The Deep Space Network Large Array

Mark S. Gatti

Jet Propulsion Laboratory, California Institute of Technology

The Deep Space Network (DSN) is primarily used for telecommunications with scientific spacecraft engaged in solar system exploration. The network consists of three deep-space communications complexes, which are located on three continents. Each of the three complexes consists of multiple deep space stations equipped with ultra-sensitive receiving systems and large (34-m and 70-m diameter) parabolic dish antennas. Both the number of spacecraft and the data rates planned for the future will demand even more performance from these assets. Technologies to support the higher data rates include even larger antennas, optical receiving systems, or arrays of antennas. This paper describes a large array of small antennas that would be implemented for a fraction of the cost of an equivalent 70-m aperture. Adding additional antennas can increase the sensitivity many fold over current capabilities. The array will consist of from 50-400 parabolic reflector antennas, each of which is 12-m in diameter. Each antenna will operate simultaneously at both X-band (8-9 GHz) and Ka-band (30-38 GHz) and be configured with RF electronics including the feeds, low noise amplifiers, and frequency converters, as well as the appropriate servo controls and drives. The array also includes the signal transmission and signal processing to enable the system to track from between 1 and 16 different signals. A significant feature of this system is that it will be done for relatively very low cost compared to the current antenna paradigms. This is made possible by the use of low cost antenna reflector technology, the extensive use of monolithic microwave integrated circuits (MMICs), and finally, by using commercially available equipment to the maximum extent possible. Cost can be further reduced by the acceptance of lower antenna element reliability. High system availability will be maintained by a design paradigm that provides for a marginal set of excess antenna elements for any particular tracking period. Thus the same total system availability is achieved for lower element availability. The "plug-and-play" aspects of the assemblies will enhance maintainability and operability. The project plans include a modest start of 50 antennas at each complex and the installation of an infrastructure that is capable of growing to a full compliment of 400 antennas per complex.

Introduction:

The telecommunications link between the earth and spacecraft engaged in solar system exploration includes the Deep Space Network (DSN). This network, consisting of large antennas located approximately equally spaced around the earth, is responsible for the delivery of telemetry to scientists from a multiplicity of spacecraft currently on mission, as well as for those planned in the future. There is a cluster of antennas at each of the three longitudes that make up the DSN. Each cluster currently consists of from one to three 34-m beam waveguide antennas and one 70-m cassegrainian antenna. These are located at Goldstone, CA USA, Madrid, Spain, and Canberra, Australia. While the current DSN assets support existing mission scenarios, it has been suggested that future missions will desire greatly increased data rates. The choice has to be made as to how best support these needs by the ground system. The options typically considered include the construction of new large apertures, the development of even lower noise receivers, the use of novel coding schemes, and the development of higher power uplinks. Often, a combination of these is done to improve capability. These options are costly and result in a capability that is an incremental improvement in the overall capacity of the DSN. This paper describes an alternate concept to the typical options; a large number of small antennas that are arrayed to produce high effective area-to-noise temperature (A_e/T) ratio, which is the figure of merit , or sensitivity, for ground systems.

The concept of arrays to increase the sensitivity is not new for radio telescopes, or to the DSN. What is new about this concept is the cost goals that have been identified to complete a project capable of replacing the downlink capacity of the 70-m antennas. The concept leverages the advances made in electronics such as monolithic microwave integrated circuits (MMICs), cryogenics, and in particular the inexpensive fabrication of smaller reflector antennas. The result is that we expect to duplicate the downlink capability of a 70-m antenna for 1/10 to 1/5 of the cost of the 70-m antenna. This paper describes the DSN Large Array System that is being considered for the future.

Requirements and the Prototype Array:

In spite of the great promise of RF arrays, significant uncertainties in cost and performance remain. Reducing these uncertainties is a prime consideration in the development of the array concept for the DSN in the coming year. One way to reduce these uncertainties is the development of breadboard hardware and a prototype array. The cost of a prototype will be significant, therefore, when completed the prototype will form the basis of the first cluster of new apertures at the US longitude, in Goldstone, CA.

The development of the array system has started with a significant level of system engineering. Currently, a Prototype Array System Requirements document has been written that defines the main parameters and functional requirements. We will be considering operability, availability, and maintainability factors in the development of the array. However, a critical aspect of the array concept is it's scalability. Specifically, once the size of the array elements is chosen, the number of them, i.e., the array size, can be increased as a function of time (and available funding) such that the critical figure of merit, A_e/T, can be improved to match any future requirements. This important aspect of arrays suggests that for the Prototype Array, the array size need only be as large as required to minimize the uncertainties in cost, performance, and operations. Currently, we have chosen to focus on an array of size N = 50 for an element size of 12-m, at GDSCC. This size provides us with a sample size large enough to test all aspects of the array, and provides us with a system that has greater than 70-m performance when completed. We have also considered cost models for arrays of N = 100 and N = 400. The final DSN configuration would be arrays of equal size at each longitude. The top-level requirements for the array of N = 50 elements are given in Table 1 below.

The rationale for the element size comes from the desire to minimize the total array cost. A cost model has been developed that relates the total array cost to the size of the antenna for a fixed A_e/T. Keeping in mind that for the same A_e/T, as the antenna size becomes smaller, a greater number of antennas is required, one recognizes that the cost of multiple sets of electronics for each antenna will define the low end of the scale. As the antenna size becomes larger, the cost is dominated by the antenna manufacture. Figure 1 illustrates this effect and shows that for the current state of technology, an antenna in the range of between 8 to 15 meters will provide minimum cost for a 100 element array. As mentioned earlier, we have chosen to develop a system based on 12-m antennas.

FIGURE 1. Cost Model of Array of 100 Elements illustrating minimum cost at 12-m

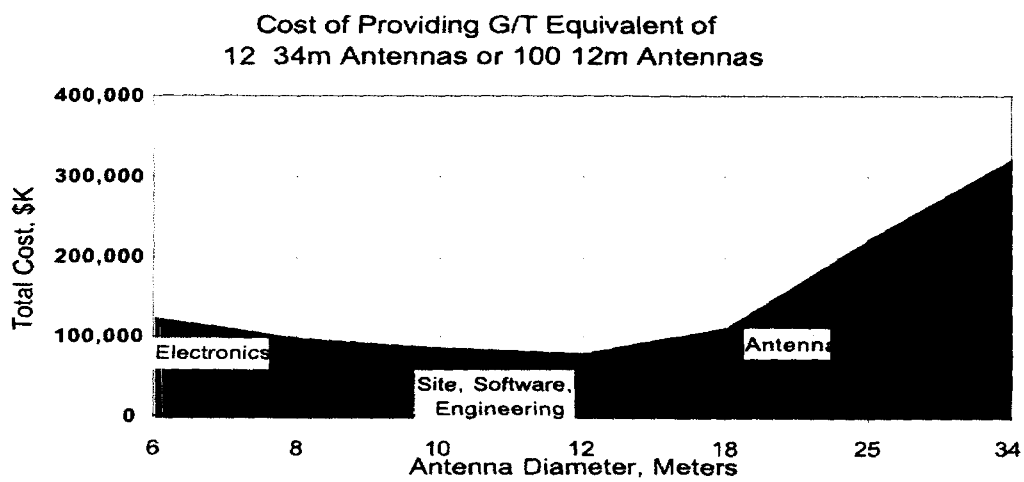


TABLE 1. Proposed Requirements for DSN Array of size N = 50

Requirement		Value X-band	Value Ka-band
Element Size (diameter, m)		12	12
Array Size (N)		50	50
A/T (m^2/K)		82.5	180
Sky Coverage			
	Elevation	6° - 90°	6° - 90°
	Azimuth	0° - 360°+	0° - 360°+
Tracking rate, max (°/min)		24	24
Slew rate, max (°/min)			
	Elevation	45	45
	Azimuth	180	180
RF Frequency Band (GHz)		8.0 - 8.8	31 - 38
IF Bandwidth (MHz)		500	500
Signal Processing Bandwidth (MHz)		100	100
Polarization		Dual CP	Dual CP
Array Beams/cluster		16	16
Gain Variation (dB)		< 0.2	< 0.2
Phase Noise (dBc/Hz)			
	1 Hz offset	-65.7	-65.7
	10 Hz offset	-73.3	-73.3
	100 Hz offset	-75.2	-75.2
	1000 Hz offset	-75.2	-75.2
	10000 Hz offset	-75.2	-75.2
Allan Deviation			
	1 s integration	3.9×10^{-13}	3.0×10^{-13}
	10 s integration	4.6×10^{-14}	3.0×10^{-14}
	1000 s integration	4.5×10^{-15}	1.4×10^{-15}
	3600 s integration	4.5×10^{-15}	1.4×10^{-15}

A Simple Comparison of Arrays and Single Apertures:

To quantify the benefits of a large array, some simple comparisons can be made. In order to make these comparisons, it is useful to identify a simple metric for comparison. The operating system noise temperature and efficiency at Ka-band (32 GHz) for the DSN 34-m antennas is currently $T_{op}(34m)$=45 Kelvin, $\eta(34m)$=0.55. By using an array element antenna of 12-m, and a system temperature and efficiency of $T_{op}(12m)$=40 Kelvin, $\eta(12m)$=0.60, one can arrive at an equivalent number of 12-m elements, the array size N, to match the single 34-m antenna. Relating the effective aperture to the physical aperture of the antennas by the efficiency does this.

In particular, the effective area, A_e, and the physical area, A_p, of an antenna are related by the efficiency, η, by:

$$A_e = A_p * \eta \quad [1]$$

To determine the size of array needed to be equivalent to the current 34-m antennas we write

$$N\left(\frac{A_e(12m)}{T_{op}(12m)}\right)=\left(\frac{A_e(34m)}{T_{op}(34m)}\right) \quad [2]$$

$$N=\left(\frac{A_p(34m)}{A_p(12m)}\right)\left(\frac{T_{op}(12m)}{T_{op}(34m)}\right)\left(\frac{\eta_{34\mu}}{\eta_{12\mu}}\right) \quad [3]$$

Using the values above we arrive at an array size of N = 6.54; however, we must choose an integer number for the array, so we choose N = 7. Finally, the total availability of each system must be the same. In the case of the single 34-m aperture, an availability of 0.95 is typical. For the 12-m array, the component elements may have an individual availability as low as 0.85. For an array, the total system availability can be increased above the level of the individual elements by the addition of extra 12-m apertures. For our case we find we should add 3 apertures to make up the difference. Therefore, a final array of 10 x 12-m apertures is equivalent to the capability of a 34-m antenna. Similarly, we can show that for a 70-m antenna, a 40 x 12-m array will produce the same performance, all including the availability requirement.

Considerations for a Final DSN Array Size:

It was suggested earlier that the prototype array would be an array of 50 elements located in a single location. The considerations for this prototype size were limited to what were necessary to reduce risk with respect to the uncertainties in cost, performance and operations. Here is discussed the considerations for choosing a final array size to support spacecraft operations through the year 2020. Again, in this context, the final size is fixed within a certain era. If implemented properly, an infrastructure will exist after the initial construction phase that is capable of increasing the array size to meet any conceivable requirement. In practice, the limit is defined by available funding for any such project.

There are four main considerations to be made in determining a final array size. These considerations are:

a. To maintain the current downlink DSN capability, while systematically eliminating the large apertures currently in the DSN.

- Currently the DSN longitudes are populated with the following number of apertures:

  i. Goldstone: 4 x 34-m, 1 x 70-m
  ii. Canberra: 2 x 34-m, 1 x 70-m
  iii. Madrid 3 x 34-m, 1 x 70-m

- Given the simple metric of 10 x 12-m being equivalent to a 34-m, and 40 x 12-m being equivalent to a 70-m we can suggest that to meet this consideration Goldstone should have an 80 x 12-m array, Canberra should have a 60 x 12-m array, and Madrid should have a 70 x 12-m array.

b. To provide an array sized sufficiently large to enable tracking of all current and planned spacecraft at their maximum data rates for all phases of the mission, e.g., for a Mars mission at both max range and min range. In the case of existing spacecraft, the maximum data rates are limited by the on-board hardware. Future spacecraft could include much higher data rate hardware. Referring to Table 2, one can conclude that an array of 100 x 12-m antennas at each longitude will meet all current and planned future needs through 2015. The corollary to this conclusion is that future missions can be designed for even higher data rates until the array limits the communications link, after which a larger array would be necessary.

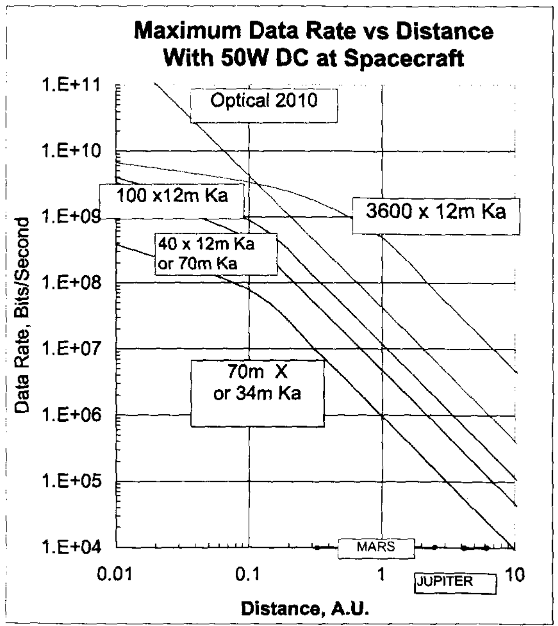
c. To enable the DSN to track spacecraft in different parts of the sky at the same time. This suggests that there be a factor, A, which is dependent on how many missions, the probability of needing to track two separate missions at the same time at the same longitude, the probability of this occurring when the involved missions are at their maximum range, and the number of antennas needed to guarantee maximum data rates for each involved mission. One note is that all spacecraft at a single location, e.g., Mars OR Jupiter OR Saturn, can be simultaneously tracked with a single array of 100 x 12-m antennas since all will be in the main beam of the array element antennas. The current estimate for the factor A is 4, suggesting a final array size of 400 x 12-m antennas.

d. There is a consideration for the largest size array that is practical for the next 20 years. As the array size grows, the maximum data rate that can be supported in an end-to-end system becomes more limited. This is due to the available bandwidth for a particular RF channel, either in the X-band or Ka-band frequencies. Figure 2 illustrates this effect. The figure shows the maximum data rate that a link can support as a function of the earth-to-spacecraft distance. Shown on the plot are curves for a 40 x and 100 x 12-m array. Also shown on the chart for reference is a curve for the proposed optical communications demonstration planned for the Mars Telecommunications Orbiter (MTO). A 400 x 12-m RF array at Ka-band would be equivalent to the performance of the optical communications demonstrator.

Table 2. Illustrating the Array Size to Guarantee a Mission can Operate at Maximum Data Rate

Mission	Location	Max Data Rate (min range)	Min Data Rate (max range)	Data Rate at all ranges with Array	Array Size that guarantees Max Data rate	Year of operatio
MRO	Mars	5.3 Mbps	500 Kbps	5.3 Mbps	75-100	'05 - '10
MRO (Ext msn)	Mars	5.3 Mbps	500 Kbps	5.3 Mbps	75-100	'10 - '15
MTO	Mars	10.6 Mbps	535 Kbps	10.6 Mbps	100	10/09 - 8/20
MSL (DTE)	Mars	10 Kbps (34m)	1 Kbps	8.5 Kbps (34m)	<100	'09
Cassini (Ext msn)	Saturn	165.9 Kbps	40 Kbps	165.9 Kbps	60-100	6/08 - 6/10
JIMO	Jupiter	20 Mbps	10 Mbps	20 Mbps	100	4/11 - 3/21
New Horizons	Pluto, Kuiper Belt	104 Kbps	10 bps	104 Kbps	100	10/06 - 3/17
Solar Probe	Solar	62 Kbps	25 Kbps	62 (25) Kbps	100 (40)	5/10 - 7/17

Figure 2. Chart Illustrating Data Rate vs. Distance for Various Array Sizes

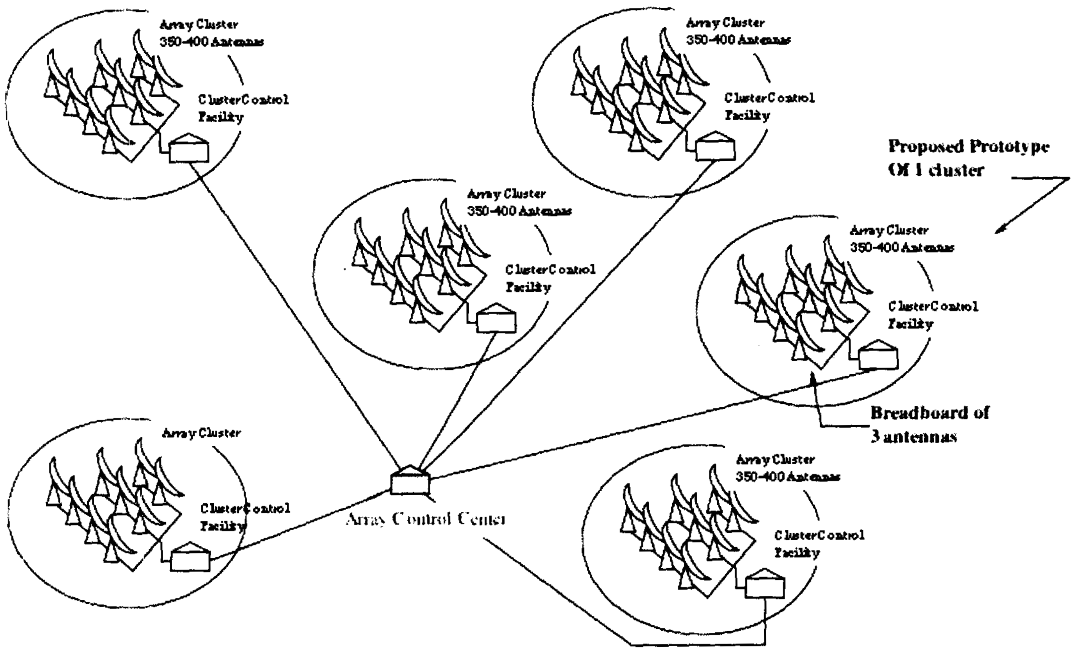


Array System Description:

The techniques used to phase up the elements of an array must account for variations in the atmosphere. For a telecommunications array the placement of the individual elements is most efficient when the elements are tightly clustered. This improves the ability of the array combiner software to phase up on the weak sources. This is in contrast to a radio telescope array that is more likely to include elements that are widely separated in order to increase resolution of the combined signal.

An architectural consideration for a telecommunications array is to create widely separated set of clusters of many closely spaced elements. This concept is illustrated in Figure 3. Each cluster is controlled by a cluster control center. Each cluster control center is connected in turn to an array control center. Such a system configuration enables both a certain amount of tolerance to local weather conditions, and for direct plane of sky measurement of the spacecraft for navigation purposes. While this architecture provides many advantages, one serious drawback is the added cost of the system due to the development of the facilities and the transport of the very wide bandwidth signals between the array clusters.

Figure 3. Architecture of an Array Consisting of Many Clusters of Antennas

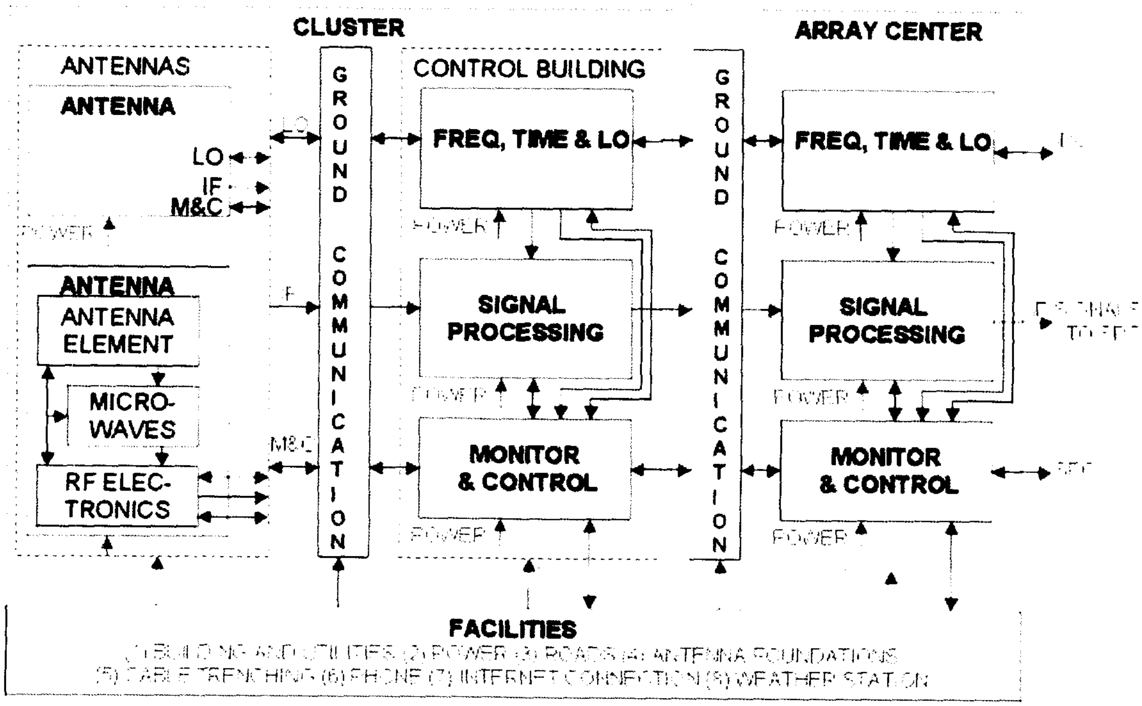


As described earlier, the architecture that the DSN is currently pursuing consists of a single cluster of closely spaced antennas at each of the three longitudes around the earth. This is both cost effective and provides the initial infrastructure for an expansion that might eventually consist of multiple clusters. Each of the clusters includes the antennas, electronics, a signal combiner, the control and analysis software, and the infrastructure including the control buildings, roads, fences, security system and intra-array communications system.

The array system consists of eight major subsystems as shown in the block diagram of Figure 4. These are:

a. Antenna Element, including the main and sub-reflectors, motors, drives, and servos
b. Microwave, including feeds, optics, and low noise amplifiers
c. RF Electronics, including the RF/IF frequency converters and Local Oscillators
d. Signal Processing, including the signal conditioning, beam splitters, beam combiners, and correlator
e. Monitor and Control, including the software and hardware needed to control and monitor the array, and interface it with the existing DSN equipment
f. Frequency and Timing, including the reference frequency generation, timing signal generation, and central local oscillator system
g. Ground Communications, including the fiber optic cables between antennas and the control building
h. Facilities, including the control building, roads, power, HVAC, weather station, etc.

FIGURE 4. Block Diagram of the DSN Array Showing Subsystems and Interconnections



Current Project activities include technology investigations and demonstrations in each of these areas with emphasis on minimizing the total system cost. The extensive use of monolithic microwave integrated circuits (MMICs) will replace the larger bulky components in older systems. This lends itself to low cost replication in great quantities. Furthermore, the development of reflector manufacturing techniques is progressing to break the currently accepted rule of thumb for the cost of antennas as a function of the diameter. Currently costs are thought of as being approximately proportional to the antenna volume. This is given by Cost = $D^{2.7}$. Our goal is to reduce the exponent from 2.7 to 2.0, thus making the cost proportional to the antenna area. We are making significant advances in this area by the use of specially hydroformed aluminum reflectors. As a final note, we are designing the system in modular form, such that replacement components are "plug-n-play". The repair of failed components may depend on the cost to simply replace the components. We will investigate how best to implement this philosophy in the future.

Operations Concept:

The paradigm currently used by the DSN consists of providing a set of services with fixed performance. Spacecraft telecommunications system engineers design their systems to use this fixed services. The paradigm proposed in this array concept is for the system designers to request a particular A_e/T and an associated total system availability. Doing so allows the array scheduling system to allocate only those antennas required to meet the performance required in addition to the marginal extra antennas to meet the availability requirement. In this way the number of multiple missions to be supported can be maximized. The projects and the DSN can negotiate performance as a function of cost and availability.

Summary:

An array concept has been described that includes the use of off-the-shelf components to the extent practicable. This array, when initially implemented will provide downlink capability greater than a 70-m antenna. However, the concept has the promise of being expanded to be roughly equivalent to 10-100 70-m antennas. The cost goals are to do this for a fraction of the cost of the current large antennas. The initial implementation will have developed the technologies, engineering, and infrastructure such that future expansion will be a matter of available funding. This concept will ultimately be a replacement for the existing downlink capabilities of the DSN.

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