

An Introduction to Very Large Arrays for the Deep Space Network

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Abstract

Development of very large arrays of small antennas has been proposed as a way to increase the downlink capability of the NASA Deep Space Network (DSN) by two to three orders of magnitude. This would enable much greater science data return from deep space missions than at present, at greatly decreased cost per bit. It would also enable new mission concepts that result in signals too weak to be received by the current DSN. Arrays would be deployed at two or three different longitudes, and in the northern and southern hemispheres. Each array would have thousands of antennas, located at several different sites. The sites would be selected to provide weather diversity to overcome the atmospheric propagation losses encountered at Ka-band in high humidity or rain, and to provide long and orthogonal baselines for the delta differential one-way range (delta DOR) navigation data type. This paper discusses the array architecture, the resulting challenges in operations, maintenance and sustaining engineering, and preliminary operations concepts to overcome these challenges.

1. Introduction

The purpose of the proposed DSN Array System is to greatly increase the reception capability of the DSN, thereby enabling greatly increased science data return from missions similar to today's missions, and enabling new mission concepts. The specific goal is to achieve 100 to 500 times increase in DSN signal reception capability at an affordable cost, by 2020.

The Array System could:

1. Greatly increase mission science return. For example, planet mapping missions could return full surface coverage, rather than the few percent coverage returned by current missions.
2. Enable reduction in spacecraft telecom system mass and power, thus enabling new mission concepts and cost savings.
3. Reduce the cost per bit of science data by two orders of magnitude.
4. Enable high-rate communications from spacecraft well outside of the solar system.

The current status of the Array System is that development is beginning of an Operational Prototype Array System. Some goals are to complete this system by 2008, and to achieve a total array aperture equivalent to 2.8 70-m antennas.

2. Key System Functions

The Array System will be able to perform all of the signal reception functions of the current large DSN antennas, for all mission phases. The current plan is to retain the current antennas for uplink use, although uplink arrays may be developed in the future. A possible exception to supporting all mission phases is the launch and early orbit phase (LEOP). This phase requires higher tracking rates than other phases, and there will be an economic decision as to building this fast tracking capability in the array antennas, or supporting LEOP as today.

The array at each longitude must be able to support all missions and other DSN tracking, including simultaneous support of a large number of missions. To provide this simultaneous support, the array at each longitude can be divided into a number of subarrays. A subarray is defined as all antennas that are pointed in the same direction and that perform together as one large antenna. Each subarray can have a number of antennas at each site. The antennas in each subarray are assigned dynamically, and can change during a pass without disrupting spacecraft tracking.

A subarray can receive signals from more than one target at a time, provided that all of these targets are angularly within the main beam of each individual antenna in the subarray. This corresponds to the Multiple Spacecraft per Aperture (MSPA) capability of the current DSN. Also, there can be more than one RF signal from each target, such as an X-band signal and a Ka-band signal, or signals on two polarizations. Therefore, the Array System at each longitude can have more signal outputs than the number of subarrays.

The Array System operates in conjunction with other key elements of the DSN:

- Antennas for uplinks – existing or new large antennas, or uplink arrays
- Signal processing for telemetry, tracking, navigation and science
- External monitor and control or service management from the DSCC
- Planning and scheduling service management functions analogous to current capability

3. System Description

A high-level pictorial diagram of the Array System is shown in Figure 1. A large number of relatively small antennas are approximately equally distributed at approximately eight sites on each of three continents, i.e., at three longitudes. The baseline design calls for 3600 12-m diameter antennas at each longitude. This yields a total aperture at each longitude slightly greater than that of 100 70-m antennas.

At each longitude, the antennas are distributed approximately equally at approximately eight sites. The sites are located far enough from each other to provide weather diversity for Ka-band. The sites are spread out both North-South and East-West to provide good baseline geometry for acquisition of the Delta-Differential One-Way Range (Delta-DOR) data type.

Each array site has the antennas and associated equipment, a site signal processing facility, communications between the antennas and the signal processing facility, and facilities such as roads, fences and security systems.

3.1 System External Interfaces

The main external interfaces to the Array System are:

Microwave signals from the targets
 Control from other DSN systems at the Deep Space Communications Complexes (DSCCs)
 Array output signals to other DSN systems
 Monitor signals output to other DSN systems
 Frequency and timing signals from the DSN Frequency and Timing System
 Power, water and other facilities

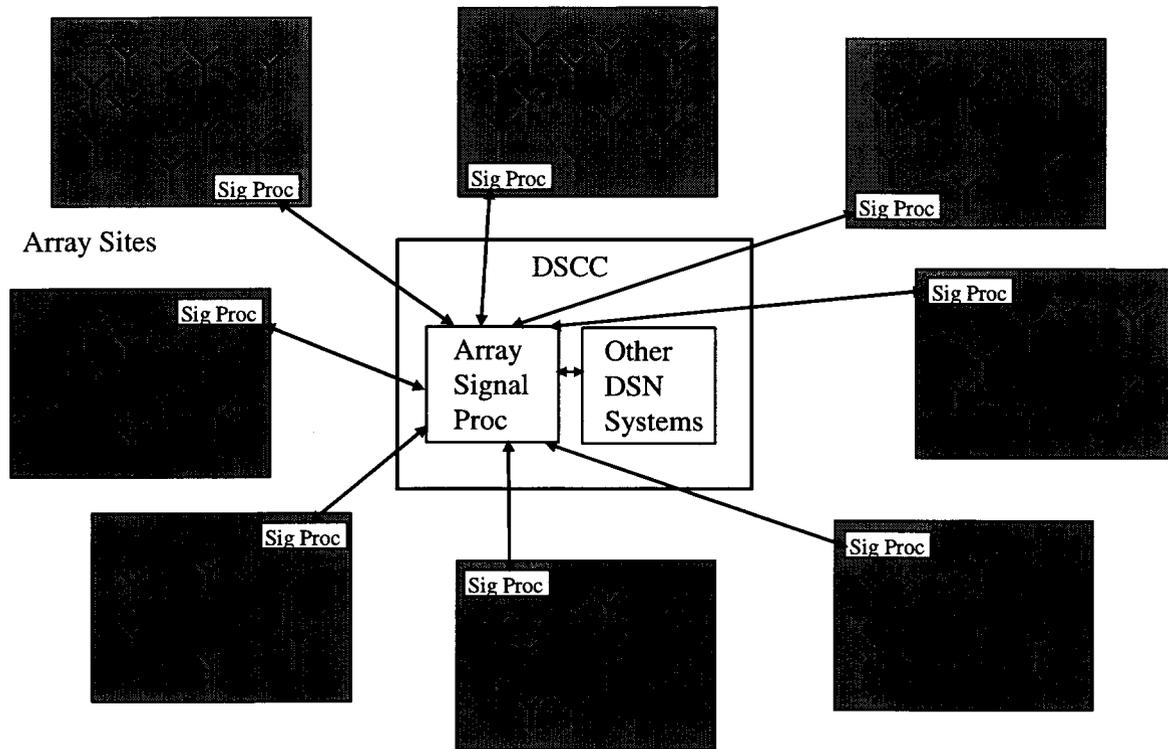


Figure 1. Pictorial Diagram of Array System

3.2 System Composition

The Array System is composed of six subsystems: Antenna and Microwave, Signal Processing, Monitor and Control, Frequency and Timing, Ground Communications, and Facilities.

3.2.1 Antenna and Microwave Subsystem

The purpose of the Antenna and Microwave Subsystem is to receive the signal energy from the targets, and perform all functions necessary to amplify the signals and convert them to a form suitable for interface to the Ground Communications Subsystem. The current plan is for the antennas to be 12-m diameter, fully steerable, shaped paraboloids. The antenna dishes are planned to be one-piece of aluminum, shaped by a hydroforming process, although alternate approaches are under investigation. There is a significant challenge in achieving an antenna, support structure, pedestal and pointing system with good Ka-band performance. If this cannot be achieved with 12-m antennas at an appropriate cost, smaller antennas may be used.

For each antenna, the Antenna and Microwave Subsystem has dual X- and Ka-band feeds; dual polarization, cryogenic, solid-state, low-noise amplifiers; Ka-band down converters; and antenna pointing equipment.

3.2.2 Signal Processing Subsystem

The purpose of the Signal Processing Subsystem is to perform all processing on the signals from each antenna that is necessary to combine these signals and output them to the other DSN systems in a form that these output signals look very much as if they had each been the signal from one large DSN antenna.

The Signal Processing Subsystem has elements at each array site and at the DSCC at each longitude. At each site, the signal processing subsystem aligns the received signals in time delay and phase, combines the signals, and outputs the combined signals to the Ground Communications Subsystem for transfer to the DSCC. At the DSCC, the Signal Processing Subsystem aligns the signals from each site, combines them, and outputs them to other DSN systems.

3.2.3 Monitor and Control Subsystem

The Monitor and Control Subsystem accepts control inputs from the monitor and control elements of the DSN, controls all other subsystems of the Array System, accepts monitor data from these subsystems, and provides monitor data to the DSN monitor and control. The Monitor and Control Subsystem also inter acts with operations personnel.

This subsystem divides the array system into subarrays, assigns specific antennas to each subarray, and controls the reassignment of antennas in real time, during the tracks. This is done based upon information provided in advance by the DSN monitor and control, but also takes into account real time control, operator inputs, the status of each array antenna, weather and weather forecasts, and the actual performance of each subarray and each element of each subarray. To the extent possible, each target must be supported with the required G/T or with a predetermined number of antennas. There may be other constraints, such as providing geometry for Delta-DOR.

3.2.4 Frequency and Timing Subsystem

The Array Frequency and Timing Subsystem accepts inputs from the DSN Frequency and Timing System, provides locally generated references as required, and provides all frequency and timing references needed by all other array subsystems. It provides monitor data to the Monitor and Control Subsystem.

3.2.5 Ground Communication Subsystem

This subsystem provides all communications services between the antennas and the site signal processing facility, and between the array sites and the DSCCs. There are two challenging requirements. First, tens of Gb/s data rates must be provided from the sites to the DSCCs. Second, high stability analog links must be provided for the frequency references, and for the wideband RF signals from the antennas to the site signal processing facilities.

3.2.6 Facilities Subsystem

This subsystem provides all of the normal facilities, including roads, signal routing ditches, power, water, buildings, bases for the antennas, fences, landscaping, security and fire protection. Facilities will be a significant element of the system cost, both in the development and operations phases.

3.3 Personnel

Operations and maintenance personnel are key elements of the Array System.

4. Array System Signal Processing

To the rest of the DSN and to missions, the Array System looks very much like a collection of large antennas, with each antenna supporting one mission. A major difference is that these large synthesized antennas can be of any size, up to the full array capability. The array signal processing functions are key to achieving this capability. They are also functions that are not in the current DSN. For these reasons, we describe the signal processing in more detail than the rest of the system.

The main signal processing functions are delay modeling and alignment, and beam forming.

4.1 Delay Modeling and Alignment

Predicts and delay modeling are used for coarse alignment of the signals from the various antennas in each subarray. This leaves residual errors in delay and phase. The residual errors are estimated using a correlator. The predicted delay and phase are then corrected by the correlator estimates. Using the corrected estimates, the signals are aligned in delay and phase, and combined in the beam former.

Alignment for each subarray is done first at the sites, and then the beam-formed signals from the sites are aligned and combined at the DSCC. If more than one target are being tracked by a subarray, separate alignment and beam forming must be done for each target. Depending on the geometry and differential predict accuracy, it may be adequate to correlate on only one of the targets, such as the one with the strongest signal.

Alignment and combining for each target is first done at each site, independently of the other sites. Then the signals from the various sites used in the subarray are aligned and combined at the DSCC.

Phasing needs to be updated throughout the tracks, to compensate for instabilities in propagation delay through the atmosphere and in instrumentation.

The correlation process can use either spacecraft signals or signals from a natural radio source. When the spacecraft signal is strong enough, it is usually used for the correlation process. A

complication in this case is that the processing needs to be matched to the carrier and subcarrier frequencies, and to the modulation bandwidth. Natural radio sources are used when the spacecraft signals are too weak to achieve correlation in the length of time over which the phase delay is stable. This complicates processing, because of the modeling and processing necessary to translate the phase corrections in the direction of the radio source to the direction of the spacecraft.

4.2 Beam Forming

Beam forming is the weighted summing of the corresponding signals from all antennas in a subarray. This summing is done first at the antenna sites, and then the signals from the antenna sites are summed at the DSCC. This results in the output signal of the synthesized beam, in digital form. To simplify the interface to the existing DSN systems, one option is to convert the digital signal at the output of the beam to an IF signal compatible with the current systems.

When more than one spacecraft are being tracked by a subarray, and when there are more than one RF signals from a single spacecraft, there are more than one beam forming operations for that subarray.

Radio frequency interference (RFI) can be suppressed during the beam forming operation. This is done by choosing the amplitude and phase weights for the signals from each antenna to form nulls in the synthesized beams, in the directions of RFI sources. This can be done with little loss in G/T performance in the target direction.

5. Operations Concept

Operations cost is critical. To first order, operations cost will be approximately proportional to array size, and to the implementation cost. Therefore, it will place a limit on array size, because there is no point in building a system that costs more to operate and maintain than is affordable.

Operations cost includes planning, scheduling, real time operations, sustaining engineering and maintenance. The dominant cost will be maintenance, because of the large number of antennas. Array design will emphasize maintenance concepts and cost in order to minimize system life cycle cost.

5.1 Reliability and Availability

The need for reliability of system elements is driven more by cost than by mission needs. For the antennas and other equipment in the Antenna and Microwave Subsystem, high availability of individual antennas is not required to achieve high system availability, because of the high redundancy. However, high reliability is required to keep maintenance costs low.

For the sites, high reliability of the signal processing and monitor and control elements is important to keep costs down. For system performance, high availability is desirable, but this is not critical, because there is site redundancy. For instance, for Ka-band reception, an equipment failure taking down a whole site is similar to a rainstorm that causes an outage.

The signal processing and control at the DSCC needs to have very high reliability and availability, because a failure could interrupt all tracking.

5.2 Planning and Scheduling

As in today's DSN, planning and scheduling will be done in advance. But there are a lot of differences in scheduling the array system than in scheduling the large DSN antennas. The flexibility to have a variety of effective antenna sizes, of G/T values, complicates the process. There are several possible scheduling approaches:

1. Assign each user a certain number of antennas, with usage and link margin up to the user.
2. Guarantee a certain G/T to each user. In this case, some antennas would be held in reserve for bad weather or other degradations. The reserve antennas could be used for low priority tracks.
3. Antennas could be assigned based on mission priorities, with lower priorities losing support in the event that all scheduled missions cannot be adequately supported.
4. There may be an advance plan to change the size of a subarray during a track, for example, to compensate for elevation effects and retain constant G/T.
5. Demand access can be supported, depending on mission priorities and weather.

Regardless of the advance planning and scheduling methods, individual antennas will be assigned to subarrays by the Array System, with operator support when appropriate.

5.3 Real Time Operations

Real time operation of each track will be similar to today. Most operator effort will be not on the array, but on the other DSN system elements necessary to perform the telemetry, command, navigation and other services. Array operation will be fully automated for nominal operations, including assignment of specific antennas to subarrays, and reassignment of antennas during tracks. To operate the Array System, there will probably be one operator for each longitude, but perhaps only one for the entire DSN. Operator intervention will be possible for situations where real time changes are necessary and can be made better by a person than automatically. These could be spacecraft emergencies, forecasted weather events, or unexpected bad weather or system outages. It is likely that an operator will be involved when not all planned tracks can be supported, and mission priorities need to be invoked.

Calibration and diagnostics will be automated, taking advantage of calculations in the correlators and beam formers to detect degrading performance of an antenna.

5.4 Maintenance

Maintenance will be done so as to minimize cost, not to minimize time to restore individual antennas to service. Sufficient antennas will be allocated to tracks so that failure of a few antennas will not cause failures in performance of services. Preventative maintenance will be done primarily to minimize cost. Thus preventative maintenance will be done when this will increase the lifetime of system elements, thereby minimizing cost. Some system elements will not be maintained until they fail, if this is the cheapest way. Maintenance of assemblies will be done in varieties of ways to minimize cost: in-place, at an on-site facility, at a DSCC or depot facility, at JPL, or by vendors.

There will be a full-time (one-shift) maintenance crew at each site and at the DSCC. In addition, personnel may need to be on-call for rapid restoration to service of critical system elements at the site central processing facilities, or at the DSCCs.

5.5 Sustaining Engineering

The system will change throughout the implementation and operations phases, due to parts obsolescence, technology advances, changing requirements, and opportunities to reduce costs. Upgrades will be made as assemblies or components fail and need replacement. Improved or lower-cost replacements will be made as appropriate. It is anticipated that there will be few system-wide upgrades for changing requirements or to improve performance, due to cost.

There will be a need for continuing sustaining engineering to develop replacements. There will also be a need for detailed configuration management, to track the status and version of each instance of each system element.

6. Summary

Very large arrays are the most promising way to obtain orders of magnitude increase in DSN RF reception capability. Such increased capacity would greatly enhance mission science return, and reduce the cost per bit of science data reception by two orders of magnitude.

Cost is the key challenge. Operations and maintenance costs are critical, because these could dominate the life cycle cost of the system.

Development of an Operational Prototype Array System is beginning. This will be used to validate performance, implementation and operations costs, and the operations concept. A fully operational Array System could be in place in about ten years, with full capability in about twenty years. This would achieve the DSN vision of improving capability by an order of magnitude each decade.

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