Challenging Implementation and Operations Traditions[1]

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The Deep Space Network (DSN) that provides for the communications link between the deep space missions and the science users currently consists of a small set of very large monolithic tracking antennas. This ground-based network includes a total of 12 antennas located in three roughly equidistant longitudes around the earth and utilizes a decentralized approach to it operations. Recently, however, studies have suggested that the number, complexity, and data throughput of the future set of space probes will be increasing dramatically. This demands more performance from the DSN than is currently available. In identifying the architecture for the future DSN required to support this mission set, one concept that proves promising is one that consists of a great many number of much smaller antennas configured in an array. This concept has been supported by the developments in antenna manufacturing technology and the consistent decrease in the cost of electronics required to receive, amplify, and combine signals from deep space probes. Furthermore, it is clear that past developments in the DSN have not benefited from the application of economies of scale.

JPL's recent benchmarking of industry best practices and capabilities has challenged the assumption that its current Project Management and Implementation and Operations traditions are adequate for the development of a system consisting of many more than the usual "one-off" elements. In particular, are the traditional approaches to implementation of such a system cost effective? Can an affordable program be identified? Can it be affordable to operate?

The results of industry benchmarking done as part of the study to implement an array based DSN of the future suggest that JPL give careful consideration to tailoring traditional implementation and operations in the following areas:

1. **Whereas JPL is expert at implementing "one-off" systems, more reliance on the capabilities of industry in implementation and test of the components that are duplicated many times. An extension of this is that technologies and processes once only in the domain of government agencies are now commonly available to industry.**
2. **Operations of such a large systems, decentralized and labor intensive in the current "few elements" architecture of the DSN, are routinely centralized and automated in the telecommunications industry.**
3. **Employ an automated service request paradigm to support science mission users.**
4. **Provide for continuous low-level updates to components to remain current with technology.**

Nomenclature

ALMA	*Atacama Large Millimeter Array*
ATA	*Allen Telescope Array*
Caltech	*California Institute of Technology*
CBI	*Cosmic Background Imager*
COTS	*Commercial Off-the-Shelf*
DSN	*Deep Space Network*
ESA	*European Space Agency*
EVM	*Earned Value Management*

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II&T	*Installation, Integration, and Test*
IT	*Information Technology*
JPL	*Jet Propulsion Laboratory*
NASA	*National Aeronautics and Space Administration*
NRAO	*National Radio Astronomy Observatory*
Ops	Operations
RAC	*Regional Array Center*
RF-ID	*Radio Frequency Identification*
SW	*Software*
TT&C	*Telemetry, Tracking, and Command*

I. Introduction

NASA/JPL has been investigating the use of a large array of small antennas as the foundation of the next generation Deep Space Network (DSN). The system envisioned will be significantly larger than the current DSN with the attendant complexity in operations and maintenance. The current methods of operating the DSN must be changed in on order to make the array approach feasible. If current DSN operations are simply "scaled up" to handle a large number of antennas (150-1200), the resulting cost will be extremely large. An operations concept that represents a significant shift in paradigm from the current system has been proposed by which this new system can be operated and maintained in a more cost effective manner. This concept will rely heavily on automated operations.

The DSN Array Project has proposed several new features in its concept of operations. Validation of those concepts by benchmarking industry was proposed as an early indicator of the ability of the Project to provide high value to science mission customers. The purpose of this benchmarking work was to determine industry best practices relative to the Concept of Operations and to determine the feasibility of the concepts for use in the DSN-Array. The benchmarking results[i] provide a set of findings and lessons learned relative to the concept of operations. These results suggest that this Project consider deep changes in the culture of the implementation, operations, and maintenance of such a new facility. From this work we propose that the Project give careful consideration to tailoring traditional paradigms as follows:

1. Rely more than before on industry for implementation and test. What was once a purely government domain is now commonly available in industry.
2. Shift to operations that are centralized and highly automated. The telecommunications industry has already completed such a shift.
3. Employ an automated service request paradigm to support science mission users.
4. Provide an infrastructure that stays technically current by continuous low-level updates to both hardware and software.

This paper describes the operations concept, the benchmarking activities and findings, and the lessons learned with respect to successfully realizing the operations concept. Our conclusion is a challenge to the standard paradigms for operations and maintenance of such a system.

II. DSN Array Operations Concept

At present, the DSN operates a variety of microwave antennas (ranging from 26m to 70m diameter) at locations near Barstow, California; Madrid, Spain; and Canberra, Australia. The goal of the DSN-Array is to replace all or part of these assets with arrays of small (12m diameter) antennas.

The basic architecture of the DSN array is shown in Fig 1. Three downlink arrays of a large number of antennas (50-400), each of which is smaller than the current DSN antennas, will be constructed at three Regional Array Centers (RACs) spaced equally around the earth. Combinations of the antennas within each RAC will be connected in phase to act as a single, large receiving (downlink) aperture. Up to sixteen separate downlink signals can be received by each group of antennas. Downlink signals will then be sent via landlines to DSN-Array Central for further processing and delivery to customers. Command data (uplink) and navigation will be handled by a separate array of antennas of size and number yet to be determined, also located at the RACs. Further assets may also be constructed at the RACs to provide other services.

Five round-the-clock (24x7) operators will staff the DSN Array Central facility to monitor schedule-driven operations and to correct exceptions. Customers (Missions) will have responsibility for correct input data files that drive operations. Central staff will also handle customer support, logistics and analysis, as needed.

A few 24x7 "rover" engineers will staff each of the RACs to conduct light repairs and for security. The bulk of the maintenance effort at each RAC will be conducted on a single-shift schedule, five days a week. This 8x5 staff

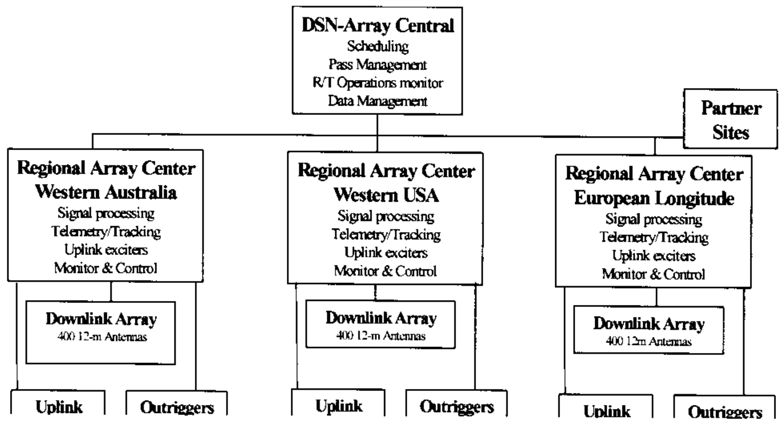

Figure 1: DSN Array Architecture.

will perform the first level of failure analysis, implement corrective actions, perform scheduled maintenance and handle logistics and ware house functions. RAC staff will be present during critical events.

The DSN-Array will leverage its large number of antennas to simplify the maintenance process and decouple maintenance from operational commitments. Present DSN antennas are much fewer in number and have unique capabilities, making decoupling more difficult. The DSN Array antennas will be interchangeable "on the fly," so that antennas can be brought on line and dropped without disturbing the communications link. As a goal, the DSN-Array will reserve 5% of the antennas in a maintenance pool.

The Array concept of operations suggests that better efficiency will result from five main features:

1. a single facility for real-time operations, staffed 24x7,
2. a centralized IT function whereby software updates and configuration will be done remotely,
3. automated use of mission-generated and DSN-Array-validated service requests to reduce manual steps during tracking,
4. schedule-driven, script-based real-time operations with rare human intervention, and
5. a system architecture that provides graceful performance degradation resulting in fewer failed passes.

III. Benchmarking Survey

For this work we defined the scope of benchmarking as an activity that compares the array's proposed design, implementation, operation and maintenance plans as given in the operations concept to industry best practices in similar areas. This activity gathers lessons learned, and identifies where the potential exists to improve plans in this early conceptual phase. It is important to note that for this work benchmarking was not done to solicit cost estimates, designs, studies, technology information or proposals. There have been other benchmarking studies where the purpose was specifically for Telemetry, Tracking and Command (TT&C) ground systems, which include many similar systems from civil, military, and commercial operators[ii]. Those studies include models of costs by which to compare systems. Since this system is unique in that it combines the features of a radio astronomy array and a TT&C system, we did not develop cost models to compare to our own estimates. Finally, The goal was not to learn what industry can do for the project. Instead, the effort was to understand what industry has done in the past and to use it to improve plans for the array project.

The scientific radio astronomy community has constructed a half-dozen or so microwave arrays around the world. Their experience is certainly valuable. However, radio astronomy pays little attention to satellite telemetry, navigation and command. So, there is no single organization with experience in all aspects of the proposed DSN Array. Industry has experience in manufacturing antennas and operating distributed communications systems, but, again, no single organization has all of the needed expertise. This might suggest that benchmarking will be fruitless since no one does exactly what the DSN Array Project is proposing: that in breaking new ground, there is nowhere to go to understand the problems facing the array. However, the benchmarking activity was structured by dividing the DSN Array into elements of competency. Multiple participants were then interviewed, each with expertise in some of the elements. When assembled, the results paint a fairly comprehensive picture of best industry practices relevant to the DSN Array.

Specifically, the elements are:

1. Manufacturing
2. Facilities
3. Software and Information Technology
4. Installation, Integration, and Test
5. Operations and Maintenance
6. Management

Given this methodology, the benchmarking effort was able to include industry participants from many diverse areas, some of which have seemingly little or no relationship to telecommunications ground systems. Nevertheless, their expertise in specific elements can now be included in this work.

The list of potential industry participants originally consisted of 30+ companies, universities and government agencies. After discussion and initial contacts, eleven participants were identified, covering a wide range of products and services. This section identifies the participants, the areas specifically targeted for benchmarking and the individuals involved.

Table 1 shows all of the participants and the area of expertise for which we were interested in benchmarking. Note, however, that some of these participants might also be proficient in other areas. Our interests were confined to those shown in Table 1.

	Expertise					
Participant	**Manufacturing**	**II&T**	**Ops and Maint**	**SW and IT**	**Facilities**	**Mgmt**
ALMA	X		X	X		
ATA	X	X	X	X		
Bechtel		X			X	X
Caltech CBI			X	X		
ESA		X	X	X		
General Dynamics	X					X
Harris	X	X	X	X		
Honeywell	X	X	X	X	X	X
Lucent/Bell Labs		X	X	X		
NRAO		X	X	X		
Verizon			X	X		

Table 1: *Participants in the Benchmarking study, and their expertise.*

In an effort to provide unbiased results, we developed a standard set of topics to discuss with benchmarking candidates. These included:

- What aspects of your system are similar to the DSN Array? (Jointly identified by the Benchmark Team and the industry participant.)
- What are your important performance metrics?
- What level of workforce is required to operate your system?
    - What is the constituency of that workforce?
    - What issues need close attention?
    - Is acquiring workforce for remote locations a serious consideration?
- Did you attain your reliability goals?
- What is your sparing approach?
- How is your system monitored?
- What data transfer/storage issues require special attention?
- How is the scheduling function handled?
- How closely did initial operations cost estimates match your actual costs?
- What are the major lessons learned in getting to the point where your system is operating in "steady state"?

- What is your program management structure?
- How are non-routine operations handled?
- What is the nature of your contingency planning? How do you determine when a contingency plan needs to be enabled?
- What is your customer interface?
- Are "production curves" used in predicting costs of mass production?
- What processes are used to identify and correct problems on highly sensitive electronics?
- What is the integration and test philosophy? In-house –vs- Out of house
- What is development philosophy? System contractor –vs- self as prime contractor.

IV. Results

The results of this benchmarking exercise were interesting in that we discovered that industry has made the shift from manually operated and labor intensive systems to that of fully automated systems. This was done in large part to the competitive nature of business. There were investments made to automate that were seemingly high, but which were returned in short order by the reduction of operations costs.

In general, automation should be applied selectively, where needed, based on risk/reward analysis. Such analysis must be performed at the beginning of a new Project. Key areas deserving particular consideration for automation include customer inputs, script-based operations, configuration management, inventory control, fault identification, testing, and calibration.

We collect our results in two main categories: how they pertain to our operations concept, and issues that will need attention during the implementation of this large system.

A. Results, as they pertain to each of the new operation features are:

1. A Single Facility For Real-Time Operations

Many functional examples of centralized real-time operations of systems were identified. Some systems are truly "lights-out" (no humans present) while others have minimal on-site support. Verizon, Harris, and Bell Labs all have in place centralized control over their IT-based systems. In each case, operation is feasible, functional, and cost-effective. Use of alternate centers in cases of emergency is standard for these organizations and should be considered for a new implementation. We note that with new IT paradigms relying heavily on standard internet web-based protocols, such an emergency center might simply be the minimal set of computing hardware required to maintain constant support. Such an alternate center could be located at one of the RACs.

Centralized, automated operation is a culture change that will require planning and leadership. We observed that automation generally required increased operator skill, education, and training.

2. A Centralized IT Function

We saw many examples of centralized control over distributed assets in highly reliable systems. The majority of these were distributed IT assets (vs. physical assets like antennas). Ongoing software and IT hardware upgrades must be a part of the operations concept. Benchmarking showed a heavy use of COTS (Commercial off-the-shelf) software along with in-house-developed "glue-ware4." Slow, continuous upgrades seemed to be the preferred approach for software updates. Several organizations referred to this as "churning" and employ the operations team to implement many of the updates not only to keep the system technologically current, but also the operators just as current.

3. Automated Service Requests

Automation of the user interface with missions seemed to be a reasonable approach. All but two of the participants being benchmarked for operations already use some level of automated service request. Most were moving towards a fully automated system in the future. Automated requests are most often delivered to the system that then performs syntax error checking and minimal logical checks. The responsibility for the correctness of the request rests with the mission customer. Such an interface requires user/customer alignment and training.

4. Script-Based Operations

Two script-based industrial systems were identified. One allows human intervention while the other is generally "hands-off." Most problems with these systems involve people interactions (operator errors, customer interfaces). These script-based systems are generally used by the operations teams to develop the full service catalog capability which in turn is interfaced with the automated service request system. As with the centralized IT function,

[4] "Glue-ware" is custom-written software than connects other software from various sources into a coherent, working system.

maintenance of these scripts are often the responsibility of the operations teams as part of the continuous system updating.

5. An Architecture With Graceful Degradation

Redundant architectures with graceful degradation were a common feature with many of the participants. The ATA and ALMA arrays both feature redundant architectures. The entire telecommunications industry provides heavy redundancy in order to meet their very high availability requirements. In particular, the telephone industry claims a 99.9999% availability. Their redundancy is of a different nature than an array, but illustrates the level of availability attainable with such a system.

B. The benchmarking team also identified the following important implementation issues:

6. Acquisition Strategy

The line of responsibility between contractors and NASA should be based on the organization's core capabilities. NASA should retain control of those areas that are its core capabilities. Industry should assume the risk for the performance of the products they deliver. Use of local capabilities promotes good relations, reduces transportation costs, and ultimately provides a local source of labor and spare parts.

7. System Design

Products should be designed in conjunction with the manufacturing process and should also take into account the assembly and test processes. A "traceable" manufacturing process that employs strong configuration management is important. The array design should embody a conscious balance between up-front construction costs and later operations and maintenance costs. A site design should be done early to establish the scope of facilities.

8. Configuration Control

Assets should be "self-identifying" in some way, either by network connection, or by RF-ID Tags. Automated inventory management then becomes much easier. Change processes should be planned, with "back-out" plans for critical changes. The team noted both the implementation of homogeneous systems, where efforts are made to keep things the same, and heterogeneous systems, where configurations are allowed to vary. Strong configuration control made either option acceptable.

9. IT Security

IT Security has become a big issue with some of the participants, either because of corporate regulatory restrictions or perceived threats. In either case, a system includes an easily maintained IT infrastructure will enable the monitoring and remediation requirements for IT security.

10. Metrics

In some cases, self-monitoring systems are used which automatically track performance parameters. Other systems execute self-diagnostic tests to assess performance. In either case, the tracking of performance is done on a regular basis. Automation is a requirement to track the performance of the larger systems we studied. Several participants that use self-monitoring systems are able to rapidly identify problems before the customer sees any performance degradation.

11. Source Strategies

JPL should focus on its areas of expertise, and subcontract the rest. We have found that it can take six months to build a supply chain, and two years for it to reach full capacity, and that such capacity enables production rates to implement our largest system in just several years. Affordability will be the limiting factor with production. Integration of the engineering and procurement processes are often done to reduce the time-to-market.

Finally, specifications should leave room for subcontractor innovation. We have identified technology areas in industry that were once only in the realm of larger government funded programs. These include all aspects of a telecommunications system, and even those areas previously unique to deep space communications such as cryogenics systems and precision tracking antennas. For these parts of an array system that are duplicated many times over, it is reasonable to review more what is available from industry.

12. Earned Value Management

Tailor EVM to the needs of the project. Some participants use it, while others do not. EVM should measure the project, not drive it.

V. Conclusion

While the DSN Array Project has made estimates of the cost to implement and subsequently operate and array based network, this study did not attempt to validate those estimates. Industry has suggested that the initial cost to build extensive automation into a system will be much cheaper than adding it afterwards, and that investment into such automation would be returned in the early phases of operation with reduced manual intervention, improved configuration control, just-in-time maintenance, and increased system availability.

We have found that the five main characteristics of the proposed operations concept are valid with respect to industry best practices. Accordingly we advance the challenge to the space communications community to give careful consideration to tailoring their traditional implementation and operations such that;

1. more reliance be put on industry for development of what was once one-off systems
2. operations be centralized
3. automated service requests be used to support science mission users
4. continuous low-level updates to components and software be employed

We feel that these considerations are a pre-requisite for the success of an array-based telecommunications system, and that by doing so science missions may receive much more capability at a greatly reduced relative cost.

Acknowledgments

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