Science Applications of Large Deep Space Network Arrays

D. L. Jones[1] and M. J. Connally[2]

The Deep Space Network (DSN) has begun work on vastly expanding its downlink capacity with the overall goal of increasing the telemetry data by about an order of magnitude every 10 years for the next 30 years. Large arrays of small antennas (several meters in diameter), operating at radio frequencies, are a leading technology being investigated to meet this goal. Large arrays promise more than just an increase in total ground aperture for reception of telemetry signals. They also could be used for direct scientific observations in the fields of radio astronomy, radar astronomy, and flight radio science, much like the single-aperture antennas of the DSN are now. In this context, large arrays have the potential to increase the signal-to-noise ratio of these observations and provide multiple, simultaneous beams and deep radio frequency images. As with the current DSN, science observations with large arrays could provide direct benefit to NASA projects as well as create avenues for the infusion of technology and techniques that enhance spacecraft tracking. This article examines the potential of large DSN arrays to enable new scientific observations and identifies key design issues of large arrays to maximize their potential for science in addition to their primary use for spacecraft tracking.

I. Introduction

The Interplanetary Network Directorate (IND) has a strategic goal of significantly increasing the downlink capacity from deep-space missions in the decades ahead. Deployment of large arrays of smaller antennas, operating at radio frequencies (RF) on Earth, is a leading candidate technology. Arraying antennas involves combining signals from multiple antennas. Signal combining must be preceded by adjusting the delay from individual antennas to account for signal delays due to (1) the arrival of the source signal at different times because of array geometry and the plane-of-sky position of the source; (2) differences in the troposphere and ionosphere over different antennas; and (3) different electronic paths from different antennas. When these delays are correctly adjusted, signals from different antennas combine to produce a signal with a signal-to-noise ratio (SNR) equal to the sum of the SNRs from the individual antennas.

---

[1] Tracking Systems and Applications Section.

[2] Communications Systems and Research Section.

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Large arrays of small antennas are economically feasible today principally due to extreme cost reductions from mass production of components needed for the home satellite entertainment industry. These components include low-cost, high-performance parabolic antennas and broad-bandwidth, high-performance, low-noise amplifiers. Combined with advances in special-purpose integrated circuits, these cost innovations have reduced cost estimates for an array with a combined G/T (antenna gain/system noise temperature) of 100 times that of the current Deep Space Network (DSN) 70-m antenna to less than 10 times the cost of a 70-m antenna.

Obviously the potential for large, cost-effective increases in aperture and sensitivity is the primary reason for the interest in large arrays. In addition, experience with existing radio astronomy arrays, such as the Very Large Array (VLA), indicates that performance in other areas (such as frequency/phase stability, group delay stability, any amplitude calibration accuracy) could be comparable to current DSN performance.

Besides lower capital cost, RF arrays also have benefits not found in large, single-aperture antennas. By combining signals from antennas or clusters of antennas separated by long baselines, signal combining also can produce a direct measurement of the plane-of-sky position of the source and its time rate of change. By calibrating the array using a nearby natural radio source, this plane-of-sky position can be directly referenced to the International Celestial Reference Frame (ICRF). The ICRF is the most precise and most nearly inertial reference frame currently defined.

Operationally, large arrays of smaller antennas provide flexibility in resource scheduling since a large array can be partitioned into smaller arrays of any size to support multiple targets. The use of arrays also has potential to allow antennas to be added to or subtracted from support of targets based on changes in weather or equipment failure. Finally, by varying the delays from each antenna in an array, different targets in the primary beam of the antennas can be supported with the full combined strength of the sub-array.

Historically, the vast majority of scientific observations using the DSN have benefited NASA projects or the DSN itself. The occasional use of DSN facilities by outside scientists also has provided valuable contacts with technology, techniques, and expertise developed at other institutions for high-sensitivity radio observations. The designers of arrays for the DSN should carefully consider ways to maximize scientific utility as well as spacecraft tracking performance.

II. A Proposed DSN Array for Spacecraft Tracking

The basic architecture for one proposed spacecraft tracking array is shown in Fig. 1. Twelve-meter antennas are deployed in four to eight array “clusters.” Each cluster would consist of up to about 400 antennas (see Fig. 2). While the separation of individual antennas in a cluster would be very small, a few tens of meters, the separation between clusters would be quite large, hundreds of kilometers. This architecture represents a trade-off between having the antennas close together for easy array phasing even in the presence phase fluctuations from the troposphere and the need for long baselines for precise interferometry and weather diversity. The distances between clusters will be chosen to ensure that weather conditions will be largely uncorrelated between cluster sites. At each cluster, antennas will be connected to signal-processing equipment for cluster-level signal combining and local monitor and control. This array architecture is scalable; the number of clusters could grow over decades.

The array clusters may be receive-only (i.e., no transmit capability) to minimize cost, avoid regulatory complications, and allow possible co-location of some clusters with radio astronomy observatories. In this case, uplink would be supplied by a separate antenna or cluster.

Each cluster would be connected to an Array Center through fiber-optic cables. The Array Center, proposed to be located at the current DSN Signal Processing Centers, would accept the combined signal

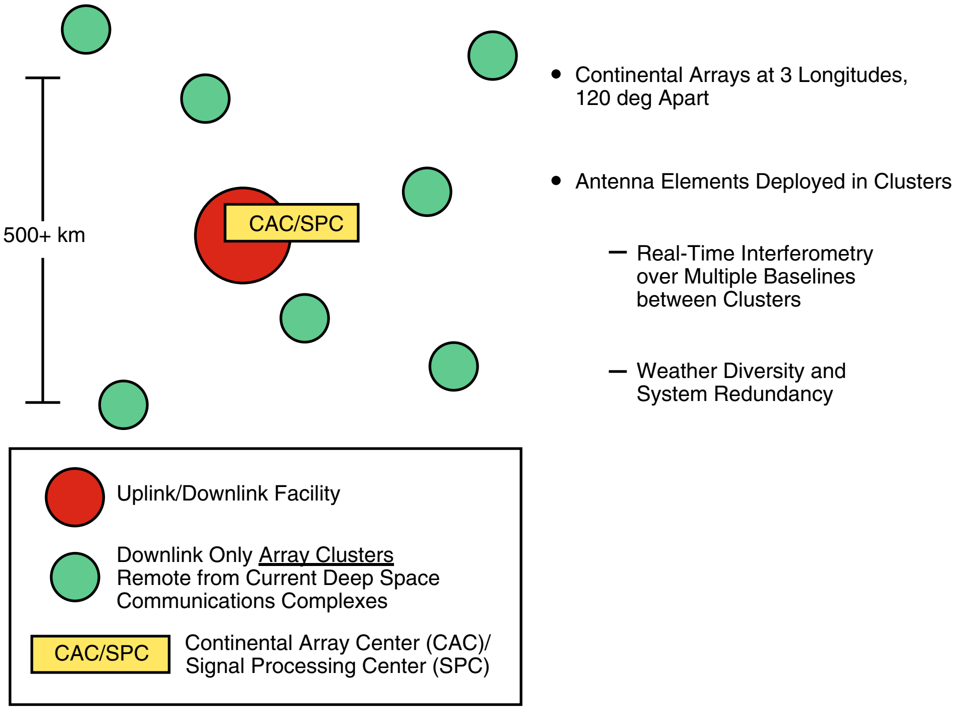

Fig. 1. Proposed DSN array architecture.

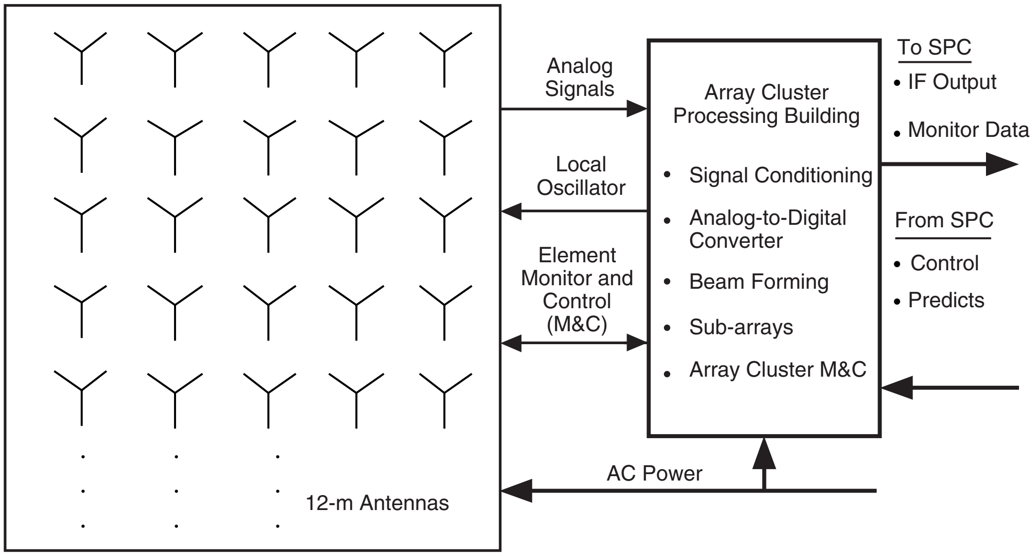

Fig. 2. Array cluster architecture.

from each cluster and perform the final stage of signal combining (see Fig. 3). It is this signal that would be provided to the DSN's telemetry receivers and/or science data acquisition equipment, although signals from each cluster could be made available separately if desired.

Currently, DSN users generally are allocated time on a specific antenna. In the era of arrays, individual antennas will not be allocated but instead the whole of the array resources will be partitioned among users, keeping some resources in reserve in contingency for equipment failure or severe weather. These reserve resources then could be released to other users when it is clear they will not be needed.

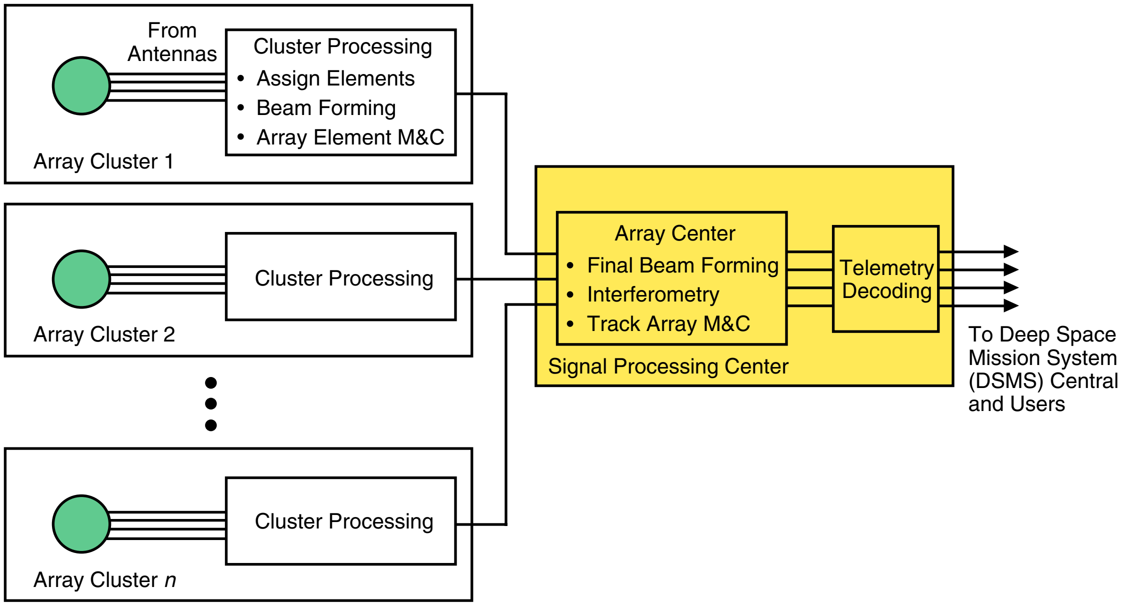

Fig. 3. Array signal processing.

III. Science Benefits of Large Arrays

A. Planetary Radar

The increased sensitivity provided by a large array translates directly into increased range for planetary radar observations. This will increase the number of accessible asteroid targets, for example. Radar follow-up observations will be possible for a much larger number of newly discovered near-Earth asteroids, including precise orbit determination, radar imaging, and shape reconstruction. These studies are important for impact hazard assessment as well as pure science. In addition, imaging and observations of spin rates and orientations will be possible for a larger and more representative sample of main-belt asteroids.

High-resolution radar observations of the surface properties of Mars would benefit from increased SNR, with applications for future landing site evaluations. Improved radio observations of Jupiter's icy moons (Jupiter Icy Moons Orbiter applications), Saturn's rings, Titan, Iapetus, and Hyperion also will be possible. In the far future, if the size of a DSN array grows to the scale of the planned Square Kilometer Array for radio astronomy, it would be possible to undertake radar studies of the moons of Uranus and Neptune (especially Triton) and the larger Kuiper belt objects.

Closer to home, radar surveys of Earth orbital debris are important for understanding the hazard such debris poses to current and future spacecraft. An increase in sensitivity will increase the range of radar cross sections that can be detected with ground-based radar.

In addition to the advantages of increased SNR and range, there are other advantages to using an array to receive radar echos. By using the angular resolution of the array to partially resolve the target object, high-resolution delay-Doppler imaging can be done without ambiguity problems. In addition, the scheduling flexibility of an array should allow more observing opportunities for targets that do not require very high sensitivity, such as chirp radar imaging of the moon and very nearby asteroids. That is, there may be frequent times when a small number of array antennas are not needed for spacecraft tracking and could be used simultaneously for astronomy or radar observations. Regular periods of observing time, even with reduced sensitivity, could be very useful for programs such as radar determination of orbits for near-Earth asteroids.

A specific application of long-range radar is to search for a silent spacecraft or to determine the attitude and spin of a spacecraft in distress. In such cases, sensitivity is critical, and the huge collecting area and sky coverage of the DSN arrays would be immensely valuable. The radar detection of the Solar and Heliospheric Observatory (SOHO) spacecraft while it was in distress, which led directly to its recovery, is a recent example of how valuable this capability can be. With the DSN array, radar detections of smaller or more distant spacecraft will be possible.

B. Radio Science

The increased sensitivity of the DSN arrays will provide at least two benefits to radio science experiments. First, radio occultation data could be obtained over a wider range of signal attenuation, and thus a wider range of atmospheric and magnetospheric densities or ring particle properties. Second, the ability to simultaneously track multiple spacecraft orbiting a planet, or orbiters and landers simultaneously, with full array sensitivity should provide much better determinations of the orbital dynamics and thus improve models of the gravitational potential. (A related scenario would be array tracking of signals from multiple landers simultaneously to determine the properties of a planetary or satellite interior.)

An important aspect of DSN array support of radio science is that it will allow useful measurements to be made using signals from very low power signals, such as multiple simple spacecraft or landers might produce. This will expand the opportunities for radio science investigations in the future.

Solar system tests of general relativity would benefit from the higher SNR provided by the DSN arrays. For example, the large increase in sensitivity at 32 GHz (Ka-band) would allow time-delay observations to be made along lines of sight passing much closer to the Sun than is possible at 8.4 GHz (X-band) because of coronal scattering and absorption. Ka-band also is expected to provide more precise catalogs of astrometric reference source positions, and thereby to improve the International Celestial Reference Frame used for spacecraft plane-of-sky navigation. An additional benefit of a dense catalog of sources at Ka-band is a likely improvement in the precision of very long baseline interferometry (VLBI) gravitational deflection measurements.

C. Radio Astronomy

The primary value of a compact cluster of small-diameter antennas for radio astronomy is high sensitivity to low surface-brightness emission on large angular scales. With a large total collecting area within a region of a few hundred meters, brightness temperature measurements can be made at a level of millikelvins. Such a cluster can cover the range of spatial frequencies between those sampled by large single antennas and those sampled by existing arrays such as the VLA in its most compact D configuration. Even in the range of spatial frequencies sampled by the VLA D array, an array with a larger number of smaller-diameter antennas will have a large advantage in survey speed, meaning that it can produce images of a large region of sky with comparable sensitivity in much less total observing time. If the cluster configuration is properly chosen, the image quality also will be better than can be obtained with the 27-antenna VLA. The combination of high surface-brightness sensitivity and outstanding image fidelity forms a unique scientific niche for DSN array clusters.

Some specific astronomy uses of a compact cluster operating at X-band and Ka-band are as follows:

(1) An unbiased survey of massive, high-redshift clusters of galaxies using the Sunyaev–Zel'dovich (S-Z) effect [3,4]. The amplitude of this effect is independent of the cluster distance, and thus it is a very powerful way to detect massive clusters at any redshift. S-Z observations of distant clusters can provide new constraints on cosmological parameter estimates and large-scale gravitational potential at early epochs (e.g., [2]). The Ka-band frequency range is particularly well suited to S-Z observations because there will be few contaminating sources to correct for and the synchrotron emission from our galaxy and from the distant clusters will be very weak. Angular resolutions of a few arcseconds (to detect and subtract point sources) to about one arcminute (the angular size of a typical distant cluster) are needed, which fits very well into the DSN array design if the total extent of an array cluster is about 1 km.

(2) An unbiased survey of star-formation rates at very high redshifts using CO line emission [1]. CO emission is highly correlated with star formation, and unlike optical or infrared emission it is unaffected by interstellar dust absorption. A DSN array cluster would be able to survey large areas of sky for CO emission at redshifts greater than about 4, with a beam area 4 times larger than the Expanded VLA (EVLA) will have. Redshifts greater than 4 cover the initial epoch of galaxy formation, the first generation of stars, and the re-ionization of the intergalactic medium.

(3) Mapping the magnetic structure in cluster halos, the galactic center, and the general intergalactic medium using Faraday rotation measurements.

(4) Detection of nonthermal flares from nearby stellar systems.

(5) Measurement of the intergalactic magnetic field strength using the Zeeman effect.

(6) Searches for extraterrestrial intelligence (SETI) and transient phenomena (gamma-ray bursts, pulsars, intra-day variables, extreme scattering events, etc.).

The sensitivity and frequency coverage of the VLA is currently being increased as part of the EVLA project. The collecting area of the VLA will remain unchanged at 1.3×10^4 m^2, which is equivalent to a 130-m-diameter antenna. The EVLA upgrade will increase the instantaneous bandwidth of the VLA to 8 GHz per polarization—a factor of nearly 100 over the original VLA bandwidth. The collecting area of a 100-antenna DSN array composed of 12-m antennas is 1.1×10^4 m^2, which is equivalent to a 120-m-diameter antenna. To remain at least similar to the EVLA in continuum sensitivity, a DSN array cluster will need to have a bandwidth significantly larger than the currently planned 500 MHz.

For spectral line observations, the very wide instantaneous bandwidths of the EVLA are not useful (except for blind searches), and only the ratios of collecting area and system temperatures determine the relative sensitivities of the EVLA and DSN arrays. Note that a 400-antenna DSN array would have a collecting area of 4.5×10^4 m^2, equivalent to a 240-m-diameter antenna. This represents a very significant improvement in spectral line sensitivity over the EVLA.

An important question in astrophysics is whether supermassive black holes formed before large galaxies, perhaps providing the seeds about which galaxies condensed, or galaxies formed first and supermassive black holes evolved in their nuclei as stellar evolution and galaxy mergers made large amounts of gas available. One way to answer this question is to compare the time evolution of starburst activity (associated with galaxy formation and mergers) with the evolution of non-thermal activity in galactic nuclei (associated with the accretion of matter into supermassive black holes). The full DSN array with multiple, widely separated clusters will be able to distinguish radio emission from distant starburst galaxies and from distant active nuclei by directly measuring the brightness temperature. Starburst sources are unable to produce brightness temperatures much above 10^4 K, while non-thermal radio emission from active galaxies can reach brightness temperatures of about 10^{12} K. To measure both low and high brightness temperatures, we need both long baselines and high sensitivity. Current VLBI arrays have sufficient resolution and sensitivity to study non-thermal sources, but the large collecting area of the DSN array will allow thermal sources to be detected with the same angular resolution as non-thermal sources.

The relatively high frequencies at which the DSN array will still have high sensitivity (30 to 40 GHz) are ideal for the detection of thermal emission from normal stars and from solar system objects. Thermal radio emission increases with frequency squared, so thermal emission at 32 GHz will be an order of magnitude stronger than at 10 GHz, and a full three orders of magnitude stronger than at 1 GHz. Because of this and the DSN array's large collecting area, it will be possible to detect the photospheres of many nearby normal stars and (with multiple clusters) measure their parallax and proper motions with high precision. Thermal radio emission from small moons, comets, asteroids, and large Kuiper belt objects also will be detectable with a large array operating at Ka-band.

IV. Array Requirements for Science Applications

A. Array Requirements for Planetary Radar

To support bi-static planetary radar observations, the array should cover the 2380-MHz frequency of the Arecibo transmitter as well as the 8.50- to 8.61-GHz DSN radar frequencies. In the future, planetary radar systems may migrate to 32 GHz, in which case the array will need to cover the appropriate Ka-band radar transmit frequency range as well. The total delay through the array signal path needs to be accurately calibrated and stable over time.

B. Array Requirements for Radio Science

Besides coverage of spacecraft downlink frequencies, the most important requirements are accurate amplitude calibration, stable signal delays, and high-frequency stability. A wide observing bandwidth and correlator are needed to allow weaker radio sources to be added to the DSN astrometric catalog for phase-referenced measurements of spacecraft plane-of-sky positions.

C. Array Requirements for Astronomy

Configuration requirements come at two levels: A compact configuration provides the highest sensitivity to extended, low-surface brightness sources such as S-Z signatures, while long baselines are needed for imaging of solar system objects and for precise astrometry. The concept of several array clusters separated by large distances is a good compromise for many astronomical goals.

A cross-correlator capable of handling all $N(N-1)/2$ baselines in each DSN array cluster is required for all imaging projects. In addition, wide bandwidths are needed by almost all astronomical observations. The current state of the art is defined by the data transport, correlator, and signal-processing systems for the EVLA and Atacama Large Millimeter Array (ALMA), both of which will provide bandwidths of 8 GHz per polarization.

Image dynamic range needs to be at least 10^3 for S-Z observations, but this should be easily obtained from a cluster of 100 or more antennas. An equally important parameter is imaging of the full field of view provided by the primary antenna beams. This implies a minimum number of spectral channels in the cross-correlator (to avoid bandwidth decorrelation at the edge of the field of view) and a maximum data accumulation interval (to avoid time decorrelation).

V. Conclusions

The benefit of large arrays to scientists can be captured by the following four categories:

(1) *Large increase in signal-to-noise ratio.* The use of large numbers of antennas arrayed together has the potential to increase the sensitivity available for scientific observations by one or two orders of magnitude.

(2) *Multi-beaming and imaging.* Arrays over long baselines could provide multiple, spatially separated, narrow beams. Use of a correlator would provide images.

(3) *"Piggy-back" observations.* Scientists could use synthesized beams from arrayed antennas already allocated to other users, such as a flight mission, to observe other, nearby, sources.

(4) *Use of unneeded array reserves.* Scientists could use array reserves for observations.

In summary, the potential science applications of large DSN arrays are both numerous and important. Many require increases in the maximum observing bandwidth or a wider range of possible observing frequencies than currently is planned. The incremental costs of these upgrades should be considered during the design of the arrays.

Acknowledgment

We thank Dr. R. A. Preston for numerous discussions and helpful comments on an early version of this article.

References

[1] C. L. Carilli and A. W. Blain, "Centimeter Searches for Molecular Line Emission from High-Redshift Galaxies," *Astrophys. J.*, vol. 569, pp. 605–610, 2002.

[2] J. E. Carlstrom, G. P. Holder, and E. D. Reese, "Cosmology with the Sunyaev-Zel'dovich Effect," *Annual Reviews of Astronomy and Astrophysics*, vol. 40, p. 643, 2002.

[3] R. A. Sunyaev and Y. B. Zel'dovich, "The Observation of Relic Radiation as a Test of the Nature of X-Ray Radiation from the Clusters of Galaxies," *Comments Astrophys. Space Phys.*, vol. 4, pp. 173–178, 1972.

[4] R. A. Sunyaev and Y. B. Zel'dovich, "Microwave Background Radiation as a Probe of the Contemporary Structure and History of the Universe," *Ann. Rev. of Astron. and Astrophys.*, vol. 18, pp. 537–560, 1980.