DEEP SPACE NETWORK – PARADIGM CHANGES FOR COST-EFFICIENCY

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ABSTRACT[2,3]

The Deep Space Network (DSN) was established in 1963, to support missions of NASA and its partner agencies into deep space. To meet this objective, the DSN has three international sites (Goldstone, in the USA; Near Canberra, Australia; near Madrid, Spain). Each site is equipped with state-of-the-art, unique equipment, primarily large (34m and 70m diameter) fully steerable antennas, very sensitive front ends (cryogenically cooled, with typical system noise temperatures well below 40 degrees Kelvin) and high-power transmitters (typically, 20 kW continuous Wave).

The DSN performance has been exceptional, from a technical perspective, as demonstrated by the spectacular results from DSN-supported spacecraft throughout the solar system and beyond. However, the performance came with a price, literally - it required a significant staff, 24x7, to operate the DSN and an equally significant staff to maintain the unique equipment.

During the last decade, the DSN has embarked on two paradigm change efforts, leveraging on best-practices available from industry, with the objective of reducing the annual cost for operations and maintenance, while at the same time maintaining (or even improving) technical performance levels. (Improvement could occur for example if the operator/technician errors are reduced).

The first effort is an operations paradigm change. The DSN is already transitioning, in multiple steps, from one-link-per-operator and 24x7 staffing at several control centers to multiple-links-per-operator, controlled from a single 24x7 control point. The second effort is a maintenance *paradigm change, unifying the maintenance practices at the three DSN sites and optimizing maintenance using metrics derived from a common, COTS tool.*

This paper describes these paradigm changes, quantifies the cost reductions, and identifies the careful monitoring to assure that technical performance is maintained.

1. INTRODUCTION

The Deep Space Network (DSN) was established in 1963, to support missions of NASA and its partner agencies into deep space. To meet this objective, the DSN has three international sites, Deep Space Communications Centers, or DSCCs. They are located in Goldstone (near Barstow, USA), Tidbinbilla Reserve (near Canberra, Australia) and Robledo (near Madrid, Spain). Each DSCC is equipped with state-of-the-art, unique equipment, primarily large (34m and 70m diameter) fully steerable antennas, very sensitive front ends (cryogenically cooled, with typical system noise

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[2] © 2016 California Institute of Technology. U.S. Government sponsorship acknowledged.
[3] The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

temperatures well below 40 degrees Kelvin) and high-power transmitters (typically, 20 kW continuous Wave). The DSN configuration is shown in Figure 1.

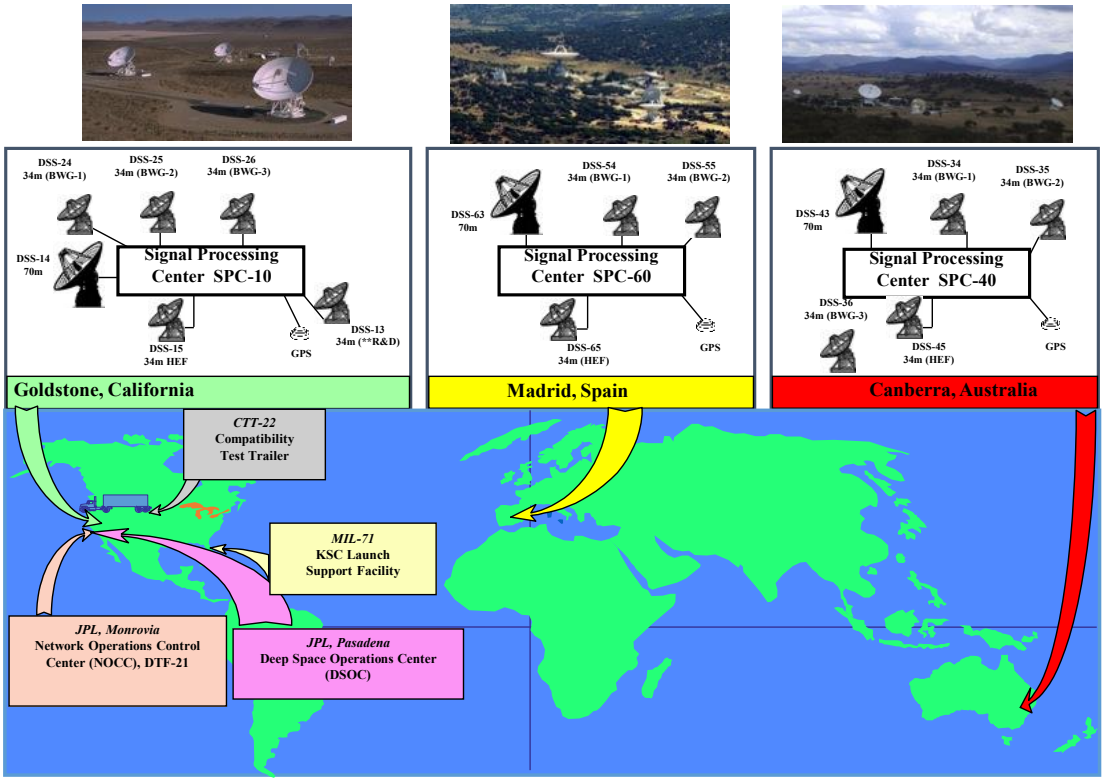

Figure 1 – DSN Configuration

The DSN performance has been exceptional, from a technical perspective, as demonstrated by the spectacular results from DSN-supported spacecraft throughout the solar system and beyond. However, the performance came with a price, literally - it required a significant staff, available 24x7, to operate the DSN and an equally significant staff to maintain the unique equipment.

During the last decade, the DSN has embarked on two paradigm change efforts, leveraging on best-practices methodologies available from industry, with the objective of reducing the annual cost for operations and maintenance, while at the same time maintaining (or even improving) technical performance levels. (Improvement could occur for example if the operator/technician errors are reduced).

The first effort is an operations[4] paradigm change. The DSN is already transitioning, in multiple phases, from one-link-per-operator and 24x7 staffing at several control centers to multiple-links-per-operator, controlled from a single 24x7 control point. This paradigm change leverages technology available in industry for remote control and less-staffed operations.

The second effort is a maintenance paradigm change, unifying the maintenance practices at the DSCCs and optimizing maintenance using metrics derived from a common, commercial tool

[4] In this paper, the term "operations" refers to real-time operations, generally "people operating equipment" locally or remotely, during a tracking pass.

(MAXIMO). Key to this effort is performing the "right" maintenance, e.g. frequency of maintenance, as determine by DSN-wide metrics.

A key challenge, fundamental to both paradigm changes, is that the DSN is (and has been since its founding) a day-in-day-out operational network, with no breaks. At any year, the DSN supports 30-40 missions. It operates 24x7 and any changes have to be incorporated seamlessly without interrupting this operational tempo. Thus, for example, there is just no option of closing the DSN for a month or two to make the changes.

This paper describes these paradigm changes, quantifies the cost reductions and identifies the careful monitoring to assure that technical performance is maintained.

2. OPERATIONS PARADIGM CHANGE

When the DSN was established, in late 1963, the technology for networking and remote control was in its infancy and largely not deployable in the DSN. The DSN thus required a large number of operators, literally one for each rack of equipment. During the mid-80's, the DSN underwent a significant remoting/automation activity, the Mark IVA project [1]. Under this project, the operations for each DSCC was centralized to a single DSCC control room, and most equipment monitor & control functions were remoted to this room. The number of operators was greatly reduced. Rather than one-operator-per-equipment-rack, the operations concept was simplified to one-operator-per-antenna.

So, by 2008, when the operations paradigm change was planned, the DSN staffed four 24x7 control centers, three in the DSCCs and one in JPL[5]. For a typical DSCC with four antennas, the staffing would be approximately 30 Full-Time equivalents (FTEs) – at any time there were 5-6 staffed positions (1 per antenna and a shift supervisor), multiplied by a factor of ~5.3 to convert from a 24x7 position to FTEs. Across the DSN, operations staffing was >100 FTEs.

The DSN supports missions acting as the "link" between the mission and the mission control center(s). As noted later, the term link is the DSN is used widely in that context – inclusive of whatever it takes to connect one mission to its MCC(s). Two key characteristics of DSN operations are:

- Most DSN links are one-antenna-one-spacecraft. There are few exceptions where the link has multiple-antennas-one-spacecraft, e.g. when arraying antennas to improve the effective Gain/Temperature (G/T), a measure of DSN sensitivity. There are also few exceptions where the link has one-antenna-multiple-spacecraft, e.g. when several spacecraft are close enough to each other be in the same antenna beam. For simplicity, this paper will focus on the link being one-antenna-one-spacecraft, which is the most common link.

- Because the DSN generally tracks spacecraft above Geo-Stationary Orbit (GEO) altitudes, most tracking passes are long – typically 4-10 hours. So the pace of setting a link, running a track, and dissolving the link is more measured than for spacecraft at Low-Earth orbits (LEO). At the same time, the tracks themselves tend to be more complex and dynamic, requiring more operator intervention.

[5] The control room at JPL has a monitor role only – it was not designed for a control role, for a variety of technical and programmatic drivers

Figure 2 shows the approach to operations paradigm change. The change was designed as a three-phase effort where after each phase there is a pause to measure performance and assure that DSN performance has not degraded. Fundamentally, there was no change to the link concept. The changes were in how the operators managed the links.

Prior to the change, the general mode of operations was one-operator-one-antenna, also known as one-link-per-operator (1LPO). In the first phase, the control span of an operator was increased to control two links, thus this phase was named two-links-per-operator, or 2LPO. To make 2LPO operational required changes in hardware (operator station reconfiguration), software (modern graphical user interfaces and automation) and procedures (how to assign links to operators, so not to overwhelm some, how to handle emergencies). The 2LPO phase also faced management challenges, transitioning staff to other roles, as the operations staff shrunk. Overall, the 2LPO phase was completed successfully, without adverse impact on data return and mission support.

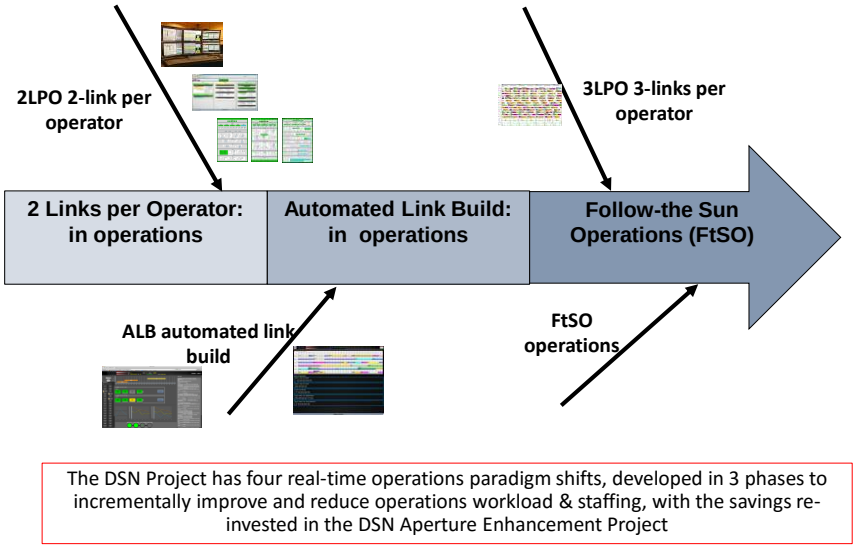

Figure 2 – Components of Operations Paradigm Change

In the next phase, Automated Link Build (ALB) was implemented. The DSN's approach to high availability is to configure a "link" by assembling available components from those operational in the DSCC. This approach allows bypassing any failed components and maximizing the utility of the operational components. Because link building required some sophistication and experience, it was usually assigned to the shift supervisor. In this phase, software was developed to automate the performance of link building. This phase was also completed and is in operations, without adverse impact on data return and mission support.

The first two phases maintained the general independence of the DSCCs. The DSN still had four 24x7 control rooms though with less staff. In the third phase, the DSN created an effective single control point for all the DSN antennas, around the world. There was a major tradeoff on the approach: should there be a single control point (e.g. at JPL), or should there be a rolling control point (e.g. use each of the three DSCC control room, each for 8 hours). The decision was to use the latter approach for two reasons:

- Redundancy. Use of a single control point, for a critical function like the DSN, would have required setting up an alternative, with the associated burdens of staffing, hardware, software, security, training, proficiency, etc, etc. Having control rotate among three DSN sites alleviates the redundancy problem automatically – each DSCC team is a natural backup to the others.

- Follow-the-Sun rotation. The DSN sites are already placed approximately 120 degrees of longitude apart. As a result, day-time work hours rotate smoothly: when the sun sets at Goldstone it rises at Canberra, when it sets at Canberra, it rises at Madrid, when it sets in Madrid, it rise at Goldstone. So having the DSCC control room at each DSCC staffed (essentially) during the normal day shift and operating all the DSN antennas, is practical.

This Follow-the-Sun-Operations (FtSO) concept quickly proved robust and attractive. It has natural redundancy (If one DSCC is not available, the others have operational staff that can step in) and it enables all the DSCCs to work (essentially) single day shift.

Figure 3 shows a graphical representation of the FtSO approach. FtSO is currently in implementation. In addition to the usual hardware and software challenges, FtSO has to deal with the fact that the three DSCC operate with staff from three different nations and respond to three different regulatory environments. As part of this phase, the DSN will also move to three-links-per-operator (3LPO). This phase is on schedule.

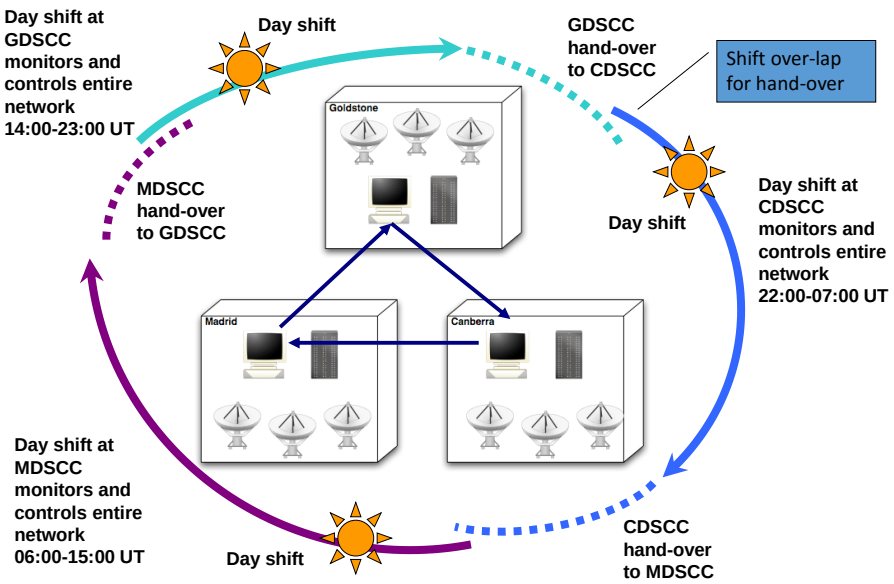

Figure 3 – Follow-the-Sun-Operation (FtSO) concept

So, how does this change in operations paradigm affect cost effectiveness? In R/T operations, the largest cost component is the staffing, so staffing levels are a good approximation to cost. Figure 4 shows the staffing levels. The red line indicates the historical and expected staffing levels, had the paradigm change not occurred. Note that because of the 1LPO concept, the number of operators was projected to increase as additional antennas were being added. Instead, the green line shows the

current path – under the paradigm change, the number of operator is declining, and continues to decline, to approximately 1/3 of the number of operators that have been projected for 2025, if the paradigm change did not occur.

But, as the number of operators decrease, is the DSN less effective? Data return to the mission, the main measure of DSN effectiveness, is largely not impacted, though the increased automation has reduced the number of human errors. The most visible change for the users is that some of the custom treatment (whether needed or not) that was possible before, when a mission had a dedicated operator, is no longer easily accessible. We noticed anecdotal evidence that some inefficient practices have been streamlined as a result, e.g. switching from telephone calls to electronic updates of configuration tables.

Finally, with the control point moving between the DSCCs under FtSO, is a 24x7-staffed position at JPL still needed? We believe that the answer is no and it will be phased out after FtSO is operational.

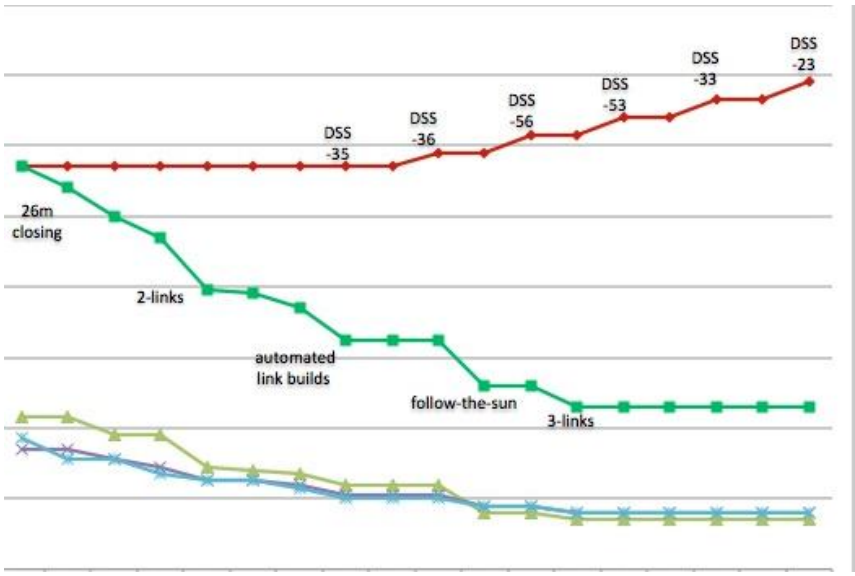

Figure 4 – Relative Staffing Needs for R/T Operations

3. MAINTENANCE PARADIGM CHANGE

DSN maintenance, in principle, is similar to those of any large operational system with significant amount of mechanical systems and electronic systems. As a result, the DSN maintenance approach can leverage on commercial maintenance approaches for such systems.

Typical maintenance methodology consists of a set of Preventive Maintenance (PM) procedures and a set of Corrective Maintenance (CM) procedures used to address any detected failure. Traditional PMs are based on fixed periods, similar to “change the oil in the car every 5000 miles” (or similar fixed measures, such as engine-hours). CMs were managed similar to “fix the leak in the car radiator, if a leak is observed”. All the parameters of the maintenance approach (size and skills of staff, level and location of spares, etc) were adjusted to the PM/CM methodology. As point of reference, the DSN has approximately 900 PMs.

Small changes were made over the years to this maintenance system. The major enabler to a significant change in the maintenance paradigm arrived with the emergence of systems for maintenance management, capturing and analyzing of maintenance data and enabling planning and management. DSN has selected the IBM MAXIMO system, but similar capabilities can be obtained from multiple commercial systems.

Capturing all maintenance work in MAXIMO required a significant start-up effort, but had an almost immediate payback. For the first time, the DSN had a large database that could be mined for significant metrics and trends.

Figure 5 shows a sample of a high-level metric, the Maintenance Ratio (MR). MR is defined as the ratio of PM hours to the sum of PM and CM hours[6]. MR indicates what fraction of the total hours are spent on PM, while 1-MR is the fraction of hours spent on CM. Intuitively, if the MR is "too low", there is "too little" PM activity, while if the MR is "too high", there is "too much" PM activity. Determining the particular values associated with "too low" and "too high" is outside the scope of this paper, but the utility should be clear: this metric allows the maintenance staff and their management to understand, at high-level, the trending in maintenance, over the desired time span (in this case five years). And management can take corrective action where needed. For the DSN, the MR is managed to be within 60% and 80% (values would vary depending on the specific requirements and expectations). When a trend is detected it is analyzed, especially if the low-high boundaries are crossed to understand whether there is an expected reason (e.g. a large number of antennas undergoing significant planned upgrades), or an unexpected worrisome reason (e.g. a design flaw affecting multiple antennas). The data in MAXIMO enabled creating a large variety of standard and custom metrics, and the broad understanding of how the maintenance effort proceeds.

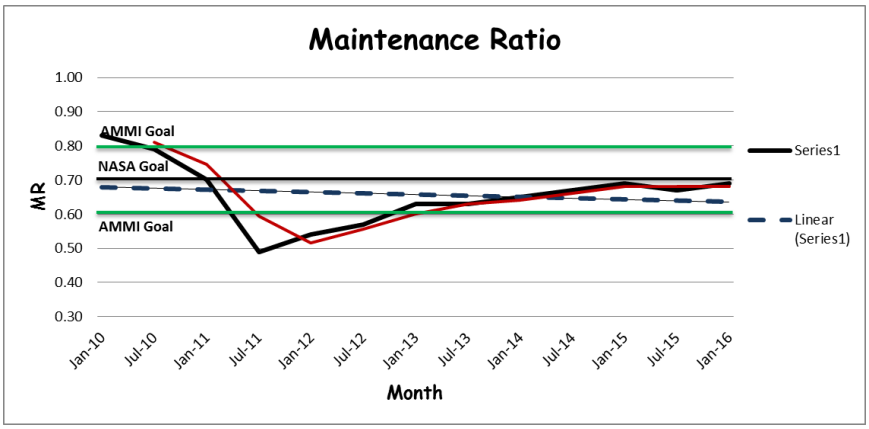

Figure 5 – Sample High-Level Metric – Maintenance Ratio

Figure 6 shows a sample of a more detailed metric. In this case, the analysis narrows the time period (focusing on one year), the scope (CM only) and the level of detail (CM hours by subsystem) for a subset of the assets (comparing just two antennas). This time of analysis enabled more detailed mining of the database to identify causes of failures, relationships between failures – in short, almost any type of analysis that can improve the system's cost-effectiveness.

[6] There is another level of detail involved in the definition of "CM hours" and "PM hours. For the purpose of this paper, a simplified definition of "hours" is the product of the number of maintenance personnel involved multiplied by the time spend performing the maintenance activity

Which leads us to the topic of this paper – how can we improve the maintenance cost efficiency. Having detailed metrics allowed careful adjustment of maintenance parameters, while monitoring the impact of system performance. For the DSN, the key system performance parameter is the DSN availability to missions. The DSN applied (and is applying) three methods to carefully adjust maintenance parameters:

- Switching from "fixed-period maintenance" to "variable-period maintenance". For example, rather than changing an oil filtration system every six months, can we monitor the state of the oil, and change the oil filtration system only when the status of the oil indicates that a change is needed?

- Maintenance based on remote sensing. Rather than sending teams of technicians to check equipment, can we achieve the same performance, by remotely monitoring the equipment? Or even better – remotely monitor the equipment 24x7 (more than technicians do), and alerting only when prescribed thresholds are crossed?

- Reliability-based maintenance. Can we schedule the maintenance based on the failure history of a part, or class of parts? If a certain pump type fails after 13,000-14,000 hours, can we simply replace the pumps after 12,000 hours and avoid the resulting damage?

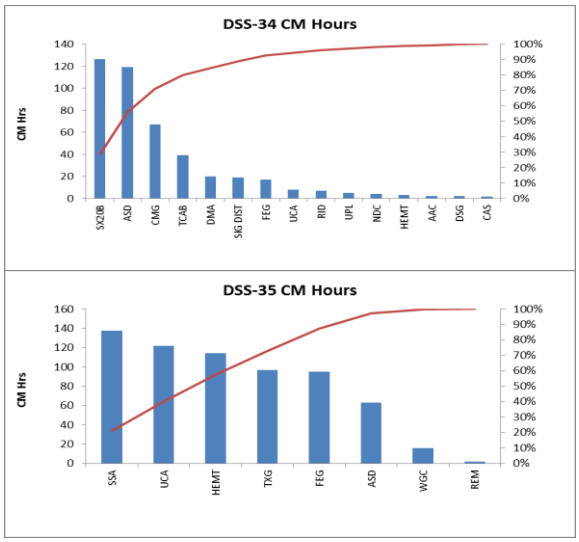

Figure 6 – A Sample Detailed Metric – Corrective Maintenance Hours Analysis

Eventually, these approaches have limited effects. The reason is that the DSN relies on a small number of very high quality instruments. So collecting statistics is limited by the modest sample size. The DSN has thus added an empirical approach: apply a modest reduction in PM frequency and carefully, very carefully, monitor the impact.

Figure 7 shows initial results of the on-going process to get more cost-efficient maintenance. The chart measures the planned number of PM hours for the DSN (for a limited set of PMs) before and after an empirical reduction in preventive maintenance was applied. With these reductions of

approximately 25% in PM hours, there has been no observed deterioration. Studies of longer-term impacts are continuing.

DSN Site	Annual hours[1]		Delta	
	Before	After	Hours	%
Goldstone	10261.8	7437.0	2824.8	27.5%
Canberra	5593.8	4126.9	1466.9	26.2%
Madrid	7362.7	5429.2	1933.5	26.3%
Total	23218.3	16993.1	6225.2	26.8%

Figure 7 – Initial Expected Maintenance Load Reductions

4. SUMMARY AND CONCLUSIONS

In the effort to improve the cost-efficiency of the DSN, there were three key enablers: modern technology provided the ability for staff to increase their span-of-control and leverage machines to reduce needed staffing, modern data collection and metrics tools provided the ability to manage the transition (if you can't measure it, you can't manage it), and management and staff cooperated in moving the organization smoothly along the way (change is never easy, especially if not managed).

While not challenge-free, progress along operations paradigm change and maintenance paradigm change enables the DSN to provide more cost-effective services to its customers.

ACKNOWLEDGEMENT

The authors thank Mike Levesque for his help with the operations paradigm change section, in particular Figures 2-4

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1. Leflang, J. G., "An Overview of the Mark IVA Monitor and Control System", TDA Progress Report 42-88, February 17, 1987