Geometric Configurations for Large Spacecraft-Tracking Arrays

Dayton L. Jones
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109, USA
818-354-7774
dj@sgra.jpl.nasa.gov

Abstract—A significant increase in the sensitivity of ground facilities used for spacecraft telemetry reception and navigation can be obtained through the use of large numbers of inexpensive, mass-produced parabolic antennas with diameters of a few meters. Planned arrays for the Deep Space Network (DSN) and for radio astronomy involve up to several thousand small antennas, providing collecting areas approaching a square kilometer. The geometric configuration of arrays intended for spacecraft tracking will differ from those for radio astronomical observations. This paper will explore the configuration constraints and tradeoffs for a prototype DSN array being developed at JPL. The optimum configuration for the 100-antenna prototype array is determined by tradeoffs between cost, maximum baseline length, shadowing, instantaneous sidelobe levels, and ease of atmospheric phase calibration.

TABLE OF CONTENTS

1 INTRODUCTION
2 BENEFITS OF LARGE ARRAYS
3 CONFIGURATION TRADEOFFS
4 PRELIMINARY RESULTS
5 ARRAY PHASE CALIBRATION
6 CONCLUSIONS
7 ACKNOWLEDGEMENTS

1. INTRODUCTION

The Deep Space Network (DSN) supports space missions in three critical ways. First, it provides an uplink telemetry capability to allow commands to be sent to spacecraft. Second, it receives downlink telemetry, primarily composed of data from on-board science instruments. Finally, it provides measurements of spacecraft range, Doppler (radial velocity), and occasionally plane-of-sky position to support spacecraft navigation. The most serious limitation of the current network capabilities are in the the telemetry downlink area. This is the result of new generations of spacecraft instruments that provide orders of magnitude more data than can be sent to Earth via the existing DSN.

0-7803-7231-X/01/$10.00/© 2002 IEEE
IEEEAC paper # 1104

Various approaches to increasing downlink data rates from deep space missions are being studied, including the use of higher RF frequencies, optical communications, and building additional ground antennas to increase the total available collecting area. The approach on which this paper is based is one version of building more collecting area, by means of large numbers of small, mass-produced antennas operating as an array. It is worth noting that at the radio frequencies used for spacecraft communication, receiver temperatures are already sufficiently low that total system temperatures are dominated by atmospheric and spillover effects. Also, error-correcting codes are approaching fundamental limits of performance. Consequently, the only way to obtain large increases in sensitivity at these frequencies is through increases in collecting area.

2. BENEFITS OF LARGE ARRAYS

For many years radio interferometer arrays have offered significant advantages over large single antennas, particularly for high resolution imaging and astrometry. However, until recently their advantages did not normally include lower cost. Three areas of technology development have made it possible to design radio arrays today whose cost per unit of collecting area is dramatically smaller than for large, steerable reflectors. These three areas are: 1) mass production of inexpensive parabolic antennas of several meters diameter for the home satellite TV industry, 2) low cost, wide band MMIC amplifiers that can provide low receiver noise temperatures when cooled with simple pulse tube refrigerators, and 3) massive reductions in the cost of high bandwidth data transmission (fiber optics) and processing (Moore's law).

By taking advantage of recent advances in these three areas, the radio astronomy community is developing the Square Kilometer Array [1]. The US concept for this international instrument is an interferometer array with thousands of small antennas that will have a sensitivity two orders of magnitude better than any existing radio telescope or array. The same opportunity to obtain much higher sensitivity per unit cost has motivated the DSN to begin studies of radio arrays with 100-500 times the sensitivity of the existing DSN 70-m antennas. An example of the value of such an increase in capability is shown in Figure 1. Note that a large ground array would allow downlinks from the outer planets at video data rates, rather than the current single image data rates.

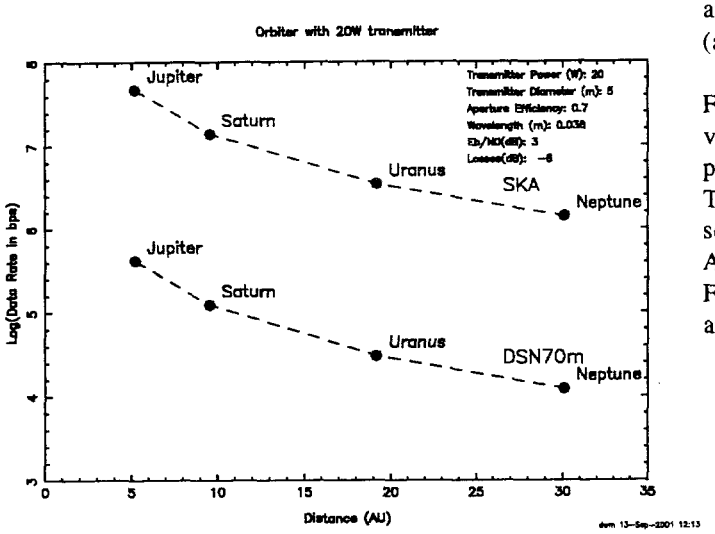

Figure 1. Comparison of downlink data rates from a spacecraft at the distance of the outer planets with the existing DSN 70-meter antennas (lower line) and with a Square Kilometer Array (upper line). The vertical axis is logarithmic, showing data rates from 10^3 to 10^8 bits/second.

From the point of view of the DSN, and advantages of large arrays include:

- Large increase in downlink sensitivity
- Smaller, lighter, and lower power spacecraft telemetry hardware
- Higher reliability – array performance degrades gracefully if individual antennas fail, and geographic diversity minimizes the effects of local weather.
- Flexible scheduling – simultaneous tracking of multiple spacecraft
- Real-time, high precision angular tracking for spacecraft navigation
- Useful data rates over low gain spacecraft antennas – entry/descent/landing phases, spacecraft emergencies, atmospheric probes, or completely new types of mission

The current plans call for a prototype DSN array of approximately 100 parabolic antennas, each 12 meters in diameter, to be built during the next several years. This prototype will be used to help answer technical questions about the most cost-effective approaches to large array construction, operations, maintenance, and performance at 8 and 32 GHz. This paper considers configuration issues for the prototype array, but many of the same considerations will apply to configurations for much larger arrays as well.

3. Configuration Tradeoffs

Several general results are known from previous work: Regularly spaced arrays produce poor aperture plane coverage leading to high sidelobe levels, very compact configurations produce too many short projected baselines and too much shadowing between antennas, and extended configurations are more difficult to keep phase-stable and can result in long (and expensive) fiber optic runs to the antennas.

For imaging, logarithmic spiral array configurations are favored because they provide dense sampling of the aperture plane over a wide range of projected baseline lengths [2] [3]. This is important for high dynamic range imaging of radio sources that contain structure on many different spatial scales. An example of a logarithmic spiral configuration is shown in Figure 2. This type of configuration is readily expandable to arbitrarily long baselines.

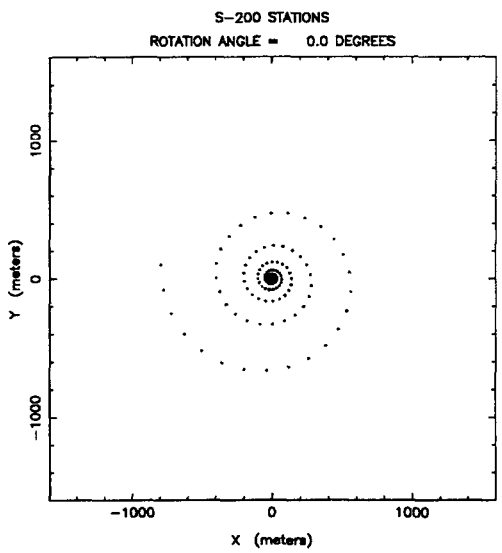

Figure 2. An example of a logarithmic spiral array configuration. This type of configuration produces a nearly Gaussian distribution of baseline lengths, and consequently low instantaneous sidelobes.

Many alternatives, including multi-arm spirals, nested circles, and quasi-random two dimensional patterns have also been studied [4] [5] [6]. One interesting variation on spiral configurations is shown in Figure 3, where most of the short baselines are distributed around the edge of the array instead of being clustered near the center. This reduces shadowing between antennas at low elevations, reduces suceptibility to locally-generated interference, and produces more long baselines that are useful for position measurements. Unlike a normal logarithmic spiral, however, this configuration is not easily expandable to a larger maximum size. It also does not produce a synthesized beam with particularly low sidelobes.

For DSN applications there are a different set of array configuration requirements. We want low instantaneous sidelobes, efficient cable runs, rapid and robust calibration of atmospheric phase fluctuations, and flexible sub-arraying. Aperture synthesis imaging is not generally an important consideration. Low sidelobes are important for three reasons: to reduce the contribution of thermal emission from a planet when tracking an orbiter, to minimize possible interference between signals when tracking multiple spacecraft within the primary beam simultaneously, and to reduce interference coming from

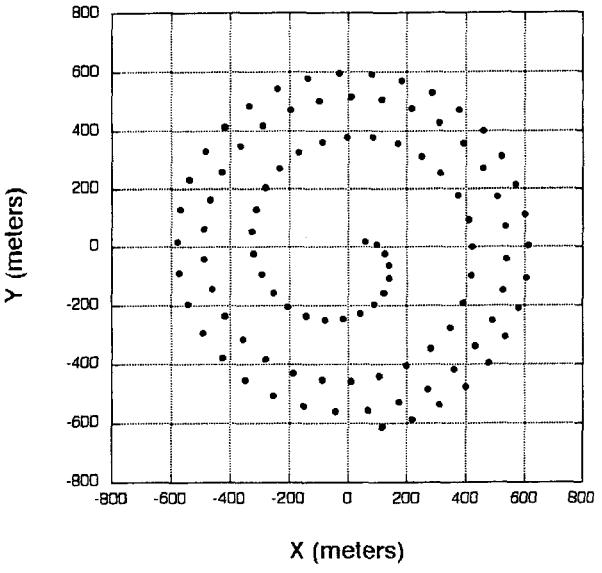

Figure 3. An "inverse spiral" configuration in which short baselines are not all clustered near the array center.

other directions.

At high frequencies such as 32 GHz (Ka band) a major issue is reliable calibration and removal of atmospheric phase errors when combining signals from the array antennas. These considerations suggest that very compact configurations should be favored. However, spacecraft tracking frequently requires observations at low elevation angles. In these situations, the mutual shadowing of closly-packed antennas will be a serious limitation.

4. Preliminary Results

A series of potential configurations was generated and the density of aperture plane coverage, distribution of sidelobes in the synthesized beam, and fraction of baseline affected by antenna shadowing were calulated using modified versions of data analysis programs in the Caltech VLBI software package. This initial effort showed that with 100 antennas many possible configurations could produce relatively low instantaneous sidelobe levels. However, many spiral-based configurations suffer from significant antenna shadowing at low elevations, and consequently starting configurations similar to Figure 3 often produced better results.

Final optimization of the configurations was done using a program developed by L. Kogan and the National Radio Astronomy Observatory [7]. This program moves each antenna in an array by small increments and calculates the effect on the sidelobe levels of the synthesized beam within the sky area covered by the primary beams of the individual array antennas. In this way it is possible to minimize the sidelobe levels within the primary beam area. Sidelobe responses outside the primary beam are generally increased by this process, but this is unimportant because of the attenuating effect of the individual antenna response. An example of an array configuration optimized in this way is shown in Figure 4. The starting point in this case was an inverse spiral similar to that shown in Figure 3.

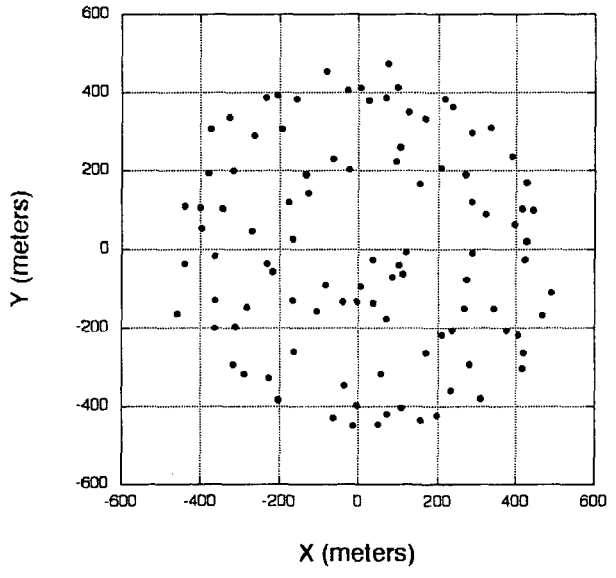

Figure 4. One possible configuration of 100 antennas for the DSN prototype array. The total area of the array is just under 1 km in diameter.

Another approach began with a hexagonal configuration of antennas, intended to minimize any initial bias towards a centrally-condensed or edge-weighted distribution of baselines. After 75000 iterations of Kogan's optimization algorithm, the configuration became slightly centrally condensed but otherwise quite random looking, as shown in Figure 5. At this point further interations did not appear to improve the sidelobe pattern.

The synthesized beam near zenith produced by the array configuration in Figure 5 is shown, with different fields of view, in Figures 6, 7, and 8. The sidelobes have been shifted out of the area close to the main beam, where the primary antenna beam response is greatest. The distant sidelobes are higher, but are attenuated by the primary beams and thus do not cause significant pickup of background radiation or interference. Note that the region of sidelobe reduction appears elliptical. This is caused by optimizing for a source elevation of 45 degrees, where the array configuration appears foreshortened while the primary beam area remains circular. It is not possible to optimize for multiple elevations simultaneously; this is a tradeoff area where work is ongoing.

The results shown in Figures 6-8 are consistent with theoretical expectations, which predict that peak sidelobes for an array with N antennas will be no lower than $\sim 1/N$ in amplitude [8] [9]. Thus, the configuration illustrated in Figure 5 is approaching the lowest possible sidelobe levels.

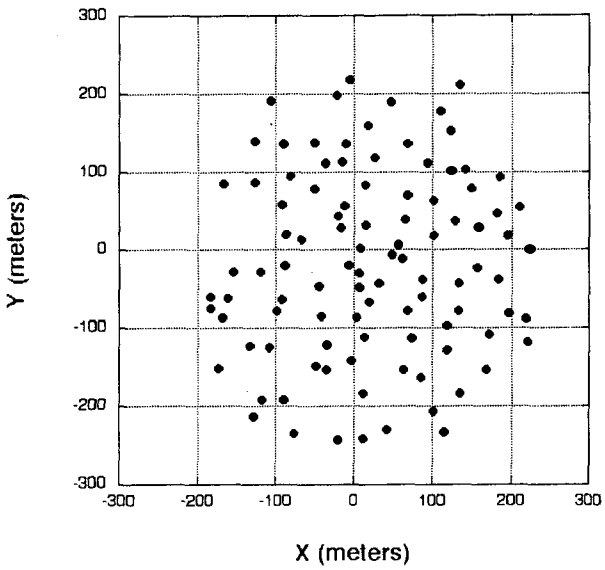

Figure 5. An improved configuration of 100 antennas for the DSN prototype array. This configuration has significantly lower sidelobes than that shown in Figure 4.

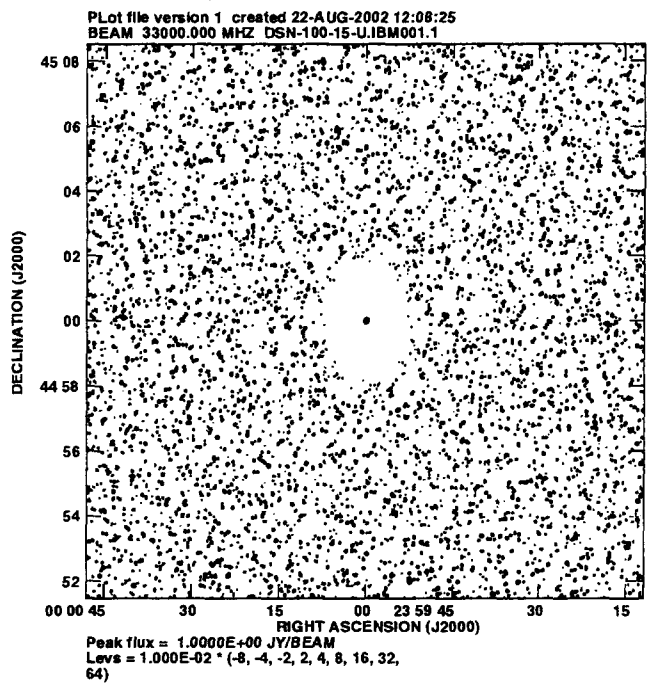

Figure 6. Instantaneous (snapshot) synthesized beam for the array configuration shown in Figure 5. The lowest coutours are ±2 percent of the peak. The region immediately surrounding the main beam (central peak) corresponds to the area of the individual antenna primary beams.

5. Array Phase Calibration

Observant readers will have noted that the configurations shown in this paper are all physically quite small – approximately one km or less in diameter. Why is this? Arrays extending over tens, hundreds, or even thousands of kilometers would be able to provide much more accurate measurements of spacecraft angular positions, and would eliminate antenna shadowing concerns. However, to obtain the full sensitivity of the array's collecting area, we need to be able to correct for phase errors when combining signals from different antennas. The most significant phase fluctuations are caused by variations in atmospheric water vapor along different lines of sight, and can be large at Ka band in poor weather. The effects of these (or any antenna-based) phase fluctuations can in principle be removed by self-calibration [10]. But this technique requires that phase measurements be obtained on time scales shorter than those over which significant phase changes occur. If phase fluctuations between antennas are large and rapid, self-calibration will only be possible on spacecraft (or background radio sources) that are relatively strong. We therefore have a strong incentive to minimize the amplitude of phase fluctuations between antennas in the array.

The spatial scale over which atmospheric phase fluctuations are correlated is a function of site, weather, and time, but in general phase fluctuations are correlated over scales of at least 100 meters at Ka band. Thus, the differential phase fluctuations between pairs of antennas that are separated by less than about 100 meters will be greatly reduced, leading to improved array sensitivity. There is a clear tradeoff between minimizing the array's sensitivity to atmospheric phase variations and minimizing the effective loss of aperture at low elevations due to antenna shadowing. A wide range of antenna separations from about two antenna diameters out to a few hundred meters appears to be a good compromise.

6. Conclusions

The promise of large arrays of small antennas to greatly increase the sensitivity of the DSN has led to initial funding for a prototype array of one hundred 12-meter antennas. The configuration for such an array must balance several competing requirements, including synthesized beam sidelobe levels, robust correction of phase errors, acceptable shadowing at low elevations, and minimum cost for both construction and operations. A preliminary configuration has been designed to meet these requirements. The result is a quasi-random two dimensional configuration with a small amount of central condensation. This configuration produces an array beam with sidelobes at or below the 1 percent level throughout the primary antenna beam area, is sufficiently compact to allow good phase calibration, and suffers only a few percent loss of collecting area at elevations down to 15 degrees at any azimuth.

Future work will concentrate on minimizing shadowing in specific ranges of azimuth (covering the range where the ecliptic plane rises and sets). In addition, the synthesized beams formed by different sub-arrays of less then 100 antennas drawn from the preliminary configuration will be cal-

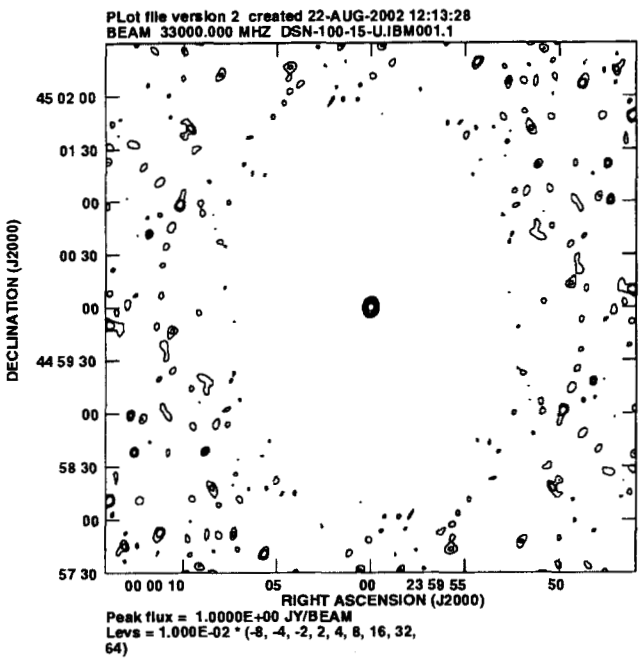

Figure 7. Inner part of the instantaneous synthesized beam for the array configuration shown in Figure 5, with the same contour levels as in Figure 6.

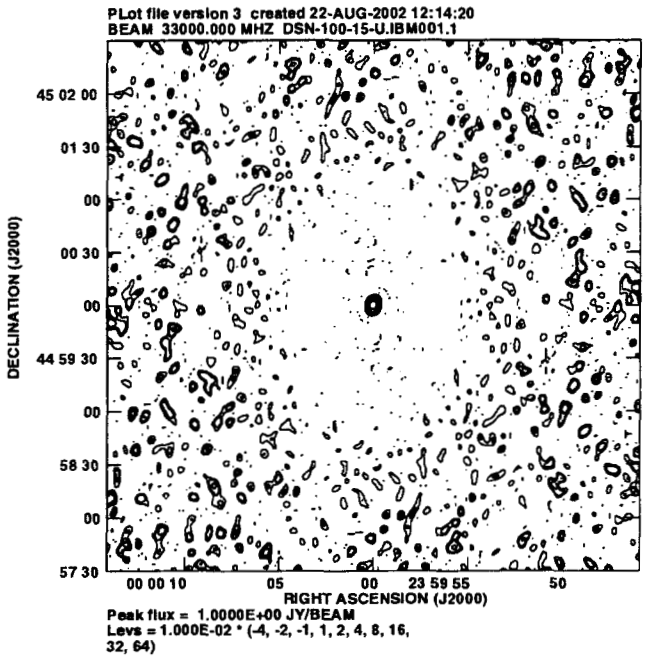

Figure 8. Inner part of the instantaneous synthesized beam for the array configuration shown in Figure 5. The lowest contours are ± 1 % in this figure. Note that the largest inner sidelobes are just at the 1% level.

culated to see how many sub-arrays could reasonably be used simultaneously. Finally, ways to extend the configuration of the prototype array to longer baselines will be studied. This is a possible way to begin development of the much larger arrays planned for the DSN should the prototype validate this approach.

7. Acknowledgements

The author thanks Drs. L. Kogen, F. Owen, and R. Perley of the National Radio Astronomy Observatory for helpful discussions, and Dr. D. Murphy of the Jet Propulsion Laboratory for creating Figure 1 and allowing its use in this paper. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Dayton Jones *is a Principal staff member at the Jet Propulsion Laboratory, Caltech, Pasadena, CA. His research interests include extragalactic astronomy, particularly high resolution imaging using radio interferometry, and the development of the Square Kilometer Array. He is an author on over 100 papers in the scientific literature. Dr. Jones obtained M.S. degrees in scientific instrumentation from UCSB in 1976 and in astronomy from Cornell University in 1979, and a Ph.D. in astronomy from Cornell University in 1981. He is a member of the International Astronomical Union, American Astronomical Society, and Sigma Xi.*