The Deep Space Network Array

Technology Progress, Recent Results, and Future Plans

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• A NASA/JPL study in 2001 looked at seven options to replace the 70-m antenna capability for deep space communications
  – Included 3 monolithic based and 4 array based options
  – The array based options provided capability in excess of the current 70-m
• In January 2002 JPL/NASA began a study focused specifically on array based options
  – One of two studies that included optical communications option
  – Began with a proposal for a prototype of 100 x 12m elements (based on initial cost modeling)
  – Extended to a proposal to replace the current DSN with 400 x 12m antennas each at three longitudes. Options for weather diversity were studied.
• In December 2004 a major review of an array based DSN replacement was held.
  – Included both the downlink and the uplink capabilities
  – Multiple new sites around the world
The concept of using an array for space communications is much less of a concern than the cost of implementing and operating such an array.

- Within the cost question, the cost uncertainty of the front-end components (repeated “n-times”) is of most importance.
- Activities at JPL have focused on both these aspects of the cost

Technical issues requiring demonstration include

- Ability to provide high reliability at lower cost
- Ability to provide functions with smaller form factor (esp. for equipment at front-end) to enable lower cost
- Ability to provide signal processing system that operates in real-time and supports ever-increasing data rate requirements
- Ability to operate and maintain array at lower cost
- Ability to track a typical deep space mission

A breadboard array of three antennas at JPL has been the vehicle to perform many (but not all) of these investigations.
## Comparison of Array Requirements for Space Communications and Radio Astronomy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Communication</th>
<th>Radio Astronomy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>8 and 32 GHz</td>
<td>.5 to 20 GHz</td>
</tr>
<tr>
<td>Array Configuration</td>
<td>Any but lower cost if closely packed</td>
<td>Sparse for better image sharpness</td>
</tr>
<tr>
<td>Element Size</td>
<td>Minimum cost probably in the 3.5 to 10 meter range</td>
<td>May be slightly larger because of more complex receivers</td>
</tr>
<tr>
<td>Data Processing</td>
<td>Digital beam forming of&lt; 10 beams</td>
<td>Correlation processing of full image; &gt; 10,000 beams</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&lt;10 MHz</td>
<td>1000 MHz</td>
</tr>
</tbody>
</table>
## High Level Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>X-band</th>
<th>Ka-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element size (diameter, m)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Antenna Efficiency (%) (6-m antenna in parentheses)</td>
<td>74-79 (65-68)</td>
<td>61-65 (55-58)</td>
</tr>
<tr>
<td>Antenna G/T (dB/K)</td>
<td>&gt;46</td>
<td>&gt;53.5</td>
</tr>
<tr>
<td>Antenna Reflector RMS</td>
<td>0.012”</td>
<td>0.012”</td>
</tr>
<tr>
<td>Sky Coverage</td>
<td>Elevation</td>
<td>Azimuth</td>
</tr>
<tr>
<td></td>
<td>6°–90°</td>
<td>6°–90°</td>
</tr>
<tr>
<td></td>
<td>0°–360°+</td>
<td>0°–360°+</td>
</tr>
<tr>
<td>Tracking rate, max (°/sec)</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Slew rate, max (°/sec)</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Azimuth</td>
<td></td>
</tr>
<tr>
<td>RF Frequency Band (GHz)</td>
<td>8.0–8.8</td>
<td>31–38</td>
</tr>
<tr>
<td>IF Bandwidth (MHz)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Signal Processing Bandwidth (MHz)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Polarization</td>
<td>Dual CP</td>
<td>Dual CP</td>
</tr>
<tr>
<td>Array Beams/Cluster</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Gain Variation (dB)</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>
• The breadboard array is architecturally similar to proposed DSN array.
  – Includes 2 x 6-m antennas (hydroform aluminum, Anderson Mfg.) and 1 x 12-m antenna (aluminum panels, Patriot)
  – Front-end electronics developed at Caltech and JPL
  – Signal processing developed at JPL
  – Monitor and Control to operate this system and enable demonstration testing

• Located at JPL

• Will evaluate issues as described above as well as:
  – Evaluate antenna performance
  – Identify technological “tall tent-poles”
Breadboard Array: 6-m Antenna
Breadboard Array: 6-m Antenna
Breadboard Array: 6-m Antenna
Breadboard Array: 6-m Antenna
Breadboard Array: 12-m Antenna
Breadboard Array: 12-m Antenna
The major elements in the breadboard include:

- **Antenna and servo system**
  - G/T controlled at this level in the system by a specified optics and RMS.

- **Electronics**
  - Includes LNAs, frequency downconverters, local oscillators, frequency and timing.
  - G/T controlled at this level by a specified amplifier gain and temperature.

- **Signal Processing**
  - Includes a correlator and a combiner.
  - Required to provide real-time amplified and phase tracking.

- **Monitor and Control**
  - Required to “glue” the system together for operations, provide data storage, and interface to single user.
• Required to maintain an RMS of 0.012” that includes the original manufacturing surface as well as throughout the range of operating conditions including gravity, wind, and thermal excursions.

• During the period between 2004 and 2005 we have constructed 6-m antennas that meet these requirements.
  – Required painting of the dish surface (front and back)

• The Patriot antenna is in acceptance tests.
  – Initial results show that the total of the manufacturing and gravity is 0.010”.
  – Thermal testing underway
6-m DSN Array Prototype
Elevation = 45°, RMS = 0.0092°
12 m DSN Array Prototype Antenna
Best Fit RMS = 0.00897", El = 30°
12 m DSN Array Prototype Antenna
Best Fit RMS = 0.00946", El = 8º
12 m DSN Array Prototype Antenna
Best Fit RMS = 0.01128”, El = 88°
DSN Array Receive Electronics: Reduced Form Factor

- MMIC Technology to Decrease Array Receiver Cost

Multifunction MMIC packaging of Ka band dual-downconverter for the DSN array reduces size and replication cost by an order of magnitude.
DSN Array Receive Electronics: Block Diagram

- Phased array of moderate size antennas, digitally beam-formed
- Two easily replaced equipment packages per antenna
DSN Array Receive Electronics: Antenna Locations

- Cryogenics Dewar
- Receiver Box
- Receiver Equipment on DSN Array Antenna
- Cryogenics Compressor
## DSN Array Receive Electronics: Feed/LNA Test Results

<table>
<thead>
<tr>
<th>Measured Quantity</th>
<th>XL</th>
<th>XR</th>
<th>KaL</th>
<th>KaR</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNA Noise</td>
<td>6K</td>
<td>6K</td>
<td>12K</td>
<td>14K</td>
</tr>
<tr>
<td>Receiver Noise, 7/23/04</td>
<td>9.6K</td>
<td>10.0K</td>
<td>22K</td>
<td>27K</td>
</tr>
<tr>
<td>Includes Feed and Window</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Predicted System Noise, 10/08/04</td>
<td>15K</td>
<td>14.8K</td>
<td>35K</td>
<td>35K</td>
</tr>
<tr>
<td>Includes Sky</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Goal Including Sky and Spillover</td>
<td>20K</td>
<td>20K</td>
<td>40K</td>
<td>40K</td>
</tr>
<tr>
<td>Measured on 6m Antenna, 11/1/04</td>
<td>17K</td>
<td>19K</td>
<td>39K</td>
<td>38K</td>
</tr>
</tbody>
</table>
DSN Array Receive Electronics:
System Noise Measurement

System Noise vs Secant Zenith Angle - 6m#2
October 10, 2005, 2pm, Az=180, Clear

![Graph showing system noise vs secant zenith angle](image.png)
• Provide a means to evaluate the performance of the Breadboard Array antennas.

• Design and build prototype hardware
  – High density IF digitizer, current design supports 6 Antennas (12 IF inputs) in one chassis
  – High speed FPGA digital signal processing board for AdvancedTCA chassis

• Demonstrate and evaluate proposed signal processing techniques
  – Polyphase FIR filter and a FFT for Analysis filterbank
  – Synthesis filterbank for reconstruction of beamformer output

• Gain experience with various technologies that may be used in the Large Array
  – High speed serial digital signal interconnects (Xilinx RocketIO 3-10Gbit/s)
  – High speed analog to digital converters (1280 Ms/s, 8 bit, Atmel)
  – AdvancedTCA Chassis with high speed serial backplane
  – Field Programmable Gate Arrays for digital signal processing (Xilinx)
  – Linux OS for use in embedded processors (MontaVista)
• Functional Blocks in green are implemented.
• Functional Blocks in blue are in development
• The correlator in the larger system will *not* be a full system.
- Built and Tested Hardware: 3 Array Sampler Modules (ASM) for the IF Digitizer (IFD) and 3 AdvancedTCA Processor Engine (APE) boards for the Real Time Signal Processor (RSP).

- Software and Signal Processing Firmware (FPGA code) for the wideband correlator completed and tested.

- Successfully demonstrated these technologies for BBA:
  - High Speed A/D (1280 Ms/sec, 10 bit digitizer)
  - Analog Fiber link from Antenna to signal processor
  - High Speed Serial links (3.2 Gb/sec) between Filterbanks and Correlator blocks.
  - Real-time Linux OS for Embedded PowerPC processors.
  - Wideband (640 MHz) Discrete Fourier Transform Analysis Filterbank implemented in FPGA.
DSN Array Signal Processing: Real-time Signal Processor APE Board
Hosted on PC platform using Debian Linux

Written in C

PythonCard used for graphical interfaces
  – 42K Logical lines of C and PythonCard source code

User-written activity scripts in Python

Central control of antennas, front-end electronics, signal processing, cameras, LO monitoring, weather stations
  – Interfaces are TCP/IP and serial

Network-based remote user interface provided for monitor and control

Capability to divide the assets in multiple subarrays
DSN Array Monitor & Control: Breadboard
Preconfiguration

Multiple Subarray Configuration
• Provide input for AIPS tools
• Replace some serial interfaces with TCP/IP
• Build up library of user scripts for common activities
• Educate more user-operators
• Add combiner interface
• Add telemetry interface
• Add interface for spacecraft tracking support products
• Schedule-driven automation
• Initiating survey of COTS products for use in larger arrays
  – Monitor and control products, infrastructure products, support products
  – Desire is to assemble COTS components with project-specific software to reduce cost

• Research underway on automation requirements/capabilities and array scheduling

• Refine software architecture
  – New cost estimate
• Testing on various natural radio sources (Venus, Cyg-A, Jupiter, etc.) and deep space missions (MRO) have been useful in checking out the system and has provided calibrations of the 6-m antennas.
  – 12-m calibrations to started beginning of March 2006

• Successfully detected interferometric fringes from two 6 meter antennas using Venus as the source in Dec 2005.

• Successfully stopped interferometric fringes using Geometric models while viewing Venus, Cygnus A, and Cassiopeia A with the two 6 meter antennas on the mesa in January 2006.

• Signal Processing Monitor plots give visibility to confirm correlation and measure delay offsets but not to do detailed analysis of data.

• Correlation Data is archived for later processing to determine more accurate antenna position.
Experiment Results: Interferometry Phase and Amplitude

Results from two 6 meter antennas looking at Cygnus A:

- Amplitude and Phase shown over 640 MHz complex sampling band.
- Large spikes in Amplitude and Phase from RF noise at X-band.
- Geometric models and offsets for path delay applied to bring delay to zero.
- For zero delay, the plot of phase versus frequency should have a slope of zero across the band.
Results from two 6 meter antennas looking at Cygnus A:

- Plot of Lag Amplitude made by taking inverse FFT of frequency channel data.

- Main Lobe of lag plot centered at delay of Antenna2 to Antenna1.

- Noisy frequency channels excluded in calculating these plots.

- Delay Time history tracks peak of Lag Amplitude plot.
• Fringe phase vs time for one fixed frequency (out of 512 available channels).
• 40 minute time span
• Initial offset is a calibration intentionally introduced
• Feb 17, 2006
• Cygnus A
• X-band
Ka Band Carrier from Mars Reconnaissance Observer (MRO)
S/N of 69 dB-Hz at ~ 0.3 AU Range

### Antenna 2
- Sky frequency = 32 GHz
- Tsys 36K
- No -92 dBm
- Pc -23.4
- Pc/No 68.6 dB-Hz
- P received (LNA) -114.4dBm
- Pointing offsets -.060 el -.060xel

### Antenna 1
- Sky frequency = 32 GHz
- Tsys 32K
- No -92.4 dBm
- Pc -23.1
- Pc/No 69.3 dB-Hz
- P received (LNA) -114.2dBm
- Pointing offsets -.080 el -.030xel
Pattern of 6m Antenna 2 Measured at 32 GHz with MRO Spacecraft, Nov 18, 2005

Angle off Boresight-Degrees

Relative Amplitude-dB

-40 -35 -30 -25 -20 -15 -10 -5 0

Elevation
Cross-Elevation
Future Activities

• The DSN Array Project is currently working with Senior Management at both JPL and NASA to develop strategies towards starting a major implementation project.
  – Several studies within NASA are concluding, all of which recommend that any future DSN capability include arraying of antennas to increase performance.
  – Support of Deep Space, Lunar, and CEV (crewed exploration vehicle) missions is included
  – High data rate and TDRSS formatting is being investigated
• Any future DSN capacity must include Uplink
  – Current studies ongoing to investigate and develop technologies for uplink arraying; provides advantages in three ways:
    • $N^2$ effect. EIRP grows as $N^2$ (-vs- $N$ for a downlink array)
    • Improved architectural options (can separate uplink and downlink)
    • Potential for more cost effective transmitters for fixed EIRP