Draft version March 8, 2019
Typeset using LaTeX twocolumn style in AASTeX62

THE DSA-2000: A RADIO SURVEY CAMERA FOR THE NEXT DECADE

Gregg Hallinan,[1] Vikram Ravi,[1] Sandy Weinreb,[1] Jonathon Kocz,[1] David Woody,[1] James Lamb,[1] Michael Eastwood,[1] Larry D'Addario,[1] Maura McLaughlin,[2] Scott Ransom,[2] and Xavier Siemens[2]

[1]*Department of Astronomy, California Institute of Technology, 1200 E. California Blvd, Pasadena CA, 91125, USA*
[2]*The NANOGrav Collaboration*

ABSTRACT

We present the Deep Synoptic Array 2000-antenna concept (DSA-2000): a world-leading radio survey telescope and multi-messenger discovery engine for the US community. As an evolution of the 110-antenna DSA, now under construction, the DSA-2000 is proposed to consist of 2000×5 m dishes instantaneously covering the $0.7 - 2$ GHz frequency band. The DSA-2000 will be the first true radio camera, outputting science-ready image data with a spatial resolution of $\sim 3.5''$. Baseline specifications include an equivalent point-source sensitivity to the SKA-mid array, but with 10× the survey speed. The DSA-2000 will be a survey instrument in advance of the ngVLA, and as a counterpart survey instrument to the LSST. In a 5-yr prime phase, the entire sky with declination $> -30°$ will be imaged over sixteen epochs, detecting > 1 billion radio sources in a combined full-Stokes sky map with 500 nJy/beam rms noise. A high-spectral resolution (24 kHz; $\sim 5\,\mathrm{km\,s^{-1}}$ at 1.4 GHz) all-sky image cube will also be delivered for spectral-line studies. In addition, the array will be a cornerstone for multimessenger science, serving as the principal instrument for the US pulsar timing array community, and by searching for radio afterglows of compact object mergers detected by LIGO and Virgo. The array will also detect and localize fast radio transients within its primary beam, and commensally participate in VLBI observations. This white paper solicits input from the community on the baseline design of the DSA-2000, before submission of a full white paper to the Astro2020 Decadal Survey.

1. DSA-2000 OBSERVING MODES

The proposed baseline specifications for the DSA-2000 are summarized in Table 1. Assuming a 5-year prime phase, four dedicated and two commensal surveys are envisaged.

1.1. The Cadenced All-Sky Survey: $\sim 65\%$ of the prime phase will be dedicated to repeatedly surveying the entire sky north of $-30°$ ($\approx 30,000$ deg^2). All-sky images for each of 16 epochs spaced at a cadence of 3.75 months will enable time domain science, with each all-sky mosaic produced from $\sim 6,000$ pointings each using 15 min of visibility data. The far sidelobes of the resulting synthesized beam drop below -55 dB from peak, obviating the need for deconvolution (Figure 1). On-the-fly calibration will utilize pre-existing catalogs and precisely measured antenna beam patterns. Calibration, gridding and imaging will all be completed autonomously within the digital backend, resulting in the production of spectral image cubes, rather than visibility data, greatly reducing the post-correlation data processing costs.

Each epoch will be archived as a spectral image cube (images in 10×128 MHz bands; 30 TB) of the entire sky as well as a single combined image. The latter will be a trillion pixel map (3 TB) with rms noise of 2 μJy/beam, assuming 35% bandwidth loss to RFI and 20% time loss to slewing and operational overhead, and will be accompanied by an associated catalog with a 10-point SED for each source. The final all-sky full-Stokes image will have an rms noise of 500 nJy/beam and will detect $\sim 10^9$ discrete radio sources. An all-sky high-resolution spectral image cube (images in $20,000 \times 24$ kHz bands; 60 PB) will also be delivered, spanning 0.95–1.45 GHz and 1.65–1.675 GHz with velocity resolution of $\sim 5\,\mathrm{km\,s^{-1}}$ at 1.4 GHz, tracing HI in galaxies out to a redshift $z \sim 0.5$, and Galactic OH.

1.2. Pulsar Timing: The DSA-2000 will serve as the principal instrument for the US effort to detect nanoHertz gravitational waves through millisecond pulsar (MSP) timing (approximately 25% of the prime phase). By the mid-2020s, the NANOGrav collaboration is expected to have made a detection of the stochastic gravitational-wave background. Observations at weekly to monthly cadence of a large number of MSPs will be necessary to characterize its spectrum, search for anisotropies, and test for deviations from the predictions of general relativity. NANOGrav will also be in the regime where the detection of a single, continuous-wave source is likely. Observations at higher (optimally daily) cadences of a few (perhaps tens) MSPs will be necessary to enable the transformative multi-messenger astrophysics that will result from single-source detection. The flexibility of the DSA-2000 will be able to accommodate both of these require-

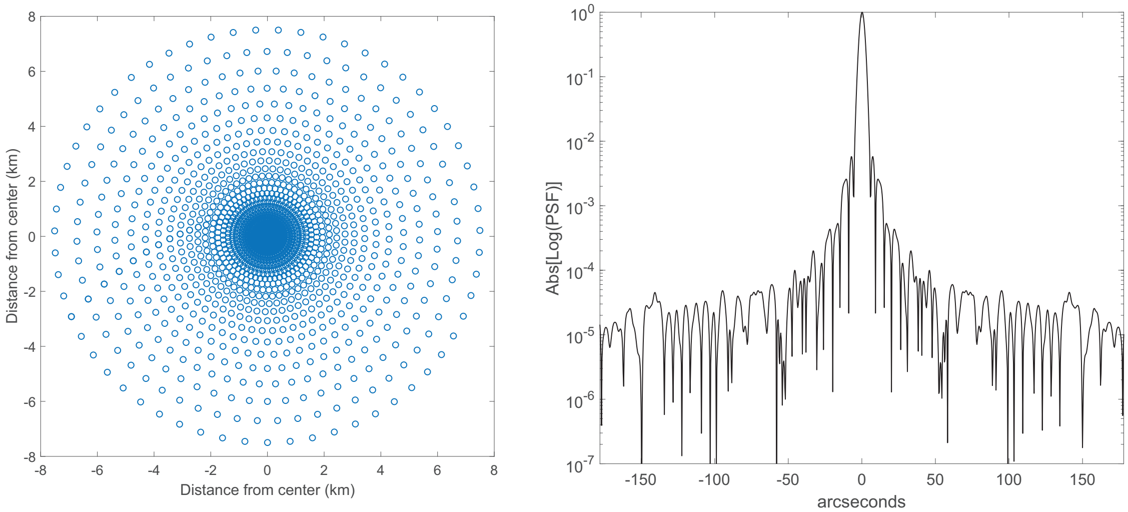

Figure 1. *Left:* A preliminary configuration for the DSA-2000 spanning a 15 km diameter area, consisting of nested rings that avoids straight lines and repeating patterns, and ultimately optimized for snapshot imaging. The final DSA-2000 configuration will be optimized for 15 minute tracks. *Right:* A cut through the point spread function for a 20 s track with this same configuration for the DSA-2000. Further improvement is expected for a configuration optimized for 15-minute tracks.

ments. The 0.7–2 GHz frequency range is optimal, as established through simulations accounting for pulsar spectra, timing precision, interstellar medium effects, and other sources of noise.

1.3. Deep Drilling Fields: The DSA-2000 will observe three of the LSST deep drilling fields (XMM-LSS, Extended Chandra Deep Field-South, COSMOS) for approximately 5% of the prime phase, with a daily cadence. Each of the final ~ 10 deg^2 images will have thermal noise contributions of 50 nJy/beam, but will be confusion-noise limited at the ~ 100 nJy/beam level (Condon et al. 2012). An additional 2,000 deg^2 of deep field data will be available with typical rms$\sim$ 200 nJy/beam due to frequent observations of ~ 200 pulsar timing fields.

1.4. Compact-Object Merger Follow-up: Approximately 1 hr per day will be used for follow-up observations of gravitational-wave events detected by LIGO/Virgo, and eventually a five-detector gravitational wave observatory (LIGO Hanford + LIGO Livingston + Virgo+ KAGRA + LIGO India). In the latter case, the median 90% credible localization region is expected to be 9–12 deg^2 (Abbott et al. 2018). The DSA-2000 is ideally specified to follow-up such events (Hallinan et al. 2017), with the capability to image an entire localization region with an rms noise of ~ 1 μJy/beam (image center) in one hour.

1.5. Commensal Mode – FRBs: As a commensal mode during all-sky observations, multiple coherent beams will be formed from a subset of the array to search the entire 10.6 deg^2 field of view of the DSA-2000 for short duration transients, particularly fast radio bursts (FRBs). The DSA-2000 will detect and localize FRBs at a rate of $\sim 10^3$ – 10^4/year, primarily for the characterization of the IGM and as a cosmological tool.

Table 1. Baseline DSA-2000 Specifications

Quantity	Value[a]
Reflectors	2000×5-m dishes
Frequency Coverage	0.7–2 GHz
Bandwidth	1.3 GHz
Field of View	10.6 deg^2
Spatial Resolution	3.5″
System Temperature	25 K
Aperture Efficiency	70%
System-equivalent flux density (SEFD)	2.5 Jy
Survey Speed Figure of Merit	1.3×10^7 deg^2 m^4 K^{-2}
Continuum Sensitivity (1 hour)	1 μJy
All-Sky Survey (per epoch)	30,000 deg^2 @ 2 μJy/bm
All-Sky Survey (combined)	30,000 deg^2 @ 500 nJy/beam
Pulsar Timing Fields	2000 deg^2 @ 200 nJy/beam
Deep Drilling Fields	30 deg^2 @ 100 nJy/beam
Brightness Temperature (1σ)	5 mK
Number of Unique Sources	> 1 billion

[a] Sensitivity calculations assume 65% usable bandwidth and 20% time loss to overheads. The field of view assumes a standard illumination taper.

1.6. Commensal Mode – VLBI: During its all sky survey, the beamformer of the DSA-2000 will be available to commensally provide the capability to conduct VLBI observations in combination with pre-existing VLBI infrastructure,

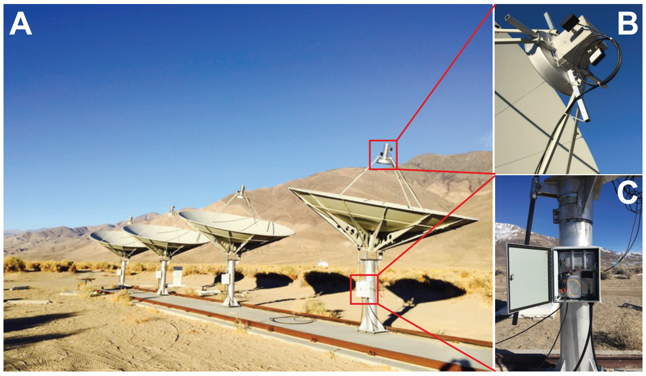

Figure 2. **A:** Four of the antennas of the DSA-10 located at Caltech's Owens Valley Radio Observatory (OVRO). **B:** The custom-designed feed attached to an antenna of the DSA-10. **C:** The front-end electronics enclosure attached to one of the DSA-10 antennas.

such as the VLBA, or with a partner array of DSA antennas installed at US university sites. Pre-selected targets would thereby form the basis for an all-sky VLBI survey that occurs simultaneously to the primary imaging survey. This same capability can also be used to provide VLBI observations of gravitational-wave events, and millisecond pulsars for distance measurements.

2. DSA-2000 ARCHITECTURE

The DSA-2000 will be the third iteration of the DSA concept, consisting of low-cost antenna/receiver packages linked by an RF over fiber network to a powerful digital backend. The concept builds on progress with the DSA-10 (operational) and DSA-110 (under construction). The DSA-10 makes use of ten commercial off-the-shelf 4.5-m dishes and mounts, the latter with manually adjusted azimuth and elevation range (Figure 2). These antennas are outfitted with custom-designed feeds and commercial ambient-temperature LNAs with noise temperatures of 32 – 38 K, resulting in an overall system temperature of $\sim$ 60 K and aperture efficiency of 62%. The DSA-10 antenna and receiver package was built for a unit cost of < \$4000, including hardware and labor, with a comparable per-antenna digital backend cost.

Fully funded through the NSF MSIP program, the DSA-110 represents a significant evolution from the DSA-10. Consisting of 110 × 5-m dishes distributed across 2.5 km, each antenna will be serviced by a motorized elevation drive and a custom-designed LNA, which has been lab-demonstrated to have a noise temperature of 12 K. The final expected system temperature is 30 K, with aperture efficiency of 70%. The DSA-110 dish package, including receiver, mount and motorized elevation drive are being constructed at a unit cost of < \$7500, including hardware and labor. Again, a comparable digital-backend cost per antenna is anticipated.

A few key technological advances over the DSA-110 are proposed for the DSA-2000. The DSA-2000 will progress to a thermoelectrically cooled LNA, motivated by a lab-demonstrated noise temperature of 6 K at −40°C for a custom-designed LNA (Weinreb et al., in prep.). A new wideband feed will be integrated into an improved optical design for the antennas. The baseline specification assumes a system temperature of 25 K, with aperture efficiency of 70%. The mount and drive will progress to a fully motorized azimuth and elevation drive with limited tracking capability. The expected unit cost for the DSA-2000 antenna/receiver package is conservatively estimated to be < \$20,000, including hardware and labor. The digital backend will enable three simultaneous modes of operation: a 4000-input cross correlator, a full-array beamformer, and a partial-array multiple-beam system tiling the primary beam.

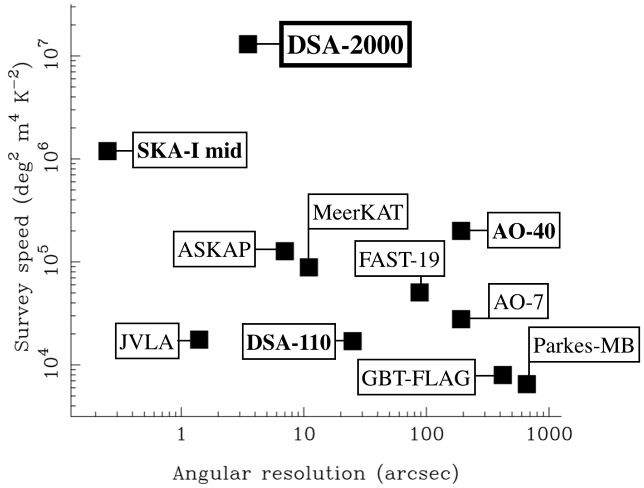

Figure 3. A comparison between the DSA-2000 and other extant (normal text) or upcoming (bold font) radio telescopes operating at 1.4 GHz. The data were largely obtained from the SKA Baseline Design Document Version 2.

Construction costs for the DSA-2000 are estimated to be less than \$100 million: (i) dish and receiver package (\$40 million), (ii) infrastructure, fiber/power network, monitor/control (\$25 million), (iii) digital backend, including imaging (\$30 million), (iv) continuum data catalog and archive (\$5 million). Detailed costing will be presented in the Decadal Survey white paper, together with discussion of potential sites in California, Nevada, and New Mexico.

The DSA-2000 will provide the US community with a radio camera with unparalleled capabilities for surveys and multi-messenger science (Figure 3). We look forward to input from the community on the baseline design of the DSA-2000 for specific science cases of interest.

References – Abbott, B. P., et al. 2018, LRR, 21, 3 – Condon, J., et al. 2012, ApJ, 758, 23 – Hallinan, G., et al. 2017, Science, 358, 1579.