

SKA Scientific Memorandum:
Telescope Response Times

T. Joseph W. Lazio & James M. Cordes

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EXECUTIVE SUMMARY

We discuss response times for observations of radio transients by the Square Kilometer Array (SKA). We consider both internal and external trigger events. We also consider propagation effects, both for their effect on astronomical signals as well as being signals in and of themselves. We recommend that the response time requirement for the SKA be approximately 1 minute; response times faster than approximately 10 seconds may be interesting but cannot be justified at this time.

TELESCOPE RESPONSE TIMES

1. INTRODUCTION

In comparison to the great success in surveying the transient sky at high energies (X- and gamma-rays), the transient radio sky remains largely unknown. Nonetheless, there are a number of indications that the radio sky may be quite dynamic. Radio observations of sources triggered by high-energy observations (e.g., radio observations of gamma-ray burst afterglows), monitoring programs of known high-energy transients (e.g., radio monitoring of X-ray binaries), giant pulses from the Crab pulsar, a small number of dedicated radio transient surveys, and the serendipitous discovery of transient radio sources (e.g., near the Galactic center) suggest that the radio sky is likely to be quite active on short time scales. There also may be unknown classes of sources.

Defining transients as objects or emission phenomena that show substantial flux density changes on time scales of one month or less, there is a vast number of classes of sources that may be transient. These range from the well-known, such as pulsars and microquasars, to the known but only poorly studied, such as extensive air showers in the Earth's atmosphere, to the hypothesized, such as exploding black holes. Improving our knowledge of the transient radio sky has been identified as a key goal of both the Square Kilometer Array (SKA) and Low Frequency Array (LOFAR). In designing either of these instruments, establishing the shortest relevant time scale may be a design aspect that enters cost equations.

We distinguish between two kinds of time scales relevant to telescope design: *time resolution* and *response time*. Time resolution refers to the sampling in time required by a correlator or other processing backend attached to the telescope. Combined with the number of (digital) bits that are processed per antenna/receiving element, the time resolution can enter cost equations because it determines the data transport rate. Response time refers to the time allowed between the notification of a transient event and when the telescope must be on-source and ready to observe. The response time requirement is perhaps more relevant for the SKA as pointing in all current concepts involves physical motion of the apertures to reach an arbitrary point on the sky.¹ Short response time requirements can impact mount design and costs.

We illustrate the difference between time resolution and response time by considering examples from pulsar timing. The accuracy of pulsar timing, particularly for millisecond pulsars, is determined in part by how well the pulses can be resolved. Time resolutions typically of order $5 \mu\text{s}$ are used. Similarly, substructure in the giant pulses from the Crab pulsar has been detected on time scales as short approximately 2 ns from observations at 5 GHz (Hankins et al., 2003). Thus, pul-

¹Of the seven current concepts, five clearly involve motion of the feed or collector in order to reach an arbitrary point on the sky: the Refracting Concentrator concept (Luneberg lenses), the Large Adaptive Reflector (LAR), the Kilometer-square Area Radio Telescope (KARST), the Preloaded Parabolic Dish Antenna concept, and the Large N-Small D concept. The Cylindrical Reflector concept provides millisecond response times via electronic beam formation along one axis while requiring mechanical motion along the other. The Aperture Array Tiles provide millisecond response times via electronic beam formation over an approximately 45° field, with mechanical tilting used to access the full sky.

sar observations can require microsecond or sub-microsecond time resolutions. However, because pulsar emission is stable over long time periods (> 1 yr), typical pulsar timing observations need to be conducted only weekly. Similarly, while the giant pulses in the Crab pulsar occur at random intervals, they occur at a large enough rate that giant pulse observations can be scheduled days or weeks in advance of the actual observations.

Consider a transient source that flares, bursts, or pulses, the width of which in time is W . The physical size of the source is then cW , by light travel time arguments. In the Rayleigh-Jeans approximation, the relation between the source's brightness temperature T and flux density S can be manipulated to yield

$$\nu^2 W^2 = \frac{1}{2\pi k} \frac{SD^2}{T}. \quad (1)$$

The source's distance is D , the emission frequency is ν , and k is Boltzmann's constant. The quantity SD^2 can be considered to be a pseudo-luminosity, while νW are related by an uncertainty-like relation that $\nu W > 2\pi$. For the Crab pulsar, $\nu W \approx 2\pi$ for the nanosecond giant pulsars, but for most sources $\nu W \gg 2\pi$.

Figure 1 shows the phase space of SD^2 (the pseudo-luminosity) vs. νW . There are two notable aspects of this figure. First, the transient radio sources observed span a large range in this phase space. The range of νW covers at least 13 orders of magnitude while the range of SD^2 covers at least 20 orders of magnitude. Second, large portions of this phase space are empty.

One of two conclusions can be drawn from Figure 1. One could conclude that no physical mechanisms or sources exist that would populate the empty regions in the phase space of Figure 1. Alternately, we regard Figure 1 as an illustration of the incompleteness of our knowledge of the transient radio sky. This latter approach has been adopted by both the SKA and LOFAR projects.

Although our upper limit on relevant time scales (1 month) is arbitrary, the lower limit is set by the physics in the source and the physics of the signal's propagation to the Earth. This memorandum considers response times for radio transients as allowed by physical processes and imposed by intervening media. In §2 we consider the physical limits on transient time scales, with an eye toward "triggered" observations. In §3 we describe two propagation effects that will limit transient time scales. We also consider how propagation effects may serve as a signal of interest. We summarize our conclusions and recommendations in §4. Our focus throughout much of this memorandum will be toward the SKA, but many of these effects are relevant to LOFAR and our conclusions can be extended easily to that instrument.

2. EMISSION PROCESSES AND TRIGGERED OBSERVATIONS

Previous and existing radio telescopes have had a productive history of "triggered" observations. For instance, for several years the Green Bank Interferometer (GBI) monitored various sources, typically radio counterparts to high-energy sources, and radio flares observed with the GBI were used to initiate or "trigger" observations at other observatories (Mioduszewski, 2001). Conversely, triggers from telescopes operating at other wavelengths are crucial to initiating observations with many existing radio telescopes (e.g., Frail et al., 1997; Taylor et al., 1997).

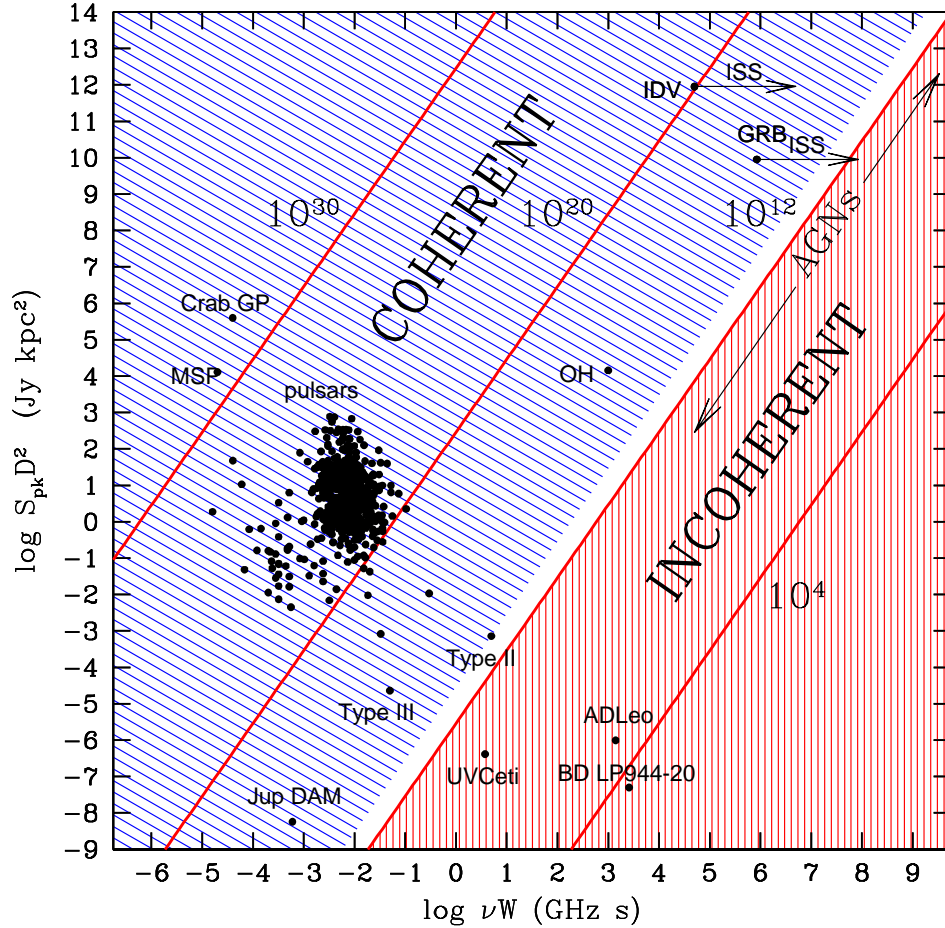


Fig. 1—The phase space for radio transients. The abscissa is the product of the emission frequency ν and transient duration or pulse width W . The ordinate is the pseudo-luminosity or the product of the observed flux density S and distance D^2 . In the Rayleigh-Jeans approximation, these quantities are directly proportional and related to the brightness temperature T (eqn. 1). The sloping lines are labelled by constant brightness temperature. A brightness temperature of 10^{12} K is taken to divide coherent from incoherent sources. Examples of transient emission from various classes of sources are indicated. The various sources plotted include Type II and III solar bursts, Jupiter’s decametric radiation (DAM), flares from active stars such as UV Ceti and AD Leo, flares from the brown dwarf (BD) LP944-20, the giant pulses seen from the Crab (Crab GP) and the millisecond pulsar PSR B1937+21, and the rapid time variations seen in OH masers. In the case of gamma-ray burst afterglows (GRB) and intraday variability (IDV) of active galactic nuclei (AGN), the apparently high brightness temperatures are not thought to be intrinsic but related to interstellar scintillation (ISS). For these two classes of sources we show how the absence of ISS would affect their locations in this phase space.

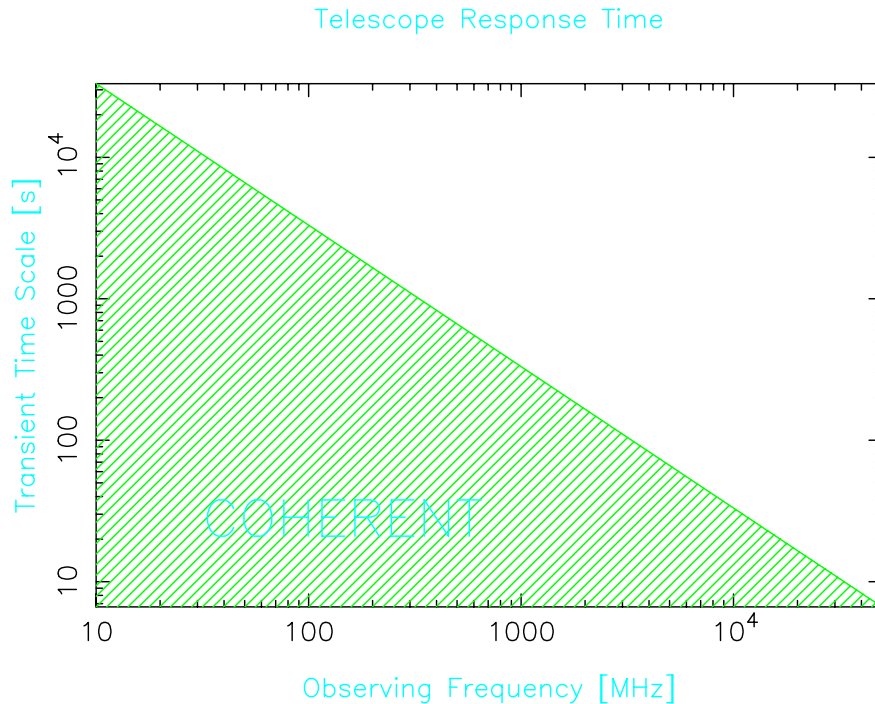


Fig. 2—Expected transient time scales as a function of observing frequency (viz. eqn. 1). Plotted is the curve for a source with a brightness temperature $T = 10^{12}$ K, having a flux density $S = 1$ Jy, and located at a distance $D = 1$ kpc. The transient time scale is given by $W \propto \sqrt{S/T}D$, so an incoherent source can have a shorter time scale only if its flux density is less than 1 Jy, its distance is less than 1 kpc, or both. Sources with brightness temperatures above 10^{12} K fall into the region labelled “coherent.”

2.1 Internal Triggers

All of the current designs for the SKA (and LOFAR) envision a substantial amount of collecting area in “stations.” In some designs, these stations would be collections of individual antennas phased together, in other designs the stations would be the individual antennas themselves. In either case, the array could be operated in several sub-arrays, each observing a different source or region of the sky. If a flare or pulse was observed, the on-going, sub-arrayed observations could be halted, and the full collecting area of the SKA brought to bear on the transient source. How fast would the SKA need to respond to such an internal trigger?

Equation (1) can be written in terms of the transient duration W as a function of frequency for a source with constant pseudo-luminosity and brightness temperature. Figure 2 shows the transient time scale expected for an incoherent synchrotron source with a brightness temperature of 10^{12} K having a flux density of 1 Jy located at 1 kpc as a function of observing frequency. As can be seen, response times of roughly 100 s would suffice for incoherent sources observed at frequencies of a few Gigahertz. Even though the SKA will detect weak sources ($\sim 1 \mu\text{Jy}$), any extragalactic sources will have a large distance, which will more than compensate for the small value of S . Only a Galactic population of incoherent sources could demand short response times, and we do not see, presently, why such sources would require study in a fast-response mode.

We emphasize that an implicit assumption in using internal triggers is that the full collecting

area is required. This is not always the case. In timing observations of pulsars, which might be targeted to studies of glitches, the arrival-time precision can be limited not by the sensitivity of the telescope but by pulse (or sub-pulse) phase jitter. Roughly, once the signal-to-noise ratio of a single pulse exceeds unity, the error on the arrival time will be jitter dominated rather than radiometer-noise dominated.

2.2 External Triggers

External triggers are somewhat more difficult to assess as they depend upon the instrumentation available at other wavelengths during the operational period of the SKA. Nonetheless, we can make some general comments based on current-day or near-future instrumentation.

- The SWIFT satellite is a NASA MIDEX mission designed to detect and localize gamma-ray bursts (Gehrels, 2000). Gamma-ray bursts should be able to be localized within 1 min.
- The Rapid Telescope for Optical Response (RAPTOR) project consists of a wide-field optical monitoring system designed to identify optical transients in real-time (Vestrand et al., 2002). The project anticipates being able to provide automated alerts to other observatories on time scales of roughly 1 min (J. Wren 2002, private communication).
- A binary inspiral event is expected to produce gravitational waves for roughly 90 s, within the range of frequencies to which the Laser Interferometer Gravitational-wave Observatory (LIGO) will be sensitive (Allen et al., 1999).

If the time scale of the transient is much shorter than about 1 min., the event will be over perhaps even before these instruments could alert the SKA. We conclude that a response time of less than about 1 min. is not required for external triggers.

3. PROPAGATION EFFECTS

There are two propagation effects that will limit the observed transient time scales. The first is *dispersion smearing*, which can be combatted by appropriate instrumental choices and pre- or post-processing software. The second is *pulse broadening*, which is fundamental to the medium and cannot be removed easily.

We first describe these propagation effects and indicate their magnitude imposed by the interstellar medium (ISM). We then consider how propagation effects can produce a signal of interest and what impact this has on the response time of the telescope.

3.1 Dispersion Delay

Dispersion delay occurs because a plasma is dispersive, with a refractive index that is frequency dependent. As a consequence, higher frequency pulses arrive sooner than lower frequency pulses. Dispersion delay has an impact on observations of short pulses at radio frequencies that we cover below (§3.2). Equally important, though, is that it results in radio pulses being delayed relative to higher frequency pulses (e.g., optical, X-ray, or gamma-ray).

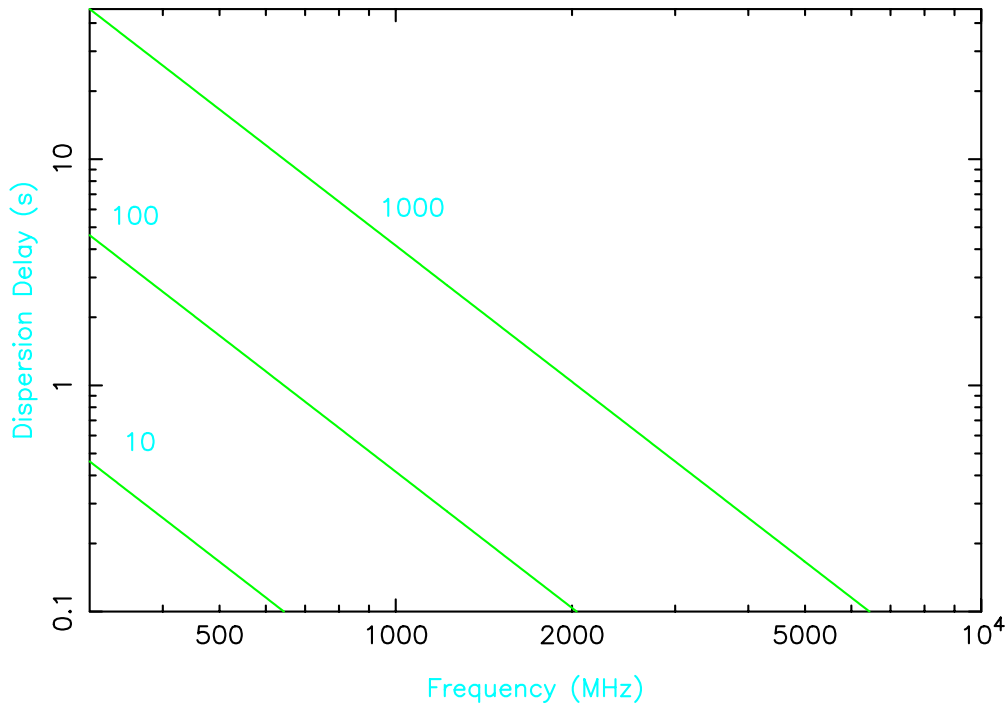


Fig. 3—The dispersion delay (eqn. 1) as a function of frequency over a portion of the SKA’s presumed operating range. The curves are labeled by the dispersion measure DM in its standard units of pc cm^{-3} .

The amount of delay, relative to the free-space propagation time, is

$$\Delta t_{\text{delay}} = 4.1 \text{ ms DM } \nu_{\text{GHz}}^{-2}, \quad (1)$$

where ν_{GHz} is the observation frequency in GHz and the dispersion measure DM is the line-of-sight integral of the electron density,

$$\text{DM} \equiv \int dz n_e(z) \quad (2)$$

measured in cm^{-2} . Typical values for DM, as determined from pulsar observations, are roughly 100 pc cm^{-3} . The maximum is $\text{DM} \approx 1100 \text{ pc cm}^{-3}$. Figure 3 shows that the dispersion delay for typical lines of sight through the Galaxy at 1 GHz will be roughly only 0.4 s, and we would not expect delays longer than about 4 s.

With the exception of pulsars in the Magellanic Clouds, no radio transient sources are known outside of the Galaxy. The expected DM contributed over intergalactic distances is $\text{DM} \approx 100 \text{ pc cm}^{-3}$ (Palmer, 1993; Cordes & Lazio, 2003a). Cosmological sources suggested to produce radio pulses include gamma-ray bursts (Benz & Paesold, 1998; Sagiv & Waxman, 2002). The latter authors in particular predict that the onset of the radio burst may be delayed by as much as a minute from the onset of the gamma-ray burst and that the peak of the emission will occur at frequencies $\nu_{\text{GHz}} < 0.3 \text{ GHz}$. In this case, because of the ν^{-2} dependence of the dispersion delay, we expect a further delay of approximately 1 min.

Thus, for Galactic sources, the dispersion delay would suggest response times of less than 1 s, but for cosmological sources response times of roughly 1 min. are probably acceptable.

3.2 Dispersion Smearing

The previous section considered the delay of a pulse between radio and higher frequencies. Because radio observations are conducted over some finite bandwidth, dispersion delay also introduces a smearing within the band. The magnitude of dispersion smearing is

$$\Delta t_{\text{smear}} = 8.3 \mu\text{s} \Delta\nu \nu_{\text{GHz}}^{-3} \text{DM}, \quad (3)$$

where $\Delta\nu$ is the receiver bandwidth in MHz. For the case of a filterbank or spectrometer, $\Delta\nu$ is the bandwidth of an individual channel, not the total receiver bandwidth.

Dispersion smearing is at least nominally under the control of the observer and will not affect the response time. By choosing either a sufficiently large observing frequency or sufficiently small receiver bandwidth or both or by dedispersing the signal coherently, Δt_{smear} can be made arbitrarily small. Dispersion smearing may impose other costs on the telescope, though, as the post-processing computation required to handle dispersion smearing when the DM is not known *a priori* can be substantial.

3.3 Pulse Broadening

Pulse broadening occurs in a medium containing plasma density fluctuations. The density fluctuations produce refractive index fluctuations that then scatter propagating radiation. Although formally a wave optics phenomenon, pulse broadening can be understood heuristically via ray optics: Scattered rays are delayed in reaching the observer relative to direct rays. The result is that a pulse is broadened. In contrast to dispersion smearing, pulse broadening is imposed by the medium and cannot be removed by the observer.

The magnitude of pulse broadening is given by (Cordes & Rickett, 1998)

$$\tau_d = \frac{1}{2c} \int_0^D ds \eta s(1 - s/D) \quad (4)$$

where c is the speed of light, D is the distance to the source, and η is the rms scattering angle per unit path length. The rms scattering angle, and therefore τ_d , scales as ν^x with $x \approx -4$; the exact value depends upon the form of the density power spectrum and on the spatial distribution of ionized clouds containing fluctuations.

Taylor & Cordes (1993) and Cordes & Lazio (2003b) have developed models for the distribution of pulse broadening within the Galaxy. Within 1 kpc of the Sun, pulse broadening will probably not exceed 10 μs at 1 GHz. The maximum value will occur through the Galactic center where pulse broadening exceed 100 s (Cordes & Lazio, 1997; Lazio & Cordes, 1998).

Over cosmological distances, the power spectrum of density fluctuations is not known. If we assume that the pulse broadening is roughly correlated with the DM (as it is in the Galaxy, Cordes et al. 1991), then the typical cosmological DM (§3.1) suggests $\tau_d > 0.4$ ms for frequencies $\nu_{\text{GHz}} < 0.3$ GHz.

Table 1—Response Time for IDV Observations

S (mJy)	Number of sources per SKA FoV	Number of FoVs to obtain 1 source
100	0.02	50
30	0.08	13
10	0.27	3.7

3.4 Propagation Effects As Signals: Intraday Variability

Thus far we have discussed propagation effects from the standpoint of their effect on propagating signals. The density fluctuations responsible for pulse broadening also give rise to *intensity scintillations*. These scintillations only occur if the intrinsic source diameter is sufficiently small (analogous to “stars twinkle, while planets don’t”), thereby providing an indirect probe of the angular diameter of sources. Recent observations of rapid variations (time scales < 1 d) have demonstrated that scintillation due to the ISM is at least partially responsible (e.g., Dennett-Thorpe & de Bruyn, 2002).

The typical time scale for intraday variability (IDV) appears to be at least hours (Kedziora-Chudczer et al., 1997) if not much longer, e.g., the quasar J1819+385 appears to have been scintillating for years. However, there has been interest expressed at SKA meetings of mapping out the distribution of scintillation around a source known to be exhibiting IDV (most recently in the SKA meeting in Groningen, 2002 August). How far would the telescope have to slew in order to find another source exhibiting IDV?

We assume that the diameter of the SKA field of view is 1° at 1 GHz. A typical frequency for IDV is 5 GHz, at which the SKA field of view is 113 square arcminutes. The source number counts at 5 GHz are $N(> S) = 0.032 S^{-1.13}$ arcmin $^{-2}$ for source flux densities measured in milliJanskys (Bridle, 1989). Observationally, it appears that weaker sources are more likely to show IDV than stronger sources (Lovell et al., 2003), which is consistent with the notion that incoherent synchrotron sources have a limiting brightness temperature.

Table 1 considers the distance the telescope would have to slew to find another source possibly exhibiting IDV. In the most extreme case, one would have to slew about 50 beams or about 10° to obtain another IDV source. If weaker sources show more IDV, one might have to slew no more than a few degrees. Slew rates comparable to those of existing arrays (e.g., $20^\circ \text{ min}^{-1}$) would appear to be adequate or nearly so.

We caution that this analysis has made no assumption about the size of the structures responsible for IDV. Inferred diameters of sources undergoing IDV are typically of order $10 \mu\text{as}$. Thus, density fluctuations (“clouds”) on AU scales could be responsible for IDV. If so, sources surrounding an IDV source may not be undergoing IDV themselves simply because the line of sight would not be affected by the same cloud affecting the IDV source.

4. CONCLUSIONS AND RECOMMENDATIONS

We have illustrated how both source physics and propagation effects can be used to guide the development of response time requirements for radio telescopes, in particular the Square Kilometer Array. We conclude that a response time of order 1 min. at 1 GHz is a sufficient requirement.

External triggers from telescopes at other wavelengths are unlikely to arrive much faster than this, while internally-triggered observations, e.g., from a subarray, are limited by the source physics, which also suggests time scales of order 1 min. (Figure 2). For incoherent sources, a shorter time scale is justified only if their flux density is significantly less than 1 Jy, their distance is significantly less than 1 kpc, or both. We are unaware of any known population of incoherent radio sources fitting this description and which justifies shorter response times. We also emphasize that factors other than the sensitivity of the array may ultimately limit the signal-to-noise ratio of the observations so that, for certain classes of objects or observations of certain phenomena, internally-triggered observations may not be worthwhile.

Coherent sources are a possible class of sources that may allow shorter intrinsic time scales. Known classes of coherent sources tend to be stronger at frequencies well below 1 GHz at which the emitting volumes grow large enough and power levels increase substantially. However, at lower frequencies, the dispersion delay can become significant. For these sources response times of order 10 s may be justified, though we can identify no known or plausibly suggested class of sources for which this would be the case. Both pulsar searching and pulsar timing do not demand such rapid response times, and observations of bursts from extrasolar planets (Farrell et al., 1999) can be targeted at stars known to host planets (at least initially).

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5. BIBLIOGRAPHY

- Allen, B., Finn, S., Prince, T., Riles, K., & Weiss, R. 1999, "LSC Data Analysis White Paper: Draft IV," <http://www.ligo.caltech.edu/%7Elazz/distribution/LSCDataWP/>
- Benz, A. O. & Paesold, G. 1998, "A Search for Prompt Radio Emission of Gamma-Ray Bursts," *Astron. & Astrophys.*, 329, 61
- Bridle, A. H. 1989, "Synthesis Observing Strategies—A 'Hitch-Hiker's Guide'," in *Synthesis Imaging in Radio Astronomy*, eds. R. A. Perley, F. R. Schwab, & A. H. Bridle (ASP: San Francisco) p. 443
- Cordes, J. M. & Lazio, T. J. W. 2003a, "Radio Wave Scattering From Cosmological Free Electrons," in preparation
- Cordes, J. M. & Lazio, T. J. W. 2003b, "NE2001. A New model for the Galactic Distribution of Free Electrons and Its Fluctuations," *Astrophys. J.*, submitted
- Cordes, J. M. & Lazio, T. J. W. 1997, "Finding Radio Pulsars in and beyond the Galactic Center," *Astrophys. J.*, 475, 557

- Cordes, J. M., Ryan, M., Weisberg, J. M., Frail, D. A., & Spangler, S. R. 1991, "The Galactic Distribution of Free Electrons," 1991, *Nature*, 354, 121
- Cordes, J. M. & Rickett, B. J. 1998, "Diffractive Interstellar Scintillation Timescales and Velocities," *Astrophys. J.*, 507, 846
- Dennett-Thorpe, J. & de Bruyn, A. G. 2002, "Interstellar Scintillation as the Origin of the Rapid Radio Variability of the Quasar J1819+3845," *Nature*, 415, 57
- Farrell, W. M., Desch, M. D., & Zarka, P. 1999, "On the Possibility of Coherent Cyclotron Emission from Extrasolar Planets," *JGR*, 104, 14025
- Frail, D. A., Kulkarni, S. R., Nicastro, S. R., Feroci, M., & Taylor, G. B. 1997, "The Radio Afterglow from the Gamma-Ray Burst of 8 May 1997," *Nature*, 389, 261
- Gehrels, Neil A. 2000, "Swift gamma-ray burst MIDEX," *Proc. SPIE*, eds. K. A. Flanagan & O. H. Siegmund, 4140, 42
- Hankins, T., et al. 2003, *Nature*, in press
- Kedziora-Chudczer, L., Jauncey, D. L., Wieringa, M. H., Walker, M. A., Nicolson, G. D., Reynolds, J. E., & Tzioumis, A. K. 1997, "PKS 0405-385: The Smallest Radio Quasar?" *Astrophys. J.*, 490, L9
- Lazio, T. J. W. & Cordes, J. M. 1998, "Hyperstrong Radio-Wave Scattering in the Galactic Center. II. A Likelihood Analysis of Free Electrons in the Galactic Center," *Astrophys. J.*, 505, 715
- Lovell, J. E. J., et al. 2003, in preparation
- Mioduszewski, A. J., Rupen, M. P., Hjellming, R. M., Pooley, G. G., & Waltman, E. B. 2001, "One-sided Highly Relativistic Jet from Cygnus X-3," *Astrophys. J.*, 553, 766
- Palmer, D. M. 1993, *Astrophys. J.*, 417, L25
- Sagiv, A. & Waxman, E. 2002, "Collective Processes in Relativistic Plasma and Their Implications for Gamma-Ray Burst Afterglows," *Astrophys. J.*, 574, 861
- Taylor, J. H. & Cordes, J. M. 1993, "Pulsar Distances and the Galactic Distribution of Free Electrons," *Astrophys. J.*, 411, 674
- Taylor, G. B., Frail, D. A., Beasley, A. J., & Kulkarni, S. R. 1997, "Position and Parallax of the Gamma-Ray Burst of 8 May 1997," *Nature*, 389, 263
- Vestrand, W. T., Borozdin, K., Brumby, S., et al. 2002, "The RAPTOR Experiment: A System for Monitoring the Optical Sky in Real Time," *Proc. SPIE*, 4845, in press