Operation's Concept for Array-based Deep Space Network[1 2]

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Abstract— The Array-based Deep Space Network (DSN-Array) will be a part of more than 10^3 times increase in the downlink/telemetry capability of the Deep space Network (DSN). The key function of the DSN-Array is to provide cost-effective, robust Telemetry, Tracking and Command (TT&C) services to the space missions of NASA and its international partners.

It provides an expanded approach to the use of an array-based system. Instead of using the array as an element in the existing DSN, relying to a large extent on the DSN infrastructure, we explore a broader departure from the current DSN, using fewer elements of the existing DSN, and establishing a more modern Concept of Operations.

This paper gives architecture of DSN-Array and its operation's philosophy. It also describes customer's view of operations, operations management and logistics - including maintenance philosophy, anomaly analysis and reporting.

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1. INTRODUCTION

The Array-based Deep Space Network (DSN-Array) is part of > 10^3 times increase in the downlink/telemetry capability of the Deep Space Network [1]. The key function of it is the provision of Telemetry, Tracking and Command (TT&C) services to the space missions of National Aeronautics and Space Administration (NASA) and its international partners. Table 1 shows level of various improvements under considerations for down link data return.

Table 1. Components of the more than 10^3 increase in return data

Source of improvement	Level of improvement	Comments
Gain/T_{sys}	X10	Three sets of 400 12m antennas, a 10-fold increase in the collecting area, relative to the 70m antenna subnet
Frequency band	X4	Transition from X-band to Ka-band
Spacecraft Components	X50	Increase transmit antenna to 10 meter inflatable antennas
	X25	Increase transmitter power from tens of Watts to a few kilo Watts

This paper describes architecture of the Array-based DSN briefly and its operations concept.

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[2] IEEEAC paper #xxx, Version draft, dated September 24, 2004

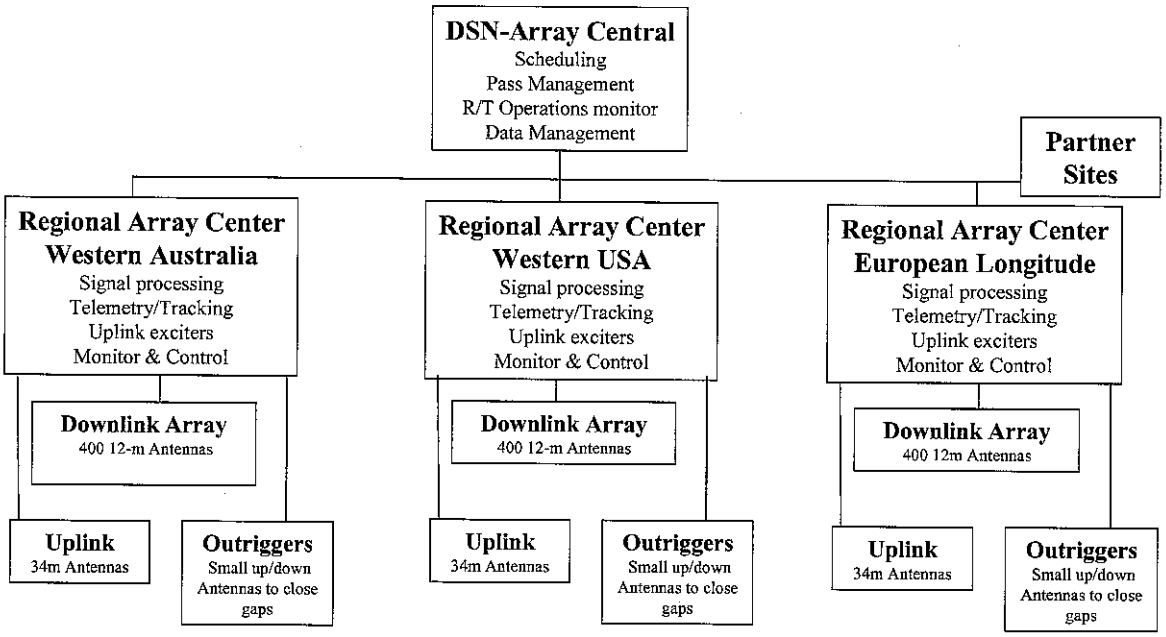


Figure1. DSN-Array Block Diagram

2. ARCHITECTURE

System Architecture

The architecture of DSN-Array is shown in Figure 1. It will be deployed at three sites at, or near, the longitudes of the existing DSN sites.

DSN-Array Central is connected to the three Regional Array Centers (RAC's), one at each of the three longitudes. Each RAC is connected to downlink antennas at the site and to a collection of uplink assets at that longitude.

Each site will have 400[3] 12m antennas (nominal) for receive (downlink only) at X- band (8-8.8 GHz) and Ka-band (31.8-38 GHz), and 5-6 new 34-meter class antennas for uplinks at transmit band near 7.2 GHz. Existing 34-m beam waveguide antennas will also be used for uplink. The site will also include the electronics and facilities needed to support the DSN functions.

Each site will occupy approximately 10-12 square kilo meters, including the downlink antennas, new uplink assets, processing facility, and support facilities.

Most TT&C applications will use arrays of 12-m antennas for downlink and a single 34-m antenna for uplink. Uplink arraying will be used as needed, including for the synthesis of "very-high" power for emergencies.

If the existing 34-m antennas are included to meet uplink needs, they will be equipped with limited downlink capability so that radio science observation or other non-standard science capabilities like low Allan Standard Deviation (ASD)/Phase noise performance can be supported.

The DSN-Array Architecture and Concept of Operations (ConOp) should allow for straight-forward, modular expansion of the downlink capability by adding clusters and/or antennas and/or uplink assets. Under consideration are the following possible expansions:

- Addition of S-band capability on selected antennas
- Addition of near-earth Ka-band downlink capability (26 GHz).

[3] The requirement on Array-based DSN is for X-band Gain/Tsys that is 10-fold that of the 70-m subnet of the DSN. This can be accomplished by 3x400 12m antennas with appropriate noise temperature and efficiency. Note that the final design may use slightly different combination of parameters to meet the 10-fold requirement.

Regional Architecture

The components of the regional assets are shown in Figure 2. Each of the 12-m downlink antennas will have right circular polarization (RCP) and left circular polarization (LCP) capability at X-band and RCP and LCP capability at Ka-band. Each antenna will produce two simultaneous IF signals, having selectable polarization and frequency band, each with up to 500 MHz bandwidth. (Option: each antenna will produce all four simultaneous IF signals). The IF signals from all antennas in a cluster will be brought together to the cluster control building for further signal processing.

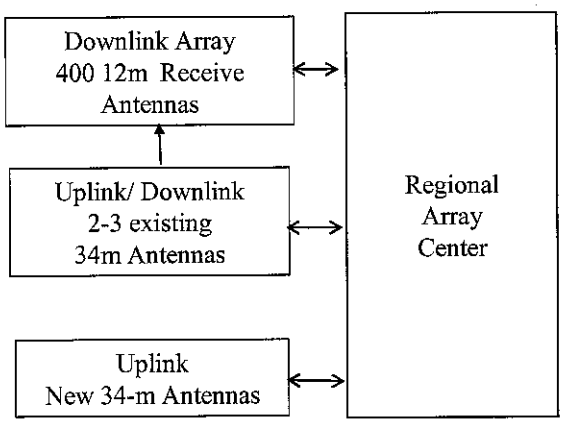


Figure 2. DSN-Array Site Block Diagram

The signal processing equipment for each site will produce up to 16 phased array signals. In the initial deployment, each phased array signal would represent a (sampling) bandwidth from 125 kHz to 128 MHz, within the 500 MHz bandwidth of the antenna intermediate frequency (IF) signal. It will be possible to increase bandwidth of any beam to twice or four times 128MHz by reducing the total available number of beams, the limit being product of the number available beams and sampling bandwidth equal to 16*128 MHz.

Subsequently, if the mission needs justify it, the digital electronics can be upgraded to the full 500 MHz bandwidth. IF bandwidth expansion beyond 500 MHz, if required, will necessitate upgrade of the frequency Down-Converter/IF, local oscillator (LO) electronics, and the digital electronics.

The phased array IF signals will be routed by monitor and control (M&C) for extraction of telemetry and radio-metric data by DSN-type or commercial telemetry processing equipment at the RAC to produce telemetry data in Consultative Committee on Space Data System (CCSDS) format. The IF signals may also be routed to other special processing equipment for other applications like generating tracking data using very long baseline interferometry (VLBI) or differential delay one-way ranging (ΔDOR) measurements for navigation applications. There may be further arraying of symbol streams between sites, if required.

There will also be a correlation capability to measure autocorrelation and cross correlations between IF signals from individual antennas over any part of the signal with bandwidth ranging from 125 kHz to 512 MHz. The correlation measurements are required for smooth operations and calibration of the array, and may enable use of the array for emergency search for a class of "lost" spacecraft.

The uplink antennas may be physically separated, from the downlink antennas to minimize radio frequency interference (RFI) and regulatory concerns.

When an existing 34-m antenna is used with the array, its receive system will be useable as part of the receive array (i.e. the 34-m antenna will be one of the receive element in the array).

DSN-Array will include safety devices & procedures to assure that the equipment and the operations do not pose risk to the staff & equipment and to surrounding areas, including the airspace. This is in particular critical for the uplink assets of DSN.

Outrigger facilities (telemetry and command only, on few antennas) may be added for application to launch and early orbit phase (LEOP) and Lunar mission support, to close any gaps in coverage. Requirements for this are still to be determined (TBD).

Partner sites may be used for such applications as additional support for spacecraft tracking or developing catalog of calibration radio sources, earth's polar motion, etc.

3. OPERATION'S APPROACH

Link and Pass

The basic components of DSN-Array support are links and passes, used in a similar way to their use in the current DSN.

A pass is a continuous period of support. The support can be to a single customer, or multiple customers (the latter occurs in relay operations and in multiple spacecraft per antenna (MSPA) scenarios). Each pass contains periods of setup and teardown before and after the actual tracking support.

A link is defined as the logical aggregation of assets, for a pass. A link will consist of some dedicated assets (antennas, arraying equipment, transmitters, and telemetry equipment) and portions of shared assets (Frequency and Timing, communications lines, switching equipment). The link gets formed in the beginning of the pass, from assets in a general pool, and dissolved after the pass, returning the assets to the general pool. A link can include assets in a single region or multiple regions.

When the tear-down of one pass is immediately followed by the setup of the next pass, potential efficiencies could be achieved by reducing the transition between passes. If cost-effective, DSN-Array will incorporate pass-combining optimization for such scenarios.

Automation and Staffing

DSN-Array will not be operated as a "lights-out" network – the complexity of space operations, and the uniqueness of each mission would make such a capability not cost-effective. Instead, this ConOp is based on managing the real-time operations with a small number of 24x7 personnel at DSN-Array Central (nominally at the Jet Propulsion Laboratory in Pasadena). "Automation" will be focused on providing real-time, and non-real-time, tools that will handle, without human intervention, nominal operations and selected non-nominal failures, and free the 24x7 staff to attend to non-routine events.

Automation tools will also be provided for the non-real-time operations, to both reduce the manual/human intervention and to enable extensive data-mining in the resulting data bases.

DSN-Array will maximize schedule-driven operations, and minimize human-in-the-loop intervention. Real-time 24x7 operations will primarily monitor the schedule-driven operations and correct exceptions. The RACs will optionally have 24x7 rovers for light repairs, if needed to meet reliability, maintainability, and availability (RMA) requirements.

Resource allocation will be performed on-line, based on a priority algorithm approved by NASA head quarters (HQ), with minimal human intervention at the DSN-Array central facility.

DSN-Array Central real-time will be staffed by 5 24x7 operators. The operators will monitor real-time performance, and intervene if needed. Recall that the default is for the passes to be run from the schedule, and the customers are responsible for the provision of correct inputs, via proper mission parameter files (MPFs).

Across all assets in a longitude (RAC, downlink, uplink) there will be 50 full time equivalent (FTE) 8x5 staff that will perform all the maintenance on the 400 12m antennas, the uplink antennas, and the other equipment. Estimates of work-hours, delivered by Ball Aerospace suggest that this level of support is adequate. These staff will handle the logistics, and perform the first level of failure analysis and corrective actions.

DSN-Array Central non-real-time-operations will be staffed by approximately 40 FTE 8x5 positions. These staff will conduct customer interfaces, handle the logistics, and perform analysis, as needed.

DSN-Array Central will be supported by an engineering organization that has the ultimate expertise in the details of the equipment. These staff, in addition to designing and deploying new equipment, will be available to provide support to the staff at the sites, and conduct the final root-cause-analysis and closure of Failure/Anomaly Reports (FARs).

At this time, we defined 2 24x7 rovers at each RAC. The rovers may be required to perform light maintenance (e.g. some board replacement), as needed to keep the system operational. With experience, and better RMA data, the need for the rovers will be re-assessed – the function may be performed cost-effectively by on-call staff, or be overtaken by the antenna redundancy.

Antenna as Least Replaceable Element

DSN-Array will, to the extent possible, treat an antenna as the least/lowest replaceable element (LRE). If the antenna becomes unusable during a pass due to mechanical or electronic component problem (and cannot be restored quickly to service), the support will continue with the remaining antennas, if the margin allows, or another antenna will be brought into service. The fault isolation and restoration will be deferred to the next 8x5 shift. The antenna allocation process will include provision to add reserve capacity consistent with the criticality of the supported event.

DSN-Array will be designed with 5% more antennas than needed to service the missions. At any time, 5% of the DSN-Array antennas will be designated as off-line and can be used for maintenance, testing, development test bed, or other non-operational support. Note: based on the initial RMA data from Ball, less than 5% excess may be enough.

Real Time Operations

In general, the generation of TT&C products (e.g. frames for telemetry, radio-metric observables for tracking) will be script- and schedule-driven, minimizing the need for human intervention. The operators at DSN-Array Central will oversee all the processing, including at the RACs, and will intervene only during anomalies or when an override is required.

Where practical, processing will be conducted at the RAC. Processing at DSN-Array Central will occur only for the cases that involve participation of multiple regions, such as:

- 3-way Doppler & ranging, between regions
- Automatic acknowledgement protocols (e.g. CCSDS file delivery protocol (CFDP))
- Handover between regions
- Etc
- Again, the processing at DSN-Array Central will be schedule/script-driven.

Non Real Time Operations

DSN-Array Central will perform several functions, in addition to overseeing the real-time operations of the assets in the three regions. Most of these functions will be controlled by software/scripts. The list below identifies the functions to be performed by the 24x7 staff, and those performed by the 8x5 staff.

- Priority & array Time Allocation – software(SW)/Script driven, with overrides by the 24x7 staff
- Resource allocation and scheduling - SW/Script driven, with overrides by the 24x7 staff
- Validation of customer provided MPFs - SW/Script driven, with instant feedback to the customer
- Generation of observation control files (OCFs) - SW/Script driven
- Addition of pre-pass and post-pass calibrations to OCFs, if required - SW/Script driven, with overrides by the 24x7 staff
- Instrument calibrations and routine test observations (passes) – 8x5 staff
- Maintenance of calibration catalogs and tables – 8x5 staff, with support of SW/Scripts
- Maintenance planning – 8x5 staff, with support of SW/Scripts
- Data calibration – 8x5 staff, with support of SW/Scripts
- Data quality analysis – 8x5 staff, with support of SW/Scripts and engineering staff

4. CUSTOMER'S VIEW OF OPERATIONS

Resource Allocation and Scheduling

DSN-Array resource allocation and scheduling process is shown in Figure 3. There are three control files and three activities as shown in the figure. These are described below.

- A mission-produced MPF. The MPF should require little knowledge of the DSN-Array. It should include data on spacecraft trajectory, modulation formats, data rates, and timeline of spacecraft events. DSN-Array will provide tools (e.g. "friend of the telescope") to perform syntax and sanity checks on the MPF.

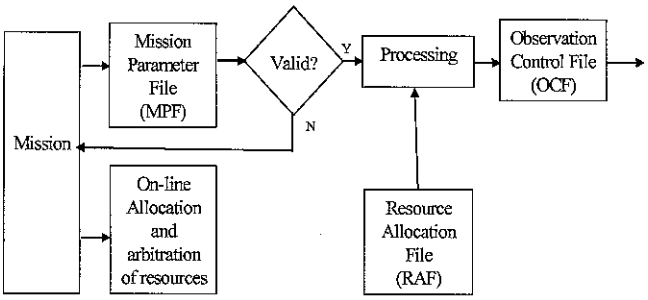
- A DSN-Array-produced Resource Allocation File (RAF). This file has the allocated pass data. Different formats of RAF's will be available to address long-term, mid-term, and near-term resource allocations – all will be visible on-line.

- A DSN-Array-produced OCF that is the set of directions to the hardware (HW)/SW and the teams in the DSN-Array

The resource allocation and scheduling activity is facilitated on-line but will require human intervention and judgment. There is a DSMS team developing a candidate process.

The validation activity is conducted, automatically, every time, once an MPF is submitted. The DSN-Array validation tool will validate the MPF for syntax correctness and for the data being within global legal limits (Optional: missions will develop mission-specific limit files). DSN-Array will reject any deficient MPFs, with a notification to the customer. Passes without a validated MPF will not be executed.

Correctness of the parameters in the MPF is user responsibility – DSN-Array will supply the validation tool to the customers so they can self-validate the MPF's prior to shipping them to DSN-Array.



•RAF defines all the resources that require an allocation (antenna, comm capability, etc)

•MPF defines the pass parameters, that the mission must define.

•MPF & RAF can be produced long before the pass, or during the pass

•OCF is generated, just-in-time

Figure 3. DSN-Array Resource Allocation and Scheduling

While the nominal customer interface is via validated MPF files, the DSN-Array real-time operations staff will be available to support the customers, as needs arise (e.g. "friend of the telescope").

The customer can update the MPF as often as needed; however, updating the MPF during the pass may result in data discontinuity and/or loss of data.

The processing activity will convert the MPF and the RAF to data ready for the DSN-Array subsystems, encapsulated in an OCF.

Real Time Operations

During the pass, the customers will be able to supply modified MPFs, if needed, to be applied by the DSN-Array. The customers will also be able to monitor the progress, through a web-based interface, and will be able to view the applicable subset of the monitor displays available to DSN-Array Central.

Post Pass Operations

After the pass, the customers will get a pass report, accounting for the actual performance as evaluated by DSN-Array. The customers will also be encouraged to feedback to DSN-Array, as soon as practical, any discrepancies they identified in the pass results. Note that some discrepancies in DSN-Array cannot be detected without active feedback from the customers, e.g. errors detectable only by comparing radio-metric data to the actual trajectory.

5. OPERATION'S MANAGEMENT

Functional Modes

Various nominal functional modes are:

- *TT&C* - The most common operational mode will be TT&C. DSN-Array will have Telemetry, Tracking (ranging, Doppler, Δ DOR), and Command capabilities, with largely the same functional capabilities as those of the DSN, but at significantly higher telemetry and command rates.
- *Calibration/Science* - Less common operational mode will be calibration/science mode. This mode will be used for clock calibration, antenna location determination, array gain and delay calibration, direct acquisition of radio-science data, etc. DSN-Array will have largely the same functional capabilities
- *Maintenance & testing* - Maintenance & testing will be conducted generally during times (and with assets) that are reserved on the schedule for non-operational use.
- *User-controlled mode* - DSN-Array will allow for a set of assets to be partitioned and assigned to a user for a non-operational (or non-committed) pass. In a user-controlled pass, the user takes responsibility of operating these assets, and for the success of the pass. The DSN-Array operators are involved only as needed to assure the equipment and personnel safety and the compatibility with the other users during any overlaps.

Operations scenario

Following is an example of various activities for a nominal standard spacecraft pass.

- A customer (user) requests a DSN-Array pass using a web interface. The request will be generally focused on time and capability (e.g. required G/T), not on specific assets.
- DSN-Array validates the completeness of the request, and either asks for a corrected request (if

an error was found) or acknowledges acceptance of the request (if the request is error-free).

- DSN-Array assigns priority and commits certain capability based on HQ provided algorithm and resources available.
- DSN-Array schedules the requisite allocatable resources (primarily antennas, but could also include array signal processing and telemetry equipment, Comm bandwidth, etc). These are documented in a Resource Allocation file (RAF). The RAF may contain reserve equipment, if it is a high priority pass.
- User prepares and provides appropriate MPF in advance to DSN-Array Scheduling. DSN-Array checks the MPF and informs the user of any problem with its validity.
- Prior to the pass, DSN-Array Scheduling merges the user-provided and validated MPF with the RAF containing resources allocated to the pass, and generates an OCF.
- The link is formed, based on timed schedule, by drawing equipment from the equipment pool and the pass is conducted, including set-up and calibrations.
- During the pass

    1) The equipment performance and status of the pass can be checked by the customers, operators, and other interested (and authorized) parties, using monitor data accessible using the Internet.
    2) The customer can make changes to the MPF, if needed. Any change is then sent to DSN-Array Central where it is automatically merged with the RAF to generate a new OCF. DSN-Array will be designed to minimize the adverse impact of the change, but it should be noted that at times the change will interrupt the data flow. An end-to-end change should last no more than xx (one minute?), from the time the customer submit the updated MPF, until it is applied at the cluster.
    3) If performance falls below committed level, reserves (if available) are applied, by internal DSN-Array process.

- At the end of the pass (including post-pass calibrations) the assets are released to the equipment pool.

Post Processing and Feed back

To the extent practical, DSN-Array will conduct consistency checks on the collected data and either take automated corrective action, or report discrepancies. Examples are checking for missing telemetry blocks, or checking (and eliminating) outliers in radio-metrics data.

However, some flaws cannot be detected internally by the DSN-Array. A typical case could be a flaw in the ranging/doppler data that can be detected only when the navigators compare the ranging/doppler data to the trajectory data. The feedback from the post-DSN-Array analysis will be provided through a failure analysis report (FAR), and will be processed using by the FAR process.

Setup and Tear down

Each pass will have a period of setup and a period of teardown. During setup the following activities will be conducted.

- Construction of a link, i.e. assigning assets to a link
- Creation and receipt, at the RAC and cluster, of equipment configuration data
- Configuration of all equipment, based on the configuration data
- Other preparations, range calibration, moving of antennas, warm-up of transmitters, etc.

During tear-down, the reverse will be conducted, as needed for the next use of equipment. Setup time will not exceed 15 minutes (5 minutes for more than 95% of the passes), plus the time to move the antennas and warm the transmitters. Teardown time will not exceed 5 minutes, plus the time to move the antennas and restore the transmitter to a standby state.

Critical Events

DSN-Array will use same definition for critical events as used by DSN presently.

Demand Access and Beacon Mode

In Demand-access and Beacon mode, the spacecraft will initiate an unscheduled transmission, either confirming a healthy state, or alerting the mission operations center that attention is required. The beacon, or demand-access signal, is either a tone, or a very-low-data rate signal, that can be detected with a smaller ground antenna.

DSN-Array will support detection of Demand-access and Beacon mode signals. The support will be provided, normally, by a single 12m antenna. Method of requesting the service is TBD. DSN-Array will not provide automated response – it will be the mission's responsibility to define the response and issue appropriate support requests to DSN-Array.

Spacecraft Emergencies

DSN-Array will process spacecraft emergencies in a similar manner to the DSN. The key difference is that the decision process on which allocated assets will be de-allocated, if needed, and assigned to the spacecraft in need of emergency support will include the HQ-defined priority algorithm.

DSN-Array will have a limited capability (TBD) to identify deviations from the spacecraft sequence (MPF) and notify affected parties. This will include events such as loss-of-signal due to safe mode. Response to these non-sequence events will require human intervention.

6. LOGISTICS

Maintenance Philosophy

To the extent possible, DSN-Array will leverage the fact that there will be a large n umber of identical 12m antennas to simplify the maintenance process and decouple maintenance from operational commitments. (The DSN antennas tend to be more unique, thus the decoupling is more difficult). As a goal, DSN-Array will reserve 5% of the antennas, at any time, to be in a maintenance pool.

The technical staff at the clusters (including RAC and uplink assets) will work 8x5. However, contractual provisions will be included to facilitate presence of staff at the clusters during critical events. The key roles of the cluster staff will be the maintenance & repair of hardware and the initial disposition of the FARs.

Cluster staff will have access to monitor data, test tools, and suitable checking algorithms to support these roles. Cluster staff will also conduct array calibrations and diagnostic observations periodically, or as needed to pin point problems. There will be three levels of repair:

- Equipment swaps and simple repairs can be performed by the 24x7 rovers. Recall that the design will incorporate redundancy to minimize the need for intervention by the rovers.
- More complex swaps, and modest repairs will be done/coordinated by the 8x5 cluster staff, either during the regular working hours or, in rare cases, during an emergency visit to the cluster.
- More complex repairs ("Depot level") will be done by the original vendors (or by the engineering staff), coordinated via the logistics function at DSN-Array Central.

Failure reporting and analysis responsibilities

Failure reporting and report closing responsibilities are:

- Opening FAR – all personnel in DSN-Array are authorized, and encouraged, to initiate FARs. The FAR system will be available to entry by user/customer representatives
- Initial processing of FARs – Initial processing will be by the 8x5 staff at the RACs/Clusters. We estimate that 90% or more of the FAR's will be resolved by the RACs/Cluster staff.
- Final Processing and Closure of FAR's – The final root cause analysis, and the confirmation of closure, will be conducted, at DSN-Array Central.

DSN-Array will use a single FAR processing/tracking system to capture failures, anomalies, or other issues/concerns in:

- Hardware
- Software
- Procedures
- Documentation
- Data capture and delivery (Discrepancy Report)
- Etc.

FARs will be tracked and closed. Closure could be via repair of hardware, or new hardware design, new software, updated procedures or documents, or by acknowledgement that the root cause is outside DSN-Array control (e.g. weather, radio frequency interference, or spacecraft event).

The FAR tracking system will be an on-line system, similar to the advance anomaly management system (AAMS), and will be accessible, world-wide, via the web.

Shipping, Inventory and Configuration Control

DSN-Array will use a methodology for shipping and inventory control and configuration Management, similar to that used by the current DSN. It will investigate whether the DSN tools and processes can be adopted, as-is.

7. STATUS

Requirements

The TT&C requirements from NASA for deep space mission system (DSMS), level-1 requirements, have been developed. Presently work is in progress on developing space segment and ground segment (level-2) requirements, based on level-1 requirements. Once that is done we will finalize the requirements for the DSN-Array.

Proposed Time line

It is proposed to build a prototype receive array of 12 12m antennas (12X12 array), during the fiscal years FY2006-07 and use it for spacecraft observations in shadow mode during FY2008, to understand routine operations. We propose to build 100 12m downlink antennas and 2-3 34m class uplink antennas at each of the three longitudes during FY2009-10 (phase 1). During phase 2, in FY2011-12, we will add 200 12m antennas to each of the three longitudes and convert existing 34m beam waveguide antennas for remote operations. By FY2013 (phase 3), we plan to have total of 400 12m antennas for downlink and total of 6 34m antennas for uplink at each of the three longitudes.

Current activities and status

Presently we are working on a breadboard system consisting of three 6m and 12m antennas. Two 6m antennas, using hydroforming technology for fabricating primary reflector, have been fabricated and are at various stages of installation and testing at this writing. Work on construction of a 12m conventional panel type antenna is in progress at a contractors place, and the contractor is required to deliver the completed antenna assembled at JPL by April 2005.

Simultaneously we are developing electronics for these antennas to test in array use. These tests are scheduled for July-Sep 2005.

We plan to have DSN-Array project definition and cost review (PDCR) in December 2004 and an independent technical review (ITR) for the project in July 2005, before starting work on the prototype 12x12 Array in FY 2006.

8. SUMMARY

This paper describes operations concept of the DSN-Array for deep space communication. It will have 10 times more Gain/T_{sys} over existing 70m antenna subnet of DSN, and will be capable of receiving 40 times more data using Ka-band than current 70m sbnet.

DSN-Array design will allow use of modern technologies and architecture to minimize operating cost. It will allow optimal utilization of available resources using arraying approach to synthesize just needed aperture.

REFERENCES

[1] Deep Space Mission System Telecommunications link Design Handbook at http://eis.jpl.nasa.gov/deepspace/dsndocs/810-005/

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BIBLIOGRAPHY

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