radio astronomy in transition?

The early development of European radio astronomy is characterized by many local initiatives in countries like the UK (Jodrell Bank, Cambridge), the Netherlands (Dwingeloo), France (Nançay), Germany (Effelsberg), etc. However, even with local interferometers in operation, the desire for still higher angular resolution led to the development of the very-long-baseline interferometers, first in the US, and then in Europe by networking telescopes hundreds and thousands of kilometres apart. This necessitated firm agreements for international collaboration, which existed before in astronomy but now involved institutions that own and/or operate the respective facilities. In Europe, the creation of the EVN and then of JIVE have been two success stories that still continue. However, as outlined above, they work so well because the majority of resources needed for VLBI experiments are made available "in kind", and only limited amounts of money are transferred "in cash" from one institution to another. The operation of JIVE as an ERIC will show if this new framework will be able to overcome the limitations of the previous MoU-based structures in which the centralized activities were of limited scope.

The landscape of European radio astronomy that has arisen in this manner is scientifically varied and vital, and has spawned a rich science, and bright prospects for the future, as outlined in the earlier chapters of this report. It is also greatly varied in method of organization, funding, and planning, as each country or sometimes even institutions within countries have evolved these according to local custom and with local optimizations. To first order, radio astronomy in Europe is anchored locally. Our committee has clearly experienced that the funding justification for observatories and their astronomers and engineers, as well as for radio astronomers in universities, heavily relies on distributed, often local interests and resources. This sometimes results in a tension between nationally funded and justified facilities and their ambitions for international orientation, driven by the increasing scale and rising demands of modern astronomy. This was one of the considerations that led ASTRONET to commission this study.

Going forward, we feel that the transnational aspects of radio astronomy will become even more important and more prominent for a number of reasons. For example, the recent difficulties with maintaining CRAF, and with making e-VLBI more versatile and more ambitious (as outlined above) have both demonstrated the limits of the current organizational and funding structures, and the future scientific ambitions of radio astronomy are rightly even greater. The corresponding scale for the next generation of radio facilities, most prominently the SKA, is such that they require stronger, and more upfront, international collaboration. The prominent examples of ESO and ESA demonstrate that European astronomy can be world leading if well organized. In the next chapter, we explore ways in which radio astronomy can meet its future challenges, benefiting from its own past experience and of that of other areas of astronomy.

10.6 – Conclusions

In summary, European radio astronomy has a strong need for transnational collaboration and facilities. These have thus far grown organically from collaborations between existing, usually local or national, facilities. Given the diversity of funding arrangements, traditions, and agency and community requirements, these collaborations are, however, all more or less fragile, and sometimes cumbersome. Responding to changes in the environment has been difficult at times, as illustrated, for example, by the search for a new home of CRAF, whose work is crucial. We find all the European structures that we investigated to provide a valuable contribution to radio astronomy, but worry to a lesser or greater extent about their future continuity due to the way they are currently organized. With the advent of the ERIC structure in Europe, there is some hope that this may be resolved in the future, since it provides an intrinsically transnational organization form with European support and high-level longer-term commitments from the partners. JIVE will pioneer this for radio astronomy in Europe. It is also clear, however, that national or funding agency rules in various countries do limit, for the time being, the ability of significant players to become full partners in such an ERIC. For the largest planned project in European radio astronomy, the (participation in) SKA, we deem none of the existing structures in radio astronomy robust enough to provide the vehicle for an optimal partner role of European radio astronomy at the global level.

Chapter 11: Future requirements and scenarios

11.1 – Introduction

In the previous chapter we noted the increasing tension between the current national and local funding and strategy development in European radio astronomy and the increasing need for transnational efforts to meet the demands and ambitions of modern radio astronomy. In this chapter we consider the requirements for the future success of European radio astronomy, as well as several scenarios that could meet such requirements.

11.2 – Future requirements and scenarios to consider

In order to advance significantly European radio astronomy and meet the challenges set for the medium and longer term by the ASTRONET Science Vision, we identify the following requirements:

- The ability to set priorities and strategy in radio astronomy at a transnational level;
- The ability to build and operate large transnational facilities, e.g. for global VLBI sessions, European-African VLBI, and Europe's share of the SKA;
- The ability to have coordinated, distributed developments of technology and instrumentation in institutes with specialized skills in order to benefit from their respective strengths;
- The ability to muster resources transnationally (money and expertise);
- The ability to operate in a stable and sustainable manner for decades;
- The ability to attract and support a broad user community, both in observatories and universities.

Several scenarios can be envisaged that would be adequate to fulfil one or more of these requirements. They will be discussed in turn.

11.2.1 – A stronger legal and financial basis for on-going joint activities

European radio astronomy groups have a long tradition in developing joint activities as described in Chapter 10. RadioNet is a particular example of special relevance here. The possibility to pursue joint projects during 4 – 5 year periods with financial help from the European Commission has led to the successful completion of a number of JRAs, and it has allowed to launch the Trans-National Access program which compensates (to a limited extent) the operators of large facilities for observing time that is made available to scientists from institutes/countries that qualify for this kind of EC support. Various reviews over the course of time have confirmed that the work performed within RadioNet has produced important results, and added value that could not have been achieved without the collaborative effort. The fact that the EC is involved means that the participating institutes have to focus their activities on a number of work packages, a list of deliverables and according to an agreed schedule. To achieve these goals, both the manpower and the financial resources needed to deliver results in a timely manner are required from the participating institutes mostly as "in kind" contributions to which they must commit when submitting the joint proposal.

A similar situation holds for the EVN and the operation of the European Correlator Centre at JIVE. To make VLBI experiments possible, the participating observatories have to make large "in kind" contributions in the form of manpower and expensive hardware, and in addition they have to help finance the central activity at JIVE. The framework for the latter has previously been an MoU. As of January 1st, 2015 it has taken the form of an ERIC.

The smallest of the current joint activities is the support of CRAF, which receives financial support from a small number of institutions on a voluntary basis.

The current distributed but coordinated activities, which depend so heavily on substantial "in kind" contributions, have undoubtedly produced excellent results. The question arises, however, if the same mechanisms of coordination and collaboration will still be adequate if the user community is greatly expanded, i.e., if the majority of users of current and future facilities will no longer have close connections with radio observatories.

Two changes could be envisaged that would help the general user. One follows the model of the ARCs, established in several European countries in support of the ALMA users. The other model is the ESO model, where users of the ESO facilities can obtain help at the ESO Headquarters. Such a centralized support does not exist for radio astronomy except for VLBI experiments, where JIVE is mandated to provide this help (also e-MERLIN to some extent).

Can JIVE serve as a nucleus, and its activities be greatly expanded to provide a single interface for the general user, not only for VLBI but also for any other radio-astronomical experiment? How could such a central structure be created, and what would then be the role of the existing institutes in such a structure? Or, is it more realistic to think of a network of ARC-type structures? Before attempting to answer these questions, we shall first turn to a related issue.

11.2.2 – Possible organizational structures for new large projects

Looking for examples of major European collaboration in large international radio-astronomical projects, the first that comes to mind is the ALMA project. This international astronomy facility is a partnership between Europe, North America and East Asia in cooperation with the Republic of Chile.

In the ALMA project, Europe is represented by ESO. The European share in the construction of ALMA, as well as the running costs, are handled by ESO. In addition to ESO, ALMA is funded in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC) and in East Asia by the National Institutes of Natural Sciences (NINS) of Japan in cooperation with the Academia Sinica (AS) in Taiwan.

The Joint ALMA Observatory itself is not a legal entity. It relies on its constituent bodies for providing services and signing contracts. This is sometimes regarded as a weakness. In fact, some aspects of the international ALMA agreement are presently under review to see if, for practical purposes, matters can be simplified.

ESO has involved, on the European side, a number of institutes for hardware and software developments, and it has created a network of ALMA Regional Centres (ARCs) to support the user community (see below). The ARC nodes are operated by 7 institutes, located in different European countries. These function on the basis of an MoU between ESO and these institutes, which outlines the respective roles. Each node relies on local/national funding.

The other project that can provide a model for an SKA organization in Europe, albeit at a much smaller scale, is the APEX project in which ESO is a partner together with the MPIfR and the Onsala Space Observatory. ESO is the managing partner in Chile and provides a single interface with respect to the Republic of Chile as a legal entity, but otherwise is an equal partner in APEX, representing the ESO user community. Both the organizational forms chosen for ALMA and for

APEX facilitate the building and preservation of the technical and scientific competence that has developed in Europe over decades in dedicated institutes. This has undoubtedly been crucial to the success of these projects. Any organizational form that is chosen for the SKA should build on, preserve, and eventually strengthen relevant European technical and scientific competence in a similar manner.

The successful history of ESA and ESO, and the recent adoption by ESO of the European share in ALMA, show the power of a full treaty organization in providing long-term stable support for large transnational projects in astronomy. The price one pays is, of course, that establishing such a treaty organization is a somewhat slow and cumbersome process. At the same time, the ways in which ESO is involved in ALMA and APEX, which is different from the way it built and operated its optical observatories, show that such an organization – once established – can be quite flexible and versatile in adapting itself to new challenges, and it can get involved in new projects in different ways.

At a lower level than a treaty organization, subsets of European countries and/or institutions have come together to build and operate the EVN and LOFAR. As we saw above, these two have quite different histories. LOFAR was first funded from a single country, the Netherlands, and designed and built by its national radio observatory, ASTRON. The international partners joined later, via an MoU and bilateral contracts between the International LOFAR Foundation and individual partners in each country, which are hosting and operating LOFAR stations, and the central facilities. Its formal structure is a foundation under Dutch law, as the International LOFAR Telescope (ILT), with a board constituted by the partner countries. The EVN grew more organically as a collaboration between long-established institutes, first on an ad-hoc basis, and since 1984 based on a MoU. To create and operate the necessary centralized facilities, JIVE was set up in 1993 as a foundation under Dutch law, funded by a subset of the EVN members. None of these models seems very suitable for creating a new, very large transnational project.

11.3 – Scenarios for the future

It appears that both for the on-going joint activities and for Europe's participation in the SKA project new organizational structures are needed to keep European radio astronomy at the forefront worldwide, with a strong mandate and long-term funding commitments from the partners. On the other hand, astronomy thrives by the active involvement of many individuals and institutions, and so these structures must co-exist productively with those individuals and institutions, and leave room for smaller-scale initiatives that are often the source of innovation and invention. We can identify a number of issues that need to be dealt with in creating such a transnational organization:

- The time factor: creating a transnational organization takes time. An MoU may be signed relatively quickly. More partners may join at any time. An international treaty organization is likely to take much longer if the approval by national parliaments is required.
- Talent and expertise are now in national and local institutes. They must be preserved.
- A balance of power and funding between local and transnational level needs to be established.
- There will have to be a transfer of resources and effort from local facilities to larger facilities at some level. Local institutes will become less owner-operators of their own facility and more stakeholders in a large facility.
- The cost of such an organization will have to be compared with the cost of more local organizational solutions.

These issues need to be addressed thoughtfully in any roadmap leading to the creation of stronger transnational structures for which we have identified the need. The strategy for European radio astronomy should therefore both have a long view of its new state, and carefully stage the steps towards it. The VLBA may serve as an example where the construction of a large centrally organised facility without paying enough attention to this has led to the loss of much local, university expertise.

The solutions one can think of range from the creation of an all inclusive European Radio Observatory (ERO) that receives the necessary investment and operations budget directly from the governments of the participating countries under a high-level agreement, to an MoU-based European Radio Astronomy Network (ERAN), similar to the EVN's structure. In the latter case, one would probably still have to appoint or create a legal entity that represents the network to the outside world.

The top-level, all inclusive solution would mean that all joint activities in European radio astronomy, the biggest one being Europe's participation in the SKA, would be centrally organized and funded. The observatories and institutes that participate in these joint activities would be made available "in kind", i.e. their running budgets and investment costs would remain a local/national responsibility. Technical developments that will benefit the joint activities could be stimulated by the Centre through central funds as has been done by ESO for the VLT, ALMA, and the E-ELT.

The lower-level, MoA or MoU-based solutions can be derived from existing structures such as JIVE, before it became an ERIC, and LOFAR. However, as outlined above, their current legal and financial basis is totally inadequate for a project of the scope of the SKA and the very long-term commitment that is needed.

11.3.1 – The European participation in the SKA

It is clear from the above that the SKA will need to take a very strong and stable transnational form. The SKA organisation itself has expressed the aim to establish itself as a treaty organisation under international law, and is seriously examining the steps towards this goal. In view of the considerations we outlined above, we can only applaud this. Assuming this path is pursued, the question remains, however, what Europe's position in that context should be. Should European countries with the ambition to be partners in the SKA project directly join this treaty organisation, or combine forces within Europe first, and join the global SKA project through a European consortium that is represented in the SKA project through one of its member organisations that assumes this role?

Judging from the examples of space science and optical astronomy, we see significant benefits to the latter model, in which Europe organises its participation in the global SKA through a European consortium. This model has successful precedents in ESA and ESO, so that many of the countries in Europe with an interest in astronomy, and their governmental bodies responsible for astronomy, are already familiar with it. Via this route, it seems more likely that relatively small countries would feel comfortable with joining the SKA as compared to a situation in which they are directly a partner, albeit only a very small one, in a global SKA. Added up, these smaller countries will bring significant resources, both material and intellectual, to the European SKA effort, and thus will strengthen the European contribution to the SKA.

If such a model is pursued, a natural question is whether a new transnational organisation should be created, or whether in fact ESO could be that organisation. We feel this is a complex question on the one hand, but on the other hand may provide still one of the most straightforward ways of organising the European participation in the SKA. ESO's statutes allow for the possibility of adopting other ground-based observatories into its programme, as the case of ALMA has demonstrated. ALMA and APEX have also demonstrated that ESO can collaborate with and organise new communities beyond its traditional optical-infrared domain, and do so in a manner that preserves and even enhances local expertise and institutions, in these cases for (sub-) millimetre-wave astronomy. There could also be substantial benefits in time and effort from the fact that one will then not have to create a new treaty organisation, and that this new organisation will have to build up experience in running a very large international project, with facilities that are far from Europe.

While we do agree with the SKA project that constituting the SKA organisation via an international treaty has major advantages over other forms, we also find that re-using the existing ESO structure to organise at least the European part of this organisation would save significant time and political effort, and re-use valuable experience in constructing a major international observatory.

There are of course also hurdles to be overcome in this route: ESO already has a full agenda of projects, and it cannot provide Europe's share of building and operating the SKA within its current budget envelope or its current expertise. The recent ESO Council decision to start building the E-ELT in a two-phase approach leads to expected first light in 2024 – 2026. If the building of SKA has to wait until close to this date, this would constitute a far too long delay for many of the international parties involved in the SKA. The process of setting the science requirements, designing, and costing the SKA is already well underway, and following a timeline that is set by the ambitions, abilities, and needs of its participants. For those institutes and countries that have set the SKA as a major priority for the coming decade, a drastic change of the schedule for the SKA could have serious consequences. Clearly, the effort of designing the SKA and building support for it has been going on for quite some time, and has built up momentum independent of ESO. All parties are aware that new money will be required to realise so powerful a global radio observatory as the SKA. It is therefore not necessary to seek the technical capacity and funding only within the present envelope of ESO, and to consider that envelope to be the major limiting factor for the building of the SKA. Careful discussions with the partners should decide what funding profile and timelines are achievable; this will no doubt involve being realistic about the availability of funding for large astronomical projects, but also an acute awareness of the need to preserve the momentum that has built up for the SKA.

We have also considered whether a European consortium could be formed at a lower level, with less effort than a treaty organisation. While it is difficult to exclude this, we feel that our analysis of the current structures in radio astronomy in Europe (Chapter 10) makes it very clear that none of the present structures are even close to adequate. It also seems unlikely that if the international SKA organisation were a treaty organisation, that it would accept as a partner on behalf of Europe an organisation that is itself less strongly established than a treaty organisation. Especially the difficulty of current European radio astronomy organisations (including, it seems, ERICs) to channel the required significant exchange of funds and the stability over multiple decades, precludes in our opinion a lower level organisation than an intergovernmental treaty for the involvement of Europe in the SKA.

Apart from building and operating the SKA for Europe, the treaty organisation would also naturally assume a significant role in setting the agenda and strategy for European radio astronomy by providing a focus for the leading science and instrument development. The projects that it organises would always be the largest and most cutting-edge that European radio astronomers could get involved in. This should naturally attract a large fraction of the European astronomical community with many scientists ready to help to shape the organisation's programme and to participate in its science and instrumentation development plans.

Creating a separate treaty organisation might have the benefit of providing a stronger focus, since only the SKA would be its concern. One would have to weigh that benefit against the extra cost in time and energy to create a new treaty organisation. Furthermore, there will inevitably at times be some competition for resources between radio and optical astronomy, because both have high ambitions and need large facilities. This will occur irrespective of whether the two are organised by the same organisation or not, but it may well be better to have this debate as an internal debate within one organisation that takes its guidance from the whole astronomical community than to have two treaty organisations vie for the support of the same governments in each European capital.

In summary, we conclude that on balance, Europe will make a stronger contribution to the SKA if it organises that contribution as a joint effort, via a treaty organisation that can provide the confidence and long-term stability needed to embark on such a large effort. We also conclude that ESO should be very seriously considered as that treaty organisation, to handle at least the European SKA involvement.

11.3.2 – Other transnational European activities

If one organises Europe’s participation in the SKA in a treaty organisation, would it then make sense to also let this organisation run the other transnational activities that have been mentioned above, like JIVE/EVN, LOFAR, CRAF, etc.? After all, for many of these we also concluded that they need a stronger organisational and financial basis.

Our general answer to this question is no. Organising and funding Europe’s participation in the SKA is a formidable enough task, and inheriting all the complexities and diversity of the already existing European collaborative efforts would make it more difficult, for example because the present radio facilities that contribute to them are owned by a large number of diverse partners, each with their own local or national sources of funding and mode of operation. It is not clear that these efforts require the full weight of a treaty organisation to safeguard their role at the cutting edge of astronomy. Also, for Europe to play a significant role in the SKA, strong national radio communities and technical institutes with organisational structures that work well locally are needed. The ESO optical/IR facilities and ALMA have greatly benefitted from this and continue to do so. One therefore does not want to centralise the activities too much.

The development towards the ERIC form of organisation may well prove to be an interesting one. The initial impression from JIVE’s transition into an ERIC structure are cautiously optimistic: the partner countries are committing themselves to a longer funding period of five years, as opposed to 2 – 3 years before, depending on the partner, and the commitment seems to be anchored at a higher level within the governments than before. It still remains difficult for some countries or organisations to join as full partners for local political reasons, and so one is still left with a mix of full partners and associates that commit via MoU’s or other bilateral forms of agreement. Nonetheless, the ERIC structure may prove very useful as a means to continue some of the existing European collaborations on a more stable basis.

Organisationally, JIVE and EVN are different bodies with separate boards, and so the other question that may remain is how the stability of JIVE-ERIC will influence the future stability of the EVN collaboration and *vice versa*. This, too, is an important matter, since much of the technical updating of the instrumentation as well as the priority setting of VLBI relative to other activities of the participating observatories goes via the EVN. Another important matter that should be noted here is that there continue to be initiatives to link up new nodes to the EVN, often existing dishes that could be refurbished for the purpose. This should be encouraged, and perhaps a concerted European view of such possible extensions of the EVN could be helpful in realising them.

Furthermore, global VLBI experiments are sometimes performed, either via the EVN or via other collaborations of EVN partners with observatories on other continents, such as the African VLBI Network (AVN). Thus far, some inflow of European money (such as the TNA money from RadioNet) has played a significant role in keeping the activities of the EVN going, and it is not clear at the moment that this source of income can be maintained. At the same time, there is broad political and scientific support for these collaborations, so it should be feasible to find support for them. An example is AERAP – the African-European Radio Astronomy Platform, which has received strong support from the European parliament. We express concern that the discontinuation of RadioNet funding, which at the very least will lead to a funding gap for European coordination of radio astronomy activities during 2016 – 17, might have a negative impact on important joint activities.

With a number of pan-European collaborations on-going, and at least one other explicitly called for, it makes sense to investigate whether some of the other activities we mentioned could be brought under the umbrella of one of these for better continuation and stability. For activities purely among radio astronomers, such as YERAC, transferring the responsibility for at least the organisation and continuity (rather than also the financial responsibility) to an organisation that already includes many of YERAC's traditional supporters, such as RadioNet or EVN, makes good sense. For an activity with more political implications and involving strong lobbying, the international treaty organisation that we propose to take care of SKA might make more sense, given that such an organisation has more natural access to the appropriate diplomatic channels. In particular CRAF, with its heavy burden of defending the interests of RFI-free frequency bands in a world with increasing commercial pressure to make other uses of those frequencies, might best be hosted by such a treaty organisation.

More generally, we note that there is little reason or desire to subsume all of European radio astronomy into one large organisation that is responsible for everything. There is no precedent in any other field of astronomy or other science for this, nor do we think it is healthy or beneficial to the field. How various transnational activities will be coordinated should be judged on a case-by-case basis, and our recommendation for an international treaty organisation is specific to the SKA.

Chapter 12: Conclusions and recommendations

12.1 – Introduction

The ERTRC has found European radio astronomy in a very healthy and vibrant state. It provides strong contributions to many of the Science Vision goals, and provides a unique and crucial contribution in a number of areas: probing HI at cosmological redshifts, strong gravity (e.g., pulsar timing), compact structures on the smallest angular scales (through VLBI), cosmic magnetism, and molecular astrophysics, as well as important contributions to many other areas.

Ambition in radio astronomy remains very high: exciting new science is being explored by upgrading existing facilities the premier existing facilities which continue to have significant scientific impact, and by building entirely new ones. The scale of these ambitions has led to increased European collaboration. Important examples are the EVN, JIVE, LOFAR, and the EPTA, each producing world-leading science, and organising bodies such as RadioNet. The need for collaboration keeps increasing as the ambitions of and opportunities for radio astronomy continue to grow. Key to the most ambitious Science Vision goals are the largest facilities, such as global VLBI and SKA. The latter requires an unprecedented level of global collaboration and effort.

Radio astronomy is also adapting to the impact of the transition from wavelength-centred expertise to object- or phenomenon-centred, multi-wavelength science focus. This creates a trend towards the use of radio observatories and radio data by astronomers who are not seasoned experts in the techniques of radio astronomy, implying a demand for user-oriented standardised data reduction software and data products. It also drives the attraction of new talent to radio astronomy and the involvement, as well as the training, of a wider group of users.

Mindful of the fact that this document serves both the expert scientists in the field and astronomers and agencies less involved in the daily business of radio astronomy, we give our recommendations twice. In Section 12.2, we give them in the briefest possible, “headline” form. In sect. 12.3, we give the full set of detailed recommendations. The brief versions reference the detailed recommendations they summarise, and these in turn contain references to the sections of the report with the background material on which they are based. Finally, in Section 12.4, we give a brief preview of what we foresee European radio astronomy might look like in 2025.

12.2 – Summary recommendations

The numbers listed at the end of each summary recommendation indicate the detailed recommendations on which they are based.

1. Radio astronomy, with existing and upcoming facilities, including the SKA, will make unique and essential contributions to our knowledge of the Universe in key areas described in the ASTRONET Science Vision (1 – 3).

2. Continued and coordinated efforts in technical development and in attraction, training, and career management of talent are required to keep radio astronomy vital and relevant (5-8, 15).

3. Protecting radio frequencies for scientific use continues to be essential (4).

4. Key capabilities and excellent science are delivered by old and new pan-European collaboration and coordination of facilities (9 – 11).

5. Key science is delivered by coordination of radio observations with observations at other wavelengths; such coordination should therefore be facilitated (12).

6. Wide and easy access to radio astronomical observatories and data significantly increases the amount of excellent science delivered. This should be promoted through “open skies” policies (i.e., merit-based access to telescopes by all astronomers) and the use of archives and standardized data reduction techniques (13, 14).

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). (16, 18)

8. We recommend that the European involvement in the SKA be organised through a treaty organisation that is robustly mandated and funded, to ensure the strongest impact of and participation in SKA by Europe. The ERTRC considers ESO to be a prime candidate to be that organisation. (17).

12.3 – Detailed conclusions and recommendations

.

1. Both new and existing radio observatories are vital to achieving key Science Vision goals. Radio astronomy provides a unique probe of HI at cosmological redshifts, strong gravity (e.g. pulsar timing), compact structures on the smallest angular scales (through VLBI), cosmic magnetism, and molecular astrophysics. (Ch.4)

2. The SKA will constitute a major leap forward in radio astronomy’s capabilities and scientific breadth; it will be key to delivering the most ambitious Science Vision goals in areas such as probing strong gravity and exploring HI throughout cosmic history. Scientifically and technically, Europe is in a strong position to play a leading role in this future project. (Ch.4)

3. Existing radio observatories will continue to deliver key contributions to Science Vision goals well into the SKA era, because they provide capabilities complementary to SKA, such as multi-wavelength coverage of Northern Hemisphere objects and observing at long baselines and high frequencies not provided by the SKA (including follow-up of objects and phenomena discovered with SKA). (Ch.4)

4. Protection of key radio frequency bands is becoming ever more essential. Steps should be taken to ensure that key radio frequencies corresponding to important spectral lines are sufficiently protected – both in Europe and worldwide. (Ch.4,10,11)

5. Key features that are required for front-line radio astronomy instrumentation include multi-frequency capability, frequency flexibility, large bandwidth/high sensitivity, polarization sensitivity and good polarization purity, timing accuracy, wide-field capability and good spectroscopic capability. Broad bandwidth can simultaneously provide high sensitivity and some multi-frequency observing capability. (Ch.5)

6. As the scale and complexity of international radio astronomy projects increases, so does the demand for careful system engineering of hardware and software systems. Careful

system design is critical to taking advantage of the full flexibility that a radio telescope can offer. (Ch.6,9)

7. Training is needed at multiple levels:
    a. To train the next generation of 'black belt' radio astronomers who can develop and optimise new observing facilities and their data analysis tools. This is particularly important in view of the need to convey strong scientific and technical skills and experience with large projects to a new generation of astronomers, to help guide the development of the SKA. (Ch.9)
    b. To train the wider astronomy community in the use of standardised radio data products, ensuring radio data are well utilised by multi-wavelength astronomers and thus useful to a wide community. (Ch.9)
    c. Retention of talent is as important as training, and this requires proper career management of all types of talent, whether more academically or more technically oriented. (Ch.9)

8. Excellence in training in science, engineering and computing is crucial to keeping European radio astronomy a key player worldwide, both currently and into the SKA era. For this reason, only facilities that are capable of being used for publishable research or cutting-edge technological development should be used as educational facilities in MSc and PhD education. (Ch.9)

9. The EVN/JIVE delivers a wide range of excellent science. (Ch.4)
    a. There is great potential for increasing EVN science, by expanding its availability much beyond the current 6-9 weeks per year, and expanding its user base.
    b. A modest-sensitivity sub-array of EVN telescopes of medium size that would be able to observe a much higher fraction of the time is a desirable option, if some large dishes cannot be made available more often. This sub-array would be invaluable for monitoring of variable objects, rapid-response observations, and multi-wavelength campaigns. An individual, relatively small single dish could make a strong contribution as part of such a medium-sensitivity, high-time-coverage VLBI array.
    c. Extension of the EVN to all continents, by collaboration with existing or emerging arrays on those continents, will provide a valuable platform for global collaboration in radio astronomy.

10. The International LOFAR Telescope (ILT) is a pioneering instrument in a number of respects that are relevant to future developments in European radio astronomy. (Ch.4)
    a. It will deliver key Science Vision goals, such as the detection of signs of the Epoch of Reionization, probing of extreme gravity and extreme astrophysical sources, studies of the origin of cosmic rays, deep surveys of the distant Universe, cosmic magnetism, and solar astrophysics.
    b. Its innovative design and the greater role that computing and software play in it make it the premier pathfinder for the SKA-Low. The software effort is thus very large, and its management and planning a correspondingly great challenge.
    c. Its organisation and funding have explored novel ways of collaboration within Europe, which are instructive for future planning.

11. The science case for single dishes is very strong, and it is further amplified by their use in larger arrays and collaborations, such as EVN and EPTA. (Ch.4)
    a. Single dishes play important roles in specific, well-targeted areas such as surveying, monitoring and transient searches, provided that they are outfitted

    with modern equipment and exhibit a coherent and coordinated approach to their observing programmes.
    b. New telescopes should be constructed such that they can "hook into" larger networks of telescopes, so that they are not constrained to single-dish observing alone.

12. Coordinated observations with facilities at other wavelengths are key and should be supported. Such observations can be logistically difficult, however. Therefore, increased synergy between observations at different wavelengths could be facilitated by increased flexibility of scheduling, making some fraction of time explicitly available for such observations through joint, multi-telescope proposals, etc. (Ch.8)

13. There is a strong and valuable tradition of radio astronomy facilities having an "open skies" policy. (Ch.4,6,10)
    a. We strongly recommend that radio observatories be required and adequately funded to provide open skies access based on a peer-reviewed proposal process.
    b. We recommend that this also include some mechanism to provide practical support for observers, to ensure that they are able to reduce and analyse their data in an efficient way. The existing TNA mechanism provides an excellent starting point for such support, and should be further developed. This support could be provided either through training or the use of sufficiently user-friendly data-analysis software.
    c. Furthermore, although we acknowledge the need for various partners to obtain a return on their investment, we feel it is important that future facilities, including the SKA, continue to make some significant fraction of their observing time available through a peer-reviewed open-access policy.

14. Radio astronomy needs to move to a model where its data products are more easily accessible and useable by the wider astronomy community. (Ch.4,9,10)
    a. A number of European radio astronomy facilities routinely archive their data and make them freely available after an initial proprietary period. We recommend that individual observatories likewise make their own data accessible through public archives after an appropriate proprietary period.
    b. This should be implemented using standardized formats and software, and should ideally be centrally coordinated. It would also be worthwhile to explore the possibility of making more radio data available through multi-wavelength databases, such as CDS or IVOA.
    c. It is also desirable for the individual observatories to provide pipeline processing of their data, to maximize the ease with which particularly non-specialists can use these data.
    d. Investments in these post-processing systems, user-oriented software pipelines and easily reachable online public archives will be necessary.

15. A vibrant programme of technical development (in hardware and software) is required to keep European radio astronomy at the forefront, and to ensure a strong role for Europe in the new global radio astronomy into the SKA era. (Ch.5,11)
    a. Given the cost, such programmes need to be well coordinated across Europe; RadioNet is already providing important coordination of this type. Some already available technologies could be used to provide European radio telescopes with more uniform sets of equipment, providing more uniformly excellent capability and data quality. Newly developing technologies, such as focal plane arrays, flexible aperture arrays, and multi-beam capabilities will also play important roles.

    b. Coordinated efforts between institutes and technical universities with specialized expertise, on the one hand, and observing facilities, on the other hand, would be a great aid in developing and installing state-of-the-art equipment in an efficient and centrally coordinated way; for example, a particular technical group might develop a receiver that could then be installed in many telescopes across Europe.
    c. Both large and small facilities can contribute substantially to key technical and software developments. Some technical developments will require specialized institutions with a critical mass of technical expertise, but smaller groups in a variety of institutions can also make appreciable contributions, particularly in the early phases of development.

16. We are concerned that current arrangements for European collaboration in radio astronomy are not robust and secure enough to safeguard such collaboration towards the future, especially given that this collaboration will need to become more intense. (Ch.10)
    a. The EVN and JIVE need to be put on a more secure and stable financial footing. This requires that financial commitments be secured on a multi-year basis, minimizing year-to-year uncertainty in the EVN and JIVE budgets, and that the bodies funding the individual observatories of the EVN support the participation of those observatories, either individually or through joint action.
    b. The continuity of activities such as RadioNet, YERAC, and CRAF, needs to be guaranteed.

17. We recommend that the European involvement in the SKA be organised through a treaty organisation that is robustly mandated and funded, to ensure the strongest impact of and participation in SKA by Europe, and ESO be considered the prime candidate to be that organisation. (Ch.11)

18. The increasing internationalisation of radio astronomy and the involvement of Europe in SKA create crucial opportunities for radio astronomy; optimally exploiting these opportunities however comes with very significant challenges in technical expertise, manpower, and funding. (Ch.10,11)
    a. The internationalisation will require a very significant transformation of focus, from institutes predominantly running their own observatories to the radio-astronomy community as a whole working together and investing the bulk of its effort into running a small number of large, international facilities.
    b. This transition must be managed carefully, making use of experience in fields where this has successfully been undertaken, such as particle physics and space astronomy.
    c. The expertise in existing radio observatories and institutes is crucial to exploiting these opportunities. Existing facilities can help create a technical bridge towards the SKA.
    d. The increasing focus on jointly operated facilities also has other ramifications, such as the need to agree on data formats, conventions, software packages, etc.

12.4 European radio astronomy in 2025

In order to make the results of our analysis and the effects of our conclusions more tangible, let us sketch where we hope and expect to find radio astronomy in Europe a decade from now.

12.4.1 A vibrant science

In 2025, in the Northern hemisphere, e-EVN/JIVE and LOFAR will have become mature instruments at the peak of their performance. Their calibrations understood, and novel algorithms and computer hardware having risen to the grand data challenge of modern radio astronomy, these instruments will routinely produce excellent images, with high resolution over wide fields of view. Surveys of unprecedented depth will be conducted, and time domain astronomy will come to full fruition also in radio. Standard data pipelines and well-archived results therefrom will make radio astronomy an accessible and useable technique for the majority of astronomers, while black-belt experts continue to push the radio telescopes to their limits, and new instruments and new techniques into new territory. Detailed follow-up observations of specific objects with large dish telescopes will produce a wealth of additional data pertaining to, e.g., strong gravity.

In the southern hemisphere, the SKA pathfinder projects have successfully been completed, with strong European involvement, and Phase 1 of the SKA is starting operations, with a strong contribution from Europe, with an extensive commissioning and shared-risk initial science programme. No doubt its calibration and data analysis challenges will be so profound that it, too, will achieve all its new results gradually over a significant time period.

The vastly increased resolution, sensitivity, and spatial and temporal coverage will define a frontier of radio astronomy far enough from the present one that we cannot possible think of all that we will find at those new limits, though of some things we can be reasonably confident. Newfound pulsars and even better timed old ones will allow us to probe the fundamental nature of space-time and gravity and the extreme states of matter and magnetic fields to new limits. They may allow us to tell the presence of gravity waves over a vast range of frequencies, and elucidate the populations of objects that produce them. We will be staring down to the horizons of massive black holes at the foundations of gravity itself, and probe the highly energetic flows into and out of the cores of galaxies better than ever, constraining their influence on the growth of their host galaxies and the clusters around them. Radio telescopes will probe the bulk gaseous content of the Universe out to very high redshift, and help determine when and how the first stars and galaxies came to be, and how the complex interaction between gas and stars in galaxies gives rise to the evolution of the elemental content of the Universe. Closer to home, the highest resolution observations and detailed polarization studies will help clarify how the interstellar medium is energized, and how its complex mix of gas, magnetic fields, and radiation gives rise to molecular clouds and they, in turn, spawn stars and the planets around them, and the building blocks of life itself. Radio astronomy will be at the frontier of astrophysics, in some cases in the lead, in others as a strong partner in the multi-wavelength, multi-messenger mix that many astrophysical problems demand.

12.4.2 A vibrant radio community

Our radio community is much bigger, and has become even more international. The European SKA Observatory has issued its first calls of proposals, and a large number of astronomers, including those not mainly working in the radio domain, have responded. These astronomers receive significant help from their nearby radio astronomy institutes in the preparation of proposals and the understanding of the data products they receive as a result of successful applications. Their training in radio astronomy has come from working in the many collaborations between universities and radio observatories working on the SKA pathfinders.

The radio observatories themselves have considerably altered their mission. Their technical development and support activities are now more focused on European and global facilities, to which they contribute instrumentation and support via competitive bidding on calls issued by the organizing bodies of those facilities. This has brought instrument development to the required higher level; local telescopes have become more the vehicles for development of novel instrumentation and software, destined to support the next generation of radio telescopes such as SKA-2. This change of emphasis will have affected the staffing of these observatories, both in terms of staff profiles and numbers.(numbers going up/down?)

Meanwhile, the science at higher radio frequencies and very long baselines, not well represented in SKA-1, has also received new impulses. The stronger organization of JIVE that started a decade ago, has also inspired a gradually closer and more common-purpose organization of the EVN members. *As the advent of SKA-1 has decreased the demand for single-dish, standalone use of the member telescopes,* the focus has shifted to joint observing modes, such as e-VLBI and high-precision pulsar astronomy. This shift has brought more resources to common receiver development and better common infrastructure, making all telescopes more agile. Gradually, *a joint European Long Baseline Observatory* (ELBO) appears to be emerging from the Europe-wide interest in this high-priority science, due to gradual evolution to closer collaboration of the existing observatories. In Africa, a substantial similar effort has been established, and is maturing fast. Not infrequently, ELBO pools its resources with the African VLBI network and its more traditional global VLBI, and even sometimes the SKA itself, into a global VLBI network of unprecedented sensitivity.

By the time the scientific operations of the SKA-1 are starting, the necessary staff will have been recruited. Most of it will have come from the existing observatories, in some cases as "in kind" contributions, and on a time-limited basis. Such staff members would later return to their home institutes, and make their in-depth knowledge of the instrument available to the European SKA users.

The novel and greatly improved facilities have attracted a wave of young talent into radio astronomy, and training programmes have had to intensify and increase their capacity significantly to absorb this influx. Somewhat behind the scenes, another revolution has taken place to enable this community growth: the data storage and processing infrastructure of radio astronomy have undergone a true transformation. Both algorithmic innovation and hardware breakthroughs have made automated processing of the vast data volumes possible. At the same time, transparency and user-friendliness of the data analysis is now regarded as a sine qua non, as is the accessible archiving of processed data for later re-use. More papers are now written based on pipeline-reduced data and re-use of archival observations than from first-time analysis by dedicated radio astronomers.

The connections between radio astronomy and society have also greatly intensified. Its increased pace of discovery and accessibility has led to more public exposure of the results of radio astronomy and concomitant greater public appreciation. The new radio telescopes and their software have also gained notoriety as great feats of engineering and drivers of technical innovation. The connections between radio astronomy, engineering, and industry were always close, but they have intensified further as the new observatories require not only the highest achievements in technological finesse, but also the practical skills of making novel inventions fit for cheap mass production. These areas of skill require their own forms of specialized training and common understanding between curiosity-driven science and practical applications of technical sciences. Novel educational collaborations between classic universities, technical universities, and industry have risen to this challenge, and have increased the number of people with a background to work at the interface of astronomy, computer science, and engineering from an irregular trickle to a small but steady stream.

Appendix A - ERTRC Terms of Reference

The European Radio Telescope Review Committee (ERTRC) is appointed by the ASTRONET Board in coordination with RadioNet. Its remit is to deliver to ASTRONET, in concert with RadioNet, a strategy to optimize the use of radio telescopes by the European astronomical community, both in the short as well as and medium to longterm. Special attention should be paid to develop this strategy in close interaction with the telescope owners and with extensive feedback from the community at large. The ERTRC should take into account that a review of European (sub)mm facilities will be conducted later.

To fulfil its remit, ERTRC will in particular:

1. Identify those goals of the ASTRONET Science Vision that are most effectively delivered by the current and future European radio facilities;

2. Identify which observational capabilities (e.g., site, operational frequencies & operation modes) are required;

3. Establish an appropriate balance between the scientific, technological and educational goals of the facilities, taking into account contributions from both larger and smaller facilities;

4. Among the scientific tasks, consider the appropriate balance between single-dishes and VLBI science as well as between major programmes in support of large European facilities at other wavelengths and free access by individual researchers;

5. Develop a realistic roadmap, including any necessary technical developments and upgrades, and organisational/financial arrangements, which would enable a set of European radio facilities to deliver the best scientific output for European astronomy in the most cost-effective manner;

6. Analyse major needs and opportunities for collaboration on the global stage;

7. Propose arrangements for open access to all data, e.g., through the Virtual Observatory.

Appendix B - ERTRC Membership

The membership of the ERTRC was established by the ASTRONET Board as follows:

Aalto, Susanne	S	
Alberdi, Antxon	ES	
Corbel, Stéphane	F	
Dettmar, Ralf-Jürgen	D	
Fender, Rob	UK	
Gabuzda, Denise	EI	
Grewing, Michael	D	(co-chair)
Hessels, Jason	NL	
Scaramella, Roberto	I	
Wijers, Ralph	NL	(chair)
Zdziarski, Andrzej	PL	

The executive secretary to the committee was initially Frank Molster (NWO), who was later succeeded by Saskia Matheussen (NWO). The work of the committee took longer than expected, and over the course of the work Aalto, Gabuzda, and Zdziarski could no longer participate in the committee's work due to personal circumstances and conflicts with other duties.

Appendix C - ERTRC Questionnaire and Detailed Grades Table

The European Radio Telescope Review Committee (ERTRC) is appointed by the ASTRONET Board in coordination with RadioNet. Its remit is to deliver to ASTRONET and in concert with RadioNet, a strategy to optimize the use of radio telescopes by the European astronomical community, both in the short as well as in the medium to long term. Special attention should be paid to develop this strategy in close interaction with the telescope owners and with extensive feedback from the community at large. The ERTRC should take into account that a review of European (sub)mm facilities will be conducted later.

1. General information about the facility

Name of the facility:
Location of the facility:
Director of the facility:
  Name:
  Email:
  Phone:
Name of the institute responsible for the operation of the facility:
Location of the institute responsible for the operation of the facility:
Website of the facility:

Please add a photo of the facility

2. Technical characteristics of the facility

- Number of telescopes
- Diameter
- Surface accuracy
- Pointing accuracy
- Date of construction
- Date(s) of major upgrades
- Frequency range(s) covered by existing receivers
- Available observing modes and backend capabilities, (do also include here polarization availability, frequency agility and slewing speed of the telescopes).
- Indicate which capabilities can be considered unique in Europe

- Give some typical sensitivities realistically obtained with the observing system in a few representatives modes/settings
- What is the RFI environment like and what are the major RFI related challenges

3. Statistical information

- Actual observing time per year
- Maintenance/repair time per year
- Downtime due to weather conditions per year

4. Scientific Usage

- Who are the users? Can you indicate the fraction of users that is coming from:
  a. Within the facility/operating institute
  b. From other institutes and/or universities within the country
  c. Within Europe
  d. Rest of the world
- What is the oversubscription factor?
- What is the time allocation mechanism?
- What is the share between continuum and spectroscopic observations?
- What is the most requested instrument?
- What is the typical number of projects executed per year?
- And what is the fraction of time allocated a priori for large (key) programs (if applicable).
- What are the main scientific topics addressed by these projects?
- What is the number of resulting publications per year?
- Can you include here the references to 5 recent (characteristic) papers produced with data from this facility?
- Are the data from this facility being archived? Please specify the type of data (raw/calibrated etc.) and how these can be accessed, and what is the policy for making data public?
- Are there any commitments with international networks and/or other astronomical observatories (ground and space). What fraction of the time is used for that?
- What is the number of resulting publications per year?
- How many PhD theses are being or were done in the last 5 years working on telescope/instrument/data reduction?

5. **Which of the key questions identified in the Science Vision document are being addressed or could be addressed by the facility? Briefly explain for each how your facility addresses the question, and whether you expect that contribution to be a leading/dominant one on that question or an auxiliary/supporting one.**

   A1 … A7
   B1 … B7
   C1 … C6
   D1 … D7

6. **Technical development plans (please, indicate schedule and funding situation - already committed, high/low chance – whenever possible).**
   -
   - Are major maintenance and/or upgrade activities foreseen for the facility?
   - Are upgrades and/or new (array-) receivers foreseen?
   - Are new backends planned?
   - Are software changes/upgrades planned?

7. **Does/will the facility play a role during the preparation of the SKA or precursor pathfinder projects?**

   - In the scientific preparation?
   - In the technical preparation (e.g. to test certain components)?
   - In the preparation and testing of SKA relevant software?

8. **Human Resources (please indicate everywhere how many permanent staff and how many are on temporary contracts/money)**
   - How many people are involved in the daily operation of the facility?
   - How many people are involved in data reduction/analysis/archiving?
   - How many people are involved in technical development work for the facility?
   - How many people are involved in software development work related to the facility (on-line and off-line software)?
   - Manpower needed per year for maintenance and repair?

9. **Financial Resources**

   - Costs for manpower per year?
   - Costs of consumables per year?

- Investment budget per year?
- Who is funding the running costs?
- Who is funding the investment costs?

10. Preparedness for the Future

- Which are the science questions that will drive the future of the facility?
- Which special know-how of the staff and which unique capabilities of the facility will in your opinion play a key role in the future?
- Who will decide on the above questions (e.g. internal, advisory bodies, external bodies …)
- Are there any evaluation processes foreseen in the next year in the national/European frame?

11. Are there any issues about your facility or comments on the ERTRC and its evaluation process that have not been addressed above that you would like to convey to us?

12. This questionnaire has been sent to the names that we have, but if we have additional questions who can we best contact for:

•

Technical questions:
Name:
Position:
Email:
Phone

Scientific questions:
Name:
Position:
Email:
Phone

Managerial questions:
Name:
Position:
Email:
Phone

SCIENCE VISION KEY SCIENCE GOALS	**EVN**	**LOFAR**	**eMERLIN**	**Effelsberg**	**WSRT**	**Lovell**	**Sardinia RT ***	**Medicina**	**Noto**	**Torun**	**Nancay RT**	**Metsa**	**Yebes ***	**Onsala**
GRADES: C: Coverage; U: Unique;D: Decisive	C+U+D													
A.- THE EXTREMES OF THE UNIVERSE														
A.1 How did the Universe begin?	2+1+1	1+1+1	1+1+1	2+1+1	1+1+1	1+1+1	1+1+1	1+0+1	1+0+1	1+1+1				
A.2 A consistent picture of Dark matter and dark energy	1+1+1	1+1+1	2+1+1	1+1+1	1+1+1	1+1+1					1+0+1			
A.3 Strong Gravity in action	2+3+3	3+3+1	3+1+1	2+1+3	1+1+1	2+1+1	2+1+1				2+1+3		1+1+1	1+1+1
A.4 How do Supernovae and Gamma-Ray Bursts work?	2+1+1	1+1+1	2+1+1	2+1+1	2+1+1	1+1+1	1+1+1	1+0+`1	1+0+1		1+0+1			
A.5 Black Holes: Accretion, Jets and Outflows	3+1+3	3+1+1	3+1+1	3+1+1	2+1+1	1+1+1	1+1+1	2+1+1	2+1+1		1+0+1	1+1+1	1+1+1	1+0+1
A.6 What do we learn from Energetic radiation and Particles? Understand the origin and acceleration mechanisms of CRs	2+1+1	2+3+1	1+1+1	2+1+1	1+1+1	1+0+1		1+0+1	1+0+1		1+0+1			

A.+ Pulsar Astrophysics European Pulsar Timing Array (EPTA) (A1+A2+A3+A4+A5+C3)	2+1+1	2+1+1	2+1+1	3+3+3	3+3+3	3+3+3	2+1+1				3+3+3			

Table 3A: Detailed observatory grades with respect to the ASTRONET Science Vision. C (Coverage: 3-2-1; complete-significant-minor); U (Unique: 3-1-0; unique-one of few-one of many); D (Decisive: 3-1-0; very-fairly-not very). See Ch.4 for details.
*Grades based on first results and telescope specifications

SCIENCE VISION KEY SCIENCE GOALS	**EVN**	**LOFAR**	**eMERLIN**	**Effelsberg**	**WSRT**	**Lovell**	**Sardinia RT ***	**Medicina**	**Noto**	**Torun**	**Nancay RT**	**Metsa**	**Yebes ***	**Onsala**
GRADES: C: Coverage; U: Unique;D: Decisive	C+U+D													
B.- FORMATION AND EVOLUTION OF GALAXIES														
B.1 How did the Universe emerge from its Dark Ages?	2+1+1	3+3+3	2+1+1	1+1+1	1+0+1									
B.2 How did the structure of the cosmic web evolve?	2+1+1	2+1+1	2+1+1	1+1+1	1+1+1		1+0+1	1+0+1	1+0+1	2+1+1	1+1+1		1+0+1	
B.3 Where are most of the metals throughout cosmic time?		1+0+1			1+0+1									
B.4 How were galaxies assembled? Measure the build-up of gas, dust, stars, masses of galaxies and the evolution of the Hubble sequence with time	3+3+1	2+3+3	3+1+1	3+3+1	3+1+1		1+1+1	2+1+1	2+1+1		1+1+1		1+1+1	1+1+1
B.5 Formation of the Milky Way	2+3+1	2+1+1	2+1+1	2+3+1	2+3+1									

Table 3B: Detailed observatory grades with respect to the ASTRONET Science Vision. C (Coverage: 3-2-1; complete-significant-minor); U (Unique: 3-1-0; unique-one of few-one of many); D (Decisive: 3-1-0; very-fairly-not very). See Ch.4 for details.

*Grades based on first results and telescope specifications

SCIENCE VISION KEY SCIENCE GOALS	**EVN**	**LOFAR**	**eMERLIN**	**Effelsberg**	**WSRT**	**Lovell**	**Sardinia RT ***	**Medicina**	**Noto**	**Torun**	**Nancay RT**	**Metsa**	**Yebes ***	**Onsala**
GRADES: C: Coverage; U: Unique;D: Decisive	C+U+D													
C.- ORIGIN AND EVOLUTION OF STARS AND PLANETS														
C.1 How do stars form? Determine the initial conditions of Star Formation	2+3+1		2+3+1	2+3+1	2+1+1		1+1+1	1+1+1	1+1+1	1+1+1	1+3+1		1+1+1	1+1+1
C.2 Do we understand stellar structure and evolution?	2+1+1		2+1+1	1+1+1	1+1+1	1+1+1	1+1+1	1+1+1	1+1+1		1+1+1		1+1+1+	1+1+1
C.3 What is the life-cycle of the ISM and stars?	2+3+1	2+1+1	2+3+1	2+3+1	2+1+1	1+1+1	2+1+1	2+1+1	2+1+1		1+1+1		1+1+1	1+1+1
C.4 How do planetary systems form and evolve?	1+3+1		3+3+1								1+1+1			
C.5 What is the diversity of planetary systems in the Galaxy?	1+3+1		1+1+1			1+0+1								
C.6 Determine the frequency of Earth-like planets and push towards direct imaging		1+1+1												

Table 3C: Detailed observatory grades with respect to the ASTRONET Science Vision. C (Coverage: 3-2-1; complete-significant-minor); U (Unique: 3-1-0; unique-one of few-one of many); D (Decisive: 3-1-0; very-fairly-not very). See Ch.4 for details.
*Grades based on first results and telescope specifications

SCIENCE VISION KEY SCIENCE GOALS	**EVN**	**LOFAR**	**eMERLIN**	**Effelsberg**	**WSRT**	**Lovell**	**Sardinia RT ***	**Medicina**	**Noto**	**Torun**	**Nancay RT**	**Metsa**	**Yebes ***	**Onsala**
GRADES: C: Coverage; U: Unique;D: Decisive	C+U+D													
D.- HOW DO WE FIT IN?														
D.1 What can the Solar System teach us about astrophysical processes?		1+1+1		1+1+1				1+1+1+	1+1+1		2+1+1 **			
D.2 Develop a unified picture of the Sun and the Heliosphere	1+1+1	2+1+1	1+1+1	1+0+1							2+1+1 **	1+1+1		
D.3 What drives solar variability on all scales and transient activity?		2+1+3		1+1+1							1+1+1 **			
D.4 Understand the role of turbulence and magnetic fields in the evolution of the primordial nebula														
D.5 Determine the dynamical history of TNOs and the composition of comets		1+1+1		1+1+1			1+1+1	1+1+1	1+1+1		3+1+1			
D.6 Constrain the models of internal structure of planets	1+1+0		1+1+0	1+1+1				1+1+1	1+1+1				1+1+1	1+1+1
D.7 Where should we look for life in the Solar System? Understand Titan's atmosphere, search liquid water on Mars and below the surface of Europe														

Table 3D: Detailed observatory grades with respect to the ASTRONET Science Vision. C (Coverage: 3-2-1; complete-significant-minor); U (Unique: 3-1-0; unique-one of few-one of many); D (Decisive: 3-1-0; very-fairly-not very). See Ch.4 for details.
*Grades based on first results and telescope specifications
**Contribution of the Nancay Radio Heliograph

Appendix D - Cost of European radio astronomy

The current funding situation of radio astronomy in Europe is rather difficult to assess in a quantitative manner for several reasons:

- The legal status of the existing institutions ranges from that of national facilities to that of university departments;
- The nature of the funding sources differs accordingly, i.e. it can occur at national level through a national funding organisation (e.g. CNRS, STFC), or at local level through an individual university budget;
- Especially, when it comes to investment, additional funding sources may play an important role, like e.g. foundations (e.g. Volkswagen Foundation);
- In addition to the regular budgets, soft money often plays a very important role. Depending on the institution, it can account for 25% (or more) of the total annual budget. This includes e.g. money provided through EC and ERC grants. As with any soft money, the level of funding generally varies with time;
- The way costs are accounted for, varies enormously from institution to institution. A full cost accounting is rather the exception than the rule. The key cost elements like personnel, operations and investment costs (and overheads) are not always defined in the same way.
- There is a growing user community of radio astronomical data that is based outside the existing radio astronomical institutes. The related personnel costs remain completely unaccounted for at present.

In order to obtain at least a rough estimate of the current financial situation in European radio astronomy, we have tried to assess the annual costs for the operation of the observing facilities that have been considered in this report. They comprise personnel, running and regular re-investment costs, but not the costs for major facility upgrades. The numbers are given in **Table 4**. They are based on input from the facility operations, and from RadioNet. The latter includes the subset of facilities that participate in the EU supported TNA program.

Table 4 shows that the facilities that participate in the TNA program account for an annual cost of about 17 M€ without any (re-)investment. Adding the personnel and running cost, and the costs for small (re-) investment for all facilities together, we come to a total amount that is about 40 M€.
Still, this does not represent the full picture. The major institutions comprise total staff numbers that are much bigger than the staff necessary for running the facilities considered above. This staff is made up of scientists, engineers, technicians, postdocs etc., and the related budgets can exceed those of the facilities by a large factor. Two examples are MPIfR, which is listed in the table for the cost of Effelsberg as 2.2 M€/year, but of which the total annual budget is about 20 M€; and ASTRON, which is listed in the table for the cost of WSRT and LOFAR as 5.4 M€/year, whereas its total annual budget is 18 M€.

Annual Operations Costs of Major European Radio Telescopes (MEUROS)

Country	Facility / Inst.	Personnel	Running	Invest.	Funding Agency
joint	EVN-JIVE	4.500	0.500	1.500	Joint effort
	LOFAR/joint	2.655	1.257	0.475	NL, D, S, UK,…
	LOFAR/ASTRON	0.354	0.762		ASTRON
	LOFAR/partners				
Finland	Metsahovi	1.800	0.270	0.075	Aalto University
France	Nancay	0.414	0.026	0.070	CNRS
Germany	Effelsberg	1.700	0.650	0.200	MPG
Italy	Medicina	1.100	0.600	0.300	INAF
	Noto	0.600	0.500	0.350	INAF
	Sardinia	1.500	1.000	1.000	INAF + Italian Space Agency

Latvia	Irbene (16m)	0.400	0.089	0.400	European structural funds
	Ventils (32m)	0.643	0.225	1.499	
Netherlands	Westerbork	0.750	0.450	0.100	/without APERTIF) NWO
Norway	Ny Alesund	0.398	0.133	0.133	Norwegian Mapping Authority
Poland	Torun	0.198	0.170	0.024	Nicolaus Copernicus University
Spain	Yebes	1.100	0.500	0.700	IGN
Sweden	Onsala	3.050	2.920	0.980	Swedish research council, Chalmers
Switzerland	Bleien	0.017	0.005	0.015	ETH Zurich
U.K.	AMI	0.211	0.114	0	STFC
	eMerlin	2.169	1.084	1.446	STFC + U. Manch.
	Lovell/Jodrell	0.843	0.361	special	U. Manch., STFC
Ukraine	UTR-2	0.200	0.100	0.005	Nat. Acad. Sciences Ukraine (NASU)
	RT-70	0.150	0.100	0.250	State Space Agency of Ukraine (NASU)
TOTAL		**24.752**	**11.817**	**9.521**	

Appendix E – list of acronyms

Acronym/name with web link	**Expansion of acronym and/or brief explanation**
AARTFAAC	*Amsterdam-ASTRON Radio Transients Facility And Analysis Centre:* All-sky experiment with the LOFAR core stations to detect bright radio transients
ACT	*Atacama Cosmology Telescope*: Cosmic microwave background experiment at the ALMA site
AERAP	*African-European Radio Astronomy Platform*:
AETHER	*Advanced European Terahertz HEterodyne Receivers:* RadioNet3 Joint Research Activity for receiver development
AGB	*Asymptotic Giant Branch*: A late stage in the evolution of certain stars
AGILE	*Astro-rivelatore Gamma a Immagini LEggero:* Italian gamma-ray imaging satellite, launched in 2007
AGN	*Active Galactic Nucleus*: A black hole at the centre of a galaxy that shines brightly due to matter falling into it
AIPS	*Astronomical Image Processing System:* A radio interferometer imaging software package
ALBUS	*Advanced Long Baseline User Software:* RadioNet3 Joint Research Activity on VLBI software development
ALFALFA	*The Arecibo Legacy Fast ALFA (ALFALFA) survey: Second generation blind extragalactic HI survey*
ALMA	*Atacama Large Millimetre Array*: World's largest observatory at millimetre wavelengths, collaboration between Europe, US, and East Asia
AMI	*Arcminute Microkelvin Imager*: radio interferometer in Cambridge (UK)
AMSTAR	*Advanced Millimitre and Submillimetre Technology for astronomical Research:* RadioNet3 Joint Research Activity for millimetre-wave receiver development
APERTIF	*APERture Tiles In Focus*: Phased-array antenna feed upgrade to the WSRT, being built in 2014-5, with first science planned in 2016
APEX	*Atacama Pathfinder EXperiment*: submillimetre telescope of ESO and partners at ALMA site
ARC	*ALMA Regional Centre:* Regional support centre for ALMA users in Europe; organised as a headquartered at ESO, with nodes in Bologna, Bonn-Cologne, Leiden, Manchester, Ondrejov, Onsala
Arecibo	Radio observatory in Puerto Rico, with the largest (300-m), though non-steerable, dish in the world
ARTEMIS	*Advanced Radio Transient Event Monitor and Identification System:* data processing system for fast transient detection on the LOFAR station at Chilbolton, UK
ASKAP	*Australia SKA Pathfinder*: radio interferometer being built in Australia, with phased-array feeds
Astro-H	X-ray satellite of the Japanese space agency (JAXA), to be launched in 2015
ASTRON	*ASTRON Netherlands Institute for Radio Astronomy*: National institute for radio astronomy in the Netherlands, part of now

ASTRONET	ERANet for astronomy in Europe
ASTROSAT	Indian satellite for X-ray astronomy, planned launch in 2015
ATCA	*Australia Telescope Compact Array*: Radio interferometer in Australia
ATHENA	*Astrophysics of The Hot and ENergetic universe*: ESA large mission for X-ray astronomy, planned launch 2028
ATNF	*Australia Telescope National Facility*: Radio astronomy observatories in Australia operated by CSIRO
AU	*Astronomical Unit*: Unit of distance, equal to the mean distance between Earth and Sun
AVN	*African VLBI Network*: Plan to create a VLBI facility in Africa by refurbishing and connecting a variety of unused communications dishes throughout the continent
Bands, Radio	Radio astronomers and engineers have their own jargon for denoting frequency bands. The most commonly encountered ones in radio astronomy are the IEEE standard letter codes UHF (0.3-1 GHz), L (1-2 GHz), S (2-4 GHz), C (4-8 GHz), X (8-12 GHz).
BAO	*Baryon Acoustic Oscillations:* phenomenon of varying density of visible matter in the Universe that are a relic of early density fluctuations also seen in the cosmic microwave background
BETA	*Boolardy Engineering Test Array*: PAF Test Array for ASKAP
BORD	*University of Bordeaux*
CASA	*Common Astronomy Software Applications:* software package primarily for radio astronomy data reduction
CABB	*Compact Array Broadband Backend*: New broadband backend system for the ATCA
Cassini-Huygens	NASA-ESA mission to the Saturn system, including a lander that descended into the atmosphere of Saturn's moon Titan. Named after French-Italian astronomer Cassini and Dutch physicist/astronomer Huygens
CDS	*Centre de Données astronomiques de Strasbourg:* Data Centre for information on objects, surveys, sky atlases, and many other things astronomical
CEPT	*European Conference of Postal and Telecommunications Administrations*: Organises the use of the radio spectrum in Europe
Chandra	*Chandra X-ray Observatory:* NASA X-ray satellite, launched in 1999, named after Indian/American astrophysicist S. Chandrasekhar
CMB	*Cosmic Microwave Background:* Fossil radiation at millimetre wavelengths from the hot and early universe
CNRS	*Centre National de la Recherche Scientifique:* Franch national science funding agency and research council
CO	Carbon monoxide: one of the abundant molecules in the interstellar medium often observed at radio wavelengths
COBALT	*COrrelator and Beamformer Application platform for the LOFAR Telescope:* GPU-based correlator for the LOFAR telescope, installed in 2014
CODALEMA	*COsmic ray Detection Array with Logarithmic ElectroMagnetic Antennas:* Cosmic-ray detection experiment using radio waves at Nançay radio observatory
CRAF	*Committee on Radio Astronomy Frequencies*: Within Europe, represents the interests of radio astronomers and observatories in matters of radio frequency management
CSIRO	*Commonwealth Scientific and Industrial Research Organisation:*

	Autralia’s national science funding agency
CTA	*Cherenkov Telescope Array*: Planned future observatory for TeV gamma-ray astronomy
DDT	*Director’s Discretionary Time:* Observing time that an observatory director can use or award outside the normal time allocation process, typically quickly and for special cases
DiFX	*Distributed FX-style software correlator:* Specific type of correlator for radio interferometer data
DIVA	*Developments In VLBI Astronomy:* Joint Research Activity of RadioNet3 to develop ultra-wideband receivers
DRAGNET	*Dynamic Radio Astronomy of Galactic Neutron Stars and Extragalactic Transients:* ERC-funded experiment with the LOFAR core to search for fast radio transients all-sky
EBC	*Expert Boards and Committees:* legal structures at the EU, now under ESF, to house advisory boards such as CRAF
E-ELT	*European Extremely Large Telescope*: Approved future optical telescopes of ESO of 39-m diameter, to be built on Cerro Armazones (Chile) by 2024-2026
e-EVN	Real-time fibre-connected version of EVN
Effelsberg	Radio observatory of the Max Institut für Radioastronomie, most famous for its 100-m dish
EHT	*Event Horizon Telescope*: Planned global array of millimetre-wave telescopes, designed to image some black holes on the scale of their horizons.
EMBRACE	*Electronic Multi Beam Radio Astronomy ConcEpt:* Experiment to test dense aperture-array radio telescope technology at GHz frequencies
e-MERLIN	Real-time fibre-connected version of MERLIN
eLISA	*Evolved Laser Interferometer Space Antenna*: Proposed space mission for the detection of gravitational waves, based on the previous project LISA
EPTA	*European Pulsar Timing Array*: Collaboration between large European radio observatories for precision timing of pulsars to detect nanoHz gravitational waves
ERANet	*European Research Area Network*: EU FP7 to organise Europe-wide planning of research in definite areas. Examples are ASTRONet and ASPERA
ERIC	*European Research Infrastructure Consortium:* New EU legal structure for organizing transnational research infrastructures
eROSITA	Imaging medium-energy X-ray telescope built by Germany (MPE) for the Russian Spectrum-Roentgen-Gamma (SRG) satellite, due for launch in 2016
ERTRC	*European Radio Telescope Review Committee:* ASTRONet committee to review the status of European radio astronomy
ESA	*European Space Agency*: With 20 member countries, founded in 1964
ESF	*European Science Foundation:* EU-level funding body for science, founded in 1974
ESO	*European Southern Observatory*: 14-member European organisation for ground-based astronomy, founded in 1962
ET	*Einstein Telescope*: Future third generation gravitational wave detector, currently in the design phase
EU	*European Union*

Euclid	ESA mission for deep survey of the extragalactic sky , to investigate the nature of dark energy and dark matter, expected launch in 2020
EURO-VO	*European Virtual Observatory:* European part of IVOA
e-VLBI	VLBI using a real-time fibre-connected network
EVN	*European VLBI Network*
EWASS	*European Week of Astronomy and Space Science:* Annual large meeting of astronomers and space scientists in Europe
EXPReS	*Express Production Real-time e-VLBI Service*: EXPReS was a three-year project to create a distributed astronomical instrument of continental and intercontinental dimensions using e-VLBI.
Fermi	*Fermi Gamma-ray Space Telescope:* 0.1-100 GeV imaging gamma-ray mission plus gamma-ray burst monitor of NASA and DOE, launched in 2008, named after Italian-American physicist Enrico Fermi
FFT	Fast Fourier Transform: A mathematical technique for analysing time series data and imaging with radio interferometers.
F-GAMMA	*FERMI-GST AGN Multi-frequency Monitoring Alliance*: Monitoring program of the broad-band spectra of about 60 AGN
FAST	*Five hundred meter Aperture Spherical Telescope*: Chinese radio telescope currently under construction
FIRST	*Faint Images of the Radio Sky at Twenty-cm:* 1.4 GHz continuum radio survey of the sky with the VLA
FoV	*Field of View:* The size of the amount of sky a telescope can see instantaneously
FP7	*Framework Programme 7*: EU seventh framework programme for science and technology funding, 2007-2013
FPGA	*Field-Programmable Gate Array*: Logic hardware that is very fast for certain types of calculation
Gaia	*Global Astrometric Interferometer for Astrophysics:* ESA satellite for astrometry, launched in 2014
Gbps	*Giga-bits per second*: unit of speed of data transfer
GBT	*Green Bank Telescope*: 110-m dish radio telescope in West Virginia, USA
GeV	*Giga-electronvolt*: microscopic unit of energy
GHz	*Giga-Herz*: 1000 million Herz, unit of frequency
GMRT	*Giant Metre-wave Radio Telescope*: Radio interferometer array in India
GMVA	*Global Milimeter VLBI Array:* Group of radio observatories that performs global VLBI observations at milimeter wavelenghts
GPU	*Graphics Processing Unit:* Specialised computer hardware, originally for graphics applications, but now widely used for ultrafast computing
GRAVITY	Four-way beam combining second-generation instrument for the interferometer on ESO's VLT observatory
GRB	*Gamma-Ray Burst:* flash of gamma rays from highly energetic explosions in the distant universe
GREGOR	1.5-m solar telescope at Observatorio del Teide, Tenerife
Hartebeesthoek	See HartRAO
HartRAO	*Hartebeesthoek Radio Astronomical Observatory:* near Johannesburg, South Africa, hosting a 26-m VLBI dish

HEASARC	*High Energy Astrophysics Science Archive Research Center:* NASA's primary archive centre for data from its (and other agencies') high-energy satellites and their data reduction software
Herschel	ESA space infrared observatory, launched in 2009, named after German-born British astronomers William and Caroline Herschel
HESS	*High Energy Stereoscopic System:* multi-dish Cherenkov telescope for TeV gamma rays in Namibia
HI	(pronounce "hitch-1") Neutral atomic hydrogen, the most abundant and most observed (in radio) material in galaxies, using its line transition with wavelength of 21 cm
Hilado	*HIgh performance processing of Large Astronomical Datasets in an Open-source environment:* Radionet3 Joint Research Activity on software development
Hinode	Solar physics mission of Japanese space agency JAXA, named after the Japanese word for 'sunrise'
HIPASS	*HI Parkes All Sky Survey*: All sky survey for neutral atomic hydrogen
HST	*Hubble Space Telescope:* NASA/ESA mission for optical astronomy from space, launched in 1990, named after US astronomer Edwin Hubble
IBIS	*Imager on-Board the INTEGRAL Satellite:* coded-mask imager for gamma rays
IceCube	Observatory for cosmic neutrinos, embedded deep into the Antarctic ice at the South Pole
ICM	*Intra-Cluster Medium:* The (hot) gas between the galaxies in a galaxy cluster
ICRF	*International Celestial Reference Frame:* astronomical coordinate system established through (VLBI) radio observations of extragalactic sources; most precise system known, adopted by IAU since 1998 and updated to ICRF2 in 2009
IF	*Intermediate Frequency:* Term from radio detection, where it is the frequency to which a radio signal is reduced for better processing in further telescope electronics
IGM	*Inter-Galactic Medium:* The tenuous gas pervading the universe in between galaxies, outside galaxy clusters
IGN	*Instituto Geográfico Nacional:* funding partner in the IRAM submillitre array
ILT	*International LOFAR Telescope:* Extension of the originally Netherlands LOFAR telescope to European partner countries (D, F, S, UK, with PL and possibly others yet to join)
IMT	*International Mobile Telecommunications:* Set of telecommunications standards
INAF	*Istituto Nazionale di AstroFisica:* Italian national organisation for astronomy and astrophysics
INTEGRAL	*INTErnational Gamma-Ray Astrophysics Laboratory:* ESA gamma-ray satellite, launched in 2002
IPS	*Inter-Planetary Scintillation:* Variations in radio sources caused by scattering of radio waves in the hot plasma of our solar system
IR	*Infra-Red:* Type of electromagnetic radiation (light) with wavelengths of about 1-100 micro-metres
IRAM	*Institut de RadioAstronomie Millimétrique:* International institute for millimetre-wave astronomy, headquartered in Grenoble, with telescopes on Pico Veleta (Spain) and Plateau de Bure (France)

IRIDIUM	Large group of communication satellites
ISM	*Inter-Stellar Medium:* The gas between stars, within a galaxy
ISS	*International Space Station:* Space station in low-Earth orbit, launched in 1998, collaboration of most large space agencies world-wide
ISS	*InterStellar Scintillation:* Variations in radio sources caused by scattering of radio waves in the hot plasma between the stars in our Galaxy
ITN	*Initial Training Networks:* EU funding programme for training young predoctoral scientists in European networks of researchers
ITU	*International Telecommunication Union*
IVOA	*International Virtual Observatory Alliance:* global alliance aiming at making astronomical data available in easy and general ways
IVS	*International VLBI Service for geodesy and astrometry*
JAXA	*Japanese Aerospace eXploration Agency:* Japan's national space agency
JBO	*Jodrell Bank Observatory:* Radio observatory near Manchester, UK
JCMT	*James Clerk Maxwell Telescope*: 15 m radio telescope for submillimeter-wavelengths at Mauna Kea Observatory in Hawaii
JEM-EUSO	*Extreme Universe Space Observatory onboard Japanese Experiment Module:* planned cosmic-ray observatory onboard the International Space Station
JIVE	*Joint Institute for VLBI in Europe:* Centre for correlation and data analysis for e-VLBI, located in Dwingeloo, Netherlands
Jodrell2	The 25-m Mark II telescope on Jodrell Bank Observatory
JRA	*Joint Research Activities:* One of the types of funding available within the context of EU ERANet's
JUICE	*JUpiter ICy moons Explorer:* approved mission by ESA to Jupiter's moons, especially Europa
Juno	NASA mission to Jupiter, launched in 2012, arrival 2016, named after goddess Juno (Jupiter's wife in Roman mythology)
JVLA	*Jansky Very Large Array:* Radio interferometer in New Mexico, USA, named after radio astronomy pioneer Karl Jansky
JWST	*James Webb Space Telescope:* NASA-ESA near- and mid-infrared space telescope, planned for launch in 2018
KASI	*Korean Astronomy and Space Science Institute*
Kat-7	Seven-dish MeerKAT precursor array
KM3NeT	Planned multi-cubic-kilometre sized European detector for cosmic neutrinos in the deep Mediterranean
KSP	*Key Science Project:* often used to indicate large projects that define the necessary capabilities of new telescopes
LA	*Large Antennas at the AMI*
LEAP	*Large European Array for Pulsars:* Combination of Europe's 5 largest observatories for pulsar astronomy
LIGO	*Laser Interferometer Gravitational wave Observatory:* US-based gravity-wave observatory, with sites at Hanford (WA) and Livingston (LA)
LOFAR	*LOw Frequency ARray:* Radio interferometer in the Netherlands and other European countries (see ILT)
LOFT	*Large Observatory for X-ray Timing*: Proposed ESA space mission to study neutron stars, black holes and other compact objects by

	means of rapid X-ray variability
LOPES	*LOfar PrototypE Station* for radio detection of cosmic rays at the KASCADE cosmic-ray detector in Karlsruhe
LOS	*Line Of Sight:* meaning on the line connecting the observer with the celestial object in question
Lovell telescope	The 250-foot (76-m) radio telescope at Jodrell Bank Observatory
LSST	*Large Synoptic Survey Telescope:* 8.4-m US-led telescope in Chile, to survey the sky to great depth, many times
LWA	*Long Wavelength Array:* low-frequency phased-array radio telescope in New Mexico
MAGIC	*Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes:* Cherenkov telescope for TeV gamma rays on Canary Islands
MAST	*Mikulski Archive for Space Telescopes:* Archive facility run from STScI by NASA to provide data archives for a variety of missions and instruments
MASTER	*Mobile Astronomical System of the TElescope-Robots:* Russian-led network of transient alert telescopes
Medicina	Medicina Radio Astronomical Station, observatory containing various telescopes includijg the Northern Cross and the 32-m dish used in EVN
MeerKAT	*Meer Karoo Array Telescope:* 64-dish SKA pathfinder telescope being constructed in South Africa
MERLIN	*Multi Element Radio Linked Interferometry Network:* UK national VLBI network
MEX	*Mars Express:* ESA-operated Mars orbiter, launched and inserted into Mars orbit in 2003
MeV	Mega-electron volt: million electron volt, microscopic unit of energy
MHD	*MagnetoHydroDynamics:* the study of flows of fluids in the presence of magnetic fields
MHz	Mega-Herz: million Herz, unit of frequency
mJy	Milli-Jansky: unit of brightness of astronomical sources, primarily used in the radio domain
MoU	*Memorandum of Understanding:* form of agreement between partners often chosen for scientific collaboration, that is not legally binding but to which the parties feel honour-bound
MPG	*Max-Planck-Gesellschaft zur Förderung der Wissenschaften*: Publicly funded association of German research institutes
MPIfR	*Max Planck Institute for Radio Astronomy*
MRO	*Metsähovi Radio Observatory:* Radio observatory in Finland, run by Aalto University
MWA	*Murchison Wide-field Array:* low-frequency phased-array telescope in Australia, primarily aiming at high-redshift neutral hydrogen (EoR) detection
NAIC	*National Astronomy and Ionosphere Center:* Organisation that runs the Arecibo radio telescope
Nançay	See NRT
NAOC	*National Astronomical Observatories, Chinese Academy of Sciences:*

NAs	*RadioNet Networking Activities*: The networking activities are designed to enhance the co-ordination and co-operation of the RadioNet facilities
NASA	*National Aeronautic and Space Administration:* US national space agency
NCRA	*National Centre for Radio Astrophysics:* Institution of the Tata Institute for Fundamental Research in Pune, India, that runs the Giant Metre-wave Radio Telescope (GMRT)
NEXPReS	*Novel EXplorations Pushing Robust e-VLBI Services:* EU-FP7-funded project (2010-2013) to improve aspects of e-VLBI
NICER	*Neutron star Interior Composition ExploreR:* NASA X-ray instrument onboard the International Space Station. Mission of Opportunity due for launch in 2016
NINS	*National Institutes of Natural Sciences, Japan*: Inter-university research institute corporation
NOEMA	see PdB-NOEMA
Noto	Noto Radio Observatory in Sicily hosts a 32-m EVN dish
NRAO	*National Radio Astronomy Observatory:* US national radio astronomy agency
NRH	*Nancay Radio Heliograph*: Radio telescope that is used for observations of the sun
NRT	*Nançay Radio Telescope:* Radio observatory with a variety of instruments and telescopes, South of Paris
NSC	*National Science Council of Taiwan*: Also called Ministry of Science and Technology (MOST) since March 2014
NSF	*National Science Foundation:* US national science funding agency
NuSTAR	*Nuclear Spectroscopic Telescope ARray:* Focusing hard X-ray telescope of NASA, launched in 2012
NVSS	*NRAO VLA Sky Survey:* Sky survey at 1.4 GHz continuum with the JVLA
NWO	*Nederlandse organisatie voor Wetenschappelijk Onderzoek:* Netherlands national science funding agency
OH	Hydrogen monoxide: important molecule in radio astronomy
OH/IR star	Certain type of very highly evolved, red giant star
Onsala	*See OSO*
ORL	*University of Orleans*
OSO	*Onsala Space Observatory:* Swedish national radio astronomy facility, run by Chalmers University
PAF	*Phased Array Feeds*: Experimental type of focal plane array using phased array technology
PanSTARRS	*Panoramic Survey Telescope And Rapid Response System:* Wide-field survey telescope for discovery of variable and moving objects
PAPER	*Precision Array for Probing the Epoch of Reionisation:* NSF-funded telescope in South Africa and Green Bank, searching for high-redshift neutral hydrogen
PC	*Programme Committee:* Name, in many observatories, for the committee of experts that advises the director which observing proposals to accept (see also: TAC)
PdB-NOEMA	*NOrthern Extended Millimetre Array:* extension of the 6-dish Plateau de Bure millimetre interferometer to 12 dishes
PHAROS	*PHased Arrays for Reflector Observing Systems:* Radionet Joint Research Activity for phased-array receivers

PI	*Principal Investigator:* Lead investigator of a project
Planck	ESA satellite for observing the Cosmic Microwave background, named of course after physicist Max Planck
PrepSKA	EU FP7-funded programme for preparation for and design study of the SKA
RadioAstron	Also called Spektr-R: Russian space-based radio telescope
RadioNet	European radio astronomy network that has received EU funding a number of times; its current version is named RadioNet3 and is funded under EU-FP7
R&D	Research and Development
RFI	*Radio Frequency Interference:* Generally human-made radio signals that hinder radio astronomical observations
RHESSI	*Reuven Ramaty High Energy Solar Spectroscopic Imager:* NASA solar physics mission, launched in 2002, named after US solar physicist Reuven Ramaty
RRL	*Radio Recombination Lines:* Spectral lines from atoms that lie in the radio wavelength range
RT-70	See Yevpatoria
RXTE	*Rossi X-ray Timing Explorer:* NASA X-ray satellite to observe fast variability (1995-2012), named after X-ray pioneer Bruno Rossi
Sardinia Telescope	*Sardinia Radio Telescope:* 64 m radio telescope on Sardinia
SDO	*Solar Dynamics Observatory:* NASA solar physics mission, launched in 2010
SEAC	*Science and Engineering Advisory Committee:* established by the SKA Board to advise director-general and board on matters of science and engineering
SED	*Spectral Energy Distribution:* The broad-band distribution of emitted radiation of an object over wavelength
SEFD	*System Equivalent Flux Density:* Technical measure of the sensitivity of a radio telescope (the lower the better)
SETI	*Search for Extra-Terrestrial Intelligence:* Efforts and programmes, primarily at radio wavelengths, to find signals from civilisations in other solar systems
SFXC	*Super FX Correlator:* Software correlator of so-called FX-type (Fourier transform before correlation) developed for VLBI at JIVE
SHAO	*SHanghai Astronomical Observatory of the Chinese Academy of Sciences:* operates two VLBI stations, with 25-m and 65-m dishes
SiO	Silicon monoxide; important molecule in radio astronomy
SKA	*Square Kilometre Array:* Next-generation large radio telescope of global scope, in the metre-centimetre wavelength range

SKA1	Phase 1 of SKA
SKA1-Low	Low-frequency part of SKA1; 70-350 MHz
SKA1-Mid	Mid-Frequency part of SKA1; lower limit 300 MHz, upper limit at least 2.5 GHz, possibly up to 20 GHz
SKA1-Survey	Wide-field survey part of SKA1; 650-1700 MHz
SKA2	Phase 2 of SKA
SKADS	*Square Kilometre Array Design Studies:* EU FP6-funded project for studying the SKA design
SkyMapper	Fully automated 1.35 m wide-angle optical telescope at Sliding Spring Observatory in northern New South Wales, Australia
SN	*Supernova*: Stellar explosion at the end of a massive star's life that can briefly outshine an entire galaxy
SPI	*SPectrometer on Integral:* primary gamma-ray spectrometer on the INTEGRAL satellite
SPICA	*SPace Infrared telescope for Cosmology and Astrophysics:* Planned JAXA-ESA infrared satellite for launch around 2025
Spitzer	NASA Infrared Space Telescope, launched in 2003, named after US astrophysicist Lyman Spitzer, Jr.
SPT	*South Pole Telescope:* U. Chicago-led telescope for observing the cosmic microwave background from the South Pole
SRG	*Spectrum-Röntgen-Gamma:* Russian satellite, due for launch in 2016
SRT	*Sardinia Radio Telescope:* New 60-m single-dish radio telescope in Sardinia, Italy, in final stages of being built
STEREO	*Solar TErrestrial RElations Observatory:* NASA solar physics mission, employing 2 satellites to get a 3D view
STFC	*Science and Technology Facilities Council:* UK national science funding agency
SUMSS	*Sydney University Molonglo Sky Survey:* radio survey at 843 MHz of the sky South of declination -30 degrees, conducted with the Molonglo telescope
SV	*Science Vision:* The ASTRONET vision document outlining the important topics for study in astronomy for the next decade; first published in 2007, update to appear in 2015
SVOM	*Space-based multi-band astronomical Variable Objects Monitor:* French-Chinese mission for finding and studying gamma-ray bursts
Swift	NASA UV-, X- and gamma-ray satellite, for gamma-ray bursts and other transient sources
SZ effect	*Sunyaev-Zel'dovich effect:* Increase of the brightness of the cosmic microwave background due to electron scattering in a foreground galaxy cluster
TAC	*Time Allocation Committee:* Name, in many observatories, for the committee of experts that advises the director which observing proposals to accept (see also: PC)
TDE	*Tidal Disruption Event:* Disruption of a star that comes too close to the central black hole in a galaxy, leading to a large outburst of radiation from the centre of that galaxy

TeV	Tera-electronvolt: 1 billion electron volt, microscopic unit of energy
TIFR	*Tata Institute of Fundamental Research:* Indian research institute for Natural Sciences, headquartered in Mumbai
TMT	*Thirty Meter Telescope:* US project for 30-m next-generation optical telescope
TNA	*Trans-National Access:* Programme for encouraging and sponsoring access of astronomers from EU institutes to facilities in other EU nations (as, e.g., run by RadioNet3)
ToO	*Target of Opportunity:* Category of telescope observation that occurs at unexpected times and circumstances, often due to sudden celestial evens
Toruń	The Toruń Centre for Astronomy in North-Central Poland is part of Nicolaus Copernicus University and hosts a 32-m EVN dish
TSRS	*Texas Survey of Radio Sources:* Survey of the sky at 365 MHz between declination -36 and +72
UBB	*Ultra Broad Band:* new very wide band receiver at Effelsberg
UMAN	*University of Manchester*
UN	United Nations
UniBoard(2)	UniBoard and UniBoard2 are RadioNet projects to develop very fast and flexible FPGA-based processor boards for radio astronomy
UV	*Ultra-Violet:* type of electromagnetic radiation (light) with wavelengths of about 10-300 nm
uv-plane	*uv-plane:* characterizes how well the radio source is being mapped by the configuration of the radio interferometer
VERITAS	*Very Energetic Radiation Imaging Telescope Array System*: Cherenkov telescope array for observing TeV gamma rays in the USA
VIRGO	Two-arm Michelson interferometer for dection of gravitational waves near Pisa, Italy, run by the INFN (Italy) and CNRS (France); now subsumed into EGO – European Gravitational wave Observatory
VISTA	*Visible and Infrared Survey Telescope for Astronomy:* wide-field survey telescope with 4-m mirror at ESO's Paranal Observatory
Vivaldi	Specific type of co-planar, broad-band antenna used, e.g., in dense aperture arrays such as EMBRACE
VLA	*Very Large Array*: Former name of the JVLA
VLBA	*Very Long Baseline Array:* VLBI array in the USA
VLBI	Very Long Baseline Interferometry: Radio astronomy technique for connecting radio antennae over very long baselines (often transcontinental or even including space missions), to achieve very high resolution
VLTI	*Very Large Telescope Interferometer*: Coherent combination of the four VLT (Very Large Telescope) Unit Telescopes and the four movable 1.8 m Auxiliary Telescopes at the Cerro Paranal Observatory operated by ESO
WENSS	*WEsterbork Northern Sky Survey:* Radio survey of the Northern sky at 325 MHz with the WSRT
Westerbork	See WSRT

WFIRST	*Wide-Field InfraRed Survey Telescope:* planned NASA mission for dark energy and exoplanet research
WRC	*World Radiocommunication Conference*: Conference organized by the International Telecommunication Union to review and revise the Radio Regulations; held every three to four years
WSRT	*Westerbork Synthesis Radio Telescope:* Radio interferometer in Westerbork, the Netherlands (opened 1970)
XAO	*Xinjiang Astronomical Observatory of the Chinese Academy of Sciences:* based in Urumqi, operates the 25-m VLBI dish at Nanshan
XMM-Newton	ESA X-ray satellite, launched in 1999, named after Sir Isaac, of course
XRB	*X-Ray Binary:* A binary star in which at least one star emits X rays through various possible causes, most commonly because it is a neutron star or black hole accreting matter from its companion star
Yebes	Radio observatory in central Spain, hosting a 40-m dish used in the EVN
YERAC	*Young European Radio Astronomers' Conference*: Annual conference for young radio astronomers from all over Europe
Yevpatoria	Observatory of the Center for Deep Space Communications in Crimea, hosting the 70-m telescope used in EVN