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WIDEFIELD SURVEYS FOR TRANSIENTS, PULSARS AND ETI WITH THE SKA
Version 0.3
23 April 2003

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ABSTRACT

Blind surveys for sources with fast time-domain signatures are especially challenging with array telescopes. This document summarizes the issues involved in searching for fast transients, pulsars, and ETI signals. Schemes for conducting searches are outlined in the context of the Large-N-Small-D concept for the SKA.

1. SEARCHING THE FULL FIELD OF VIEW

The present specifications for the SKA include an instantaneous field of view (FOV) of 1° at 1 GHz. In the Large-N-Small-D (LNSD) concept for the SKA, antennas would be configured so as to yield significant collecting area on small, intermediate and large baselines in a scale-free manner. Blind surveys of large total solid angles require full-FOV sampling, which is feasible only for a subarray comprising the innermost antennas. We call this subarray the core array and characterize it as a circular distribution of antennas with diameter \(b_c\). The core array contains a fraction \(f_c = n_a/N_a\) of the total number of antennas. For a centrally weighted (parabolic) distribution of collecting area, the array beam for the core array is

\[
\theta_b \approx 1.27 \frac{\lambda}{b_c} \approx 78.6 \text{arcsec} \left(\frac{\nu_{\text{GHz}} b_c \text{km}}{\lambda}\right)^{-1}
\]

For comparison the primary beam for an antenna diameter \(D = 12 \, \text{m} \, D_{12}\) is

\[
\theta_p \approx 1.17 \frac{\lambda}{D} \approx 1.68 \text{deg} \left(\frac{\nu_{\text{GHz}} D_{12}}{\lambda}\right)^{-1}.
\]

To pixelize the FOV requires

\[N_{\text{pix}} \approx 0.85 \left(\frac{b_c}{D}\right)^2 \approx 10^{3.8} \left(\frac{b_c \text{km}}{D_{12}}\right)^2 \text{ pixels}.
\]

We have used \(b_c = 1 \, \text{km}\) as a fiducial value because the number of operations needed to pixelize an array of even this size is daunting. We note, however, that in the LNSD Whitepaper (2002), about 25% of the overall sensitivity is contained inside an array of this size.

To image or otherwise pixelize the FOV requires channelization of the total bandwidth \(B\) into \(N_{\nu} = B/\Delta \nu\) channels. To have the ‘delay beam’ exceed the FOV requires \(\theta_{\text{del}} \approx c_b \Delta \nu > \theta_p\) or \(\Delta \nu < 9.5 \, \text{MHz} \, D_{12} \nu_{\text{GHz}} b_c^{-1}\). Another constraint on bandwidth derives from the need to dedisperse the signal when searching for pulsars or narrow pulses. The dispersion delay across \(\Delta \nu\) for an object with dispersion measure \(DM\) is

\[\Delta t_{\text{DM}} = 8.3 \mu \text{s DM} \frac{\Delta \nu/\nu_{\text{GHz}}}{c}.
\]

for DM in pc cm\(^{-3}\) and \(\Delta \nu\) in MHz. The values of DM extend to at least \(DM_{\text{max}} = 2000 \, \text{pc cm}^{-3}\), so minimizing pulse smearing to less than 2 ms at 1 GHz requires \(\Delta \nu < 0.12 \, \text{MHz} \, (DM_{\text{max}}/2000 \, \text{pc cm}^{-3}) \nu_{\text{GHz}}^3\). Thus, channel bandwidths narrow enough for dedispersion more than suffice for allowing full FOV pixelization.

\[1\]

I assume parabolic illumination of the primary that reaches 25% amplitude at the edges, i.e.,

\[g(r) = K + \left[1 - \left(\frac{2\lambda r}{D}\right)^2\right]^p
\]

with \(K = 0.25\) and \(p = 1\) (c.f. Rohlfs & Wilson (1996), Table 6.1). These parameters yield the same coefficient as for simulations of the ATA feed (G. Cortes, private communication).
2. BEAM FORMING

There are two ways to pixelize the FOV: (1) using an explicit hardware beam-former and (2) combining a correlator and a Fourier-transform (FT) operation to form snapshot images. In either case, we consider FX approaches that first channelize the signals from each antenna. On a mathematical basis, the two approaches are equivalent via the Wiener-Khinchin and van Cittert-Zernike theorems. On a practical basis, however, the two approaches diverge in terms of implementation and complementarity with imaging science.

**Direct beam forming:** Let the channelized baseband voltage be \( \varepsilon_{p\nu}(x_n, t_i) \) for the \( n \)-th antenna at location \( x_n \), for polarization \( p_i \) baseband frequency \( \nu \) and time \( t_i \). Channelization occurs in an ‘F’ stage requiring \( \Delta t = N_\nu \delta t = N_\nu B^{-1} \) Nyquist samples. The \( t_i \) are in steps equal to \( \Delta t \). From \( n_a \) antennas we form the composite voltage for beams centered on directions \( \mathbf{k}_j, j = 1, N_{\text{pix}} \),

\[
\varepsilon_{p\nu}(\mathbf{k}_j, t_i) = \sum_{n=1}^{n_a} \varepsilon_{p\nu}(x_n, t_i) e^{-i\mathbf{k}_j \cdot \mathbf{x}_n}.
\]

To form each beam given the phase factors requires \( n_a \) complex multiply/adds per polarization, channel, and time step. Phase factors need not be calculated as often as the beam voltages, so we ignore those operations in calculating the data rate. The number of operations is then \( n_a N_{\text{pol}} N_{\nu} \) per time step, corresponding to an operations rate per beam

\[
\dot{N}_{b,1} = n_a N_{\text{pol}} N_{\nu} / \Delta t = f_c N_a N_{\text{pol}} B \approx 10^{12.24} \text{op s}^{-1} \left( \frac{f_c}{0.5} \right) \left( \frac{N_a}{4400} \right) \left( \frac{N_{\text{pol}}}{2} \right) \left( \frac{B}{400 \text{MHz}} \right),
\]

where we have chosen a bandwidth of 400 MHz as a reasonable choice for surveys conducted in the 1 to 2 GHz range and consistent with the overall guideline specification of 20% bandwidth. The data rate for all beams needed to pixelize the FOV is

\[
\dot{N}_b = f_c N_a N_{\text{pol}} N_{\text{pix}} B.
\]

For \( N_a = 4400 \) antennas and a core array comprising a fraction \( f_c = 1/2 \) of these antennas, a bandwidth \( B = 400 \text{MHz} \) and the number of pixels calculated previously, we have

\[
\dot{N}_b = 10^{16.0} \text{op s}^{-1} \left( \frac{f_c}{0.5} \right) \left( \frac{N_a}{4400} \right) \left( \frac{N_{\text{pol}}}{2} \right) \left( \frac{b_{c,km}}{D_{12}} \right)^2 \left( \frac{B}{400 \text{MHz}} \right).
\]

**Beam-forming through correlation:** An alternative approach is to correlate all signals from all antennas and combine them at appropriate time intervals into snapshot images. Using the channelized, complex baseband voltage previously defined, \( \varepsilon_{p\nu}(x_n, t_i) \), we calculate auto-and-cross correlations between the \( n \)-th and \( m \)-th antennas,

\[
C_{mnp\nu}(t_i) = (\varepsilon_{p\nu}(x_n, t_i) \varepsilon_{p\nu}^*(x_m, t_i)) \Delta t, \quad p, p' = 1, 2,
\]

where \( \Delta t \) is the integration time. For pulsar searching, \( \Delta t \approx 100 \mu s \). The number of computations per correlation value is \( \Delta t/\delta t = \Delta t B/N_\nu \) per polarization, frequency channel and integration time. At each integration time the number of correlations to be computed is

\[
N_c = \frac{1}{2} n_a(n_a - 1) N_{\text{pol}} N_{\nu}.
\]

Then the operations rate for computing correlations (including cross products, so \( N_{\text{pol}} = 4 \)) is

\[
\dot{N}_c = N_c B/N_\nu \approx \frac{1}{2} n_a(n_a - 1) N_{\text{pol}} B
\approx \frac{1}{2} \left( f_c N_a \right)^2 N_{\text{pol}} B
= 10^{15.6} \text{op s}^{-1} \left( \frac{f_c}{0.5} \right)^2 \left( \frac{N_a}{4400} \right)^2 \left( \frac{N_{\text{pol}}}{4} \right) \left( \frac{B}{400 \text{MHz}} \right).
\]

To pixelize the sky requires an \( N \times N \) Fourier transform where \( N \approx (4N_{\text{pix}}/\pi)^{1/2} = 87b_{c,km}/D_{12} \), or roughly \( (2N \log_2 N)^2 \) operations per \( \Delta t \), or about 20 Gop s\(^{-1}\), which is negligible compared to \( \dot{N}_c \).

**Comparison of Direct and Correlation Beam Forming:** The correlation method requires a lower rate of operations than the direct beam method for nominal parameters. Note that the operations rate was calculated for \( N_{\text{pol}} = 4 \) for the correlation method and half that for beam forming. The correlation method
also can be used to image outside the FOV defined formally as the FWHM of the primary antenna beam. Moreover, a correlator will be used with all antennas of the SKA, including those on VLBI baselines, for imaging. Thus a correlation approach with native dump times not unlike those currently used (~100 μs) for imaging applications is an economical way to enable time-domain intensive surveys.

Direct beam-forming, on the other hand, can develop modularly to allow targeted surveys first, and then full-FOV blind surveys as cost/performance of hardware increases. Direct beam-forming also allows greater mitigation of RFI through placement of nulls in appropriate directions and through use of less-coarse quantization than correlators are likely to use.

It is useful to compare the operations rates for the two methods more directly and in terms of the sensitivity specification for the SKA, \( A_c/T_{sys} = 2 \times 10^4 \text{m}^2 \text{K}^{-1} \). The ratio of operations rates is

\[
\frac{\dot{N}_b}{\dot{N}_c} = \frac{2}{f_c N_a} \left( \frac{b_c}{D} \right)^2 = \frac{\pi}{2} \frac{\eta}{A_c/T_{sys}} T_{sys} \left( \frac{b_c^2}{f_c} \right),
\]

where \( \eta \) is the aperture efficiency. Note that the ratio is independent of dish diameter. We can relate \( b_c \) to \( f_c \) given a configuration for the SKA. Using Figure 3.4 of the USSKA LNSD Whitepaper (2002 version), which shows sensitivity vs. baseline for the scale-free configuration, we can relate the fraction of the SKA’s collecting area to the baseline:

\[
b_{c, \text{km}} \approx 10^3 (f_c - 0.25), \quad 0.05 \lesssim f_c \leq 1.
\]

This implies that for direct beam forming to be computationally favorable requires that \( \dot{N}_b/\dot{N}_c < 1 \) or

\[
10^{10 f_c} \lesssim 100 \frac{A_c}{(\eta/0.72)} \left( \frac{A_c/T_{sys}}{2 \times 10^4 \text{m}^2 \text{K}^{-1}} \right) \left( \frac{T_{sys}}{18 \text{K}} \right),
\]

which implies \( f_c \leq 0.10 \) in order for direct beam forming to be favorable. This result is independent of dish diameter but depends on configuration and system temperature. A more compact core array obviously reduces the operations rate of direct beam forming because the rate scales as \( b_c^2 \).

### 3. SEARCH PROCESSING

Here we consider the processing that might take place on the baseband voltage defined in Eq. 5 for the \( j \)-th antenna. We simplify the notation to \( \varepsilon_{\nu \nu,j}(t_i) \equiv (\varepsilon_{\nu \nu, \{k_j,t_i\}}) \). Pulsar analysis increasingly involves coherent dedispersion of the baseband voltage, which corrects voltage phases for dispersive propagation through the interstellar medium. At present, blind surveys are too computationally expensive, while on the time scale of the SKA, such searches may become feasible for subsets of the parameter search space. It is likely also that search schemes for signals with time-frequency signatures more complex than those seen from pulsars, and on shorter time scales, may be entertained.

We focus here on post-detection analyses for blind surveys that involve searches in dispersion measure as well as spin period (for periodic sources). Let the intensity be defined as

\[
I_{\nu \nu,j}(t_i) = |\varepsilon_{\nu \nu,j}(t_i)|^2.
\]

For some surveys, two polarizations might be summed early in the processing while in others, where polarization is of interest, they would be kept separate.

**Dedispersion:** Frequency channels are combined according to a set of trial dispersion measures,

\[
\{\text{DM}_\ell, \ell = 1, N_{DM}\}.
\]

Typically, the number of dispersion measure values is comparable to the number of spectral channels, \( N_{DM} \approx N_{\nu} \), though more precisely the number is determined by the spacing required to not degrade S/N of pulses of a particular width. For each DM the dedispersed time series for the \( j \)-th beam is

\[
I_{\nu \nu,j}(t_i, \text{DM}_\ell) = \sum_{\nu} I_{\nu \nu,j}(t_i - t_{\nu}(\text{DM}_\ell)),
\]

where \( t_{\nu}(\text{DM}_\ell) \) is the dispersion-delay correction needed for frequency channel \( \nu \).

\[
t_{\nu}(\text{DM}) = -4.2 \times 10^3 \text{DM} \nu^2 \text{GHz} \mu\text{s}.
\]

(Note that we use \( \nu \) to represent a frequency index at baseband but also let it label the corresponding RF). The corrections can be precalculated. For each time step there are \( N_{\nu} \) summations per trial DM. Thus for
a dwell time $T$ on a given sky position, the total number of operations for dedispersing is $N_{DM}N_pT/\Delta t$ per beam. Over the FOV, this implies a full-Stokes processing rate

$$N_{dedis} = N_{pix}N_{pol}N_pN_{DM}/\Delta t \approx 10^{14.4}\text{ op s}^{-1} \left( \frac{b_{c,\text{km}}}{D_{12}} \right)^2 \left( \frac{N_{pol}}{4} \right) \left( \frac{N_p}{10^3} \right) \left( \frac{N_{DM}}{10^3} \right) \left( \frac{\Delta t}{100 \mu s} \right)$$  \hspace{1cm} (19)

Note that the number of DM channels required is also affected by pulse broadening from scattering. For large DM, corresponding to path lengths $\gtrsim 5 \text{ kpc}$ and frequencies $\lesssim 1.5 \text{ GHz}$, pulse broadening limits the achievable time resolution, so the search grid of DM need not be as fine as otherwise. The processing of SKA data can thus be optimized according to direction and frequency. Nonetheless, the processing rate derived here is typical of what is needed.

**Periodicity Search:** The time series for each trial DM is Fourier transformed and the resultant power spectrum is investigated for harmonics associated with pulses of different periods and duty cycles. Threshold tests on the harmonic sum yield candidate signals that are further analyzed by revisiting the time series and synchronously averaging it with the candidate spin period. For a dwell time $T = N_t\Delta t$, an $N_t$-point FFT is computed. Compared to dedispersion, the number of operations per unit time is negligible. Harmonic summing and candidate diagnostics require similar numbers of operations.

**Periodic Sources in Binaries:** Current capabilities allow modest searching for binary signatures while also searching in period and DM. Binary motion even over short dwell times of minutes can smear pulses unless compensation is made. The simplest analysis is an acceleration search if $T \lesssim 0.15P_{orb}$, requiring $\sim 10^2$ to $10^3$ trial accelerations. Alternative analyses can be made for $T \gg P_{orb}$ that involve searching for orbital sidebands of the spin harmonics of pulsars. The most difficult search problem is for objects in highly eccentric orbits, in which case a 5-parameter orbital parameter space must be searched. Depending on which kind of orbital search is done and in conjunction with what kind of $P$-DM search, the analysis can easily exhaust the available computational resources.

**Single-pulse Analysis:** Dedispersed time series can be searched for strong individual pulses that can be missed in a periodicity search. Pulsars with broad, power-law amplitude distributions such as the Crab pulsar and its ‘giant’ pulses are examples. The search algorithm is very inexpensive, entailing threshold tests after matched filtering, approximated by (e.g.) hierarchical smoothing.

**Generalized Transient Analysis:** One can hypothesize signals with time-frequency structure more intricate than that of dispersed pulses. Examples include flare star emissions and various classes of ETI signals (leakage or deliberately transmitted signals). To search for such signals requires customized analysis of the frequency-time plane [e.g. $I_{pol}(t_i)$] that aims to identify signals according to specified templates. Polarization signatures are also part of the search space. Such analysis would be much more costly than dedispersion and periodicity searches.

**SETI Analyses:** (Not yet written) To include:

1. Spectral search for narrow lines.
2. Pulse search.
3. Role of scintillations and their impact on how to conduct surveys.

**4. SKY COVERAGE, DEPTH OF SURVEY ISSUES & OBSERVING MODES**

For blind searching, the sky coverage rate $\dot{\Omega}$ (deg$^2$ s$^{-1}$) needs to be maximized while also achieving the desired search depth, which we characterize as the maximum detection distance $D_{max}$. A source at distance $D$ with flux density $S$ can be seen to a distance

$$D_{max} = D \left( \frac{S}{S_{min}} \right)^{1/2}$$  \hspace{1cm} (20)

if $S_{min}$ is the minimum detectable flux density that takes into account radiometer noise, the spin period and duty cycle, and propagation effects. The search volume is $V_{max} = \frac{1}{3}\Omega D_{max}^3$ for solid-angle coverage $\Omega$. Survey design needs to take into account both the location of the target population ($D, \Omega$) and the luminosity function, $f_L$. 
Pulsars: Galactic pulsars, for example are distributed according to their birth from an extreme Population I distribution of stars and modified by the pulsar velocity distribution. The luminosity function of pulsars is a broad power law because it is determined by beaming combined with intrinsic variation that depends on spin rate and magnetic field. For pulsars we can factor $S_{\text{min}}$ as

$$S_{\text{min}} = S_{\text{min}, h_{\Sigma}^{-1/2}},$$

$$S_{\text{min}, h_{\Sigma}^{-1/2}} = \frac{m S_{\text{sys}}}{(N_{\text{pol}} B T)^{1/2}},$$

where $S_{\text{min}, h_{\Sigma}}$ is the minimum detectable flux density for a single harmonic in the power spectrum, $m$ is the threshold in units of sigma (rms flux density), $S_{\text{sys}}$ is the system-equivalent flux density and $h_{\Sigma}$ is the harmonic sum commonly used in pulsar surveys. Our definition of the harmonic sum is that it is a dimensionless quantity equal to unity if the signal is an undistorted sinusoid. For a gaussian pulse with FWHM $W$, the harmonic sum is maximized for $N_{\text{pol}, \text{max}} \approx P/2W$ harmonics (for small duty cycles, $W/P \ll 1$) and is approximately $h_{\Sigma, \text{max}} \approx \frac{1}{2} (P/W)^{1/2}$. Using nominal parameters for Arecibo and the SKA ($S_{\text{sys}} = 3.8$ and 0.14 Jy, respectively), we find that

$$S_{\text{min}, h_{\Sigma}^{-1/2}} = \left( \frac{m}{10} \right) \times \begin{cases} 94 \mu\text{Jy} & \text{AO} \\ 2.8 \mu\text{Jy} & \text{SKA} \end{cases},$$

where we have included a factor $g_0 < 1$ that accounts for off-axis gain and for the SKA a factor $f_c$ equal to the fraction comprising the core array used for blind searching. We have used a threshold of $10\sigma$ ($m = 10$). The corresponding maximum distances are

$$D_{\text{max}} = \left( \frac{m}{10} \right)^{-1/2} \left( \frac{L_p}{1 \text{kpc}^2 \text{mJy}} \right)^{1/2} \times \begin{cases} 3.3 \text{ kpc} \ (g_0 h_{\Sigma, \text{max}})^{1/2} & \text{AO} \\ 18.9 \text{ kpc} \ (f_c g_0 h_{\Sigma, \text{max}})^{1/2} & \text{SKA} \end{cases},$$

Note that $h_{\Sigma, \text{max}}$ can be larger than unity when many harmonics are detectable and it can be much smaller than unity when the pulse is so smeared that even the fundamental frequency component is attenuated, as occurs under severe pulse broadening from interstellar scattering. To evaluate $D_{\text{max}}$, we consider particular directions through the Galaxy and use an electron density model (NE2001, Cordes & Lazio 2002ab) to evaluate pulse broadening and its effects on the harmonic structure of the Fourier analysis used to search for periodicities. Figure 1 shows $D_{\text{max}}$ calculated for Arecibo and the SKA using this approach. The figure demonstrates that for a wide range of values for periods and $L_p$, the SKA can probe to the anticipated boundaries of the pulsar distribution, even after taking into account the high velocities of some objects. The SKA will provide a great leap in surveying the neutron-star population of the Galaxy. Also, for objects with $L_p \gtrsim 10^3$ mJy kpc$^2$ (of which there are a few examples in the known Galactic population), the SKA can reach the nearby galaxies M31 and M33 in standard periodicity searches.

Detection modeling of radio pulsars indicates that:

- With an Arecibo-size antenna, 400 MHz bandwidth at L band, and 300-s dwell times, some pulsars can be detected out to the far edge of the Galaxy on the opposite side of the Galactic center. However, many objects cannot be detected either because of $1/n^2$ effects (luminosity limited) or because the pulses are severely broadening by scattering (scattering limited).
- Greater sensitivity than Arecibo allows detection of pulsars that are luminosity limited with Arecibo.
- Surveys at frequencies higher than 1.4 GHz enable objects that are scattering limited at L band to be detected because the pulse-broadening time $\tau_d \propto v^{-4}$.
- Migrating surveys to higher frequencies must be traded against the generally lower flux densities (pulsar flux densities $S \propto v^{-\alpha}$ with typical spectral indices $-0.1 \lesssim \alpha \lesssim 3$ at L band) and smaller FOV and array beam sizes.

These facts suggest that pulsar surveys with the SKA can be undertaken in a number of configuration modes:
Fig. 1. — $D_{\text{max}}$ vs. spin period for pulsar detection. The four frames correspond to different values of the ‘pseudo-
luminosity’ $L_P$, which is the period-averaged flux density $\times D^2$ (for a known pulsar, say). The distribution of $L_P$ for pulsars is
broad, covering several orders of magnitude, because the emission is beamed. Shaded regions are shown for Arecibo and the SKA. Top boundary of shaded region: full sensitivity. Lower boundary of shaded region: partial sensitivities. For the SKA
the partial sensitivity represents $f_{\text{core}} = 0.25$ (e.g. 25% of the collecting area in the core array at full on-axis gain ($g_{\text{core}} = 1$), or larger fraction combined with an off-axis gain factor $g_{\text{core}} < 1$). For Arecibo, the lower boundary is given by $f_{\text{core}} = 0.5$, i.e. sensitivity at the half-power point. Other survey parameters include $\nu = 1.4$ GHz, $B = 400$ MHz, time resolution = 64 $\mu$s, integration time = 300 s. An intrinsic pulse duty cycle of 0.05 is assumed. Propagation effects, which smear the pulse, are calculated for the direction $\ell, b = 30^\circ, 0^\circ$ using the electron density model NE2001. For distances $\gtrsim 5$ kpc, $D_{\text{max}}$ is strongly
influenced by pulse broadening from scattering.

1. Full FOV surveys with full SKA/core sensitivity;

2. Full FOV surveys with partial SKA/core sensitivity (as a subarray);

3. Multiple FOV surveys with partial SKA/core sensitivity using multiple subarrays; each subarray would
survey one FOV’s worth of sky.

Strawman survey parameters: Assume an L band survey with 300-s dwell time covering the full FOV.
We consider the FOV specification of 1 deg$^2$ for the SKA that matches the actual FWHM of the 12-m
dishes of the LNSD concept. If all Galactic longitudes and latitudes $|b| \leq 10^\circ$ are surveyed$^2$, the 7200 deg$^2$
would require 25 days to complete. Higher-latitude surveys are also of interest to find millisecond pulsars,
relativistic binary pulsars, and high-space-velocity pulsars. Surveying the entire sky (41,253 deg$^2$) would
require 143 days.

Transients: We know little about the transient radio sky. To be sure, giant pulses from radio pulsars are
prototypes for fast transients along with solar bursts and flare stars while sources such as microquasars
and gamm-ray burst (GRB) afterglows exemplify longer-duration transients. We may use these sources as
initial guides for specifying blind-survey parameters. However, simple observational phase space arguments
suggest that instantaneous coverage of a large fraction of the sky with appropriate sampling of the frequency-
time plane will yield a rich variety of transient sources, including new classes of objects. Figure 2 shows
the phase space of pulse width $W$ against flux density. The lines of constant brightness temperature are calculated as

$$T_b = \frac{S}{2K} \left( \frac{D}{\nu W} \right)^2 = 10^{20.5} K S_{\text{mJy}} \left( \frac{D_{\text{kpc}}}{\nu_{\text{GHz}} W_{\text{ms}}} \right)^2$$

where $S_{\text{mJy}}$ is the peak flux density (mJy) at frequency $\nu$ (GHz), $D$ is the distance.
Fig. 2.— A log-log plot of the product of peak flux $S$ in Jy and the square of the distance $D$ in kpc vs. the product of frequency $\nu$ in GHz and pulse width $W$ in s. Lines of constant brightness temperature $T = SD^2/2k(\nu W)^2$ are shown, where $k$ is Boltzmann’s constant. Points are shown for the ‘nano-giant’ pulses detected from the Crab (Hankins et al. 2003), the giant pulses detected from the Crab, PSR B1937+21 and PSR B1821–24, single pulses from all pulsars with flux, distance and pulse width listed in the Princeton Pulsar Catalog (Taylor et. al 1993) and other possible sources of radio bursts, including Jovian and solar bursts, flares from stars and a brown dwarf, OH masers, and AGNs. The regions labeled ‘coherent’ and ‘incoherent’ are separated by the canonical $10^{12}$K limit from the inverse Compton effect. Arrows pointing to the right for the GRB and IDV points indicate that interstellar scintillation (ISS) implies smaller brightness temperatures than if characteristic variation times are used to estimate the brightness temperature.

Slow transients are defined as those with time scales longer than the time it takes to image the relevant region of the sky. Detection of such objects can be accomplished simply through repeated mapping of the sky and thus do not require special capabilities beyond those needed for imaging applications. GRBs are currently detected at $\gtrsim 100 \mu$Jy levels using the VLA at frequencies of 5 and 8 GHz. The full SKA could detect GRB afterglows to at least 100 times fainter levels.

Fast transients, by contrast, require the same observing modes and post-processing as pulsars. The Crab pulsar is the most extreme known case in terms of showing temporal structure down to $\sim 2$ ns scales (Hankins et al. 2003) and giant pulses that exceed 130 times the entire flux density of the Crab Nebula. Figure 3 shows an example of such a pulse, including the dispersion sweep in the frequency-time plane. Pulsars and giant-pulse emission may represent prototypes for coherent radiation from other high-energy objects in which collimated particle flows can drive the necessary plasma instabilities. Examples include prompt radio burst emission from GRB-type sources, perhaps even from gamma-ray quiet objects; flare stars, jovian-burst like radiation from planets, and AGNs.

Using GRBs as a guide, it may be noted that the rate of GRB detection with gamma-ray instruments has relied more on instantaneous wide-field sky coverage than on sensitivity. The same statement holds for the detection of prompt optical emission at $m_v = 9$ in at least one case (Akerlof et al. 1999; Bloch et al. 2000). For this reason, we may expect that using the SKA in modes yielding large instantaneous sky coverage but not necessarily with the full sensitivity may be productive in surveying the transient radio sky.

The signal-to-noise ratio for a pulse after dedispersion and matched filtering is

$$\frac{S}{N} = \frac{S(N_{pol}BW)^{1/2}}{S_{sys}},$$

where $S$ is the peak flux density and $W$ is the pulse width (FWHM). Requiring $S/N > m = 10$ and using $2^2$

This would imply that there are both Northern and Southern hemisphere core arrays!
nominal parameters for, we get

\[
S_{\text{min,SP}} = \left( \frac{m}{10^4} \right) \left( \frac{1 \text{ ms}}{W} \right)^{1/2} \times \begin{cases} 
43 \text{ mJy} \frac{g_\theta}{g_\theta} & \text{AO} \\
1.5 \text{ mJy} \frac{g_\theta}{g_\theta f_c} & \text{SKA},
\end{cases}
\]  

(27)

For the SKA, the minimum flux density corresponds to a minimum brightness temperature,

\[
T_{\text{min,SP}} = \left( \frac{m}{10^4} \right) \left( \frac{1 \text{ ms}}{W} \right)^{5/2} \left( \frac{D_{\text{kpc}}}{\nu_{\text{GHz}}} \right)^2 \times \begin{cases} 
10^{22.2} \text{K} \frac{g_\theta}{g_\theta} & \text{AO} \\
10^{20.7} \text{K} \frac{g_\theta}{g_\theta f_c} & \text{SKA},
\end{cases}
\]  

(28)

The SKA can see about 1.5 orders of magnitude fainter than Arecibo. However, the much greater advantage of the SKA over Arecibo will consist of the sky coverage and greater resilience against RFI. With such coverage we can expect the SKA to yield new discoveries over much of the phase space depicted in Figure 2.

**Fig. 3.** — Plot of intensity against time and frequency, showing a single dispersed pulse as it arrives at different frequencies centered on 0.43 GHz. The right-hand panel shows the pulse amplitude vs. frequency while the bottom panel shows the pulse shape with and without compensating for dispersion delays. This pulse is the largest in one hour of data, has S/N \( \sim 1.1 \times 10^5 \), and a pulse peak that is 130 times the flux density of the Crab Nebula, or \( \sim 155 \text{ kJy} \). Note that the segments at either end of the bandpass where the pulse arrival time is opposite the trend at most frequencies is caused by aliasing of the signal.

**SETI:** Not yet written.

**Summary of observing modes needed:** Not yet written.

5. CONCLUSIONS

— Not yet written —
REFERENCES