A Phased Array Antenna for Deep Space Communications[1,2]

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Abstract—This paper describes a phased array antenna that has been studied for use as the next generation Deep Space Network (DSN) for NASA. The DSN currently consists of large reflector antennas located approximately equidistant around the earth and provides communications and navigation services to the NASA science missions to the solar system planets. These individual antennas range in size from 34-m to 70-m. In the future, there have been proposals to replace these antennas with a phased array, each element of which would consist of smaller reflector antennas than currently used. The total aperture could be increased as required by future missions, with total future aperture up to or more than 10 times that of the current DSN total aperture. One possible architecture for this phased array antenna is described. A breadboard phased array was constructed to demonstrate this concept. The performance of the individual antenna elements and their corresponding subsystems, and the performance of the phased array signal combiner developed for this breadboard phased array is described.

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1. 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 and operating at S-band (2 GHz), X-band (8.4 GHz) and Ka-band (32 GHz), 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 *for the downlink receiving capability* of the DSN; a phased array antenna consisting of a large number of small antennas used 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[1]. This concept differs from previous implementations by leveraging 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 a fraction of the cost of the DSN 70-m antenna.

2. A PHASED ARRAY FOR THE DSN

The antenna engineer typically visions a phased array antenna as consisting of many (often 100's to 1000's of)

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[2] IEEEAC paper #1606, Version 3, Updated Dec. 1, 2007

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small (a few wavelengths in size) radiating or receiving elements located relatively close together (within several wavelengths) and sharing a common supporting structure. The product of an "element factor", or the field pattern of the element, and the "array factor", a function of the configuration of the array elements, mathematically represents the phased array beam. Pointing of the resulting phased array beam is done either by real-time varying of the phase and amplitude of the individual signals, or by motion of the supporting structure, or both. For the antenna described herein, the phased array will consist of many *large* (1000's to 10,000's of wavelengths) antennas located very far apart (104 – 106 wavelengths). These elements do share the same supporting structure, the earth. However, the specific locations of each element must be calibrated as part of the system integration. Such a system generates a phased array beam for which the product of the element factor and array factor results in an interferometer pattern. Very high array gain and very narrow patterns are the norm for this type of phased array. In order to realize this performance both the element performance (i.e., the performance of a parabolic reflector system) and the array signal combining system must be very well understood, stable, and calibrated.

Figure 1a illustrates one concept of an array of 400 x 12-meter diameter antennas. The figure is an artists rendition of the phased array antenna. Figure 1b is an artist's rendition of the array shown close-up. Figure 1c shows the layout of each element. Each element/antena is represented by a point in this figure, and is separated from its neighbor by approximately 60 meters, and the total extent of the array antenna is approximately 1 kilometer in diameter. The layout of the elements in this antenna was done considering two main factors, the maximum extent of the array for which the atmospheric effects begin to dominate the phase and the minimum separation of the elements such that the effect of physical shadowing is minimized to a particular lowest elevation angle. Strictly using the ratio of the total available collecting area, such an array could provide up to 11.7 times the A/T of a 70-meter diameter antenna. Accounting for differences in antenna efficiency, system noise temperature, and required availability, one could expect such an array to provide a real factor of 10 for the downlink capacity of the 70-meter antennas.

The elements making up the phased array antenna are themselves relatively large antennas in terms of wavelength. The basic requirements for these antennas are given in Table 1. In order to provide adequate arraying performance for telecommunications, this system will be required to have a total phase error of less than or equal to 18° rms at 32 GHz. This phase error corresponds to a phasing gain loss of approximately 0.2 dB. Table 2 summarizes the expected phase error contributors and expected values. Table 3 summarizes the array gain loss.

Key challenges for an array of this nature are related to cost of the array elements, stability of the RF electronics, distribution of a phase stable local oscillator, and delivery of stable time which becomes more difficult if the elements are more than just a few kilometers apart. The cost of the array element, i.e., the fully steerable reflector antennas, is the most significant hurdle to overcome, since small changes in element cost can be showstoppers for an array of many elements. For an array element 12-m in diameter, the cost range is currently estimated between $350k and $1200k depending on the expected performance and highest frequency of operation. For an array of 400 elements, the cost of just the elements alone would be between $140M and $480M. These current costs are such that an array of this nature still lies in the realm of a government asset rather than in the private sector and other technical considerations are much less worrisome.

3. BREADBOARD PHASED ARRAY ANTENNA

In order to develop the appropriate technologies for the DSN phased array antenna described in this paper, a breadboard array was constructed at JPL. Technologies of interest include low cost antennas and servo controls, low cost frequency, timing, and local oscillator distribution, low cost and compact RF cryogenic electronics, low cost cryogenics, array signal processing, and monitor and control systems. All of these technologies have come together in this breadboard array which consists of 3-elements: 2 x 6 meter antennas and 1 x 12 meter antenna. These antennas are shown in Figures 2 and 3.

Each antenna includes a cryogenic feed system capable of simultaneously receiving both X-band and Ka-band signals and routing these signals to the processing system that calculates in real-time the phase and amplitude delays required to properly sum the signal from a spacecraft.

The high level block diagram of this system is given in Figure 4.

The Array Antenna performance depends on the element antenna performance and the signal processing combiner performance. Each array element antenna must meet the requirements given in Tables 2 and 3. The performance of these antennas has been measured over the past year using the standard suite of tools available to radio astronomers as well as a set of tools developed by the test team that utilizes the interferometry capability of the array.

In a receiving system the effective area or gain and the system temperature are the figures of merit (in particular the ratio of A/T or G/T). The aperture efficiency of the antenna is nominally measured to derive the effective area, Ae, or the gain G. For parabolic reflector antennas one measure of a high performing antenna is the RMS surface deviation from the desired quasi-parabolic shape. Figures 5 and 6 show this RMS surface deviation for both the 6 meter and

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12 meter antennas. The worst case deviations are shown and should be compared to the specification of 0.012" (0.3048mm).

The system temperature is measured using the built-in radiometry capability provided by a calibrated noise source that can be injected into the low noise amplifier. A measure of the noise of this system at both X-band and Ka-band is shown in Figures 7 and 8 for the 6 meter antenna. Similar results are found with the 12 meter antenna.

This breadboard antenna is meant to serve as the test bed for a potential future ground communications antenna. Accordingly, several demonstrations of its capability to properly combine signals from deep space science mission were planned and executed. The X-band capability of this array was demonstrated using NASA's Mars Reconnaissance Orbiter (MRO). One of the telemetry modes used in the MRO X-band signal contains a data stream at 150 Mbps. This signal was detected using only the12m antenna, for which only carrier lock could be achieved. With the addition of the other two 6m antennas the symbol stream and the telemetry could also be detected. Figure 9 shows the increase in carrier-to-noise power as various antennas are added to the signal.

4. SUMMARY

A concept for a DSN phased array antenna receiving capability has been presented. The breadboard array system that was built to demonstrate the various critical technologies has been shown as well as the performance of the elements of the array. The array combining system has been demonstrated on spacecraft signals. Further analysis of these breadboard data will be required to fully characterize the performance of this phased array and its suitability for a deep space communications ground system. However, from this work it seems apparent that the ability of this array system to greatly increase the downlink performance has been demonstrated.

ACKNOWLEDGMENT

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[1] Rogstad, David H., Mileant, Alexander, and Pham, Timothy T., "Antenna Arraying Techniques in the Deep Space Network", JPL Deep Space Communications and Navigation Series, John Wiley and Sons, 2003.

BIOGRAPHY

Mark Gatti came to JPL in January of 1981 to work in the Spacecraft Antennas group. During the next 9 years he delivered spacecraft antennas, and developed the first near-field measurement facility used to officially characterize a spacecraft antenna at JPL. In 1987 Mark joined the Communications Ground Systems Section working on many different deliverables to the DSN. In 1991 he was assigned the task of outfitting the first Beam Waveguide Antenna constructed for research and development and supported the research efforts for a myriad of users. Working in the technology program Mark gradually assumed the responsibilities for the technology development in antennas, transmitters and low noise amplifiers. By 1995 he became the PEM responsible for delivery of the ground system element for the Cassini Gravity Wave Search. This ground system delivered the first operational Ka-band system to the DSN including both uplink and downlink with monopulse feedback for high precision pointing. In 2001 Mark became the Deputy Manager of the Communications Ground Systems Section and assumed leadership for a study to develop the technologies for a low cost option using an array of many small antennas to provide for the next generation DSN requirements. Mark moved into the newly created Microwave Array Project Office in 2004 as the system manager to further develop this new project capabilities. Working in this project office he managed and participated in many studies to identify the lowest cost options as well as working directly with NASA sponsors to represent this new concept in these early stages. In 2007 Mark assumed Management of the Communications Ground Systems Section.

Mark received his BSEE from New Mexico State University in 1980 and the MSEE fro Cal State Northridge in 1986.

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Table 1. Representative Requirements for an Element in the Proposed DSN Array

Requirement	X-band Value	Ka-band Value
Element Size (diameter, m)	12	12
Array Size (N)	400	400
A/T (m2/K)	620	1440
Sky Coverage		
Elevation	6° - 90°	6° - 90°
Azimuth	± 270°	± 270°
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 x 10-13	3.0 x 10-13
10 s integration	4.6 x 10-14	3.0 x 10-14
1000 s integration	4.5 x 10-15	1.4 x 10-15
3600 s integration	4.5 x 10-15	1.4 x 10-15

Table 2. Phase Error Contributors and Expected Values. ARRAY PHASING ERRORS – (Total =18° RMS at 32 GHz)

Contributor	Value (°RMS)
Atmosphere	12°
Antenna phase center - 0.35 mm Includes Antenna location (baseline)	12°
Antenna Electronics errors Microwave, RF-IF-LO	3°
FO link for IF	4°
Signal Processing Signal Conditioning ADC and sampling Fringe phase and delay update	3°
FTS-LO Reference Generation & distribution LO round trip phase	3°

Table 3. Array Gain Loss Contributors and Expected Values. ARRAY GAIN LOSS **≤ 0.6 dB**

Contributor	Value (dB)
Antenna gain loss due to pointing	≤ 0.2 dB
Antenna gain loss due to deviations from optimum geometry	≤ 0.2 dB
Array phasing loss (RMS phase 18 deg)	≤ 0.2 dB

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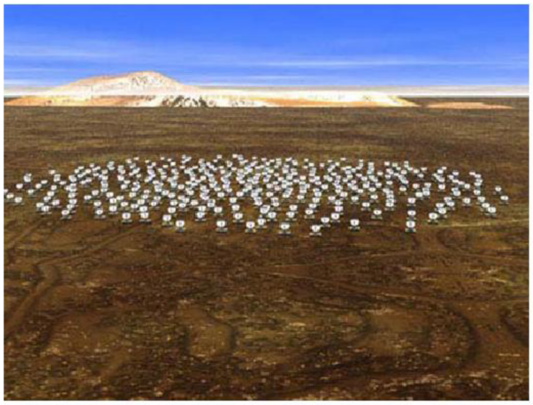

Figure 1a. Artist's Rendition of one possible DSN Phased Array Antenna

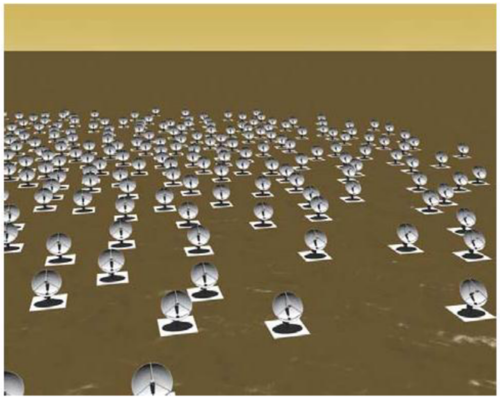

Figure 1b. Artist's Rendition of one possible DSN Phased Array Antenna, Close-up

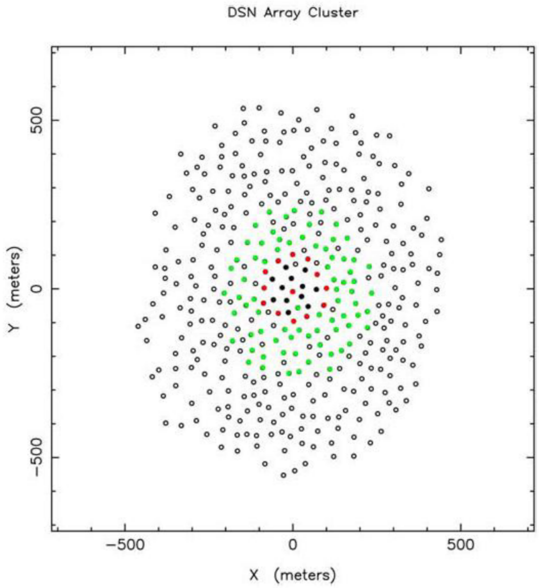

Figure 1c. Layout of the elements in one concept of the DSN Phased Array Antenna. Shown are 400 elements separated by approximately 60 meters

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Figure 2. One 12 meter breadboard antenna


Figure 3. Two 6 meter breadboard antennas

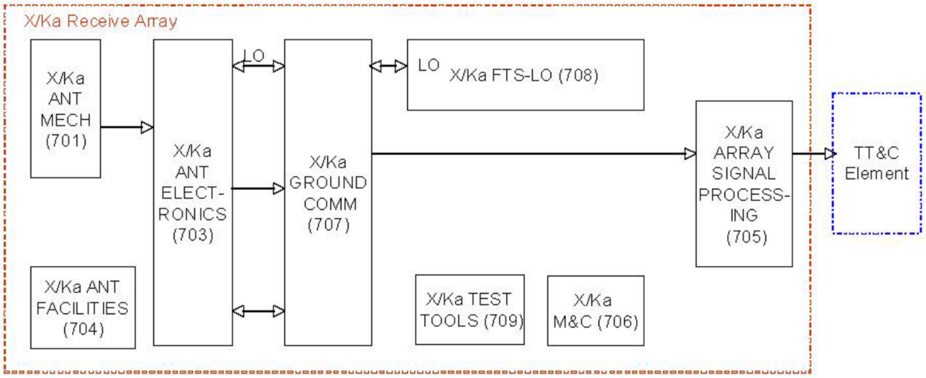

Figure 4. High Level Block Diagram of the DSN Array Antenna System

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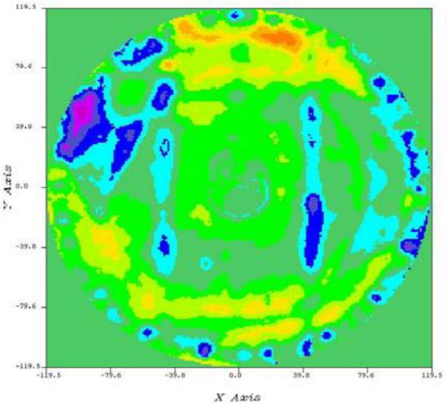

Figure 5. 6 Meter Array Element surface RMS. Elevation = 45°, RMS = 0.0092"

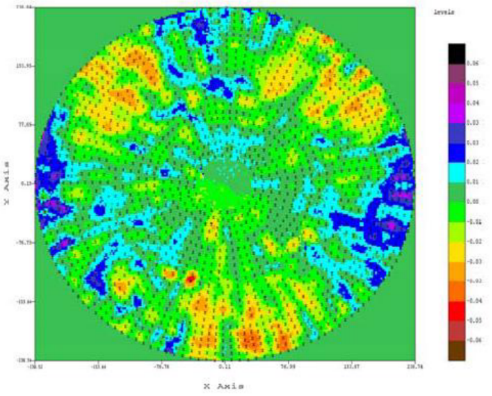

Figure 6. 12 Meter Array Element surface RMS. Elevation = 88°, RMS = .001128"

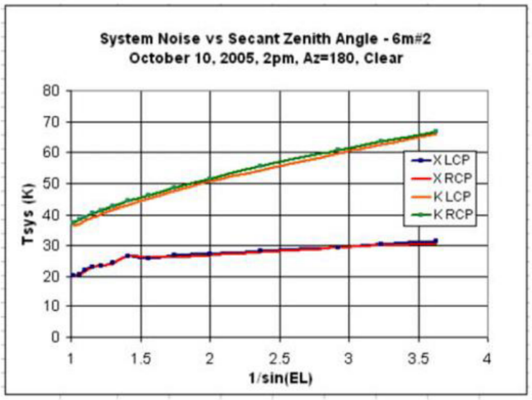

Figure 7. X-band System Noise Measurement of 6 meter antenna as function of elevation

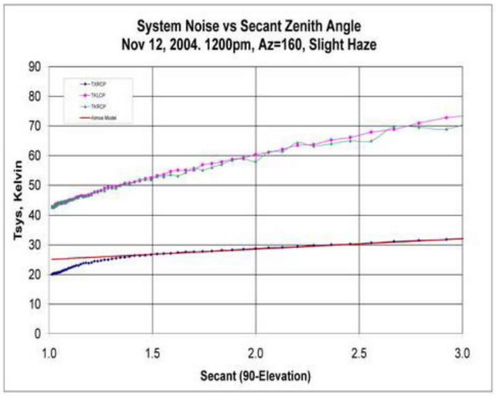

Figure 8. Ka-band System Noise Measurement of meter antenna as function of elevation

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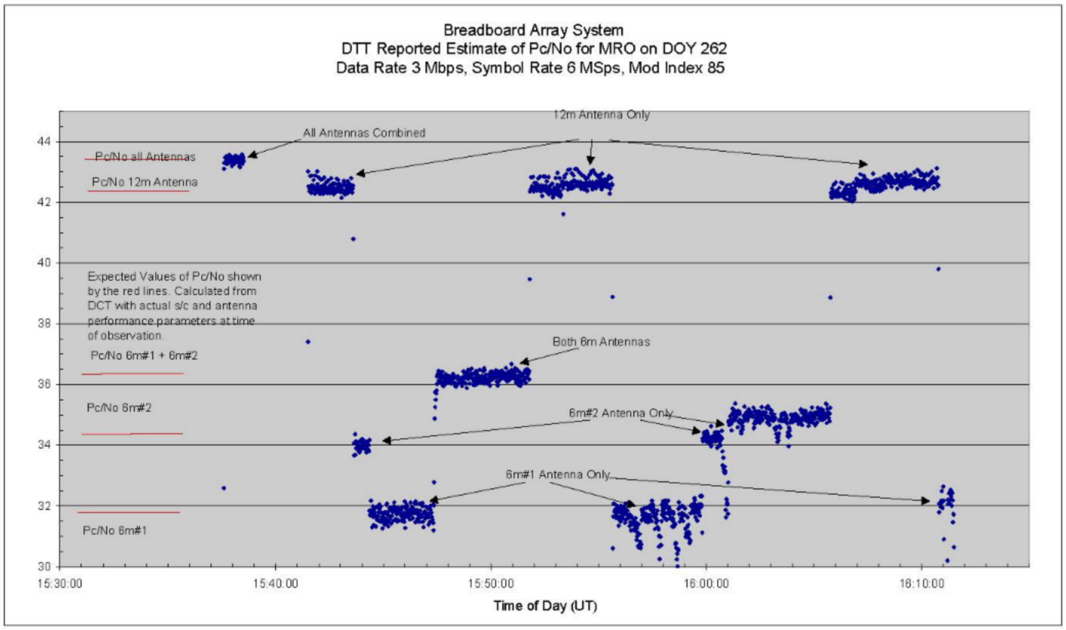

Figure 9. Carrier to Noise Power for Observation of MRO signal.

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