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.

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- *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 un-isotropic. 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

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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-coplanar 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 Llinares 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.

AMIR LESHEM, *Guest Editor*
School of Engineering
Bar-Ilan University 52900
Ramat-Gan, Israel
leshema@eng.biu.ac.il

JULIAN CHRISTOU, *Guest Editor*
National Science Foundation
Arlington, VA, 22230 USA

BRIAN D. JEFFS, *Guest Editor*
Department of Electrical and Computer Engineering
Brigham Young University
Provo, UT, 84602 USA

ERCAN KURUOGLU, *Guest Editor*
Istituto di Scienza e Tecnologie dell'Informazione "Alessandro Faedo"
National Council of Research (CNR)
Pisa, Italy

ALLE-JAN VAN DER VEEN, *Guest Editor*
Department of EEMCS
Delft University of Technology
Delft, The Netherlands

Amir Leshem (M'98–SM'06) received the B.Sc. degree (cum laude) in mathematics and physics, the M.Sc. degree (cum laude) in mathematics, and the Ph.D. degree in mathematics, all from the Hebrew University, Jerusalem, Israel, in 1986, 1990, and 1998, respectively.

From 1998 to 2000, he was with Faculty of Information Technology and Systems, Delft University of Technology, Delft, The Netherlands, as a Postdoctoral Fellow working on algorithms for the reduction of terrestrial electromagnetic interference in radio-astronomical radio-telescope antenna arrays and signal processing for communication. From 2000 to 2003, he was Director of Advanced Technologies with Metalink Broadband where he was responsible for research and development of new DSL and wireless MIMO modem technologies and served as a member of ITU-T SG15, ETSI TM06, NIPP-NAI, IEEE 802.3, and 802.11. From 2000 to 2002, he was also a Visiting Researcher at Delft University of Technology. He is one of the founders of the new School of Electrical and Computer Engineering, Bar-Ilan University, Ramat Gan, Israel, where he is currently an Associate Professor and Head of the signal processing track. From 2003 to 2005, he also was the Technical Manager of the U-BROAD Consortium Developing Technologies to provide 100 Mbps and beyond over copper lines. His main research interests include multichannel wireless and wireline communication, applications of game theory to dynamic and adaptive spectrum management of communication networks, array and statistical signal processing with applications to multiple element sensor arrays and networks in radio-astronomy, brain research, wireless communications and radio-astronomical imaging, set theory, logic, and foundations of mathematics.

Julian Christou received the Ph.D. degree in astronomy from New Mexico State University, Las Cruces, in 1985.

He has worked is the field of ground-based high spatial resolution imaging using passive techniques such as speckle imaging and active techniques such as adaptive optics in order to mitigate the wave-front distorting effects of the Earth's atmosphere on astronomical images. He is a co-author of over 100 publications, which include image processing techniques mainly involving astronomical sources. He is currently a program officer for optical and infrared instrumentation within the National Science Foundation's Division of Astronomical Sciences, Arlington, VA. Prior to that, he was a member of the Center for Adaptive Optics at the University of California, Santa Cruz, and an Astronomer with the Air Force Research Laboratory's Starfire Optical Range at Kirtland Air Force Base, NM.

Dr. Christou has been the co-chair and has served on the committees of a number of conferences on Signal Recovery and Synthesis and Adaptive Optics.

Brian D. Jeffs (M'90–SM'02) received the B.S. (magna cum laude) and M.S. degrees in electrical engineering from Brigham Young University, Provo, UT, in 1978 and 1982, respectively. He received the Ph.D. degree from the University of Southern California, Los Angeles, in 1989.

He is currently an Associate Professor in the Department of Electrical and Computer Engineering, Brigham Young University, where he lectures in the areas of digital signal processing, digital image processing, and probability theory. Current research interests include array signal processing for radio astronomy, RF interference mitigation, MIMO wireless communications, and digital image restoration. Previous employment includes Hughes Aircraft Company where he served as a sonar signal processing Systems Engineer in the anti-submarine warfare group.

Dr. Jeffs was a Vice General Chair for IEEE ICASSP-2001, held in Salt Lake City, UT. He was a member of the executive organizing committee for the 1998 IEEE DSP Workshop, and served several years as chair of the Utah Chapter of the IEEE Communications and Signal Processing Societies.

Ercan E. Kuruoglu (SM'06) was born in Ankara, Turkey, in 1969. He received the his B.Sc. and M.Sc. degrees, both in electrical and electronics engineering, at Bilkent University, Ankara, in 1991 and 1993, respectively, and the M.Phil. and Ph.D. degrees in information engineering from the Signal Processing Laboratory, Cambridge University, Cambridge, U.K., in 1995 and 1998, respectively.

Upon graduation from Cambridge, he joined the Xerox Research Center, Cambridge, as a permanent member of the Collaborative Multimedia Systems Group. In 2000, he was with the Ariana Project, INRIA-Sophia Antipolis, France, as an ERCIM fellow. In 2002, he joined ISTI-CNR, Pisa, Italy, as a permanent member. Since 2006, he is an Associate Professor and Senior Researcher. He was a Visiting Professor at the Georgia Institute of Technology graduate program in Shanghai in Autumn 2007. He was a Visiting Researcher/Lecturer for extended periods at Bogazici University, Turkey, Izmir Institute of Technology, Turkey, University of Cantabria, Spain, Xidian University and Shanghai Jiao Tong University, China. He is the author of more than 60 peer reviewed publications and holds four U.S. and European patents. His research interests are in statistical signal processing and information and coding theory with applications in image processing, astronomy, telecommunications, intelligent user interfaces and bioinformatics.

Dr. Kuruoglu was an Associate Editor for the IEEE TRANSACTIONS ON SIGNAL PROCESSING between 2002–2006. He is currently in the editorial board of *Digital Signal Processing* and an Associate Editor for IEEE TRANSACTIONS ON IMAGE PROCESSING. He guest edited special issues in various journals on heavy tailed processes, cosmology applications of signal processing and Bayesian source separation. He was the Special Sessions Chair for EURASIP European Signal Processing Conference, EUSIPCO 2005 and was the Technical co-Chair for EUSIPCO 2006. He is also an elected member of the IEEE Technical Committee on Signal Processing Theory and Methods and a Senior Member of IEEE.

Alle-Jan van der Veen (F'05) was born in The Netherlands in 1966. He received the Ph.D. degree (cum laude) from TU Delft, Delft, The Netherlands, in 1993. Throughout 1994, he was a postdoctoral scholar at Stanford University, Stanford, CA.

He is a Full Professor in Signal Processing at TU Delft. 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 communications and radio astronomy.

Dr. van der Veen is the recipient of a 1994 and a 1997 IEEE Signal Processing Society (SPS) Young Author paper award, and was an Associate Editor for IEEE TRANSACTIONS ON SIGNAL PROCESSING (1998–2001), chairman of IEEE SPS Signal Processing for Communications Technical Committee (2002–2004), and Editor-in-Chief of IEEE SIGNAL PROCESSING LETTERS (2002–2005). He currently is Editor-in-Chief of IEEE TRANSACTIONS ON SIGNAL PROCESSING, and member-at-large of the Board of Governors of IEEE SPS.