Introduction to the Issue on Signal Processing for Space Research and Astronomy

SPACE research in general, and astronomy in particular, are some of the most challenging application areas for signal processing. Digital signal and image processing techniques have been widely used for optical astronomy and radio astronomy as well as in deep-space communication. Several new instruments are being designed for radio, optical, and other frequencies. These instruments will push our understanding of the universe even further and ambitious design goals for these instruments will rely on advanced signal processing techniques.

Traditionally, radio telescope design was in the forefront of electrical engineering technology. Technological advances in the last decade have created possibilities for large distributed interferometric radio and optical telescopes with very large receiving areas, extremely large aperture, and a sensitivity which is one to two orders of magnitude better than the current generation. Increased sensitivity implies receiving more interfering signals; therefore, RFI detection and removal is now an important topic in radio astronomy. Fortunately, massive digital phased-array technology has also greatly advanced during this period and can provide increased flexibility to filter out interference as well as the possibility of directing multiple beams simultaneously.

Several major, international research groups are working on next generations of phased-array instruments. The most ambitious one falls under the framework of the Square Kilometer Array programm (SKA), with a target commissioning date of 2020. A second instrument, which is a distributed phased-array radio telescope is the Low Frequency Array (LOFAR) currently under construction in The Netherlands, and slated for 2009. The LOFAR design calls for an instrument consisting of about 13 000 “simple,” omni-directional antennas (10–240 MHz) grouped in about 70 stations spread in spirals over an area with a diameter of about 300 km, as well as in a more densely populated central core. 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 in 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 100 MHz up to 25 GHz. Like 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.

In terms of signal processing challenges for the ambitious design of these radio telescopes, we identify three main problems that should be solved in order to meet the design goals.

- **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’s ionosphere (time- and space-varying) has to be measured and compensated for. For large distributed arrays, this is a challenging task.

- **Imaging**: In its simplest form, image formation consists of a spatial Fourier transform of the received correlation data, followed by deconvolution to compensate for the subsampling of the spatial domain. 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 self-calibration need to be extended to the case of distributed arrays with millions of unknown parameters. Also the fact that calibration parameters change within the beam of each station introduces a space varying beam that needs to be considered in the imaging process. Finally, new insights coming from real-time RFI mitigation can be used to improve the quality of the image formation, by considering strong sources as spatially located interference. This leads to a new generation of image formation techniques.

- **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).

A second exciting application of signal processing is in the analysis of the cosmic microwave background radiation. Work over the last two decades has shed light on the fine structure of the cosmic microwave background, demonstrating that it is anisotropic. Currently, a major excitement in the field of astrophysics and cosmology is the interpretation of observations from Wilkinson microwave anisotropy probe (WMAP) with the fifth year results announced recently. The preparation for processing the anticipated observations of the Planck satellite, which is scheduled to be launched within this year, is another important instrument milestone. The objective of both satellites is the recovery of the cosmic microwave background (CMB) radiation which is the most important confirmation of the hot, big-bang model. CMB data will help us to answer crucial questions about the past, present, and the future of our universe. The observations of CMB contain several contaminants, which are signals of cosmological interest themselves. It presents various...
challenges for signal processing experts due to the blind nature of observations and the nonstationarity of the data.

Infrared and optical observations are also very important to astronomy. Optical interferometry is an important tool for achieving high resolution with many existing and new instruments such as the Keck interferometer, the European VLTI, and the Large Binocular Telescope. Important signal processing problems in this field also include imaging and image enhancement with optical or infrared telescopes, enhanced resolution of spectrometers, and calibration of atmospheric imperfections.

Finally, an important issue for space exploration, and for satellite based observations, is the data collection and transmission from a space based instrument to earth, as well as communication required to remotely control spacecrafts and their on-board instruments.

Many of these challenges are discussed by papers appearing in this special issue. The issue contains 18 papers covering very diverse selection of astronomical data processing problems.

Four papers discuss radio astronomical imaging as well as related self calibration issues. The paper by Wijnholds and Van der Veen discuss fundamental limitations of imaging with radio telescope arrays. Cornwell proposes a new multiscale, wavelet-based approach to the problem of radio astronomical deconvolution. Cornwell et al. propose a new algorithm for the important problem of imaging with non-co-planar arrays. Ben-David and Leshem propose extension of parametric techniques to non-co-planar arrays and discuss robust parametric-imaging techniques combining imaging and calibration through convex programming. Two papers discuss calibration of radio interferometers and feed arrays. Jeffs et al. present a tutorial on the important subject of feed arrays in radio astronomy. The paper by Mitchell et al. is devoted to real-time calibration problems.

Two papers in this issue address the problem of separating CMB and various other cosmological sources from satellite observations. Wilson et al. address the problem in a full Bayesian set up which allows the incorporation of various prior knowledge into the separation process. Cardoso et al. propose a formulation based on additive components which provides a flexible model for separation. Herranz and Sanz concentrate on a specific cosmological component, namely the point sources, and describe a method that proposes matrix filters which fuse the outputs of a line of detectors for improved detection of the point sources. Barreiro et al. study the Integrated Sachs–Wolfe effect and propose a linear filter that exploits the correlation between CMB and LSS observations for the recovery of ISW. Igual and Linares study yet another source separation problem, that of astrophysical ice mixtures, and propose Nonnegative Matrix Factorization (NMF) method to recover the chemical substances in astrophysical ice mixtures.

Weddell and Web propose a reservoir, computing based approach for calibrating a space varying point spread function of CCD arrays. Hampton et al. propose a new wavelet-based algorithm for reconstruction of optical waveforms in adaptive optics based telescopes. Besnerais et al. discuss techniques for image reconstruction in very large optical interferometers such as the VLTI and the LBT. Their approach is based on constrained, non-parametric optimization techniques augmented by quadratic regularization. Roddet et al. discuss reconstruction of objects in two spatial dimensions and one spectral dimension, using novel physical modeling of the infrared slit spectrograph located on the Spitzer space telescope. Butala et al. present a three-dimensional tomographic reconstruction of the electron density and temperature field in the solar corona. Bobin et al. propose an application of compressed sensing techniques to reduce the data transmission rate in the Herschel/PACS satellite mission. The paper by Cattivelli et al. is devoted to the problem of maintaining reliable communication to Mars exploration spacecrafts during the entry, descent, and landing phases.

The signal processing techniques covered in this issue are extremely diverse, covering detection and estimation theory; blind, parametric, and Bayesian source separation and imaging; Bayesian techniques and wavelets; various array signal processing techniques such as robust and blind beamforming; as well as feed arrays signal processing, high dimensional reconstruction, and compressed sensing.

We are certain that the challenging applications and the techniques already discussed in this special issue will stimulate the development of new signal processing algorithms as well as hardware architectures suitable for coping with the significant and growing of data and the very weak signals that are typical to this field of research.

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