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Astronomy and Cosmology

Astronomy is one of the oldest fields of science. Since ancient times, the night sky has sparked the imagination of people all around the world—from Egypt, Mesopotamia, Persia, and Greece to India, China, and Central America—and the myths and legends that these early civilizations created to explain the mysteries of the universe are still remembered today. Though ancient astronomy was limited to naked eye identification and tracking of celestial objects, the precision of these early observations was key to the historical development of both agriculture and navigation. Even today, calendars are synchronized to the perceived movements of astronomical objects such as the Sun and the Moon.

After the invention of the telescope by Galileo Galilei, astronomy quickly became an important scientific field, advanced by discoveries of planets, asteroids, galaxies, and nebulas. Computational aspects of astronomy contributed to the development of many existing techniques used today as standard signal processing tools. Most notably, the discrete Fourier transform and the computationally efficient fast Fourier transform were first used by Carl Friedrich Gauss to predict the location of the lost asteroid Ceres in 1801. Since the 20th century, astronomy has significantly expanded its scope beyond single optical frequency observations to exploit the full electromagnetic spectrum from gamma rays to radio waves.The advent of spectroscopy, which enabled the detection of atomic and molecular species via their spectral emission line signatures, was a particularly crucial development for observational astronomy, along with interferometry. Many computational spectroscopic and interferometric techniques developed initially for astronomy have been subsequently adopted in other disciplines. A remarkable example was the use of antenna arrays and synthetic aperture techniques by Martin Ryle around 1952. Ryle implemented radio interferometers by putting his antennas on rails and moving them to generate synthetic aperture. Later, he also used the Earth's rotation to achieve an extended baseline for the distinct vantages. Similar techniques are now used for synthetic aperture radar. Radio astronomy is also one of the first fields where sparse reconstruction techniques have been implemented regularly since the early 1970s, where image sparseness is used to compensate for sub Nyquist sampling.

Digital Object Identifier 10.1109/MSP.2009.934928

Edwin Hubble's discovery in 1929 (based on spectroscopic analysis of the Doppler red shifts of characteristic emission lines) that more distant galaxies are moving away from us faster than nearby ones served to revolutionize our understanding of the structure and evolution of the universe and formed the foundation of modern cosmology. Though competing theories were developed to explain Hubble's observations, the discovery in 1964 of cosmic microwave background emission (CMB) by Penzias and Wilson confirmed the "Big Bang" theory for the origin of the universe, which postulated that the universe is expanding from a single point. However, the uniformity of the CMB could not account for the nonuniform structure observed today. To explain the origin of the large-scale structure of the universe, cosmological inflation was proposed to have occurred very shortly after the Big Bang, a theory later confirmed by the COBE experiment. Since the anisotropy is about five orders of magnitude weaker than the CMB emission itself, the investigation required an integration time of several years along with sophisticated signal processing to remove artifacts and foregrounds. Further studies by the Wilkinson microwave anisotropy probe (WMAP) provided much better resolution and larger frequency sampling of the CMB distribution, and the Planck mission, launched in 2009, will provide even better spatial and frequency coverage. The success of these investigations has relied on the development of signal processing techniques for signals defined on a sphere as well as advanced Bayesian source separation techniques in addition to sophisticated algorithms able to remove foregrounds from compact objects.

One of the major challenges for observational cosmology is the detection of the first objects in the universe, created during a time known as the epoch of reionization (EoR), to understand their origin. To this end, several huge antenna arrays are being built around the world to generate tomographic maps of the early universe based on highly red shifted hydrogen spectral lines at 21 cm, a tracer of gas that existed during and before the EoR. The primary challenges of this effort are the calibration and compensation of ionospheric effects on the observed signals, though as with CMB studies, it is expected that detection of the EoR signals will also require processing extremely large data volumes over periods of two to three years while removing much stronger foreground signals. These requirements make the detection of the EoR one of the most complicated detection problems ever encountered by scientists and engineers.

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[dates AHEAD]

Please send calendar submissions to:
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(Colored conference title indicates SP-sponsored conference.)

2010

[MARCH]

4th International Symposium on Communications, Control, and Signal Processing (ISCCSP 10)
3–5 March, Limassol, Cyprus.
General Cochairs: Anthony Constantinides and Sanjit K. Mitra
URL: http://www.cs.ucy.ac.cy/isccsp2010/index.html

2010 IEEE International Conference on Acoustics, Speech, and Signal Processing (ICASSP)
14–19 March, Dallas, Texas.
General Chair: Scott Douglas
URL: http://www.icassp2010.com/

IEEE–Thematic Meetings on Signal Processing (THEMES)
15 March, Dallas, Texas.
General Chair: V. John Mathews
URL: http://www.ieee-themes.org/index.htm

Data Compression Conference
24–26 March, Snowbird, Utah.
General Chair: James A. Storer
URL: http://www.cs.brandeis.edu/~dcc/

[APRIL]

The 9th ACM/IEEE Conference on Information Processing in Sensor Networks (IPSN'10)
12–16 April, Stockholm, Sweden.
URL: http://ipsn.acm.org

2010 IEEE International Symposium on Biomedical Imaging (ISBI 2010)
14–17 April, Rotterdam, The Netherlands.
General Chair: Wiro Niessen
URL: http://www.biomedicalimaging.org
E-mail: isbi2010@bigr.nl

Digital Object Identifier 10.1109/MSP.2009.934726

Another major focus of modern cosmology is the inferred presence in the universe of new types of matter and energy, known as dark matter and dark energy. Though dark matter has not been directly discovered, analysis of the motion of galaxies and other observational effects suggests that there is much more matter in the universe that contributes to gravitational effects. Dark energy is sometimes identified with Einstein's cosmological constant, and it is responsible for the acceleration of the expansion rate of the universe. The standard cosmological model Λ Cold Dark Matter ($\Lambda-$CDM) assumes the existence of nonrelativistic dark matter and a cosmological constant Λ. According to the $\Lambda-$CDM model, about 74% of the matter and energy is dark energy and about 22% is dark matter. Only 4% are the standard matter and energy such as atoms, photons, and other forms of observed matter. The fact that we cannot observe 96% of the total energy and matter in the universe requires us to develop new observational techniques which might lead to the next breakthrough in cosmology.

These challenging astronomical problems require the most sophisticated signal processing techniques, as well as computationally efficient algorithms, since the amount of data in these investigations is very large. Furthermore, space-based instruments pose restrictions on the communication bandwidth, so distributed techniques are likely to be even more important for distributed space-based platforms. This special issue is devoted to advanced signal processing techniques used in astronomy and cosmology that enable progress in solving the major problems described above as well as many other problems in observational astronomy.

The first part of this issue deals with digital interferometry in the radio and optical domains. The article by Levanda and Leshem discusses various image formation techniques used in synthetic aperture radio imaging. It describes new ways to introduce modern array processing formulations into the classical Fourier inversion problem. The article by Wijnholds et al. discusses the important problem of array calibration at low frequencies, one of the most significant obstacles for low frequency radio astronomy in general and for detecting the EoR signals in particular.

The second part of this special issue deals with applications of signal processing to cosmology. Kuruoglu provides an introduction to the field of CMB measurements and describes Bayesian source separation techniques used to recover cosmological components from multichannel observations. Cardoso describes the problem of harmonic analysis and signal processing on a sphere and its connection to the analysis of the spatial spectrum of the CMB. Herranz and Vielva describe techniques for estimating and removing compact foreground sources from CMB observations. These techniques are extremely important to be able to separate the desired cosmological components from other stronger signals. Finally, Pires et al. discuss the study of dark matter using weak gravitational lensing, an interesting effect where massive bodies affect light like a lens due to the curved space around them (this is an effect predicted by Einstein in 1936, as a result of the general theory of relativity and confirmed experimentally only in 1979).

The article by Kamalabadi discusses the multidimensional reconstruction of an object such as the Sun from multiple view measurements, treating cases of both stationary and nonstationary objects. The latter requires the introduction of sequential Monte Carlo techniques into the image formation problem. These techniques are used for three-dimensional reconstruction of the solar corona parameters from stereoscopic measurements. Thiébaut and Giovannelli discuss the similar problem of interferometry at optical and infrared wavelengths. As it turns out, there are many common signal processing prolems for radio and optical interferometry. Finally, Bertero et al. describe signal processing techniques used to achieve uniform resolution in the large binocular telescope, where two mirrors are located in the focal plane of the telescope. [SP]