Challenges of Antenna in Radio-Astronomy

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Abstract— A major challenge for all high resolution low frequency radio astronomy is measuring and removing the effects of the ionosphere. The isoplanatic patch size for frequencies below a few hundred MHz is generally much smaller than the field of view. In addition, aperture arrays have beams on the sky which vary dramatically with observing geometry. These beams require careful calibration to be stable and known in order to allow imaging. It is noted that large radio telescope arrays such as the Very Large Array and Very Long Baseline Array at the National Radio Astronomy Observatory challenge the state of the art of microwave technology in many areas. Examples include the design of optimized sparse arrays and the design and the economic construction of high-performance, frequency-flexible antennas, reliable low-noise receivers, and highly phase stable local oscillator systems. Three-decade frequency range, greatly improved sensitivity and angular resolution that matches the capabilities of planned instruments in other frequency domains, are challenges that are now being investigated. Instruments for radio astronomical observations have come a long way. While the first telescopes were based on very large dishes and two-antenna interferometers, current Instruments consist of dozens of steerable dishes, whereas future instruments will be even larger distributed sensor arrays with a hierarchy of phased array elements. For such arrays to provide meaningful output (images), accurate calibration is of critical importance. Calibration must solve for the unknown antenna gains and phases as well as the unknown atmospheric and ionospheric disturbances. Future telescopes will have a large number of elements and a large field of view (FOV). In this case, the parameters are strongly direction-dependent, resulting in a large number of unknown parameters, even if appropriately constrained physical or phenomenological descriptions are used. This makes calibration a daunting parameter-estimation task.

Key words: Astronomy; Antenna Arrays; Frequency; Square Kilometer Array (SKA)

I. INTRODUCTION

Radio astronomy is a subfield of astronomy that studies celestial objects at radio frequencies. The initial detection of radio waves from an astronomical object was made in the 1930s, when Karl Jansky observed radiation coming from the Milky Way. Subsequent observations have identified a number of different sources of radio emission. These include stars and galaxies, as well as entirely new classes of objects, such as radio galaxies, quasars, pulsars, and masers. The discovery of the cosmic microwave background radiation, which provided compelling evidence for the Big Bang, was made through radio astronomy.

There are several ways to classify astronomical radio sources. Typical classifications are:

A. *Thermal Source:*

Source emitting via a thermal mechanism(e.g. blackbody radiation),

B. *Non-Thermal Source:*

Source emitting via a non-thermal mechanism (e.g. Synchrotron radiation, inverse Compton scattering, annihilation radiation, maser emission, etc.),

C. *Continuum Source:*

Source emitting over a broad range of frequencies,

D. *Spectral line source:*

Source emitting in narrow lines at specific frequencies,

E. *Galactic source:*

Source inside our Milky Way Galaxy,

F. *Extragalactic source:*

Source outside our Galaxy

II. RADIO TELESCOPES

A radio telescope is the instrument that permits us to study the radio waves from the stars, galaxies, nebulae, pulsars, and interstellar matter. From the study of these radio waves it is possible to analyze the source that produces the radio waves and the media through which the radio waves propagate from the source to the Earth. There are three main types of radio telescopes. The transit telescope has an antenna that can only move in one axis, elevation. The antenna moves only up or down along the meridian, in such a way that it can point both North or South. The telescope is pointed to the declination of the source we want to observe, and we wait until the apparent motion of the stars in the sky brings the source in front of the telescope. In this way, we can only make one observation per day of each source but this type of antenna is much cheaper to build than the other type. The second type of radio telescope is the one that can point to any place in the sky, and that can follow the daily apparent path of a source in the sky. This telescope can then point to a source and follow it for probably ten hours, depending on the geographical location of the observatory and the declination of the source. Although this type of telescope can be operated manually, with the amateur moving the antenna every 5 or 10 minutes, most of the advantages are realized when the antenna is moved with motors, controlled by the computer. The third type of radio telescope has two or more separate antennas installed over a certain area, and their signals are combined, to take advantage of the difference in phase between the signals received by them. In this way, the signals can be added or subtracted, obtaining the performance of a very large antenna, almost the size of the area covered by the antennas. If the installation uses more than two antennas, its operation requires a computer to control the phase between the different elements of the array. By combining the amplitude and phase of the different signals over a period of time, in what is called the reverse Fourier transform, and using the rotation of the Earth, maps of the sky can be derived. The precision of these maps depends of the dimensions of the array of antennas. A simple, two-antenna interferometer is within the capabilities of an amateur, since it can be adjusted to high performance for a particular frequency. The main advantage of such an interferometer is to obtain a much narrower beam width and a better resolution than with a single antenna. The main disadvantage is the free space required to mount the two antennas

The two major aperture synthesis instruments in the world today are the Very Large Array in the USA and the Giant Meter wave Radio Telescope (GMRT) near Pune, India.

III. CHALLENGE FOR ANTENNAS

A. Current and Planned Instruments:

There are several new-generation instruments planned or in current use for radio astronomy which have phased antenna arrays. Some examples are low frequency array (LOFAR) , murchison wide field array (MWA) and long wavelength array (LWA) , all of them working in the sub 300 MHz band. We also mention the SKA-aperture array low frequency (AAlo) which is projected for 2020 and which will be the next big step in low frequency radio astronomy. Its design will require ultra-wideband array performance (up to bandwidth ratios of 7:1) in impedance and radiation pattern (stable embedded antenna element patterns with beam widths up to 90 degrees).

B. System Noise:

The noise signal generated in an array antenna element from galactic radiation dominates over the noise generated by the front-end amplifier for frequencies below 200 MHz. The sensitivity of a low frequency radio telescope can be adopted as the primary figure of merit which, for the instruments mentioned above, is the ratio of the effective aperture to the system noise temperature (A_{eff}/T_{sys}) .The system temperature is also affected by the impedance mismatch and any losses between the element and the amplifier, as well as by the sky noise at lower frequencies. We therefore look closely at the different noise contributions

Both the staring sensitivity and the survey speed are proportional to (Ae /Tsys) and $(Ae /Tsys)^2$, respectively. Since the birth of radio astronomy, the capabilities of radio telescopes have increased dramatically, with a factor of ten improvements every ten years. This is almost entirely due to improvements in system noise made in existing telescopes, particularly the noise component generated in the first amplifier connected to each antenna in the telescope, the low-noise amplifier (LNA). To achieve this performance, LNAs are cryogenically cooled to 10-20 K. Because receiver systems using this technology are large, complex, and expensive, it makes sense to use as few as possible per unit collecting area, consistent with other constraints in the design of a telescope. At wavelengths around 30 cm, LNAs operating at 300K (room temperature) are showing sufficient promise that they might in future tip the balance in favor of un-cooled amplifiers at the longer wavelength end of the SKA frequency range

A common design theme for achieving low noise and high bandwidth ratio is the need to design the LNA and the antenna as an optimized integrated unit. This applies to SPFs for reflectors as well as to AAs and PAFs. This is a practical design and measurement challenge. Typically, LNAs are designed for standardized input impedances by people with different skills from those who design antennas and feeds. For AAs and PAFs, another design parameter is the noise coupled between adjacent antenna elements. Also, special measurement techniques must be adopted to measure and compare the noise performance of integrated units that are difficult to measure separately. At wavelengths longer than 1 m; noise from the sky begins to dominate system noise increasingly with wavelength. At these wavelengths, LNAs operating at room temperature (~300 K) are suitable for the SKA. Although they may be needed in large numbers, they are very inexpensive to fabricate.

C. Equations:

These spectra are characterized by a quantity called 'spectral index' α, defined by the formula:

$$S\nu \propto \nu^{-\alpha} , \qquad (1)$$

Where Sν is a quantity called the ‘flux density’ [unit: Jy (Jansky) ≡ 10−26W m−2 Hz−1],

Which is a measure of the strength of the radiation from a source. Thermal and non-thermal sources usually show different spectral indices, namely:

$\alpha = -2$ for thermal sources,

And

$\alpha \geq 0$ for non-thermal sources.

D. Mutual Coupling:

The effects of mutual coupling between closely located elements may bring about undesired effects in the performance of the array. Typically one sees the appearance of narrow-band anomalies which vary with the array geometry and type of antenna element. The anomalies appear only in certain pointing directions and frequencies (the pointing direction is also referred to as the scan angle). Several authors have addressed this problem in phased arrays of one and two polarizations for different types of elements. These include the presence of surface waves in a substrate cancelling the principal array mode, the energy transfer between common and differential modes of operation and the cancellation of the principal array mode by a horizontally-travelling wave created in the array structure. We need to analyze the effects of the anomalies in each particular application, as to remove them completely is usually expensive both in terms of performance and cost.

E. Array Beam:

The array beam (or station beam for an interferometer) has a major influence on the usefulness of the instrument. Not only does it need to be accurately characterized at every possible zenith angle, mode of operation, and frequency in order to be able to calibrate the array, but it must also provide a smooth and stable instrument response as the angle changes, so as to be able to track an object for long periods. A detailed study of these issues will be undertaken in. The expected effects, which depend on the array configuration, are:

- In regular close-packed arrays the effects of mutual coupling are strong but confined within narrow frequency bands and ranges of the scan angle.

- Regular sparse arrays (in which the average spacing between elements is about a wavelength and greater) still suffer from the negative effects of mutual coupling, but less so as the inter-element spacing increases. Side-lobes are also more troublesome.
- Random sparse arrays also normally suffer from the effects of side lobes, but because of the random grid, the effects are distributed across the parameter space, increasing the noise overall, but still providing a useful sensitivity at all zenith angles.
- Thin-sparse arrays use a sampling function to remove certain elements in the array to improve the side lobe level in specific cases. However, such arrays are still based on regular grids so the effects of the side lobes are more pronounced in certain frequency bands and angles

F. Antennas and Collecting Area:

The design of the SKA will be strongly influenced by the reduction of LNA noise in radio telescopes, to the point where further (dramatic) reduction seems unlikely. The SKA science goals require orders of magnitude more sensitivity than existing telescopes will be able to deliver. Thus the only way to increase the sensitivity is to increase the total Ae (η A), where is the aperture efficiency. Since efficiencies of existing telescopes are typically greater than 0.5, there is little scope for large efficiency improvements, but efficiency must be maintained in new designs. In the case of AAs, the efficiency subsumes a factor for average "foreshortening loss", a cos(Z) factor, where Z is the zenith angle of the pointing direction. Greater AA collecting area must be built to compensate for this factor.

G. Radio Frequency Interference (RFI):

RFI is a major problem in low frequency radio astronomy, especially for applications such as measuring interplanetary scintillations in which a short integration time is essential, and renders some bands, such as the FM band, unusable in practice. In passing some RFI occurs naturally, such as the broad-band interference from electric discharges. These pose a significant threat to the successful scientific exploitation of a given instrument and should be taken into account at the earliest stages of design and choice of site.

H. Characterization:

The large area associated with instruments of this type suggests that infinite array simulators may provide useful guidance in the design process, neglecting the edge effects present in any practical realization. Several commercial simulation packages are available for regular arrays. However, when the array is not regular these packages can, at best, provide only an approximate guide as to what to expect. Therefore, great efforts are being made to develop codes capable of simulating arrays of arbitrary size and sparseness, with the aim of obtaining full electromagnetic characterization of arrays with dimensions of hundreds of wavelengths. The commercial packages available, based on classical numerical methods such as the method of moments (MoM), finite differences in time domain (FDTD), or finite element method (FEM) are limited with respect to the maximum number of elements they can handle at once.

I. Data Transmission:

The design of the SKA as envisaged in any of its forms would be impossible without the advances in data transmission brought about by optical fiber transmission technology. Nevertheless, data transmission will limit SKA performance, in particular the usable Fovea of antennas at long distances from the array center (Long baselines).Fortunately, it is not a high scientific priority to image a large instantaneous FoV (e.g., tens of degrees squared) with high resolution (e.g., G 1 arcsec). The data rate R entering the central correlator and the distances of transmission are the driving cost factors.

For distances up to a few kilometers, analog optical transmission will be less expensive than digital, but the performance of analog systems remains to be fully established. The data transmitted over distances longer than a few kilometers will be in digital form. Clearly, the cost will also depend directly on the number of bits used to encode each sample. In the complete absence of interfering signals, radio astronomy can be done with 2 bits per sample with only a small impact on performance. However, even in the radio-quiet sites selected for the SKA, at least 4 bits per sample will likely be needed because of RFI from air and space-borne sources.

Data rates for maximum bandwidth, FoV, and collect-ing area are: SPFs with 8 GHz of bandwidth in each of two polarizations will produce 160 Gbits/s from each dish(assuming 25% encoding overhead) or, for an array of 3000 dishes , a total of 480 Tbits/s entering the correlator. PAFs with 700 MHz bandwidth per polarization in each of 30 beams will produce a total of 840 Tbits/s for an array 2000 dishes [5]. An array of 250 AA-patches covering an FoV of 250 deg2 with 700 MHz bandwidth will produce a total of 4.1 Pbits/s of data. The cost of these very high area in practice data rates is likely to limit bandwidth, FoV, or collecting.

J. Digital Signal Processing:

Digital signal processing traditionally encompasses operations on the data from digitization to the point where correlated results are written on general purpose computer storage devices. For an SKA design consisting of SPFs, the correlator is the main data processing unit. Although this will be a very large data processor, it may not cost more than a small fraction of the total cost of the SKA.

AAs and PAFs require a beamforming operation, a weighted sum of the signals from individual or small groups of elemental antennas, resulting in a single data stream. AAs also require the insertion of delays in the signal path from each input to compensate for geometrical delay. In the case of AAs, the weights are used to form and steer the telescope beam, whereas for PAFs, the weights are used to form beams that are displaced from the optical axis of the dish. For PAFs, the weights will be a function of frequency within the observing band . Thus it will be necessary to use digital filtering techniques to split these signals into a number of frequency channels before summing them. The filtering is efficiently done using a fast Fourier transform like operation called polyphase filtering . Because the presumed data rate is very large, it is important to minimize the number of channels needed at this stage

K. Calibration, Image Formation, and Non imaging Processing:

Image formation and calibration operations are carried out using software running on general-purpose computers or supercomputers on data emanating from the correlator, from which the output data rate is significantly reduced compared with the input.

The algorithms for image formation are a combination of 2-D gridding of data, Fourier transformation, de-convolution, and self-calibration. Wide-field imaging may require more steps or that these steps be carried out on subfields. These operations are carried out in a large iterative loop to reach an acceptable image, where the sidelobes of the synthesized beam and artifacts from inaccurate calibration are lower than the thermal noise level.

Searching for pulsars, especially millisecond pulsars, and carrying out sensitive timing analysis of pulsar signals is a key non imaging SKA science requirement. Since neutron stars, the sources of pulsar signals, are point-like, making images is not the main scientific requirement. Currently, most pulsar observations are made with very large single reflectors rather than arrays of antennas.

L. Scalability of Solutions:

The SKA will be considerably larger than the largest radio astronomy project to date. Although such scaling is often proposed, many of the technologies and designs used in smaller radio telescope projects cannot be scaled to the SKA. Non-optimum use of resources is of little consequence in such projects, but they become major obstacles when scaled up. The most obvious examples are power, space, interconnection in signal-processing equipment and long-distance data transmission; the required computational performance, and the development and maintenance of software. The final SKA design will have to attain very high utilization of resources to reach fruition. This will require efficient architectures supported by the very latest electronics packaging, cooling, and interconnection technology.

M. Cost:

Every project to build a new radio telescope has a limited budget. The largest arrays of many thousands of elements require the design of low-profile ultra-wideband antennas which are inexpensive, easy to build, and easy to maintain. The choice of cheap but resistant materials is crucial, so also is the proper design of protection systems, such as radomes and lightning protection.

The target budget for the SKA project, based on preliminary cost estimates, is 1500 million euros (2007). Of this, 1000 million euros are set aside for system, or hardware, costs. Software costs are estimated at a further 200 million, infrastructure at 200 million, and project delivery costs at 100 million euros. The latter includes larger scale non recoverable engineering costs (e.g., antenna manufacturing plant) and cost-loading for remote area construction. The costing process is being refined continuously, with verifiable cost estimates being an aim of the Prep SKA program.

N. Power:

Present estimates place the SKA power demand at 30-50 MW for the array proper, with a further 20-30 MW for supercomputing and associated facilities. While still quite uncertain, numbers such as these make it clear that power provision is a major challenge for the project. First, the isolated nature of the candidate sites means that over 100 million euros of capital expenditure will be needed to feed power to the central and remote parts of the array. Secondly, consumptions of this order mean that power will be a large factor in the total cost of ownership, with charges of tens of millions of euros per year being unavoidable. In capital terms, it is likely that the optimal infrastructure differs between South Africa and Australia, with grid-connection and self-generation options, respectively, being favored at this point. Part of the project investigation over the next few years will be to examine the suitability and possible use of renewable energy solutions in an effort to reduce supply costs and, perhaps, to break the nexus between SKA power costs and rising world parity prices. Regardless of the solutions chosen for the central site, it is certain that renewable power will be required for remote, isolated array stations; a present estimate puts individual station requirements at > 100 Kw.

While normally prosaic considerations, available and affordable energy solutions will define, in large measure, the capability of the SKA.

O. Receiver Element Complex Gain Variations:

Astronomical signals are very weak, and radio telescopes therefore need o be very sensitive. This sensitivity is inversely proportional to the (thermal) noise. This dictates the use of low noise amplifiers, which are sometimes even cryogenically cooled. Variations in environmental conditions of the

receiver chain, such as temperature, cause amplitude and phase changes in the receiver response. Signals must also be propagated over long distances to a central processing facility and, depending on where digitization occurs, there can be significant phase and gain variations over time along these paths.

P. Propagation Effects:

Ionospheric and tropospheric turbulence cause time-varying refraction and diffraction, which has a profound effect on the propagation of radio waves. In the simplest cases this leads to a shift in the apparent position of the sources

Q. Data challenge:

Not only are large surveys such as EMU changing the observing mode, but the way that we process the data is changing too. Until recently, astronomers would observe at the telescope, then take their data home on disks and spend weeks or months processing it. However, next-generation large surveys will generate data volumes that are too large to transport, and so all processing must be done in situ. To keep up with the data flow from the telescope, data processing must be done in near-real-time, which requires that it must be automated. Almost all next-generation telescopes now being designed offer automated pipeline reduction of data.

IV. CONCLUSION

This paper summarizes the main issues in the design of an antenna element for use in an ultra-wideband large aperture array, such as the SKA-AAlo. The most relevant codes in electromagnetic simulations currently available are described and a design process is presented. This is based on the system noise and the effective aperture of a unit cell in an infinite regular array, which define the instrument sensitivity, taken as the figure of merit for a radio telescope. An analytical study has been described here of a bow-tie antenna element immersed in an infinite array, as a potential candidate for the SKA-AAlo, and it both questions some well known rules of thumb about array antenna theory and gives designers some useful hints on how to design a radio astronomy station. We find that larger elements, with sizes comparable to the wavelength, are likely to give better sensitivities at low frequencies because of better matching to the amplifier, but at the cost of a more expensive antenna. However, large elements have multiple lobes and it is therefore necessary to find the maximum size above which the sensitivity falls off at the high frequency end of the band. The higher system temperature delivered by a smaller element can be partially mitigated by taking advantage of mutual coupling and placing antennas in a denser configuration, which improves the sensitivity at the high end of the band. However, at the low end of the band, the high sky brightness dominates the system temperature and a sparser array delivers better sensitivity because of the larger effective aperture for a given number of elements. All of these effects, taken together, indicate that a sparse array of ultra-wideband elements (electrically small at the low end of the band) is, overall, a better option than a dense array for the SKA-AAlo band. We find that a bow-tie antenna element is a suitable candidate for this type of array, offering the necessary flexibility in a wide band of frequencies. Furthermore, a modification of the basic bow-tie element, in which the arms are inclined at an angle to the ground, has been used to improve the sensitivity without modifying the overall antenna size or the inter-element spacing. With this new degree of freedom, it becomes easier to find a compromise to fulfill the SKA-AAlo requirements. Next generation radio telescopes offer us a profound change in the way that we do astronomy, with the promise of major discoveries by exploring fresh areas of observational phase space and applying new data-intensive techniques to extract the science from the data. But they will also require a level of computing power that place them amongst the most computer-hungry projects on Earth and also assume that our current approaches are all scalable. .

V. FUTURE CHALLENGES

Instruments like LOFAR and SKA will have an unprecedented sensitivity that is two orders of magnitude higher (in the final image) than current instruments can provide. The increased sensitivity and large spatial extent requires new calibration regimes, i.e., scenarios 3 and 4, which are dominated by direction dependent effects. Research in this area is ongoing. Although many ideas are being generated, only a limited number of new calibration approaches have actually been tested on real data. This is hardly surprising since only now the first of these new instruments are producing data. Processing real data will remain challenging and drive the research in this area of signal processing. Apart from the challenges discussed already throughout the text, some of the remaining challenges are as follows.

A. The Sky:

Because of the long baselines that are part of the new instruments, many sources which appear point-like to existing instruments, will be resolved. This means that they cannot be treated as point sources, but should be modeled as extended sources using, e.g., shape lets .The new instruments will have wide frequency bands, so that the source structure may change over the observing band. For these reasons the source models will have to be more complicated than currently assumed. At the same time, due to the increased sensitivity, many more sources will be detected and will have to be processed. This will not only affect the calibration of the instruments, but also the imaging and de-convolution. Because of their high sensitivity the new instruments are capable of detecting very weak sources, but they will have to do so in the presence of all the strong sources already known. Some of those strong sources may not even be in the FOV, but may enter through the primary beam side lobes.

B. The Instrument:

Both aperture arrays and dishes with FPAs have primary beams that are less stable than single pixel primary beams from dishes. The primary beam is time dependent (if it is not fixed on the sky) and varies with frequency and over the different stations or FPA systems. These beam pattern variations have a negative impact on the achievable image quality. Calibrating for these beams is a real challenge, as is the correction for such beams during imaging.

C. The Atmosphere:

For low frequency instruments, ionospheric calibration is a significant challenge. Current algorithms have been shown to work for baselines up to a few tens of kilometers and frequencies as low as 74 MHz However, for baselines of a few hundreds up to a few thousands of kilometers and frequencies down to, say, 10 MHz these algorithms may not be valid.

D. Polarization Purity:

Calibration and imaging have to take the full polarization of the signal into account. The primary beam of an instrument introduces instrumental polarization due to the reception properties of the feeds. If the feeds do not track the rotation of the sky, as is the case in any radio telescope that does not have an equatorial mount, the instrumental polarization varies over the observation. The ionosphere alters the polarization of the incoming electromagnetic waves as well due to Faraday rotation. These effects require calibration and correction with high accuracy.

E. The Large Number of Elements:

Classical radio telescopes have at most a few tens of receivers (WSRT has 14 dishes and the VLA has 27). Instruments like LOFAR, MWA and EMBRACE will have about 104 receiving elements while SKA is envisaged to have over 106 signal paths. The corresponding increase in data volumes will require sophisticated distributed signal processing schemes and algorithms that can run on suitable high performance computing hardware.

F. Equations and Unknowns:

It is clear that in order to deal with these challenges more complicated models are needed, which in turn contain more unknowns that need to be extracted from the data. The increase in the number of stations will yield more equations, but this may not be enough. Modeling of the time-frequency dependence of parameters by a suitable set of basic functions will decrease the amount of unknowns that need fitting.

G. Interference Mitigation:

The radio frequency spectrum is rather crowded, and it is expected that many observations will be contaminated by (weak or strong) RFI. Array signal processing techniques can be used to suppress interference, e.g., by active null steering or covariance matrix filtering. For LOFAR and SKA, no techniques have been proposed yet. Research from cognitive radio and compressive sensing may be very relevant for interference avoidance.

Finding suitable answers to these challenges will be of critical importance for the next generation of instruments

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