Copyright Notice

Warnick, K.F., Ivashina, M., Hay, S.G. (2011) Guest editorial for the special issue on antennas for next generation radio telescopes. *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 6, pp. 1786-1789.

http://dx.doi.org/10.1109/TAP.2011.2156510

Guest Editorial for the Special Issue on Antennas for Next Generation Radio Telescopes

Beginning with Karl Jansky's pioneering work early in the last century, the challenge of detecting extremely weak emissions from deep-space radio sources has motivated important advances in antenna technology. The first topical special issue in the IRE Transactions on Antennas and Propagation, published in January 1961, was on Radio Astronomy. This special issue on antennas for next generation radio telescopes will be published on that issue's 50th anniversary.

Lloyd V. Berkner, President of the Institute of Radio Engineers at the time of that first special issue's publication, observed in the opening editorial that "antenna and feed characteristics in radio astronomy represent the limits of progress in radio optics at any time...[and] these developments have provided to all radio science and technology a wellspring of fundamental knowledge that is applicable in almost every advanced endeavor in radio technology." Kraus, Nash, and Ko's paper on the Ohio State University 360-Foot Radio Telescope, Swenson and Lo's report on the 400 $\times$ 600 foot parabolic cylinder University of Illinois Radio Telescope, and other papers on advances in interferometers and receiver technology represented the state-of-the-art antenna technology of the day.

Berkner's characterization of radio astronomy as a driving force in microwave systems and antenna design has held true over the ensuing 50 years. Milestones include massive reflector antennas, of which the 100 meter Green Bank Telescope and 300 meter Arecibo Telescope are the largest, and sparse arrays such as the Westerbork Synthesis Radio Telescope (WSRT), the Very Large Array (VLA) in Soccoro, NM, and the global Very Large Baseline Interferometer (VLBI) network. Newer instruments include the Atacama Large Millimeter Array (ALMA) in Chilé, the Giant Metrewave Radio Telescope (GMRT) in India, and the Allen Telescope Array (ATA) in California. Dozens of other important specialized and general purpose instruments are in operation around the world.

Key enabling technology developments of the past few decades include synthesis array image formation algorithms, stable clocks and recording systems for VLBI, digital spectrometers and correlators using custom integrated circuits and FPGAs, high efficiency feeds such as corrugated horns, signal processing techniques for pulsar detection, and low-noise receivers. The latter area has been particulary important, as amplifiers have progressed over the last several decades from parametric and maser to discrete cryogenic transistor amplifiers achieving equivalent noise temperatures remarkably close to absolute zero, as well as MMIC amplifiers and superconducting tunnel junction (SIS) mixer front ends.

Radio astronomy continues to be a forward looking endeavor as breathtakingly bold plans for future instruments take shape. In China, ground has been broken for the 500 meter aperture spherical telescope (FAST), which will become the largest contiguous single aperture antenna. Upgrades to existing instruments are in various stages of design or build-out, including the Expanded Very Large Array (EVLA) and phased array feeds for WSRT, GBT, and Arecibo. The Precision Array to Probe the Epoch of Reionization (PAPER), the Murchison Widefield Array (MWA), the Long Wavelength Array (LWA), the European Low Frequency Array (LOFAR), MeerKAT in South Africa, and the Australian Square Kilometre Array Pathfinder (ASKAP) are laying the groundwork for the Square Kilometer Array (SKA), a distributed array of antennas over thousands of kilometers. The SKA could be by almost any measure the largest scientific instrument ever built.

Building on a rich heritage of astronomical instrument development work, research that supports these recently completed and planned facilities continues to drive progress in antenna technology. Detecting weak astronomical signals pushes receiver performance requirements to the absolute limits. Extremely stringent design specifications for antenna and feed systems include multi-decade or even octave bandwidths, system gain stability of a few parts per thousand or better, dynamic range when discriminating weak sources from nearby bright sources as high as 60 dB, ultra-low equivalent system noise temperatures (e.g., below 20 Kelvin at L-band), immunity to radio frequency interference, and wide angular field of view. Systems in use at the time of the 1961 special issue already met some of these requirements, but achieving tight stability and sensitivity requirements over a wide field of view and broad bandwidth with modern phased array technology is an unprecedented challenge for antenna systems designers.

A. *Papers in the Special Issue*

This special issue includes 28 full-length papers, representing state-of-the-art work being carried out at more than 20 institutes around the world in ten geographically dispersed countries. This collection provides a comprehensive overview of the research and development progress on innovative antenna technologies for existing and future radio telescopes, and outlines the challenges ahead in operating such complex systems.

a) Antenna analysis and optimization (10 papers): The issue begins with a set of 10 theoretical papers that present a framework for analysis and optimization of new-technology antennas for array-based radio telescopes. These technologies include ultra-wideband single-pixel feeds (SPFs) and wide field of view phased array feeds (PAFs) for reflector antennas and large aperture synthesis arrays with densely packed or distributed antenna elements. An accurate full-wave analysis of such array antenna structures represents a challenging problem with characteristic dimensions beyond the size that commercial modeling tools can typically handle. This is because large wide-band array antennas exhibit multiscale features and array elements are composed of both dielectric and metal materials and may be strongly coupled. Moreover, given the computationally intensive nature of the full array simulations as well as a wide range of frequencies and scan angles that must be considered, optimization of the relative position and geometry of array antenna elements by evaluating the entire structure in full details is difficult.

To improve the computation efficiency for multiscale designs, a number of numerical approaches have been proposed that collectively can be referred to as domain decomposition techniques. The methodology of decomposing a large and complex antenna problem into many smaller subproblems is based on solving for local subproblems independently from each other (such as partial arrays or subarrays of smaller number of elements) and then accounting for their mutual interactions in a simplified manner before forming a total solution. By resolving for the adjusted subproblems only, the large antenna structure can be analysed by using moderate computing power. Furthermore, it can be locally optimized with the aid of numerical algorithms or optimisation procedures that exploit the *a priori* available knowledge on the partial solutions or sub-optimal analytically-derived solutions of the entire problem.

Another important contribution surveyed in this group of papers is the understanding that the interaction between antenna element mutual coupling, receiver noise and beamformer weighting scenario is critical when designing high-sensitivity wide-band array systems. Due to the mutual coupling and associated excitation dependent noise contributions, characterization of active array antenna systems is no longer an antenna or low noise amplifier problem alone, but it becomes a combined antenna-receiver and signal processing problem. An accurate solution of such complex problems requires new multi-disciplinary system modeling approaches, such as those proposed in the last three papers of this theoretical framework. A few of these approaches have been applied for characterization of practical AA and PAF systems including the Long Wavelength Array (LWA) and the Westerbork Synthesis Radio Telescope and Arecibo on which new-technology PAF prototypes have been tested. The agreement between the measured and predicted sensitivities and system noise temperatures is very good and within 20-30% over a wide frequency band and scan angle range. One of the papers argues that at very low frequency regime (below 100 MHz), when Galactic noise constitutes a dominant contribution to the total system noise, it is possible to reduce the effect of mutual coupling in the phased array such as variation of the beam shape with observation direction by using an antenna element with low receive coupling. Roy and George report on a noise wave theory and measured results for a two-antenna test setup which suggest that the coupled noise contribution in the system noise budget for the SKA will be small. Since the active impedance concept used in other papers on noise coupling can be derived from the noise wave model, it will be of interest in future work to verify that predictions using the various available theoretical frameworks are in agreement.

b) System and prototype development (10 papers): The next group of 10 papers gives an overview of ongoing and completed developments on sub-system designs for existing and future instruments. The first five contributions present horn feeds for reflector antennas and transducers for UHF/VHF, L-, C-, K-, W and Q-band receivers for the Karoo Array Telescope (KAT-7), Expanded Very Large Array (EVLA), a new radio telescope at Yebes Astronomical Observatory, the 1.4m telescope in Chile, Water Vapour Radiometer, and 1D PAF design concept for the Northern Cross Radio Telescope. The main focus of these activities is on compact and lightweight designs to enable cryogenic cooling and very low receiver noise temperatures, while achieving an improved antenna efficiency, low side lobes and cross-polarization levels, a simplified manufacturing process, and a cost-effective design. Results obtained so far for these sub-systems predict the 30-50% bandwidth with the sidelobe level and cross-polarization better than 30 to 40 dB with a 20-30% reduction of the feed system dimensions.

The next four papers deal with wide-band SPF systems for operation at frequencies from 0.4 GHz to 14 GHz.

To realize a full decade of operating bandwidth, two alternative solutions have been studied. The first solution is based on introducing an additional (tertiary) offset mirror into the reflector system that can be rotated and re-focused to use several feeds with narrow frequency bands. The second solution represents a combination of a deep wide-angle reflector antenna (such as prime-focus or displaced axis dual reflector system) and a wide-band feed to simultaneously cover the full decade bandwidth. The wideband feeds presented in the papers are different in concept, but are similar in terms of beamwidth and phase center location, both being rather constant with frequency. Two of the papers present results with cooled integrated antenna-receiver systems, demonstrating high aperture efficiency (>40-50%) of the illuminated reflector over a decade bandwidth, but the results indicate that more research is needed to achieve system noise temperatures closer to what the low-noise amplifiers can deliver.

c) Experimental verification and in-situ performance (4 papers): The third group of papers describes the system design and in-situ performance of new technology array-based telescopes including the Q/U Imaging Experiment (QUIET), Allen Telescope Array (ATA), Low Frequency Array (LOFAR) and the Aperture Array Demonstrator for SKA (EMBRACE). The focus of these contributions is on characterization of the antenna beam scan performance, beam shape stability during observations, dish quality under various solar heating conditions, receiver noise temperature and overall system sensitivity. For accurate assessment of these key performance parameters, several traditional and novel experimental techniques are considered, and steps are made towards translating the measured results to requirements for performing efficient calibration and accurate imaging. Although the described antenna technologies and operating frequencies are different, we can conclude that a full characterization of a phased array telescope is needed due to the direction and time dependent effects of the beam shape, correlated receiver noise and sensitivity, the presence of multiple sources on the sky, and manufacturing differences between many antennas or receiver units of the instrument. It has to be demonstrated by future studies to which extent these non-systematic effects can be reduced by improving the system design and what challenges must be solved in post processing when constructing the image.

d) Open questions and future challenges (4 papers): The special issue ends with four theoretical contributions which outline open questions and practical challenges that engineers and astronomers would likely face when operating new-technology telescopes. The first paper emphasizes the importance of mechanical factors such as the deformation of the antenna platform under the operation of the telescope in the design procedure and supports this conclusion by both numerical and experimental results for the AMiBA Telescope in Hawaii. The following two papers deal with PAF systems and propose, respectively, a broadband signal beamforming method based on the use of real-time spatiotemporal 3D digital filters and an efficient method for reducing the computational cost of the correlator by arranging the reflector antennas into linear arrays. The last two papers open a discussion on the polarimetric performance figures of merit and beamforming and calibration methods which need to be developed to enable high-precision polarimetry with future phased-array radio telescopes.

The Guest Editors thank the authors for outstanding contributions and the reviewers for their excellent work in ensuring that papers in this issue are of the highest quality. We express gratitude to the IEEE Transactions on Antennas and Propagation Editor-in-Chief, Dr. Trevor S. Bird, for support and encouragement as this issue was conceived and prepared, and Prof. Michael A. Jensen for overseeing its finalization and publication. As the writing of this editorial coincides with Dr. Bird's departure as Editor-in-Chief, we recognize his outstanding work, many hours of tireless service, and the significant progress of the Transactions during his tenure. We end with the hope that this special issue will help to promote future research and development efforts that will be as stimulating and energizing to the field of antennas and propagation as has been the last fifty years of progress on astronomical instrumentation and technology.

Karl F. Warnick
Department of Electrical and Computer Engineering, Brigham Young University, 459 Clyde Building, Provo, UT 84602, USA. E-mail: warnick@ee.byu.edu.

Marianna V. Ivashina
Department of Earth and Space Sciences, Chalmers University of Technology, S-41296 Gothenburg, Sweden. E-mail: marianna.ivashina@chalmers.se

Stuart Hay
Commonwealth Scientific and Industrial Research Organisation (CSIRO) ICT Centre, PO Box 76, Epping, 2121, Australia. E-mail: Stuart.Hay@csiro.au