Proposal for a special session at ICASSP 2005:

TOWARDS A NEW GENERATION OF RADIO ASTRONOMICAL INSTRUMENTS: signal processing for large distributed arrays

This session was organized at the request of the ICASSP'05 General Chair, Prof. Athina Petropulu.

Organizers

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Motivation

Radio astronomy forms an interesting application area for array signal processing techniques. Technological advances in the last decade have created possibilities for large distributed interferometric radio telescopes with very large receiving areas and a sensitivity which is one to two orders of magnitude better than the current generation. Increased sensitivity implies receiving more interfering signals, and therefore RFI detection and removal is now an important topic in radio astronomy. Fortunately, massive phased array technology will also provide increased flexibility to filter out interference.

International efforts for this new generation are coordinated under the framework of the Square Kilometer Array programme (SKA), `http://www.skatelescope.org`, with a target commissioning date of around 2012. Another example of a distributed phased array radio telescope will be the Low Frequency Array (LOFAR) which is currently under construction in The Netherlands (`http://www.lofar.org`), and slated for 2006–2008. Prior to this, the international Atacama Large Millimeter/Submillimeter Array, or ALMA, will be constructed in a desert in Chile.

ALMA will be the latest and most advanced example of the more 'traditional' generation of telescopes, with 64 transportable and mechanically steerable 12-meter dishes (fig. 1(*a*)). In contrast, the preliminary LOFAR design calls for an instrument consisting of about 13,000 'simple' omni-directional antennas (10–240 MHz), grouped in about 50 stations spread in spirals over an area with a diameter of about 360 km, as well as in a more densely populated central core (fig. 1(*b*)). The 200 antennas in each remote station are used as a phased array and are combined in such a way that a beam is formed into a desired look-direction. The resulting output of each beamformer is similar to the output of a telescope dish pointing into the same direction, but is obtained without the use of any moving parts. LOFAR can be seen as a stepping stone for SKA, which should have an effective aperture area of one square kilometer, in the frequency range from 150 MHz up to 20 GHz. Just as as LOFAR, it will be a large distributed telescope with many individual elements. The telescope concept for SKA is not yet defined, but several designs are currently being worked out.

The purpose of this special session is to let radio astronomers and engineers involved in the system design of the future generation telescopes present their plans to the signal processing audience at ICASSP,

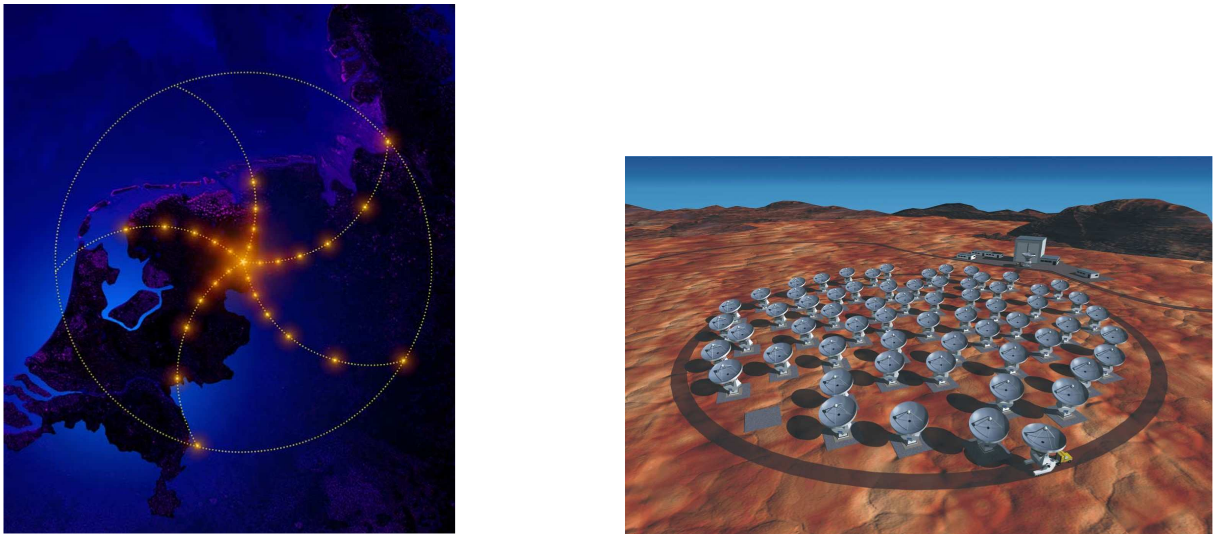

Figure 1. (*a*) Layout of the LOFAR stations; (*b*) ALMA telescope concept.

and thus to stimulate the interaction between the two fields. Prominent among the challenges of designing and building the new telescopes (apart from the costs) are the mitigation of radio interference, the calibration of the system, and the sheer signal processing complexity. Of particular interest are the following signal processing aspects:

Calibration. Initially the locations and frequency-dependent gains and phases of each receiver unit are unknown and need to be estimated. Additionally, the disturbance due to the propagation through the earth ionosphere (time- and space-varying) has to be measured and compensated for. For large distributed arrays, this is a challenging task.

RFI mitigation. The frequency bands of interest to radio astronomers contain many sources of RFI (radio frequency interference). RFI mitigation techniques will (necessarily) have to form an integral part of the system design. Interesting issues arise because of the hierarchy in the new generation of telescopes: RFI mitigation is possible at the station level (beamforming) but also at the central level (before or after correlation).

Postcorrelation processing and imaging. In its simplest form, image formation consists of a spatial Fourier transform of the received correlation data. Accurate array calibration parameters are needed to perform this step correctly. After initial image formation, iterative deconvolution algorithms are used to find the locations of the point sources and subtract their effect in the image, so that the more subtle structures become visible. This step can be combined with a gradient search to improve the calibration parameters. Current techniques such as SELFCAL need to be extended to the case of distributed arrays with millions of unknown parameters,

Outline of the session

The session consists of 6 invited oral presentations; the first presentation gives an overview. The presenters are all senior researchers associated with radio astronomical institutes, and deeply involved in future telescope projects. Note that most of them are not regular ICASSP attendees, thus making this session truly “special”.

The talks in the session cover the following topics (see the list of abstracts below for more details):

1. Overview of SKA, the science case, and the various design concepts
2. ALMA system design

3. LOFAR system design
4. Imaging problems for SKA telescopes
5. Postcorrelation techniques for RFI mitigation
6. Calibration, sensitivity and RFI mitigation requirements for LOFAR and SKA

Organization

The session consists of invited papers only. Full versions of the papers are collected by the session organizers by 15 November and will receive a “friendly review” to ensure their quality and adherance to the ICASSP format. The final versions will be submitted to the ICASSP web site before 13 December.

Abstracts of the session presentations

1. **Overview of SKA science and technology drivers**

   Steve Rawlings, Oxford University, UK

   There are many parallels between the probable future of astronomy and the recent history of particle physics. Astronomy too is becoming a “big science” in which large numbers of researchers rely on huge, but flexible instruments. The Square Kilometre Array (SKA), currently being designed as the next-generation radio telescope, is likely to be the first of these instruments to be built. Provided severe signal processing challenges can be overcome, the SKA can be built as a multi-beam instrument which, like particle accelerators, can be shared simultaneously by many teams of researchers.

   The presentation will outline the main science goals of the SKA: (i) the study of the origin of earth-like planets and life; (ii) pulsars as tools for pushing studies of General Relativity towards its breaking point; (iii) probing the origin of magnetic fields; (iv) studying galaxy evolution and cosmology, including the mysterious dark energy; and (v) observing the first galaxies in the Universe and the neutral gas from which they formed. It is then shown how science return is simply related to how signal processing capabilities will develop over the next ten or so years. Finally, an overview is given of the various telescope designs which are currently being proposed.

   Prof.dr. Steve Rawlings is a research astronomer in the Department of Astrophysics, Oxford University, and a Physics Professor at Oxford University. He is the Chair of the International SKA Science Working Group.

2. **ALMA: Imaging at the Outer Limits of Radio Astronomy**

   Darrel Emerson and Al Wootten, National Radio Astronomy Observatory (NRAO), Tucson (AZ) and Charlottesville (VA)

   The Atacama Large Millimeter/Submillimeter Array, or ALMA, is an international telescope project currently under construction in Northern Chile. Antennas arrayed over baselines up to 18 km in extent constitute over 7000 m^2 of collecting area, enabling ALMA to provide images of unprecedented clarity and detail. Unlike existing radioastronomical arrays, ALMA will combine interferometric and single telescope data, providing a complete range of spatial scales with complete flux recovery. Six of a planned ten planned receiver bands will be built during the construction phase; eventually ALMA will cover all atmospheric windows in the spectral wavelength range from 7mm to 0.3 mm. The combination of sensitivity, directivity, full UV coverage from the large number of individual antenna elements, precision calibration and the breadth of coverage, along with the extremely dry Chajnantor site at 16500 feet, will enable the creation of superb images of the celestial structures which emit millimeter and submillimeter photons, the most abundant photons in the Universe. Special equipment will continuously monitor atmospheric parameters, in particular the water vapor content along the telesopes? line of site, to permit real time correction of atmospheric perturbations to the observed wavefront. The observer will have a range of sophisticated data analysis techniques to be able to compensate for atmospheric and instrumental perturbations to the raw data.

Observing scripts generated at the astronomer's home institute will be transferred to the instrument, where a dynamic scheduler will match the needs of a science program to atmospheric conditions. When matched, the script is queued for observation and the data are archived. ALMA's average data output rate will be 500 GB per day. Data is then transferred to a pipeline which will produce the images, which are transmitted to regional centers for distribution to the astronomer user. The final product to the astronomer will normally consist of calibrated data cubes.

Dr. Darrel Emerson is a radio astronomer at NRAO, and one of the chief system designers of the ALMA telescope. Prof.dr. Al Wootten is a scientist at NRAO and a Professor of Astronomy at the University of Virginia. He is the IPT Science Leader of the ALMA telescope, and in particular involved in calibration and imaging requirements.

3. **LOFAR: The first of a new generation of Radio Telescopes**

   Marco de Vos, ASTRON, Dwingeloo, The Netherlands

   The Low Frequency Array (LOFAR) project opens a previously largely unexplored frequency domain, 10-240 MHz. The scientific drivers for a new generation of radio telescopes ague for roughly two orders of magnitude increased sensitivity. The conventional design paradigm for radio telescopes, employing large parabolic dish antennas does not scale well to the huge collection areas needed for this. To reduce total cost as well as to optimize flexibility, it is unavoidable to move to designs consisting of large numbers of relatively small antennas, where most signal processing functions are realized in digital electronics and software. At the LOFAR operating frequencies it is feasible to emply very large numbers of simple, all-sky antennas with wide-band early digitization. This means that almost the complete signal processing chain can be realized in (embedded) software. This approach makes it possible to deal with earth-based radio signals in effective and novel ways. The signal processing challenges in LOFAR are manifold, since the ultimate dynamic range in astronomical images depends on the quality of the full chain of operations that combines 10,000s of antenna signals into a single multi-channel image cube, while correcting for a large variety of instrumental and environmental effects.

   Dr. C.M. (Marco) de Vos works at ASTRON, the Netherlands Foundation for Research in Astronomy. He is Engineering Manager of the LOFAR project, and is involved in several other projects related to astronomical calibration, software engineering and modelling of large-scale systems, in particular Wide Area Sensor Networks.

4. **Wide-field imaging problems in Radio Astronomy**

   Tim Cornwell, National Radio Astronomy Observatory (NRAO), Socorro (NM)

   The new generation of synthesis radio telescopes now being proposed, designed, and constructed face substantial problems in making images over large fields of view. Such observations are required either to achieve the full sensitivity limit in crowded fields or for surveys. In either event, imaging may be difficult because of physical limitations in measurement accuracy and computational load. The Square Kilometer Array now being developed by an international consortium of 15 countries will require advances well beyond the current state of the art. In addition, the large increase in sensitivity (a factor of 50 over the next most sensitive telescope) will uncover problems that we don't even know about now. However, progress can be made using simulations and observations with existing telescopes. The presentation will review the theory of synthesis radio telescopes and how it must be modified for large fields of view; in addition the computational problems to be overcome will be discussed.

Dr. Tim Cornwell is at NRAO in Socorro, New Mexico, where he was Associate Director for Data Management until 2003, and is currently involved in research on imaging algorithms for radio synthesis array telescopes, in particular for the Extended VLA and the Square Kilometer Array. He is a member of the SKA International Engineering and Management Team.

5. **Radio Frequency Interference (RFI) Mitigation in radioastronomy**

   Michael Kesteven, Australia Telescope National Facility, CSIRO, Epping, Australia

   RFI is increasingly a problem for radioastronomy with the ever expanding use of the radio spectrum by both the communications industry (transmitting) and the radioastronomers (receiving). Regulation can protect a few windows in the radio spectrum, but many experiments now need to access parts of the spectrum outside the reserved regions. Spectral lines, for example, may be significantly doppler-shifted, and therefore require an observation window far from their rest frequencies.

   A variety of RFI mitigation techniques have been developed in recent years. Most of these will have analogues in other disciplines, but the specifics of the radioastronomers' experiments allow for some interesting refinements. The astronomer is generally not interested in recovering a symbol stream in the data, but rather wants a more general description of the statistics. This makes a number of post-correlation techniques valuable and computationally viable.

   Dr. Michael Kesteven is with the Australia Telescope National Facility, CSIRO, since 1983. His research interests are antenna metrology (holography); RFI mitigation, and observatory control system software.

6. **Calibration and interference mitigation for future radio telescopes**

   Albert-Jan Boonstra , ASTRON, Dwingeloo, The Netherlands

   In radio astronomy, cosmic sources are observed which are many orders of magnitude weaker than the telescope system noise levels. This sensitivity is achieved by large telescope collecting areas, long integration times, and large bandwidths. In the coming two decades, telescopes are planned which are even one to two orders of magnitude more sensitive than the current generation. Examples are the Low Frequency Array (LOFAR), currently under construction in the Netherlands, and the Square Kilometer Array, for which the envisaged start of construction is in 2012. For these next generation of telescopes a dynamic range in the sky maps is required of over 10^6. In order to reach these numbers, accurate calibration is required. As these telescopes will observe with relatively large bandwidths, and because of the changing spectrum environment, interference mitigation techniques become increasingly important. In this paper, approaches and techniques for calibration and interference mitigation are described. Results from the LOFAR initial phased array test station (ITS) will be presented.

Biographies of the session organizers

Prof.dr.ir. Alle-Jan van der Veen (S'87, M'94, SM'02) is a Full Professor in the Signal Processing group of DIMES, Delft University of Technology. He is the recipient of a 1994 and a 1997 IEEE SPS Young Author paper award, and was an Associate Editor for IEEE Tr. Signal Processing (1998–2001). He is currently chairman of the IEEE SPS SPCOM Technical Committee, and Editor-in-Chief of IEEE Signal Processing Letters. His research interests are in the general area of system theory applied to signal processing, and in particular algebraic methods for array signal processing, with applications to wireless communication and radio astronomy. He was the PI of a project on RFI mitigation algorithms for the Westerbork Synthesis Radio Telescope (WSRT), and is a member of the Technical Advisory Committee of the LOFAR project.

Ir. Albert-Jan Boonstra is head of the digital and embedded signal processing group of the ASTRON R&D department. Previously he has been leading the system maintenance group of the WSRT. His research interests lie in the area of signal processing, specifically interference mitigation by digital filtering. He is also pursuing the Ph.D. degree at the Delft University of Technology, Delft, The Netherlands.