Widefield Surveys for Pulsars, Transients and ETI Using a Large-N Concept for the Square Kilometer Array

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Abstract: The trademark attributes of the Square Kilometer Array that will allow it to achieve current key science goals are (a) high sensitivity, (b) wide field of view (FOV), (c) a configuration that allows low surface brightness as well as high resolution ("VLBI") capability, and (d) flexibility in configuring and using the collecting area for wide FOV surveys. I will discuss issues associated with wide FOV surveys that involve exploration in the time, frequency, and/or spatial domains. Pixelization of the FOV (nominally 1 square degree at 1 GHz) using direct beam forming or correlation approaches is the first issue. Next is the manner in which the sky will be observed. Fast transients and slow transient signals require different sky-sampling methods, namely "staring" observations and raster-scanning, respectively. The division between fast and slow transients depends on the amount of sky being surveyed and other factors but is in the range of one to a few days. Each pixel needs to be analyzed with the appropriate search algorithm. For pulsars this includes dedispersion, Fourier analysis, harmonic summing and candidate identification. Dedispersion is also required for fast transients with time scales ~ 1 sec or less, followed by matched filtering analysis of the time series. For signals with time-frequency signatures more exotic than those of giant pulses from pulsars, matched filtering can be conducted in the two-dimensional time-frequency plane. Interstellar scintillations (ISS), particularly diffractive ISS (DISS) that induces time and frequency modulations of celestial signals from compact sources, suggests that detection algorithms can be optimized through appropriate weighting in the time-frequency plane. SETI has a very large search space, ranging from nearly monochromatic, time-steady signals to broadband or spread spectrum signals that are heavily modulated intrinsically and also by DISS. I will discuss some of these cases in particular detail and will estimate processing requirements for large-N architectures for the SKA.

1. INTRODUCTION

The SKA can be designed to conduct unprecedented deep surveys for pulsars, transient radio sources, and signals from ETI. To do so places distinct constraints on the configuration and signal-processing capabilities of the SKA, which are discussed in this article.

Why search for more pulsars? Radio pulsars provide unique opportunities for testing theories of gravity and probing states of matter otherwise inaccessible to experimental science. In large samples, they also allow detailed modeling of the magnetoionic components of the interstellar medium (ISM). Of particular importance are pulsars in short-period orbits with relativistic companions, ultrafast millisecond pulsars (MSPs) with periods $P < 1.5$ ms that provide important constraints on the nuclear equation of state and MSPs with stable spin rates that can be used as detectors of long-period ($\gtrsim$ years) gravitational waves. Long period pulsars ($\gtrsim$ 5s) are of interest for understanding their connection, if any, with magnetars. Additionally, any objects with especially large space velocities, as revealed through subsequent astrometry, will help constrain aspects of the formation of neutron stars (NS) in core-collapse supernovae.

One of the five key projects identified for the SKA is the usage of pulsars for strong-field tests of gravity and for gravitational wave detection (Kramer et al. 2004 and references therein). Such tests can provide answers to one of the questions posed in *Connecting Quarks with the Cosmos:*

Eleven Science Questions for the New Century[1]: “Was Einstein right about gravity?” To do so requires timing of pulsars like the extraordinary double-pulsar binary J0737-3039 (Lyne et al. 2004), which comprises a recycled pulsar with 23ms spin period and a canonical pulsar with 2.8s period in a 2.4-hr orbit. Additional such binaries remain to be discovered, some with even smaller orbital periods, allowing correspondingly stronger tests of gravity. We envision a Galactic census of radio pulsars that aims to detect at least half of the active radio pulsars that are beamed at us. Taking beaming and the radio lifetimes of pulsars into account, the fiducial NS birth rate of 10^{-2} yr^{-1} implies $\sim 2 \times 10^4$ detectable pulsars in the Galaxy.

Why search for transients? The radio transient sky is known to exist, with examples ranging from 2 ns and longer in time scale and brightness temperatures from thermal to 10^{38}K. However, compared to the high-energy transient sky, we know next to nothing about the overall constituency of the transient radio sky. A highlighted science area for the SKA is “Exploration of the Unknown,” (Wilkinson et al. 2004), which includes the overall phase space opened up by the SKA and the likely discovery of new classes of objects and phenomena. Another chapter in the SKA science book, “The Dynamic Radio Sky” (Cordes et al. 2004) discusses the payoff from an SKA design that combines widefield sampling of the sky with high sensitivity and flexibility in analyzing likely or hypothetical event signatures and time scales.

Why search for ETI? Detection of any technological activity from extraterrestrial intelligence would be truly transformational. Depending on one’s views about the evolution of complexity in the universe, the assessed odds of detecting signals from ETI range from the inevitable to the impossible. An empirical stance is one that recognizes that if we don’t search for a wide range of signal classes, we can be almost certain that we will not detect signals from ETI. Whether the radio band or some other electromagnetic band is the optimal signal channel, we can also debate. The fact of the matter is that human transmissions would be detectable to significant Galactic distances if an SKA were used on the receiving end. However, the duty cycle of such transmissions into a particular direction is small. By reciprocity, we need an SKA that is versatile and which provides the largest duty cycle for sampling the sky appropriately for the range of signal classes that we agree should be searched for.

2. SEARCH DOMAINS

Deep censuses for the three source classes suggest that the following regions on the sky need to be searched with high sensitivity and efficiency.

Pulsars:

1. Galactic plane: for young pulsars associcated with supernova remnants, possible magnetar-like objects;
2. Intermediate latitudes: for millisecond pulsars and relativistic binaries (pulsars with other neutron star [NS] and black-hole [BH] companions);
3. Galactic center: pulsars in the star cluster orbiting the $\sim 4 \times 10^6$ $M_\odot$ black hole, which are difficult to detect because radio wave scattering from material in the GC region broadens the pulses at standard pulsar search frequencies;
4. Globular clusters;
5. Nearby galaxies ($\lesssim 1$ Mpc)
6. Galaxies out to ~ 5 Mpc in searches for giant pulses like those typically seen from the Crab pulsar in 1 hour to the Virgo cluster for plausible amplitudes of giant pulses.

[1]National Academies Press, 2003, ISBN 0-309-07406-1

Transient Sources:

1. Spatial domains similar to those for pulsars (with overlap for giant pulses from pulsars);
2. Local regions in the Galaxy (nearby planets and stars) require sampling of an approximately isotropic distribution of sources;
3. Low frequencies for coherent sources;
4. Fast transients ($\lesssim 1$ day);
5. Slow transients ($\gtrsim 1$ day);

SETI:

1. Targeted searches of nearby stars, especially those with suitable planetary systems;
2. Blind surveys of the Galactic plane and other regions.

3. TYPES OF ANALYSIS

Backend processing is specialized for the three broad classes of source, though there is some overlap in the kinds of operations that are needed for detection and analysis of the sources.

Pulsars:

1. Dedispersion with trial values of dispersion measure (DM);
2. Matched filtering detection of single pulses of unknown width and shape;
3. Fourier analysis (including harmonic summing); and
4. Statistical tests and confirmation observations of candidate signals.

Transient Sources:

1. Fast transients: analyses similar to those for single-pulse searches for pulsars, with perhaps a generalized matched filtering procedure operating in the frequency-time plane.
2. Slow transients: Processing of images obtained at requisite intervals, perhaps with spectral resolution to identify fine structure.

SETI:

1. Generalized frequency-time analysis similar to that needed for dispersed, broadband pulses from pulsars but with much smaller channel bandwidths and frequency drift rates ($\dot{\nu}$) consistent with anticipated Doppler accelerations.

4. The Role of Multipath Propagation: Scintillations, Refraction and Broadening in Angle, Time, and Frequency

At radio wavelengths, multipath propagation is caused by density fluctuations in intervening plasmas, including the ionosphere, the interplanetary medium, the interstellar medium (ISM) and, though not yet revealed in any measurements, the intergalactic medium (IGM). Galactic components other than the ISM *per se*, such as supernova remnants, HII regions, the Galactic center, and the ionospheres and interplanetary media of other stars and their planetary systems will also contribute to propagation phenomena. Observable effects from multipath propagation include:

1. Angular broadening ("seeing");

2. Temporal broadening;
3. Refractive intensity scintillations (RISS) on time scales of hours to years that are broadband ($\sim$ octave correlation bandwidth);
4. Diffractive intensity scintillations (DISS) on time scales of seconds to hours with narrowband frequency structure ($\Delta\nu/\nu \ll 1$).

Such effects are manifest in compact sources that are smaller than a critical angular size: $\sim \mu$as for DISS and ~ 1 mas for RISS. Fast transients are necessarily compact and thus are expected to show multipath effects, which are very strongly frequency dependent.

5. BASIC DATA UNITS

The basic data unit for a particular pixel $\boldsymbol{\theta}$ is a dynamic spectrum, $I(t, \nu, \boldsymbol{\theta})$, the intensity vs. time and frequency. For an SKA that allows wide FOV searching, the FOV may be pixellated with a large number of pixels, e.g. $> 10^4$ for a 1 deg^2 FOV, and a dynamic spectrum will be available for each pixel. Search algorithms would be applied that are matched filters for signals in the frequency-time plane, with cross-pixel tests performed to distingush between celestial and RFI transients. For periodic, dispersed pulsars the matched filter is dedispersion combined with a folding algorithm, often approximated with a Fourier analysis combined with harmonic summing. For aperiodic transients, the matched filter involves dedispersion and correlation with a large family of signal templates. One can imagine a still greater level of complexity in the f-t plane for ETI signals or for natural signals that are chirped in multiple ways, e.g. by interstellar dispersion and orbital motion.

6. FIGURES OF MERIT FOR SKA SEARCHING

Figures of merit (FOM) can be devised that depend on the source class being targeted. For pulsars the FOM is the rate at which volume is surveyed as a function of spin period and intrinsic luminosity. For transients, one possible FOM is a *completeness coefficient* that measures the fraction of a source population that is detected given the FOV and sensitivity. Slow transients are those that can be sampled using a raster-scanning approach. Fast transients involve "staring" observations that require large *instantaneous* FOV. Estimates of these FOMs will be given in the talk.

References

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