European Science Foundation

33 CRAF News

The newsletter of the ESF Expert Committee on Radio Astronomy Frequencies

Autumn 2020

Contents

Editorial

In recent years there has been an increasing awareness by the general public that our view of the 'wonders' of the heavens is becoming more and more restricted because of light pollution. Many photographs of the 'dark side' of the Earth have been taken from satellites and combined together to clearly show the Earth's continents illuminated and defined.

Radio astronomers, operating in the radio wave part of the electromagnetic specrum, where the view that we have of the Universe is very different from the one that is visible at optical wavelengths, have been aware of 'light pollution' or interference to their radio frequency observations for many years. This has been increasing year by year as the demand for the use of the radio spectrum, primarily for tele-communications, has been increasing. It has partly been alleviated by locating radio observatories well away from urban conurbations, although these latter have spread out so much that major new radio observatory developments, such as the SKA, are having to be located in very remote parts of the world, well away from human habitation, such as in the West Australia desert and in the Karoo desert in South Africa. Unfortunately, as noted in the last issue of the CRAF Newsletter and also in the report from the CRAF 63 meeting in this issue, this doesn't appear to be far enough as there are proposals to fill the skies with communications satellites, which will be visble from even the remotest parts of the world.

In addition to the few hundred Space-X satellites already in orbit, there are now proposals for frequencies allocated for mobile phone use on the ground to be used on airborne platforms and high-flying aircraft, thus extending currently ground-based mobile phone use to the skies. This would mean that studies already undertaken to enable ground-based mobile phone use without interference to radio observatories would almost certainly no longer be valid.

Cover
The Lovell Telescope at Jodrell Bank Observatory, photographed late on a winter's day from the approach to the SKA building. The telescope (the oldest fully steerable, large telescope still functioning scientifically) is 76-m in diameter and came into operation in 1957 and is still in daily use. The white posts in front of the SKA building are flagpoles. At other times of the year each would have a flag representing one of the countries involved in the SKAO.

An additional threat from the skies are Synthetic Aperture Radar Systems (SARS) in which powerful microwave radars at frequencies in the range 9.2 to 10.4 GHz transmit downwards to the Earth's surface with the aim of producing a map of every square metre of the Earth's surface every hour, which is what is intended, It doesn't really matter eactly what is the frequency of transmission of these radars, if the main beam of a telescope operating at centimetre wavelengths intercepts the radar, the telescope receiver will simply be destroyed.

There is now a real concern, expressed in a film produced in the US some 20 or perhaps it was even 30 years ago, that our radio frequency window on the wonders of the Universe will close.

Peter Thomasson

Report from the 63rd CRAF Meeting

The 63rd CRAF Meeting was organised by the University of Manchester, Jodrell Bank Observatory and the Square Kilometre Array Organisation (SKAO) and took place from 12 to 14 June 2019 inclusive at the SKAO headquarters based at Jodrell Bank, UK, located ~20 miles South of Manchester University. Professor Dr. Philip Diamond, Director General of the SKAO welcomed all the participants and wished them a fruitful meeting. He also gave a general presentation on the SKA project from the points of view of both the scientific and instrumental objectives. Peter Thomasson, the acting CRAF Chairman / Spokesperson for the CRAF Management team, thanked Professor Diamond for the hospitality provided by the SKAO and also Professor Simon Garrington, the Director of Jodrell Bank Observatory, who was also present and who had also made available the Observatory facilities as required during the meeting. There were 12 CRAF members physically present at the meeting, in addition to which V. Tóth, the CRAF Member for Hungary attended remotely. There were also 6 observers physically present; G.H.Tan from ESO, F. DiVruno from the SKA, H. Smith, a consultant to CRAF, I. Dedze, representing Latvia, H. Liszt, the IUCAF Chairman, J-C. Worms, the ESF - CRAF Liaison, and 2 other observers, B.A. Zauderer (USA NSF CRAF Liaison) and L. van Zee (USA CORF Cahirman) attended remotely.

Following a review of the Action Items from both the CRAF 62 Web meeting held in October 2018 and also the CRAF 61 meeting, the minutes of the CRAF 62 Web meeting were reviewed and approved.

RadioNet H2020

Bolli presented a very clear report on the activities that had been undertaken by CRAF for which funding had been obtained under the heading of Work Package (WP) 4, in particular WP 4.2, entitled Spectrum Management. Residual funding was still available and there were a number of suggestions for its profitable use. These included a Pycraf workshop, funding for CRAF members to attend WRC-19 and other CEPT meetings, and a 2020 Summer School in Stellenbosch, South Africa.

CRAF Frequency Manager

Following the resignation of the CRAF Frequency Manager (FM) earlier in the year, an appropriate replacement process had been instigated to find a good candidate to fill the position, Interviews had already been held, and it was expected that a new FM would be appointed by the end of June and be in post by September. In the meantime, H. Smith, a former CRAF FM, had agreed to become a consultant with a particular brief to assist the new CRAF FM when appointed to prepare for the World Radio Conference (WRC19) later in the year and also to act as an advisor to the FM concerning the many issues that would arise. The appointment would be until the end of October 2019

Interference from future satellite constellations

In addition to having a break for lunch from the considerable discussions and reports, a tour of the Jodrell Bank Observatory was arranged for all wishing to take part. Following this, the Director of Jodrell Bank Observatory, Professor Simon Garrington, gave a review of the work being undertaken at the observatory and its plans for the future, and Federico DiVruno gave an overview of the SKA's current state. Following this latter talk, the issue of future spectrum allocations to satellites, in particular to the proposed Space X and OneWeb organisations, was raised, and an official statement from the Director-General of the SKA read out, which was of great concern to all attendees.

WRC19 preparation and reports from important preliminary meetings

Many preparatory meetings for the WRC19 were taking place and also being planned in preparation for the month long meeting to take place in October / November in Sharm el-Sheikh, Egypt. It was noted that Winkel (Germany) could not attend this CRAF meeting because of attendance on behalf of CRAF at the important Electronic Communications Committee (ECC) PT1 meeting*. There was much discussion of the planned ECC, CEPT* and ITU** meetings with emphasis on the ones at which CRAF attendance was required. Lindqvist presented a report from the Conference Preparatory Group (CPG) of the CEPT, which had taken place in Stockholm. It was suggested by Zauderer, the US National Science Foundation (NSF) representative, that the NSF, CRAF and CORF should work together to identify the meetings prior to the WRC, which were of most importance to radio astronomers.

* Note that the ECC is a part of the European Conference of Postal and Telecommunications Administration (CEPT)

** International Telecommunication Union

The CRAF Budget

There was a discussion of the budgets for the years 2017 to 2020 inclusive. It became clear that there had been delays in invoices being issued by the ESF for the 2019 contributions compared with normal and that a small number of contributions appeared not to have been paid. Appropriate action was taken to remedy this. There were some discrepancies in the initially presented budgets, which were further discussed during the Stakeholders' meeting, when it became clear that there was a need for an annual increase in the contributions. There was general agreement on the proposed 'full' annual contributions to be paid, but with some reservations. Consequently the budgets for 2017 & 2018 were approved, but the final budgets for 2019 & 2020 would not be completed until after the meeting.

CRAF Studies Working Groups

Pietro Bolli presented the Work Item (WI) process proposed at the CRAF 61 meeting by Benjamin Winkel and described the progress that had been made. The main idea for the WIs was a formal sharing amongst CRAF members of work primarily concerned with studies by ITU & ECC working groups. Five 'Work Items' had been identified to be considered initially. These were concerned with Radio Astronomy as seen at the ITU (Working Party 7D [WP7D]), International Mobile Telecommunications (IMT), ECC Spectrum Engineering Groups (SE), ITU Focus Group (FG) on Wind Turbines and the VLBI Global Observing System (VGOS). A group concerned with ECC Spectrum Engineering groups SE21, SE24 and Short Range Devices, co-ordinated by Bolli, had already met and work had been carried out using Pycraf to produce a document on the "Compatibility between RAS and Radio determination in the frequency range 120-260 GHz", which had been submitted to ECC SE24 by the French administration on behalf of CRAF. It had also been noted by those concerned with ITU-R WP7D that the US administration had started a Preliminary Draft Report (PDNR) on co-existence between IMT Services in the frequency range 42.5 - 43.5 GHz.

The Stakeholders' Forum

Nine directors from the CRAF Member institutions attended the Stakeholders' Forum (3 by remote access), which has become a part of the CRAF face-to-face meetings. The CRAF liaison at the ESF, Jean-Claude Worms, also attended and confirmed that he would be leaving the ESF, to be replaced by Nicolas Walter. The meeting was chaired by Rene Vermeulen from ASTRON, the Director of LOFAR. A summary of CRAF's activities during the previous year was given by Peter Thomasson, who also provided a work plan for 2019 and listed the participation of CRAF members in ITU and CEPT meetings. He also indicated that, in addition to the employment of a new frequency manager, the main priority for CRAF in the immediate future was the approaching WRC.

Vermeulen considered that there were still too few CRAF members participating in the work of CRAF and made suggestions as to how this might be improved. Pietro Bolli presented the work being undertaken as part of the Work Items, which was endorsed by the Stakeholders' Forum. There was also a suggestion that there could perhaps be an involvement of other stakeholders in the radio spectrum in the Work Items; e.g the space community.

As Rene Vermeulen had been the Chairman of the Stakeholders' for his allotted two years, Simon Garrington would now be replacing him as the Chairman for the next 2 years. The considerable work and contributions of Vermeulen during the past 2 years were acknowledged.

Observatory Reports

As at every CRAF plenary meeting, each CRAF member present gave a report on new or ongoing interference from which their observatories were suffering.

New CRAF Chairman and Vice-Chairman

It was announced that Michael Lindqvist would become the new CRAF Chairman, and that Pietro Bolli would become the first CRAF Vice-Chairman, as it had been deemed necessary to have this position recognised. Gratitude was expressed to Peter Thomasson for having guided CRAF with intense dedication during what had been a very delicate transition period.

Peter Thomasson and **Vincenza Tornatore**

Report from the 64th CRAF (Web) Meeting

The 64th CRAF meeting was held in the Autumn of 2019 on October 2nd into which 17 participants dialled, two of whom were observers and the remainder CRAF members. The Chairman, Michael Lindqvist, welcomed all the participants, in particular the new Frequency Manager, Waleed Madkour, whom he introduced to all the participants. It was decided not to review the Action Items resulting from the 63rd CRAF meeting, but to leave them open until the next face-to-face meeting, as the most important item to be discussed was the CRAF position paper for the WRC-19, which was to take place in Sharm el-Sheikh, starting before the end of the month. It was also necessary to approve the minutes of the 63rd CRAF face-to-face meeting held at the SKA headquarters at Jodrell Bank during the previous June, and to consider the Budget 2020 and RadioNet funding, bearing in mind that this latter would finish at the end of 2020.

The minutes of the CRAF 63 meeting were approved subject to two minor modifications, and the Action Items from the CRAF 63 meeting were to be included as Action Items in the minutes of this meeting to be discussed at the next CRAF plenary meeting.

RadioNet Funding & Budget 2020

Pietro Bolli gave a reminder that as the current cycle of RadioNet funding would cease at the end of 2020, then all RadioNet money nominally allocated to CRAF should be spent by then. At present the money actually spent was less than that expected. It had also been noted that travels of the Frequency Manager, who was intending to attend the WRC-19 in Sharm el-Sheikh starting on 28 October, could not be claimed from the RadioNet funding.

A Spectrum Management School is being organised to take place in Stellenbosch in South Africa early in 2020. RadioNet funding from WP3 was available to support travel of participants from 'RadioNet' Institutes. The sum of money available should enable ~12 participants to attend.

Pietro Bolli then presented the budget for 2020, which was based upon the expected member contributions. However, these were based upon the increased full contribution as discussed at the CRAF 63 meeting, but this had not been finally agreed. Assuming that there would be a final agreement, it was anticipated that there would be a carryover from 2020 into 2021. It was also decided that any unspent allocations for 2019 should carry over to 2020.

It was noted that some contributions had not as yet been paid, but that was perceived to be for administrative reasons. Good news was that Spain is expecting to restart its full contribution.

CRAF Management Issues

It was noted that the contribution of Harry Smith (the consultant to CRAF) to the preparation of a position paper for WRC-19 and the training of the new frequency manager was very valuable.

The latest version of the Newsletter had been completed and sent to the ESF. First proofs were awaited.

Following the sudden resignation of the Dutch CRAF member prior to the CRAF 63 meeting, a replacement had as yet not been appointed, which was of great concern. Winkel had reported that it was very important for a CRAF member to have a very good relationship with his/her national administration and to attend their meetings. If this were the case, it was more likely that CRAF lobbying for radio astronomy would have a better outcome than otherwise, and this had been the case in the past for the Netherlands.

There is pressure from many European countries for the use of frequencies from 24.25 - 27.5 GHz for 5G. In addition to this some countries are also considering using the frequencies immediately adjacent to the 24 GHz band for indoor radio microphones. Both of these are a concern as there is an increased probability of interference to the 23.6 - 24.0 GHz passive band.

Work Items (WI) Teams' Reports

a) CRAF-VGOS

A first meeting of the group had taken place on 7th September for which Hayo Hase had prepared a document, which was eventually submitted to a meeting of the IVS Board on 30th September. A next meeting of the WI Team had been arranged for 22nd October.

b) CRAF -SE-nn

Pietro Bolli is coordinating the monitoring of the ECC Spectrum Engineering (SE) working groups SE 7, SE21, SE24 and SE40, work for which is being undertaken by small groups of the WI Team, whose total number of CRAF members taking part is currently 7. The WI Team meets every few weeks. In addition to monitoring any activity of SE7 and SE21, considerable work has already been undertaken to produce documents to be or already have been submitted to SE24 concerned with

1. High definition ground-based Synthetic Aperture Radar (SAR) at ~77 GHz

2. Ultra Wide Band (UWB) Radar at frequencies greater than 120 GHz.

SE40 is concerned with Iridium.

Benjamin Winkel, Waleed Madkour and Axel Jessner had attended an SE40 meeting in Germany, at which it became apparent from the most recent Leeheim satellite observatory report that the new Iridium satellites are still emitting above the limits required for non-interference with radio astronomy.

c) CRAF PT1

The greatest concern for the RAS currently being discussed is the proposed use of existing mobile bands on airborne platforms or even high flying aircraft. If this were to be approved, it would negate all previous studies for the protection of radio observatories which has been shown to be possible because of terrain attenuation. Further protection for observatories in the form of no-fly zones may be essential.

d) CRAF-Windmills

A paper concerning interference from wind turbines to radio telescope operations has been submitted to the CEPT forum group on wind turbines. This was based upon experience gained from compatibility studies involving the Effelsberg telescope.

WRC-19

Considerable work had been undertaken, in particular by Harry Smith, to determine CRAF's position for all the WRC-19 Agenda items, which were presented. Work undertaken by the previous CRAF Frequency Manager, Talayeh Hezareth, had been either simply adopted or modified appropriately by Benjamin Winkel and Pietro Bolli, to provide a significant contribution. Contributions had, of course, also come from other CRAF members.

Waleed Madkour, the new frequency manager, would attend the full WRC-19 meeting, and Michael Lindqvist would attend approximately half of it. In preparing the CRAF positions, there had also been some liaison with IUCAF.

Next CRAF Meeting.

The next CRAF face-to-face meeting was planned to take place in Latvia in the Spring of 2020 - the exact dates to be defined.

Joe McCauley and **Peter Thomasson**

Spectrum compatibility studies with Python: the pycraf package

The radio spectrum is a precious resource. It has been from the beginning of its use some 100 years ago, but the pressure on administrations to allocate more and more bandwidth to a large variety of services and applications has continually increased. Among these are communications networks, safety of life services, radio and TV broadcasts, radars, and also many scientific applications such as remote Earth sensing, meteorology and radio astronomy.

Whereas some people tend to think spectrum management is mostly a question of lobbying and economic value, the 'bread and butter' of successful sharing is to work out the technical conditions under which a peaceful coexistence of two or more services is possible. In most cases, a new service or application, which seeks access to the spectrum, has to demonstrate that existing services at the same or adjacent frequencies are not affected in a way that limits their operations. This is also true for the same application to be used by different operators. For example, spectrum authorities need to make sure that cell phone providers do not interfere with their business competitors.

At its core, spectrum compatibility studies are a simple three-step procedure.

1. Determination of how much power is radiated towards a potential victim receiver. For this, the power fed into the transmitter system and also the antenna pattern (the gain towards certain directions) are both important parameters that must be incorporated into the calculations.
2. The attenuation along the propagation path must be estimated as it determines the total power that is received at a victim station. For the latter, again the antenna pattern can play a role.
3. The receiver technology and the susceptibility of the interfered-with application to certain kinds of signals must also be considered. Often, spectrum authorities have defined power levels that must not be exceeded at the victim station in order to ensure smooth operations.

Compared with other services, radio astronomy is difficult to protect, as it uses cryogenically cooled receivers and long integration times to reach the sensitivities necessary to observe the extremely weak signals from the distant parts of the Universe. Astronomers have even defined a special physical unit, the Jansky, which is 10^{-26} Wm^{-2} Hz^{-1}, to avoid working with tiny numbers for the received flux densities. Modern day radio astronomy is able to detect micro-Jansky signals. In fact, a cell phone operating on the Moon would produce a signal in radio astronomical systems as strong as the ones received from the most powerful sources in the Universe. Likewise, signals from all-kinds of terrestrial or air- and space-borne services can outshine astronomical signals by many orders of magnitude.

Although the three-step process outlined above is conceptually simple, calculating the actual numbers can be quite challenging. This process starts with the antenna patterns when one immediately notes that the far-side lobe sensitivity of a 100-m class radio telescope cannot be determined experimentally and is difficult to model. It is also the case that state-of-the-art antenna technology in other fields is complex to describe with the required accuracy. Consider for example active antenna systems that use a large number of antenna elements in the aperture plane to produce a beam, which can be electronically steered. Especially for the case of out-of-band emission, where the beam-forming is less efficient, the various technical study groups are still working on proper models. Active antenna systems are ubiquitous in modern telecommunication, but a major boost of the technology is now seen with the advent of 5G cell phones. At higher frequencies, above 24 GHz, their base stations will utilise up to 64 antenna elements, which can form beams in quasi- real time to optimise the link budget between base stations and user equipment, such as smartphones or IoT devices. For compatibility studies, not only the gain in the beam direction is important, but the (side-lobe) gain towards the victim station must be computed, which is time- and frequency-dependent.

Even more complicated is the path loss computation. A proper treatment of the problem would involve a complete analysis of the electromagnetic wave propagation over real terrain with all types of different electromagnetic properties. Thus, wet leaves will influence the wave very differently compared with a city with its street canyons. A numerical solution of the size, which is needed for most compatibility problems, is beyond the capabilities of super computers. Therefore, approximation models have been developed from very simple ones to more complex algorithms, which take into account effects such as diffraction at real terrain obstacles, atmospheric absorption and tropospheric scatter.

As such models are an important ingredient for compatibility studies, the Radiocommunication sector of the International Telecommunication Union (ITU-R) has published a large number of so-called recommendations, which contain propagation models for a variety of usage scenarios. Furthermore, recommendations exist, which propose (simplified) antenna models for all kinds of services, e.g., mobile communication, fixed links, or radio telescopes. Protection levels are in part specified in the Radio Regulations of the ITU-R or also defined in Recommendations. For example, the thresholds relevant for the radio astronomy service (RAS) are detailed in Recommendation ITU-R RA.769-2.

The Committee on Radio Astronomical Frequencies (CRAF) is an expert committee of the European Science Foundation (ESF) and was founded by European radio astronomical organisations and institutes. CRAF represents the interests of radio astronomy at all levels of spectrum management, from solving local compatibility issues at observatories to participating in European and international meetings, e.g. the working group meetings of the European Conference of Postal and Telecommunications Administrations (CEPT) or the ITU-R study groups and World Radiocommunication Conferences (WRC).

As explained above, fighting for our (i.e. radioastronomers') interests is strongly linked to the ability to present spectrum compatibility studies that explore under which circumstances protection of RAS stations can be ensured. To increase its effectiveness, CRAF has undertaken considerable work to produce Python software to ease and streamline the creation of compatibility calculations. This tool is named *pycraf* and is not a stand-alone software, but a library for the Python programming language (a so-called package). While this demands some familiarity with the Python language, which however is not too hard to learn, it makes the software very flexible and versatile, easy to extend, and allows a sharing of our studies under permissive open-source licences with other parties. In the following, a small overview will be given of the features included in pycraf, together with some examples and future plans.

Probably the most-used feature of pycraf is its implementation of the Rec. ITU-R P.452 path propagation model. The method includes line-of-sight (free-space) loss including correction terms for multipath and focussing effects, diffraction (at terrain features), tropospheric scatter, and anomalous propagation (ducting, reflection from elevated atmospheric layers). It also proposes an approach to include clutter effects, but this only accounts for the endpoints of the propagation path, which is why there is often considerable debate as to how realistic the prediction could be. One should emphasise that the model is not fully derived from physics, but is based to a large extent on empirical modelling, which best describes the results from a huge number of measurement campaigns. As the

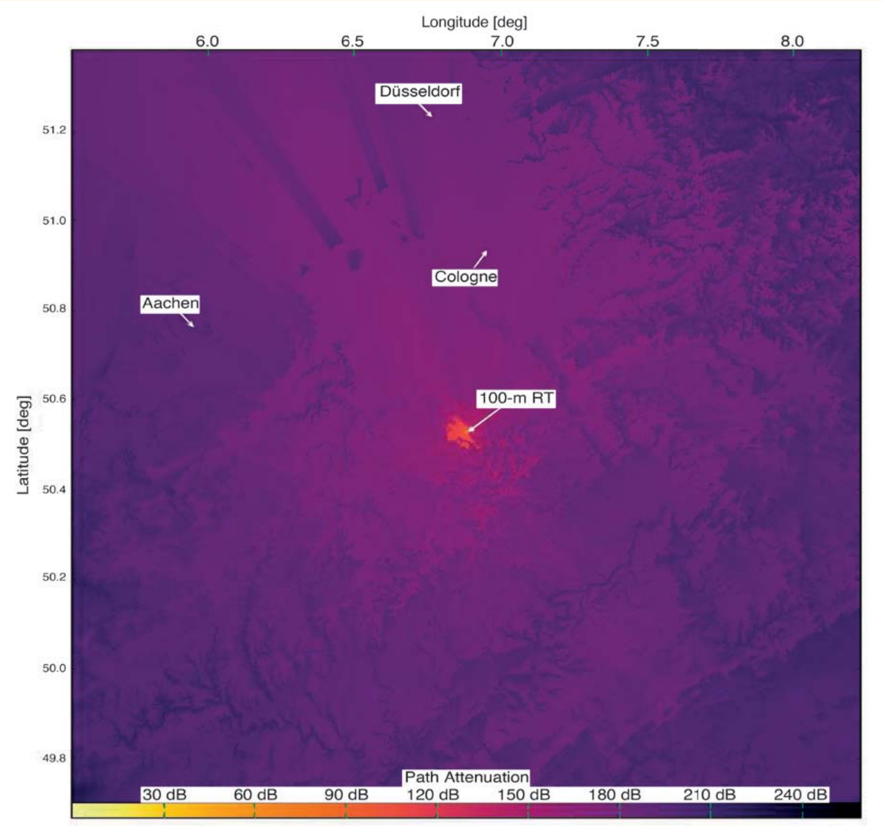

Figure 1.
Path attenuation map for the region around the 100-m radio telescope at Effelsberg (Germany) for a frequency of 3.5 GHz. Transmitter height was assumed to be 40 m. Terrain heights play an important role representing obstacles for the diffraction loss calculation in the model (the telescope is situated in a valley in the Eifel mountains).

P.452 model requires topographical information along the path of propagation, pycraf provides easy access to terrain-height data measured by the space shuttle radar mission (SRTM). It is also planned that the next release of pycraf will provide access to the Corine landcover data of the European continent (based on the Copernicus mission), which can be used to derive the clutter zone types with high spatial resolution. In Figure 1 an example path loss map is shown for an area around the 100-m telescope at Effelsberg (Germany). The colour in each pixel of the map describes how much path loss/attenuation is predicted by P.452 if the receiver is in the centre of the map and the transmitter is located at the respective pixel.

Such maps are a key ingredient for the studies which explore the compatibility between the RAS and the 5G cell phone networks, which are currently being deployed in Europe using several existing, but also new spectrum allocations. The European 5G pioneer band covers the frequencies from 3.4 to 3.8 GHz. As 5G technology is heavily reliant on active antenna systems (AAS), studies also have to account for beam-forming and the (quasi-) random deployment of cell phones. Given that there are a number of cell phones active in the 'footprint' of a 5G base station antenna, the AAS will form a beam towards each of the user devices in rapid succession. The effective gain of the AAS towards the RAS station, probably being situated in the sidelobes of the antenna, is thus also time-dependent. In Figure 2 the geometry of the situation is depicted. Three base stations (BS) have a varying number of cell phones ("user equipment" - UE) within a certain area in front of them. Antenna normal vectors of the BS are visualised with black arrows. The smartphones can have a random orientation of their antennas. As the connecting line between a BS and the associated smartphones is not necessarily aligned with the antenna normal vectors, the beams which are formed are also not aligned with the antenna normals. At the same time, the direction to the RAS receiver (grey arrows) is usually also distinct. Therefore, the effective gain towards the RAS station depends on several free parameters and must be determined for each individual device independently. In reality, the link budget between BS and UE is also subject to power control mechanisms, which try to even out some of the spread in the effective path loss between BS and UE depending upon the distance between and the orientation of the two. Obviously this also needs to be taken into account.

An actual antenna gain pattern for a 5G base station is displayed in Figure 3 for a few exemplary beam directions.

Another useful pycraf feature is its implementation of an atmospheric absorption model, as defined in Rec. ITU-R P.676. Whereas this is not as sophisticated as some

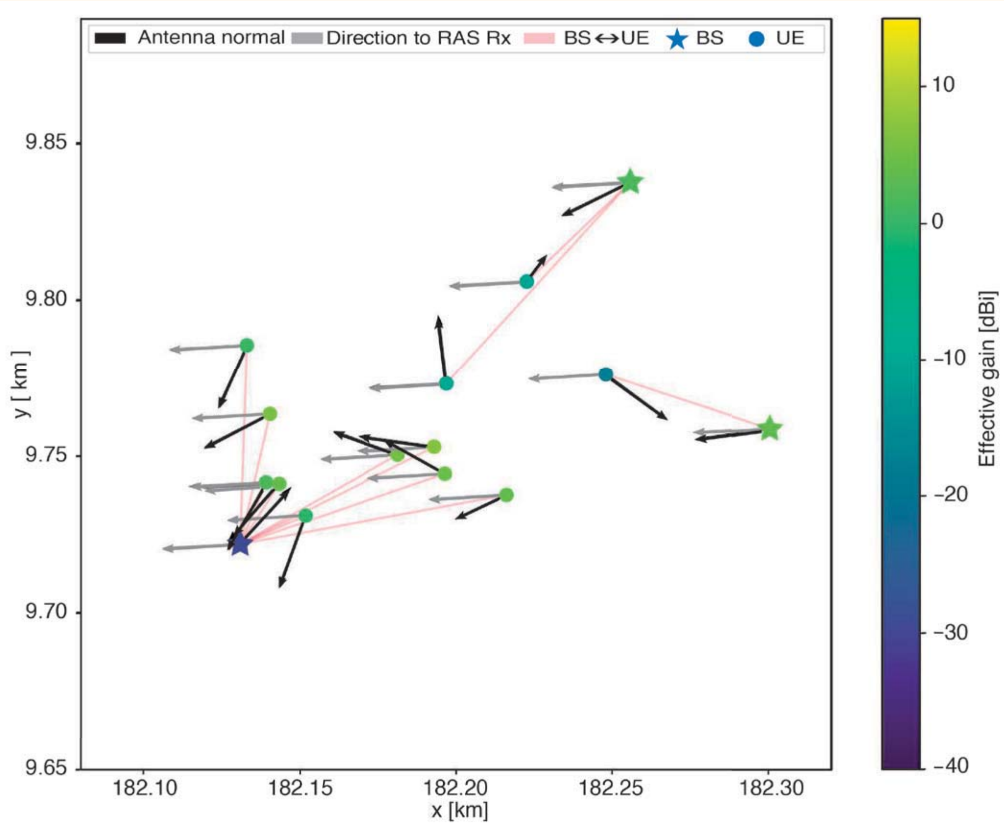

Figure 2.
Effective antenna gain of BS & UE devices towards the RAS station for 5G active antenna systems.The figure displays a 2D projection of the 3D simulation.

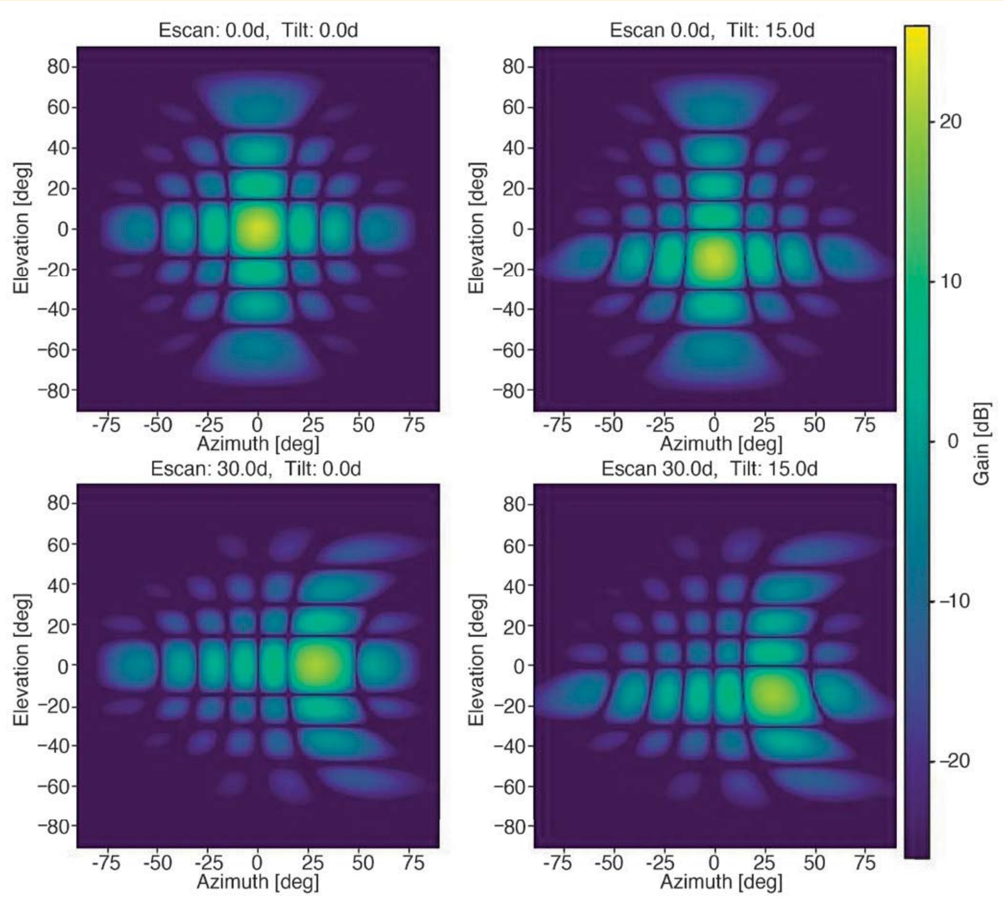

Figure 3.
Example antenna gain patterns for 5G active antenna systems, for four different beam directions.

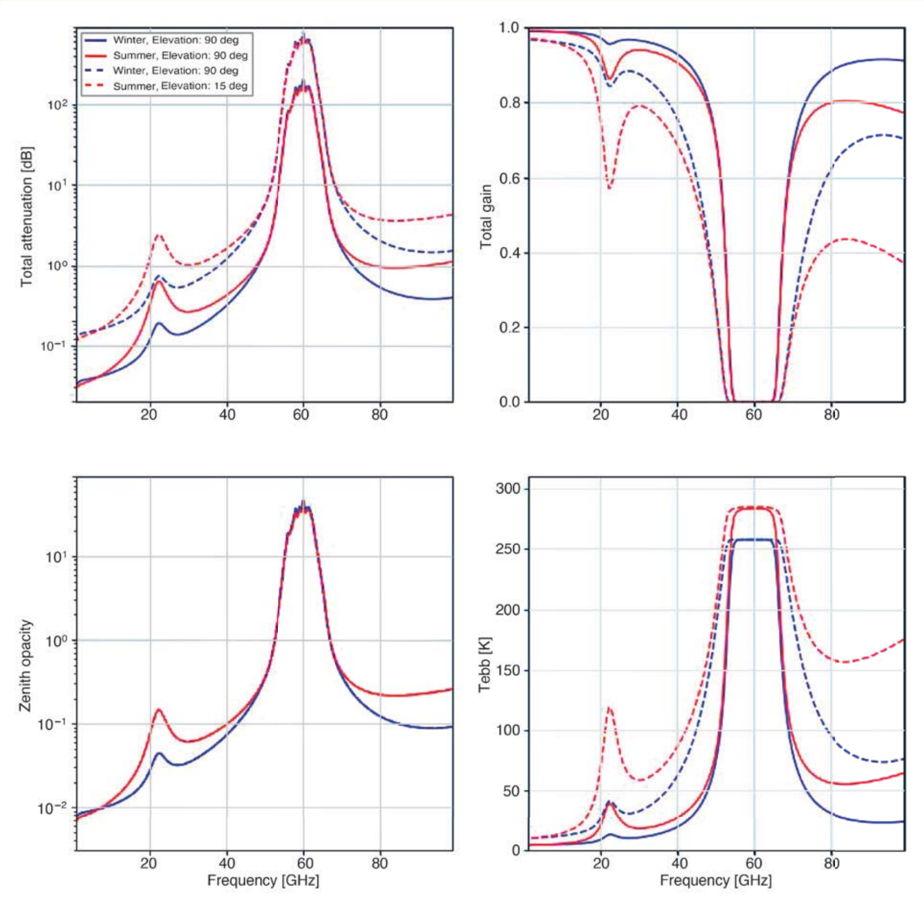

Figure 4.
Atmospheric attenuation predicted by Rec. ITU-P.676 for frequencies up to 100 GHz under various conditions.

of the models used in radio astronomy, it provides useful predictions. Furthermore, it must be stressed that most parties involved in the spectrum management process would only accept results, which are based on ITU-R models. Even if these do not always represent the latest state-of-the-art scientific models, this is a reasonable approach as it makes consensus on the technical details of compatibility studies somewhat easier if everyone is using the same models. The P.676 algorithm performs a raytracing of a ray of (radio) light through a layered atmosphere and integrates the overall attenuation along the ray; see Figure 4.

In collaboration with SKAO, the pycraf team is currently working towards integrating functionality to perform simulations of entire satellite constellations and their aggregated power received at a radio telescope. This becomes more and more important as mega constellations such as SpaceX/Starlink or OneWeb, consisting of thousands of small satellites, are being launched into low-Earth orbits, with the aim of providing broadband Internet all over the world. As satellites can cross the main beams of radio telescopes, they represent a high potential for harmful interference, and astronomers are very worried about the situation. First results have been submitted to the CEPT spectrum engineering group SE40, which deals with satellite systems.

The pycraf package is hosted on GitHub[1] under open source licence (GPL v3). The team would very much welcome contributions, feature requests, and also bug reports. There is also a lot of documentation, including a user manual[2] and several tutorial notebooks (for the Jupyter web frontend) are available.

Further reading:

1. B. Winkel & A. Jessner, Spectrum management and compatibility studies with Python, Advances in Radio Science 16, p. 177, 2018; https://arxiv.org/abs/1805.11434
2. B. Winkel & A. Jessner, Compatibility Between Wind Turbines and the Radio Astronomy Service, Journal of Astronomical Instrumentation 8, Issue 1, 2019; https://arxiv.org/abs/1812.04731

Benjamin Winkel, Max-Planck-Institut für Radioastronomie, Bonn, Germany

The Low-frequency Radio Telescope NenuFAR

Introduction

The Square Kilometre Array (SKA) telescope is a 'next generation' radio telescope being developed and planned by a consortium of countries throughout the world. It will operate over a wide range of radio frequencies and is expected to come into operation in the late 2020s (See CRAF Newsletter No. 30). Not surprisingly very considerable technical development is required before its construction and subsequent operation can take place. Consequently three 'official' precursor telescopes - the Australia Square Kilometre Array Pathfinder (ASKAP) and the Murchison Widefield Array (MWA), both located in Western Australia, and the KArroo Telescope (KAT, but now renamed MeerKAT after the small mongoose creatures that live there) located in South Africa - have been built at / close to the ultimate, main locations of the SKA. All are now producing scientific results as well as providing test beds for telescope and receiver design and construction, signal and data processing implementation, and operations. In addition to these there are a number of pathfinder instruments, which include the LOw Frequency ARray (LOFAR), initially constructed in the Netherlands, but now extending throughout Europe and already producing scientific results. LOFAR operates in two frequency bands (10 - 80 MHz and 120 - 240 MHz), thus avoiding the FM radio transmission bands. In France it was felt that, in addition to developing an extension to LOFAR, there was a need for a very sensitive radio telescope operating in the range 10-85 MHz between the Earth's ionospheric cutoff and the FM band. Thus, during a study period for an extension to LOFAR (2009-2013) to be located at the Nançay observatory site of the Observatoire de Paris, a design evolved for a large standalone radio telescope to satisfy both this need and also to contribute to the LOFAR observations. Thus, a New Extension in Nançay Upgrading of LOFAR (NenuFAR) is currently under construction at Nançay, which has been granted official status as an SKA Pathfinder by the SKA Organisation. Figure 5 shows the current locations of the LOFAR stations, including the new site at Nançay, and also a planned site at Medicina in Italy, where a 'standard, but upgraded station, capable of operating simultaneously in both frequency bands, will be installed by the Italian National Institute for Astrophysics (INAF).

Technical Description of NenuFAR

Figure 6 shows a sketch of the NenuFAR concept. The LOFAR station, FR606, is surrounded by the NenuFAR core, comprising 96 mini arrays (MAs), denoted by green coloured discs. In addition to these MAs in the core region, there are an additional 6, which are randomly distributed at distances of up to 3 km from the core region, thus providing the telescope with an increase in resolution from that of the core of 43/f degrees to ~6/f degrees, where f is the frequency in MHz; i.e. 23 arcmin. at 15 MHz and 4 arcmin. at 85 MHz for the full array. Elements of the receiver system are indicated by the 'partially grey' boxes in Figure 6.

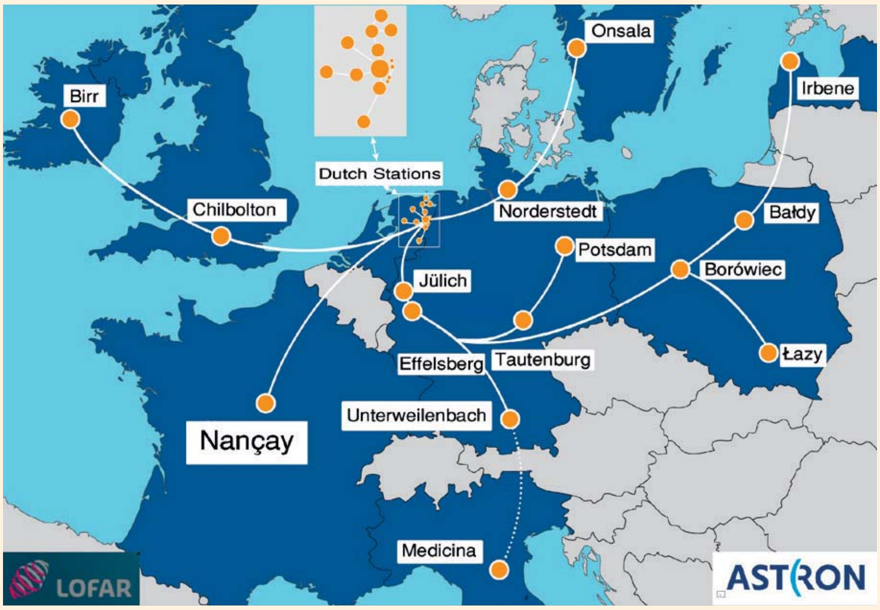

Figure 5.
Map of Western Europe showing the locations of the current LOFAR stations with emphasis on the position of Nançay. Also shown is a further planned site at Medicina in Italy.

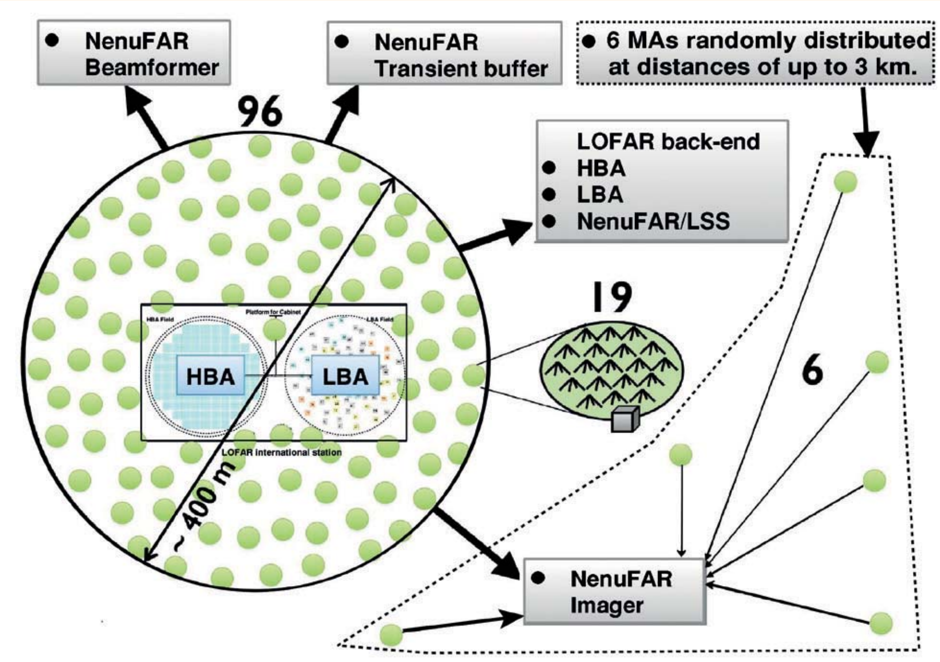

Figure 6.
Sketch of the NenuFAR concept

Figure 7. View of an area of the NenuFAR core, showing a number of the mini-arrays and their associated receiver boxes. Each dipole antenna has an associated pre-amplifier (in small white box at the top of each dipole antenna).

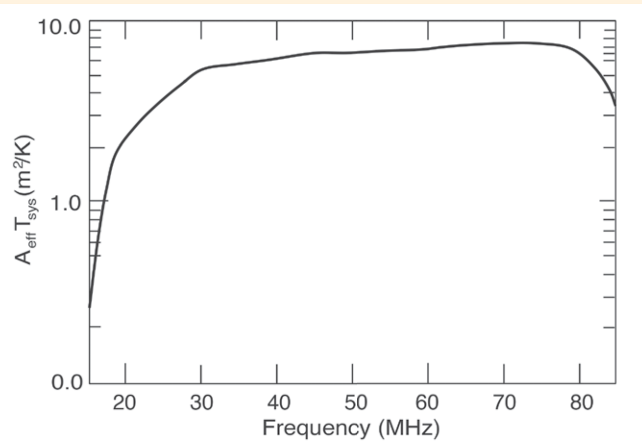

Figure 8. NenuFAR sensitivity in the 15-85 MHz range.
With a value ~6-8 m^2/K, it is 1.6 to 8 times greater than that of the LOFAR core, and greater than that of the full LOFAR outside the range 50-65 MHz.

Each MA consists of 19 inverted-V (crossed dipole) antennas (See Figure 7), similar to those in use and forming the US Long Wavelength Array located in New Mexico in the United States. Each of the 19 dipoles is mounted above a 3 m × 3 m metal grid (ground plane) to give a quasi-isotropic response at elevations of ~20°, oriented at 45° from the meridian. An associated custom-made pre-amplifier (developed by SUBATECH and USN French Labs.) is in the white box at the top of each dipole antenna. This ensures a relatively flat response across the entire 10-85 MHz band, with the sky background level several dBs above the preamplifier noise at all frequencies.

The sensitivity, displayed in Figure 8, is thus sky-limited. The dipole (+ amplifier) antennas are connected together using analogue-phased, achromatic, delay lines and arranged to form hexagonal tiles or MAs of size ~25m. These produce a broad MA beam of ~700/f degrees (f is the frequency in MHz as above), which is steerable from horizon to zenith. As already indicated above, the MAs are densely distributed within the 400m diameter core, such that when considering the MAs as individual telescopes, the 96 MAs in the core effectively provide a nearly perfect Gaussian coverage of the uv-plane, Although the 6 distant MAs only provide an additional, instantaneous, sparse coverage of the uv-plane, this becomes almost continuous when combined with the Earth's rotation and multi-frequency synthesis.

Nenufar Receiver System & Data products.

A block diagram of the NenuFAR receiver and data processing system is shown in Figure 9. The analogue signals

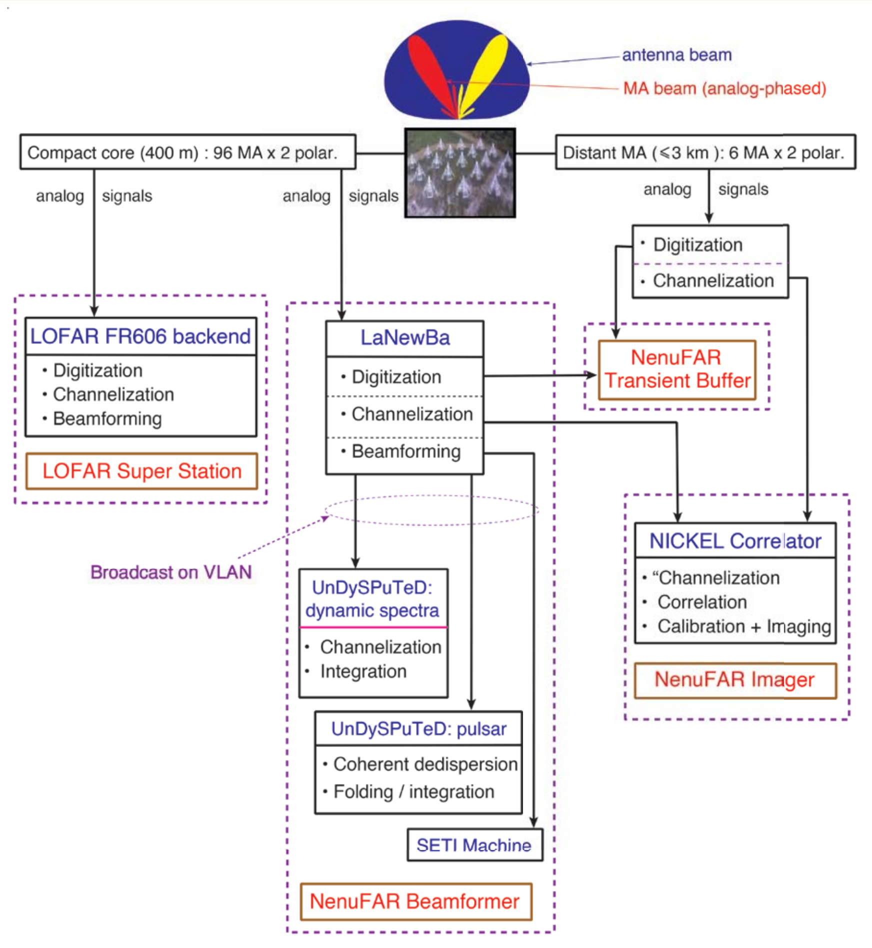

Figure 9.
Block diagram of the NenuFAR receiver and initial data processing system.

from the core MAs (96 × 2 polarisations) are split in order to feed simultaneously the LOFAR FR606 station backend as well as the main NenuFAR LOFAR-like Advanced New Backend (LANewBa) receiver system. These receivers sample the data at 200 MHz, transform it into 195 kHz wide channels and digitally (multi-)beamform these signals. Beamforming is a coherent summation of the MA signals with appropriate phase shifts. This results in 195 kHz-wide (×2 polarisations) beamlets defined by their central frequency, fc, and their frequency dependent angles in the sky. The beamlet signals are streams of 195k-complex pairs, allowing for further channelisation and computation of the 4 Stokes parameters of the incident waves.

The resulting 'LOFAR FR606' data (effectively that from 244 16-bit beamlets, equivalent to ~48 MHz of instantaneous bandwidth from a "super station") are sent to the LOFAR central correlator to enhance LOFAR's low-frequency imaging capabilities.

The LANewBa can process up to 768 16-bit beamlets at any time (630 Gb/s), equivalent to 150 MHz of instantaneous bandwidth, i.e. 2 beams each with the full 10-85 MHz band, or 10 beams of 15 MHz bandwidth, etc. Each beamlet is defined independently without any practical constraint other than it must be included in the MA analog beam. The LANewBa products are 'broadcast' on a local network that feeds in parallel several calculators. Two identical Unified Dynamic Spectrum, Pulsar and Time Domain (UnDySPuTeD) hardware devices compute full Stokes Dynamic Spectra, standard Pulsar products, or a Time Domain series of samples. A special purpose computer, procured in conjunction with the Berkeley Breakthrough Listen laboratory, will produce high spectral resolution dynamic spectra for SETI studies, mostly in 'piggyback mode', thanks to the ability of the LANewBa to broadcast the resulting data on a local network.

In parallel, LANewBa produces low-rate statistics measurements (Spectral, Beamformed, and Cross-Correlations) in FITS format, and feeds a circular Transient Buffer per MA with the 200 MHz signals, allowing up to 5 seconds of high-rate waveform capture and dump-to-disk (similar to LOFAR's Transient Buffer Boards). Finally LANewBa feeds a standalone correlator with the channelised signals per MA and per polarisation, together with digitised signals from the distant MAs.

The correlator is a clone of the new LOFAR Cobalt-2 correlator, adapted and tuned for NenuFAR use and thus named NICKEL (NenuFAR Imager Correlation Kluster Elaborated from LOFAR's). It will deliver standard Measurement Sets (MSs) that can be processed for standalone imaging or for simultaneous use with the LOFAR MS on the same fields to provide information on short baselines down to 25 m.

Status and operation

At the present time first tests of the LOFAR super station mode have already been performed. At the end of 2020 the receivers and approximately 80% of the antenna (80 core + 4 distant MAs) should be operational and construction is expected to be complete by the end of 2021.

In order to control easily the relatively complex instrument that NenuFAR is, a Virtual Control Room (VCR) has been developed. This is a web interface that enables full management and control of the telescope and its receivers, from observation scheduling, preparation and programming to real-time display of low-rate statistical information, and data access and download, Real-time status monitoring from all parts of the system, even down to that of the preamplifiers attached to the individual antennas, has also been achieved, as has a maintenance management schedule.

In order to assist in the interpretation of the beamformed observations, a beam model has been computed for each individual MA and also for the entire telescope, thus enabling simulation of the expected beamformed response with a few per cent accuracy, which can be compared with the observations. Low-frequency observations are particularly affected by radio frequency interference (RFI), that will be monitored in order to either eliminate its source or to mitigate it in the data. Pipelines are in preparation for the standard processing of beamformed and imaging data (including excision of strong sources, RFI mitigation, calibration and transient detection). Imaging pipelines will be based on the kMS/DDf software developed at the Observatoire de Paris, and a near-real-time calibration+imaging scheme, inspired by the LWA-TV (http://www.phys.unm.edu/~lwa/lwatv.html), is in preparation, the results from which will be broadcast as NenuFAR-TV live.

Scientific exploitation

The NenuFAR scientific committee has launched an Early Science phase of 5 semesters from 1/7/2019 to 31/12/2021 to run in parallel with the end of construction and commissioning. The French community and European LOFAR collaborators were invited to propose Key Programmes for this Early Science phase. At present 15 programme areas have been proposed involving ~140 scientists from France and Europe (Cosmic Dawn, Exoplanets & Stars, Pulsars, Transients, Fast Radio Bursts, Planetary Lightning, Jupiter, Galaxy clusters & AGNs, Filaments & Cosmic Magnetism, Radio recombination lines, Sun, Gamma-ray showers, SETI, Cas A monitoring, Large Scale Background Survey). Semester calls for observation proposals from these Key Programmes will result, after validation by the NenuFAR scientific committee, in a schedule in tabular format. When exported in csv format, this schedule is automatically translated by the VCR into time block reservations, the setup of which can then be programmed by the end users, thus limiting the required human support and the risk of errors. Ignoring the data quality, the number of technically successful observations during the first semester has been close to 100%, demonstrating the robustness of the entire system.

NenuFAR was officially inaugurated on 3/10/2019 (https://www.obspm.fr/inauguration-de-nenufar-un.html). On 1/1/2022 it will be opened to the international community, which will be the start of its nominal exploitation phase. Time allocation will then be managed in the standard way by an international Programme Committee. During the 5 to 10 years from then, the fraction of open time will gradually increase to 100%, whereas Key Programme time will decrease to zero.

Conclusion

Selected as an official SKA pathfinder since 2015, NenuFAR is a new, large 4-in-1 low-frequency radio telescope performing simultaneously (1) standalone beamforming, (2) capture of waveform snapshots from selected antenna signals, (3) standalone imaging, and (4) as a giant low-frequency LOFAR station. Additionally, it will perform 'piggyback' SETI searches. The only observational constraint on the simultaneous use of several modes is the necessary restriction to the portion of the sky targeted by the analogue MA beams. NenuFAR should be the most sensitive instrument in its frequency range until the advent of the SKA that will bring a tenfold increase in sensitivity above 50 MHz (in the southern hemisphere). Please see: https://nenufar.obs-nancay.fr/en/astronomer/ for further information.

Ivan Thomas, Nançay Radio Telescope Facility,
Observatoire de Paris

The Threat of New Satellite Missions to the Global ObservationSystem (VGOS)

Introduction

An introduction to the International Very Long Baseline Interferometer (VLBI) Service for Geodesy and Astrometry (IVS) was provided in CRAF Newsletter No. 32. The IVS is a non-profit making global service, which provides Earth rotation parameters from daily VLBI observations. The IVS uses radio telescopes which are operated by mapping authorities, space agencies, research centres and universities throughout the world to determine the most accurate values of the Earth's rotation parameters (DUT1 and polar motion), which are a fundamental requirement for the determination of precise orbits of satellites etc. and space navigation. As global parameters they also play a role in Global Change studies. In order to be qualified as a VLBI Global Observing System (VGOS) telescope, a modern VLBI radio telescopes must fulfill certain technical requirements, notably have broadband receiving capabilities in the frequency range 2-14 GHz, and be capable of driving at speeds of 12 deg/s in azimuth and 6 deg/s in elevation, these latter in order to make measurements of as many radio sources as possible in as shorter a time as possible to provide corrections to the data for atmospheric variations. "Legacy" geodetic VLBI observations continue to be carried out in S/X-band (2.2-2.35 GHz, 8.1-8.9 GHz), but with less observations per time interval. In order to improve the VLBI performance, the spectrum observed by VGOS has been increased, covering a wider range of the radio window of the Earth's atmosphere. Currently, the VGOS observation bands are as given in Table 1.

VGOS-Band (2020)	Start [GHz]	End [GHz]
A	3.0004	3.4804
B	5.2404	5.7204
C	6.3604	6.8404
D	10.2004	10.6804

Table 1. VGOS Observing Bands

An increase in the observation bandwidth from 480 MHz to 960 MHz (Figure 10) is being planned, which should help in the achievement of the goal of 1 mm accuracy for a global geodetic reference frame, although this will also depend heavily upon the VGOS network, as well as complementary Satellite Laser Ranging (SLR) and Global Navigation Satellite System (GNSS) activities. Solely using Satellite techniques it is not possible to distinguish Earth rotation variations from satellite orbital deviations caused by the gravitational field of the Earth and radiation pressure. Amongst the geodetic space techniques only VLBI provides Earth rotation parameters which are independent from orbital errors in the gravitational field of the Earth, and which therefore can be fed back to control satellite systems.

A Problem

The VLBI service work, which has been carried out routinely in the S/X-bands used for space-communications, is now suffering from RFI as a result of the spread of WiFi into the unlicensed 2.4 GHz ISM-band at frequencies adjacent to those used for "legacy" S-band geodetic observations. This has triggered a desire to move away from the contaminated S-band to slightly higher, interference-free frequencies. The VGOS concept to deploy broadband

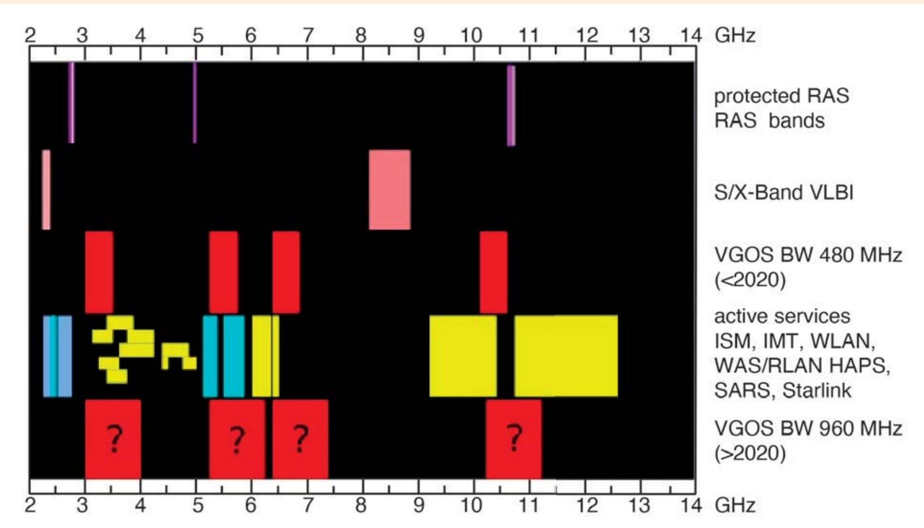

Figure 10. Showing the currently RAS protected bands and bands already allocated for use by other services.

Country/Region	5G allocation bands
Europe	3.400 - 3.800 GHz
USA	3.100 - 3.550, 3.700 - 4.200 GHz
Japan	3.600 - 4.200, 4.400 - 4.900 GHz
China	3.300 - 3.600, 4.400 - 4.500, 4.800 - 4.990 GHz
Korea	3.400 - 3.700 GHz

Table 2. Variations in 5G allocation bands per country.

Mission	Purpose	Allocated Spectrum
ICEYE	SAR mapping	9.200 - 10.400 GHz
Starlink, One Web	Internet by satellite	10.700 - 12.700 GHz

Table 3. Satellite transmissions of concern to RAS

receivers also promised to be the solution, as this should have enabled a much wider spectrum to be used, from which unused or passive bands could be selected for observation. However, other active services have also increased their demand for spectrum and have already received additional spectrum allocations, but which unfortunately vary on a global basis; i.e. from country to country. This is particularly true for 5G (See Table 2). In some countries 5G will be in conflict with the currently used VGOS band at 3.00 - 3.48 GHz. Thus, it is now unlikely that a global VGOS network can be configured to operate in the spectral range from 3.1 to 4.9 GHz. Although for cell phone users 5G has base stations which are meant to cover only 2 to 5 km, these may be detected as interference by a Radio Astronomy Service (RAS) station, such as a VGOS station, at distances up to 150 km unless some form of mitigation is introduced. In practice this means that the implementation of 5G around RAS stations must be regulated.

The situation is even more difficult with new satellite missions because an overflying satellite is mostly excluded from national regulation. This causes two problems to RAS stations in general:

1. The transmitted power may be detrimental to RAS stations.
2. The massive population of the sky by orbiting satellites, will take away the unpoluted sky and the undisturbed observation of radio souces, such as quasars, will become difficult.

New Satellite Constellations

In the age of the commercialisation of space new companies are exploiting space for business (see Table 3), and there are almost no international laws for the regulation of the use of space. Therefore it would appear to be an ideal 'playground' for start-ups. Two specific missions raise the concern of RAS-station operators. The start-up company ICEYE is flying a Synthetic Aperture Radar System (SARS) to map continuously the Earth's surface with powerful microwave radars at frequencies in the range from 9.2 to 10.4 GHz. The slogan of ICEYE is:- "every square metre, every hour" will be reached when a few more satellites are in orbit. That means that every hour there will be a threat for the RAS station to be hit by the strong radar signal, 17 dB above the burn-out level of a radio astronomy receiver according to ITU-Report RA-2188.

The SpaceX company is currently launching every month at least 60 additional satellites to add to the Starlink constellation, so that ultimately it will consist of 12,000 satellites providing Internet access from space. This system is planned to be completed by 2027. The frequency range to be used by Starlink for its downlinks is 10.7 - 12.7 GHz. A competing company, OneWeb, launched 74 of 648 planned satellites before ending in bankruptcy on March 27, 2020. In addition to bringing the internet to the whole world including very remote areas, it would appear that a main reason for the introduction of both systems is that they have a latency advantage over optical fibre networks when considering intercontinental distances; i.e. distances between international (financial) centres.

All of the above systems need to respect the existence of the ITU-registered RAS stations. For ICEYE this means that there will be white spots on its world maps at the locations of RAS sites. Starlink uses controllable downlink beams, which are currently being tested over US-territory. This system may be capable of respecting RAS sites by all of its 12.000 satellites. However, OneWeb beams illuminate much larger areas than do the Starlink ones and it is as yet unknown how the beams are to be adjusted and controlled when the downlink beam approaches a RAS-site. Currently the spectrum from 2 to 14 GHz shows a number of allocated active services to be in potential conflict with VGOS-bands. With the increasing number of satellite services, it will become more and more difficult to observe natural radio sources in the universe without interference from orbiting transmitters.

Summary

VGOS is facing a potential loss of its observation spectrum as a result of the introduction of satellite systems such as ICEYE and Starlink/OneWeb. Paradoxically, these satellite systems rely upon the Earth rotation parameters produced by VGOS observations. Passive services such as the RAS need a much stronger defence against the active services if they are not to be lost.

Hayo Hase, Bundesamt für Kartographie und Geodäsie, Germany

Report from WRC-19

World Radio Conferences (WRCs), at which representatives of the world's countries meet to decide upon the allocation of radio frequency spectrum for specific uses, are usually held every four years at the Inetrnational Telecommunication Union (ITU) in Geneva. However, the most recent, WRC-19, was held in Sharm El-Sheikh, Egypt over a period of four weeks from 28th October to 22nd November 2019. The conference was attended by a record number of more than 3500 participants from more than 160 ITU member states, in addition to sector members representing major telecommunication companies and scientific organisations. The Committee on Radio Astronomy Frequencies (CRAF), an expert committee of the European Science Foundation (ESF) and a sector member, participated in this Conference, representing the European radio astronomy observatories. The CRAF Chairman, Michael Lindqvist from Onsala Space Observatory in Sweden, and the Frequency Manager, Waleed Madkour, who is hosted at JIVE in Dwingeloo, the Netherlands, attended on behalf of CRAF (See photo 1). At the conference they 'teamed up' with other radio astronomy groups and sector members such as the International Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF) and the Square Kilometre Array Organisation (SKAO) to align the radio astronomy activities.

The agenda items of WRC19 covered frequency allocations proposed for a wide range of radio communication services, at the top of which were allocations for the new 5G tele-communications system. Proposed frequency allocations identified at the conference for this 5G were in the bands 24.25 - 27.5 GHz, 37.0 - 43.5 GHz and 66.0 - 71.0 GHz. Compatibility studies, carried out by CRAF and other RAS groups, had already shown the potential interference impact of these allocations on RAS observations using the 23.6 - 24 GHz passive band and the 42.5-43.5 GHz band. The studies recommended the introduction of separation zones around radio observatories away from the 5G services to mitigate interference. The final decisions agreed by the conference invited national administrations to take the necessary steps to protect the RAS observatories from potential interference expected from the 5G services.

Radio interference to the RAS 1612 MHz band by Iridium satellites for more than 21 years now was one of the complex issues discussed at WRC19. The Iridium satellite service will start to operate as part of the Global Maritime Distress and Safety System (GMDSS), a safety service that is primarily provided by Inmarsat.

Photo 1. Waleed Madkour (l.) and Michael Lindqvist (r.) at the WRC-19 in Sharm El-Sheikh, Egypt.

However, only a limited allocation of 5 MHz in the band 1621.35 - 1626.5 MHz was granted to Iridium for GMDSS and they were prevented from using the additional 5 MHz allocation down to 1616 MHz. The European position, supported by the RAS group, opposed the full allocation in order to ensure the frequency separation between the two services as much as possible. Moreover, hard regulatory limits were added in the final acts to urge the Iridium satellite services to keep the interference levels to the RAS band within the defined thresholds.

The conference agreed several frequency allocations and regulations for other emerging radio communication services such as the High Altitude Platform Systems (HAPS) and Land mobile and fixed services above 275 GHz. The regulatory protection conditions for the impacted RAS frequencies was correspondingly added.

The overall results of WRC19 are satisfactory for CRAF and the RAS community in general. It is now necessary for the radio astronomy observatories to closely coordinate with their national administrations in order to follow up on the implementation of WRC19 resolutions.

By mid-2020 CRAF preparations for WRC23 study cycle had started at both the ITU and CEPT levels. At the ITU level, CRAF participated in the radio astronomy WP7D meeting held in the period 14 -18 September 2020.

A number of liaison statements, including RAS protection criteria, have been sent to the responsible working parties for the agenda items of interest to RAS.

The agenda items considered to be of the most importance to the RAS at this preliminary stage are the use of high-altitude platform stations as IMT base stations (A.I. 1.4 HIBS), non-safety aeronautical mobile applications (A.I. 1.10) and Space Research Services (SRS) applications (A.I. 1.13). Other agenda items for the global maritime services (GMDSS), sub-orbital vehicles and space weather sensors are also of interest and are currently being tracked for more information. A proposal to upgrade the RAS secondary band, 608-6 014 MHz, to a primary allocation status is being evaluated according to the band usage demand in Europe.

At the CEPT level CRAF is planning to submit its preliminary positions for agenda items of interest to the CEPT Conference Preparatory Group (ECC-CPG) meeting planned for December 2020. The support of CEPT to the RAS in WRCs is of strategic importance to CRAF and therefore early alignment in both positions is necessary.

Waleed Madkour (CRAF Frequency Manager)
Michael Lindqvist, Onsala Space Observatory, Sweden

RFI Management in the SKA Observatory

Many published papers refer to the challenges that radio telescopes face regarding Radio Frequency Interference (RFI). With sensitivities several orders of magnitude higher than any communication systems, radio telescopes are not only sensitive to intentionally generated radio signals, but also to non-intentional emissions from electrical or electronic equipment (usually referred as EMI). The ITU-R recognised radio astronomy as a radio communication service (the RAS) at the World Administrative Radio Conference (WARC) in 1959 and allocated several radio frequency bands in that and subsequent WARCs in '63, '71, and '79. In the case of the Square Kilometre Array (SKA), the radio astronomy protected bands are complemented by wideband Radio Quiet Zone (RQZ) regulations on both telescope sites, creating another level of protection from active transmitters (especially terrestrial ones). Whilst intentional transmitters represent an issue for radio telescopes, the electrical equipment required to operate the radio telescopes can be also a serious problem ('internal RFI'). The control of non-intentional emission requires extra-ordinary measures when designing radio telescope facilities - completely shielded buildings, extensive use of fibre optic communication, low emission circuitry, and a very rigorous control of access and activities on site are some of the measures used to ensure that the quietness of the SKA's sites is not disturbed by their own telescope systems. This article will describe how the SKA has addressed the issue of internal RFI in the design phase and how it is intending to control it during the construction phase. A brief discussion about external RFI and its challenges is also included for completeness.

The SKA

The SKA will be one of the largest science facilities in the world, composed of a headquarters in the United Kingdom, two telescope arrays, one in Australia and one in South Africa, and a network of Science Regional Centres to process and distribute the scientific products. SKA-Low in Western Australia will cover the frequency range 50 MHz up to 350 MHz with 131,072 log-periodic antennas distributed in stations of 256 antennas with baselines up to 65 km. SKA-Mid in South Africa will cover from 350 MHz up to 15.4 GHz with 197 dishes (64 × 13.5 metre dishes from the precursor MeerKAT plus 133 new 15m dishes) with baselines up to 150 km. The extremely large amount of data that the telescope arrays will generate will be processed first on-site by a "Signal Data Processor" and

Figure 11.
Map of the world showing the countries that are currently members of the SKA Organisation (coloured light blue) and the location of the sites in Australia and South Africa where the SKA will be constructed.

then transported off-site to the "Science Data Processors" to generate the basic science products for the end user.

The SKA Organisation (SKAO), a UK limited company, is leading the effort to design and prepare for construction of the SKA Telescope. There are15 member countries in the organisation to date (coloured light blue in Figure 11) and 8 African partner countries into which the SKA-Mid phase 2 will extend. The SKA Organisation is currently undergoing a transition process to enable it to be established as the SKA Observatory, a treaty based Inter Governmental Organisation (IGO) that will construct and operate the SKA Telescope for its lifetime. This process is expected to be completed in Q1 2021.

To maximise the use of the radio spectrum for SKA observations, the telescope sites were chosen after consideration of their RFI quietness, this being the principal required characteristic. The Murchison Radio-astronomy Observatory in Western Australia and the Astronomy Advantage Geographical Areas in the Karoo in South Africa were selected after a long process. The two sites are protected by Radio Quiet Zone (RQZ) regulations in each country. These regulations define the sites as areas where the use of the radio spectrum is regulated with special regard to radio astronomical observations. RQZ regulations are enforceable on terrestrial transmitter equipment and activities conducted in or near the telescope sites; in the case of air- and space-borne transmitters these regulations are not enforceable or indeed applicable.

RFI Classification

Radio frequency interference can be broadly divided into two groups, internal RFI and external RFI, according to location and the level of control that exists over the source. Internal RFI includes any intentional or unintentional radio emission generated by SKA equipment or SKA activities (e.g. maintenance activities); these RFI sources are directly under the control of the SKA Observatory. External RFI covers all the radio transmissions that are not under the direct control of the Observatory, from other instruments on the site and their activities, to terrestrial, aerial or space borne transmitters. Furthermore, the external RFI can be subdivided into those controlled by National Regulation and those by International Regulation depending on the influence that the host country has over the source. The interface of this division is loosely defined with the elevation of the RFI source above ground level. This is illustrated in Figure 12. The following sections cover how the SKA manages each type of RFI.

Internal RFI Management

Internal RFI management is a constant process, starting from the design, continuing during construction, commissioning, and finally into the operation of the telescope. During every phase it is extremely important to consider the risk of any equipment generating radio emission that can enter the receivers and produce RFI. The SKA internal RFI management (or EMC management) has been

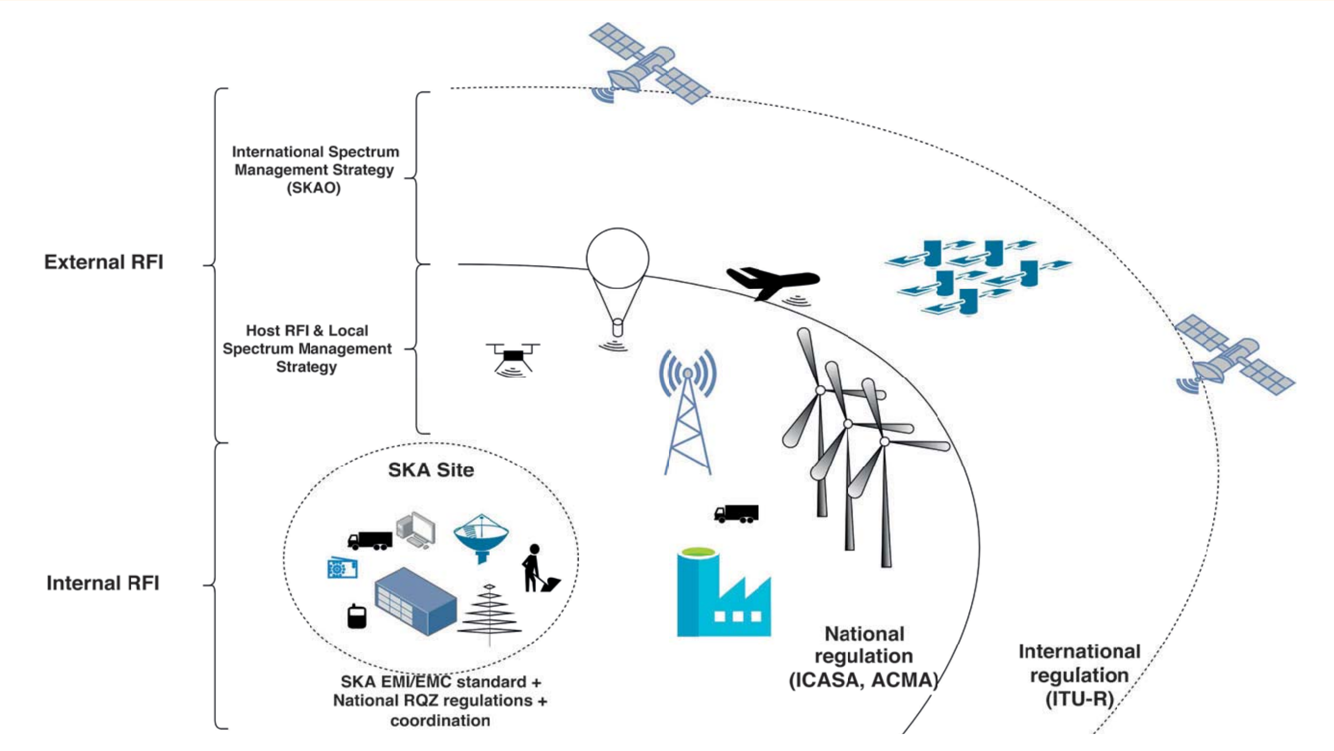

Figure 12. RFI Classification

planned from a system level point of view, with a document structure as shown in Figure 13.

Design phase

During the design phase, the system was divided into ten elements, each one assigned to a consortium composed of different research institutes and industry representatives. The SKA EMI/EMC Standard was created, based on Recommendation ITU-R RA.769-2, to set the thresholds of harmful interference for the SKA telescopes with a frequency coverage from 50 MHz to 25 GHz (see Figure 14). Also, a System Level EMC Control Plan (SLEMCCP) was created to define the process to be followed during the design phase. Individual elements of this had to be considered independently of other particular EMCCP Elements. This latter was a formal deliverable as part of each element design process. The risk assessment in each Element EMC control plan was based on the available information, measurements, and commercial standards.

For bespoke equipment to be installed in proximity to an antenna feed (such as receivers, cryo-coolers or digitizers) or equipment that is simply not designed to meet these extremely stringent requirements, achieving compliance to the SKA EMI/EMC standards is not an easy task. A comparison with typical commercial and military standards shows that equipment qualified to military

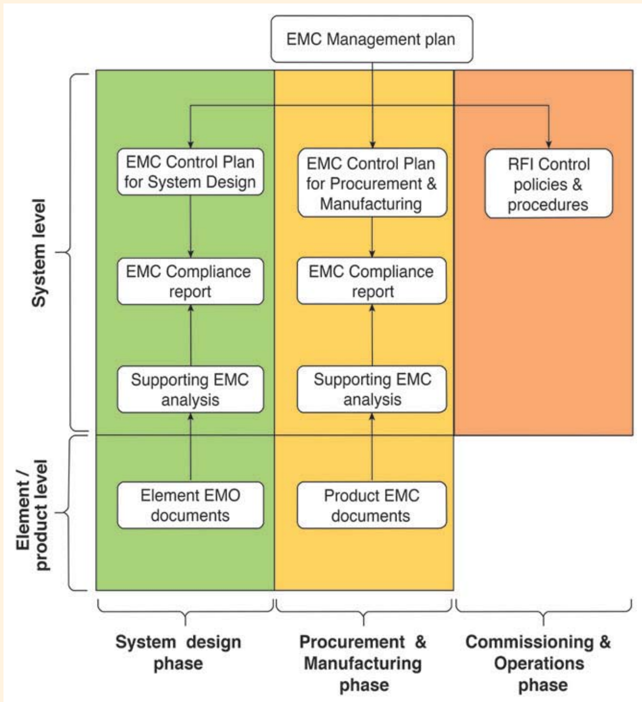

Figure 13. EMC Management Document Tree

standards (MIL-STD-461) would require an extra 80 dB of shielding, and one qualified to commercial standards would require up to 120 dB in some frequency ranges. To accomplish this, a variety of techniques were used such as completely shielded buildings for the large Central

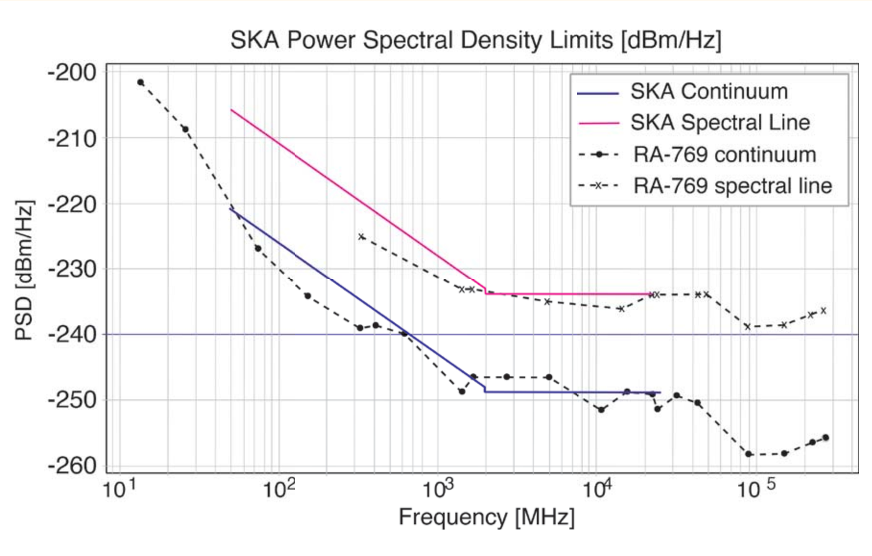

Figure 14.
SKA EMI/EMC standard limits for continuum and spectral line observations.

Processing Facilities, exclusive use of fibre optic communications, double shielded enclosures for stand-alone equipment, and screened glass for surveillance cameras to mention a few.

At the end of the design phase the consolidation of all the individual Element EMC control plans was used to generate a system level EMC analysis that evaluated the risk for each SKA antenna (or station in the case of SKA-Low) from different locations on the site (considering that each location may contain more than one product/piece of equipment). This analysis enabled the calculation of the level of margin that the design has with respect to the SKA EMI/EMC standard, and identified critical areas on which to focus during the construction phase. Thus, using information from the Element EMC control plans, the radiated emission from different, but co-located pieces of equipment were aggregated and used to calculate the total equivalent radiation level generated from a particular location. The propagation loss at different frequency intervals was then calculated using the topographical information of the site, and finally the level of received RFI by each SKA antenna was computed. The level of received RFI was compared with the SKA EMI/EMC thresholds to determine the margin. As an example, results for the interference levels at a number of antennae, and hence the margins, resulting from a repeater shelter (numbered 01), housing Signal And Data Transport (SADT) equipment for SKA-Mid, were derived from an EMC analysis. Figure 15 shows the attenuation in dB from the location of the shelter (bright region in the middle of the Figure) arising from the propagation loss, from which the interference levels at each of the antennae (white ‘dots’ in Figure 15) could be be easily determined. This EMC analysis was used as the basis for the EMC Compliance report of the SKA-Low and SKA-Mid telescopes at the System Critical Design Review, a milestone that marked the end of the design phase.

Construction phase

The management of internal RFI for the SKA is now focused on the construction phase, to start in early 2021. More than 60 large contracts will be awarded to different main contractors, who may further employ smaller contractors (who may not be familiar with EMC, and less so with the level of requirements that the SKA needs), so a clear plan has to be in place to set the requirements and guide them on how to achieve compliance. To address this, the SKA has created a System EMC Control Plan for the Procurement and Manufacturing Phase, that includes a description of how a typical product goes from the design stage up to site commissioning, with milestones and responsibility identification for each stakeholder. This document will be provided as an applicable document for each contract with an EMC control plan template in which the contractor will be able to complete the details of the product for which they are responsible, and through a decision tree identify the EMC requirements with which it has to comply.

The typical workflow of a product during construction will involve the creation of the EMC control plan, including a risk analysis to identify critical components and mitigation measures that will be implemented and verified during prototyping. The EMC control plan will identify the necessary milestones in the lifetime of the product (with involvement of the SKA Quality Assurance department) to ensure compliance with the SKA EMI/EMC requirements throughout the equipment manufacturing process.

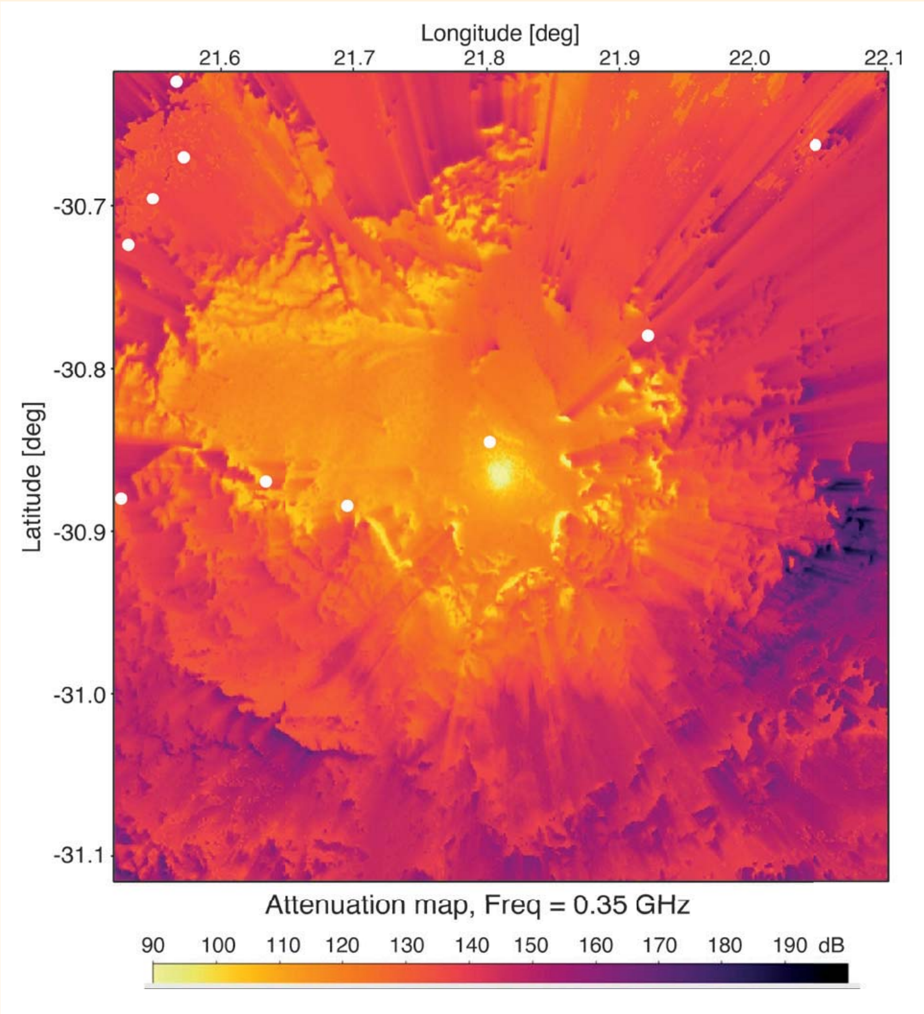

Figure 15.
Propagation loss from the SADT repeater shelter 01.
White dots are antenna locations.

Once prototyping and factory testing has been successful the product will be granted an RFI permit that will later be converted to a Certificate of Compliance after the RFI site acceptance test to verify installation and workmanship on site. A product with a Certificate of Compliance is granted permanent residence on the telescope sites.

Site controls

During construction and operation of the telescope, the access to the site must be properly controlled. It only takes a truck with Bluetooth enabled driving close to an antenna to completely saturate (and perhaps even endanger) a receiver. Both telescope sites have already working instruments, the MeerKAT and HERA telescopes in South Africa; and the ASKAP and MWA telescopes in Western Australia. Proper controls are already in place in both sites such as site access request forms, RFI inductions, RFI monitoring stations, gate checks, among others. The SKA will adopt these controls and tailor them to the specific needs of the Observatory.

The unintended emissions generated by equipment or activities of another instrument on site are also controlled by the entities controlling the site. RFI coordination groups are already in place on both sites where the owners of the different instruments can share their schedule and special events and can jointly solve RFI issues that appear.

External RFI Management

External RFI encompasses all intentional electromagnetic emissions generated by transmitters outside of the control of the SKAO. The use of the radio spectrum is regulated at the international level by the ITU-R through the Radio Regulations, an international treaty agreed by more than 190 countries that is ultimately implemented by each country at the national level. To influence these international and national regulations for the benefit of SKA telescope operations within their sites (and whenever possible for the more general interests of radio astronomy), the SKAO has created a spectrum management strategy with elements at global, regional, and national level.

The global element

As the largest radio astronomical observatory in the world, it is only natural that the SKAO will become one of the major players in international spectrum management, not only advocating for the protection of its sites and frequency ranges, but also concerned with wider radio astronomy interests. The SKAO will create a global forum to discuss spectrum management for radio astronomy where the radio astronomy community will have the opportunity to share their concerns and ideas.

As a sector member of the ITU-R, SKAO can submit documents, studies, and proposals to contribute to the work of study groups or working parties. Study Group 7 (science services) and in particular Working Party 7D (Radio Astronomy) are the natural places for the contributions from the SKAO, but it is just as important to participate in groups dealing with issues created by specific active services such as SG4 (satellite systems) or SG5 (terrestrial services). Other groups of interest to SKAO are SG1 (spectrum management, including spectrum monitoring) and SG3 (radio propagation).

While the work in the international spectrum management arena is paramount for the SKA, there will be situations where a technology with global impact represents a risk to the SKA that cannot immediately be dealt with at ITU-R level. In such circumstances, SKAO will engage directly with industry with a pro-active approach aimed at reducing the impact on SKA observations.

During each 4-year cycle leading up to a quadrennial World Radio Conference (WRC), the positions of the SKAO regarding agenda items of interest to Radio Astronomy will be presented and justified to administrations to seek endorsement and support.

The regional element

The ITU-R divides the world into three regions, each with one or several regional cooperation groups. These cooperation groups deal with the harmonisation of the use of the radio spectrum, promoting a more efficient use of it and developing common proposals to have greater influence at WRCs. Although the groups do not have binding regulatory power, their decisions can be very influential in their member countries (as is the case of the European Conference of Postal and Telecommunications Administrations, CEPT, in Europe). The SKAO will focus its regional work on CEPT, the African Telecommunications Union (ATU) and the Asia-Pacific Telecommunity (APT). Participation in these groups will allow SKAO to influence reports, recommendations and regional regulation to reflect the SKA and Radio Astronomy Service (RAS) needs.

On a regular basis, the SKAO engages and collaborates with groups dealing with the protection of the spectrum for radio astronomical use such as IUCAF (Inter-Union Committee on Frequency Allocations for Radio Astronomy and Space Science, an international collaboration between URSI, IAU and COSPAR), CRAF (the Committee on Radio Astronomy Frequencies dealing with the protection of European radio observatories), CORF (the Committee on Radio Frequencies dealing with science services in region 2 (the Americas, Greenland and the Eastern Pacific) and RAFCAP (the Asia/Pacific equivalent of CRAF and CORF). These groups have a long-standing history in the regional or international scene, and although their priorities may not always be the same as those of the SKAO, they can complement any work by the Observatory resulting in a maximisation of the effectiveness of available resources.

The national element

The national approach has two principal facets, namely the national position of the Telescope Host Countries, where regulation has created the Radio Quiet Zones, and the positions of all Member states whose governments have both a strong stake-holding in the SKA and statutory telecommunications administrations which vote in the ITU.

The SKAO will develop one-to-one relations with each national administration of its Member States, and through these liaisons will seek to influence regulation aimed at protecting radio astronomy at both national and international levels. The national administrations of SKAO Members, who may be sympathetic to radio astronomy, are among the most powerful allies when seeking protection from existing or new radiocommunication systems. A national administration wishing to protect radio astronomy has the power to request coordination from another administration attempting to file a new satellite station or to condition the licensing of ground terminals to ensure that the necessary protections are guaranteed.

Conclusions

Internal and external RFI control involve very different approaches but both must be considered to maximise the availability of radio spectrum for astronomical observations. The SKAO will continue investing effort in RFI management to protect the RFI environment in each telescope site, to advocate for the protection of radio astronomy through regulations, and to raise awareness of radio astronomy needs amongst industry and the general public.

Federico Di Vruno, Square Kilometre Array Organisation

The European Science Foundation hosts six Scientific Platforms:

- COAlition S
- The Committee on Radio Astronomy Frequencies (CRAF)
- The European Astrobiology Institute (EAI)
- The Europlanet Society (EPS)
- The European Space Sciences Committee (ESSC)
- The Nuclear Physics European Collaboration Committee (NuPECC)

In the statutory review of the Expert Boards and Committees conducted in 2011, the Review Panel concluded unanimously that all Boards and Committees provide multidisciplinary scientific services in the European and in some cases global framework that are indispensable for Europe's scientific landscape, and therefore confirmed the need for their continuation.

The largely autonomous Expert Boards and Committees are vitally important to provide in-depth and focused scientific expertise, targeted scientific and policy advice, and to initiate strategic developments in areas of research, infrastructure, environment and society in Europe.

Committee on Radio Astronomy Frequencies (CRAF)

CRAF is an Expert Committee of the European Science Foundation. Established in 1988, it represents all the major radio astronomical observatories in Europe. Its mission is to coordinate activities to keep the frequency bands used by radio astronomers in Europe free from interference.

Chairman:
Dr Michael Lindqvist, Sweden

ESF Science Support Office

Head:
Dr Nicolas Walter

Administrator:
Ms Mariette Vandermersch
Tel: +33 (0)3 88 76 71 19
Email: mvandermersch@esf.org

www.craf.eu

With over four decades of experience in all areas of research, the European Science Foundation (ESF) was originally set up in 1974 to act as a coordinating body for Europe's main research funding and research performing organisations. But as the research landscape has evolved, so has ESF's role in supporting scientific endeavours. ESF's traditional research support activities (EUROCORES, European Collaborative Research Projects, Exploratory Workshops, Research Networking Programmes) have been wound down and archives transferred to the Historical Archives of the European Union (HAEU) in Florence, Italy. ESF is now a services-based organisation that continues to contribute to the European Research Area (ERA). It is building on core strengths developed in peer review, evaluation and project management services and continues to host five Expert Boards and Committees, including CRAF, that provide in-depth and focused scientific expertise in selected disciplines. We are taking on this new endeavour with a commitment to high quality for our Member Organisations and the science community to provide valued services to Europe and beyond.

European Science Foundation
1 quai Lezay-Marnésia • BP 90015
67080 Strasbourg cedex • France
Tel: +33 (0)3 88 76 71 00
Fax: +33 (0)3 88 37 05 32
www.esf.org

Graphic design: Dans les villes
Autumn 2020 – Print run: 350