DSN Antenna Array Architectures Based on Future NASA Mission Needs

Bruce E. MacNeal, Douglas S. Abraham and Robert J. Cesarone
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California, 91109-8099, USA
818-393-3331
bruce.e.macneal@jpl.nasa.gov

Abstract—A flexible method of parametric, full life-cycle cost analysis has been combined with data on NASA's future communication needs to estimate the required number and operational dates of new antennas for the Deep Space Network (DSN). The requirements were derived from a subset of missions in the Integrated Mission Set database of NASA's Space Communications Architecture Working Group. Assuming that no new antennas are "constructed", the simulation shows that the DSN is unlikely to meet more than 20% of mission requirements by 2030. Minimum full life-cycle costs result when antennas in the diameter range, 18m-34m, are constructed. Architectures using a mixture of antenna diameters produce a slightly lower full life-cycle cost.

TABLE OF CONTENTS

1. INTRODUCTION.....1
2. IMS DATABASE 1
3. PARAMETRIC COST MODELS.....3
4. ANTENNA PERFORMANCE MODELS 3
5. DSN ARCHITECTURE ANALYSIS TOOL 4
6. RESULTS 5
7. CONCLUSIONS 7
8. ACKNOWLEDGEMENTS 7
9. REFERENCES 7
10. BIOGRAPHIES 7

1. INTRODUCTION

Over the last 50 years NASA's Deep Space Network (DSN) has grown to meet the expanding communications needs of NASA's missions. Results from an assessment of future needs suggest that, over the next 25 years, this trend will continue [1]. As NASA evolves from initial observations of the planets to much higher-fidelity surveys, the need to return more data over long distances will increase dramatically. The DSN may have to support three times as many communications links with downlink data rates two orders of magnitude larger than those supported today. Uplink rates may be two to four orders of magnitude larger.

NASA is addressing this situation in several ways. The introduction of Ka-band (32 GHz) communications, with its higher data capacity, is well under way [2]. Optical laser communication is being investigated. The expansion of antenna collecting area through coherent arrays of ground-based antennas is also being examined [3]. Improvements in error coding, data compression and RF modulation schemes continue to be developed. Finally, improvements in spacecraft communication technology are being pursued.

Future needs for additional antennas will depend on which missions are actually flying. In a previous study, a complex database of future NASA missions was assembled and validated [1]. The database includes specific information on spacecraft communications capabilities and requirements. Here, a new analysis program is used to quantitatively determine the number of new antennas needed to support future missions.

2. IMS DATABASE

NASA's Space Communications Architecture Working Group has recently developed an Integrated Mission Set (IMS), containing their best estimate of the future missions through 2030. The IMS was developed from mission databases at the Goddard Space Flight Center and the Jet Propulsion Laboratory that were originally based on NASA's plans, roadmaps and other official mission sets. The version of the IMS used for this study has been adjusted to account for more recent Constellation Program requirements (lunar and Martian manned missions) and mission cancellations proposed in the FY 07 NASA budget. It does not take into account the latest release of the new Agency Mission Planning Model (5/06). Both CAT A and CAT B missions[4] were included in this study; missions below GEO Earth orbit were not included.

1

[1] 1-4244-0525-4/07/$20.00 ©2007 IEEE
[2] IEEAC paper#1386, Version 4, Updated 2006:12:13
[3] The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

1

[4] NASA distinguishes between missions less than two million kilometer from the earth (CAT A) and those outside this limit (CAT B).

The ground antennas needed to support the communication requirements of each mission in the IMS were computed. Specifically, the downlink figure of merit, *G/T*, was computed based on frequencies, data rates, spacecraft transmitter characteristics and Earth-spacecraft separation. Here, *G* is the gain of the ground antenna, and *T* is the system noise temperature. Data from the IMS database was also used to compute the needed uplink *EIRP* (Effective Isotropic Radiated Power)[5].

To simulate the time-evolution of requirements, the IMS data were divided into five-year time blocks. In each block (2005-2030) the operational missions were determined. The required *G/T* and *EIRP* for each mission were then compiled separately for each microwave band.

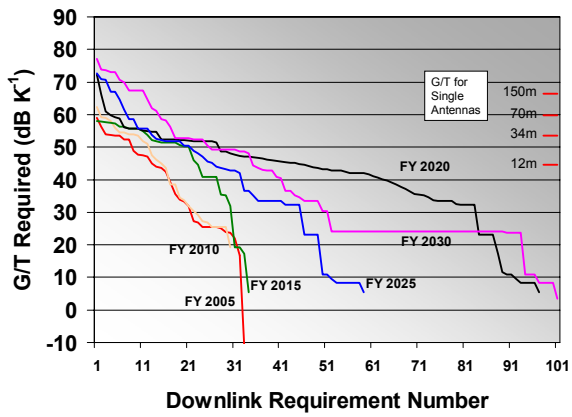


Figure 1: Required downlink *G/T* for all IMS missions in descending order by time block. *G/T* for individual antennas of different diameters is also shown.

Figure 1 shows the downlink *G/T* requirements of all IMS missions in descending order. Consider, for example, the set for the FY 05 time block. The data indicate that the most demanding mission requires a *G/T* value of 58 dBK^{-1} (slightly lower than the *G/T* of a 70m antenna in X-band). The data also show that there are 33 communication downlinks requiring service in this time block. For reference, *G/T* values in X-band for individual antennas with other diameters are also shown. Between FY 2005 and FY 2030, the *G/T* values for the most demanding individual missions increase from 58 dBK^{-1} to 77 dBK^{-1} ; nearly a factor of 100. At the same time, the number of communication links needing service increases from 31 to 101; more than a factor of three. In any given time block, the range of *G/T* values varies by some eight orders of magnitude. Most of the missions can be serviced with small antennas (below 12m diameter); but some will require unrealistically large antennas, more than 150m in diameter.

[5] Navigation, emergency communications and radar science applications will certainly impose additional requirements on the future DSN. Such requirements are not addressed in this work.

A similar graph of the required uplink *EIRP* is shown in Figure 2. As with downlink, the largest required *EIRP* values increase dramatically over the study period; and the number of individual missions requiring service increases, again by almost a factor of three. All but a few of the missions can be handled by individual antennas of 70m diameter or less.

A *Design Mission Set* (DMS) was selected from the IMS database to represent a moderately stressing but realistic design case. The set was constructed by first including all missions operating at the Moon and Mars in a given time block. One third of the remaining missions (not at Mars or the Moon), chosen at random, were also included. Each of the three DSN complexes must service the missions in this set, the DMS. However, at any given time only about 12/33 of the missions in the DMS require service (historical factor). Since the *G/T* and *EIRP* requirements vary widely, 12/33 of the missions in the DMS were selected at random (with equal probability). The process was repeated 100 times, and the results were processed to determine average results (number of antennas needed, cost, etc.) and uncertainties.

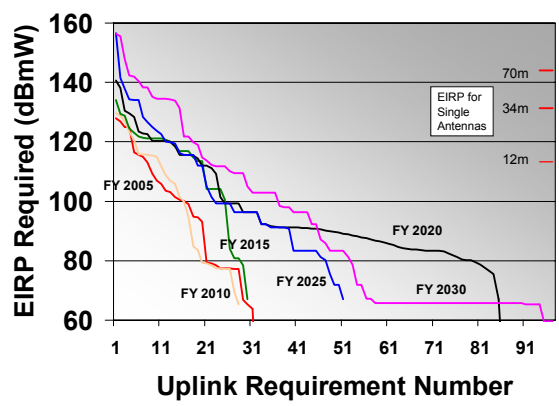


Figure 2: Required uplink *EIRP* for all IMS missions in descending order by time block. *EIRP* for individual antennas of different diameters is also shown.

The current DSN provides communications in three microwave frequency bands: S-, X- and K32-band. The operational uplink and downlink frequencies for these bands are shown in Table 1. Two additional bands may be needed in the future to support NASA's manned exploration programs[6]: K26- (near Earth) and K38-band (deep space).

Figure 3 shows the average *G/T* needed by a single complex to service the DMS, by microwave band. As can be seen, a large majority of the *G/T* needs in FY 2030 are in the K32 and K38 bands due to increasing use of these bands by robotic planetary missions (K32) and deep space manned missions (K38). A similar situation pertains to uplink communications, where steady growth in X-band and K38

[6] Precise frequencies are not known at this time, and are subject to change.

communications is evident.

Band	Downlink Freq (MHz)	Uplink Freq (MHz)[7]
S	2295	2115
X	8420	7145
K26	26000	28000
K32	32000	34300
K38	38000	40000

Table 1: Downlink and uplink frequencies for the five microwave bands considered in this study.

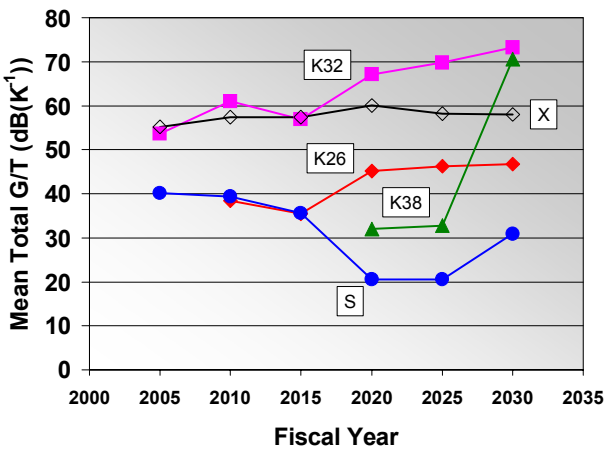


Figure 3: Average total *G/T* requirements for the DMS by band and time block.

3. Parametric Cost Models

Detailed parametric models were constructed in order to assess the full life-cycle cost of meeting future communications needs. Models were developed for the individual cost areas listed below. Unless noted otherwise, "bottom-up" costing methods[8] were used. The two areas most likely to have a large impact on overall cost are antenna mechanical structures, and antenna maintenance. Costs for these areas were estimated from independent studies and informal quotes from established vendors. Principal parametric dependencies are indicated in {*braces*}.

- Management, Mission Assurance (QA), Non-Recurring Engineering
- Construction
  - Antennas {*number of antennas*}
    - Mechanical (several antenna vendors, one independent cost study) {*antenna diameter*}
      - RF and Microwave Electronics {*antenna diameter →RF Power*}
      - Signal Processing
      - Support Facilities
      - Monitor and Control
      - Ground Communications
      - Frequency and Timing Standards
      - Integration and Test
    - Facilities (buildings, roads, utilities, fences, etc.)
- Maintenance {*antenna number*}
  - Antennas (independent reliability study and cost estimates) {*antenna diameter*}
  - Facilities {*antenna number*}
- Operations
  - Central Operations
    - Management, Contracts, Licensing, Ground Comm
    - Customer Support
    - Real-Time Operations (24/7)
    - Logistics
  - Complex Operations
    - Management
    - "Rover" Support Teams
    - Safety
    - Logistics
    - Complex Safety
    - Complex Engineering

The largest single source of uncertainty is the cost of the antenna mechanical structure.

	Diameter (m)				
Band	6	12	18	24	34
S	24.95	30.98	34.50	37.00	40.03
X	38.42	44.44	47.97	50.47	53.50
K26	41.54	47.56	51.09	53.59	56.62
K32	43.34	49.37	52.89	55.40	58.43
K38	44.84	50.86	54.39	56.89	59.92

Table 2: Downlink performance, *G/T* (dBK^{-1}), of new antennas by diameter and band for an elevation angle of 20 degrees and 90% weather.

4. Antenna Performance Models

The *G/T* values used in this study (Table 2) were derived from the performance of existing antennas, and then interpolated to different microwave bands and antenna diameters. An elevation angle of 20 degrees and a

[7] The assignment of the uplink band associated with 26GHz is not yet certain. 28GHz is assumed here.

[8] Costs of individual items are estimated based on experience, scaling of historical costs and current technology capabilities. Active surface control is not considered.

cumulative weather parameter of 90% were assumed[9]. These average results do not represent the performance of any particular existing antenna.

Table 3 shows the average *EIRP* by microwave band for various antenna sizes when operating at the maximum power allowed by safety limits.

	Diameter (m)				
	6	12	18	24	34
	Maximum Power (Watts)				
Band	872	3,488	7,848	13,952	28,000
S	101.29	113.34	120.39	125.39	131.44
X	112.24	124.29	131.34	136.34	142.39
K26	120.51	132.55	139.60	144.60	150.66
K32	122.31	134.36	141.41	146.41	152.46
K38	123.81	135.85	142.90	147.90	153.96

Table 3: Uplink performance, *EIRP* (dBmW), of new antennas by diameter and band for an elevation angle of 20 degrees and 90% weather.

5. DSN ARCHITECTURE ANALYSIS TOOL

The DSN Architecture Analysis Tool was built using Microsoft EXCEL to quickly analyze various architecture options. A schematic diagram of the algorithms in this tool is shown in Figure 4. The tool represents the assets (antennas, complexes, central facilities, etc.) of the future DSN within time blocks of five-year duration covering the years 2005 to 2030. Each asset may have a one-time construction cost, recurring annual maintenance costs, and uplink and downlink microwave performance. New assets may be constructed; existing assets may be decommissioned. Within each block, the total cost of all assets constructed during the block is computed, as is the annual operations and maintenance (O&M) cost of operational assets. Assets constructed during a block and assets decommissioned during a block do not have O&M costs. A sequence of time blocks represents one possible *scenario* for the evolution of the DSN. Performance may be calculated for individual antennas or for arbitrary combinations of antennas in multiple downlink arrays[10].

The tool begins analysis with a preface. During the preface, predetermined cost and performance data is compressed into small binary files for quick access. A baseline time block sequence is also established, in which the operation (and possible decommissioning) of existing DSN assets is described. For this study, it is assumed that the current 70m and 26m antennas are decommissioned in FY 2015. Existing 34m antennas remain operational throughout the study period.

For each time block in the base sequence, 12% of the missions operating in the block are selected at random. The tool then determines if existing antennas can meet the requirements. The needed band and *G/T* are automatically matched with operational antennas in each complex[11]. Two spacecraft are allowed in the same antenna beam if they reside in the same sky location (Mars, for example). These spacecraft may communicate in different bands, provided the ground antennas have appropriate capability. Combining of antennas into downlink arrays is allowed (optionally). The uplink algorithm is similar, but does not allow uplink arraying[12].

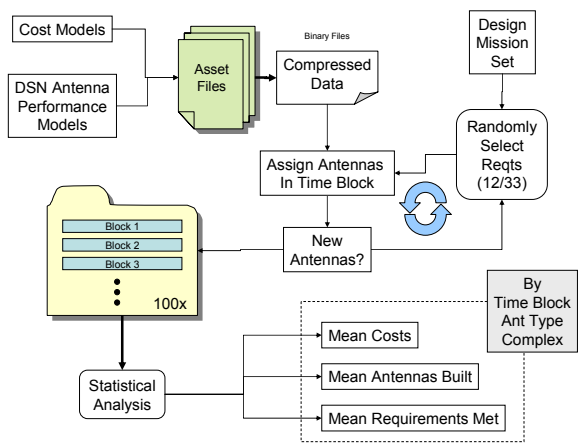


Figure 4: Schematic diagram of the DSN Architecture Analysis Tool.

If all existing antennas are assigned and some requirements are left unmet, the algorithm (optionally) constructs new antennas. Antennas are constructed in the previous time block so that they are operational in the current time block. O&M costs are added for new assets in the present and future time blocks. New antennas are added until all requirements are met.

Once all time blocks in the base sequence have been processed, a single possible scenario for the DSN is obtained. Since the scenario is based on random selection of missions, the process is repeated one hundred times in

4

[9] The tool allows any choice of elevation angle and cumulative weather parameter. These values are typical.

[10] Uplink arraying is currently being investigated; but is not considered here.

4

[11] The three DSN complexes are treated separately. Initially, they do not have the same antenna assets.

[12] Note that this algorithm is not a "scheduling" algorithm. The actual available antenna time and downlink time required by the missions are buried in the 12/33 assumption, and are not explicitly considered.

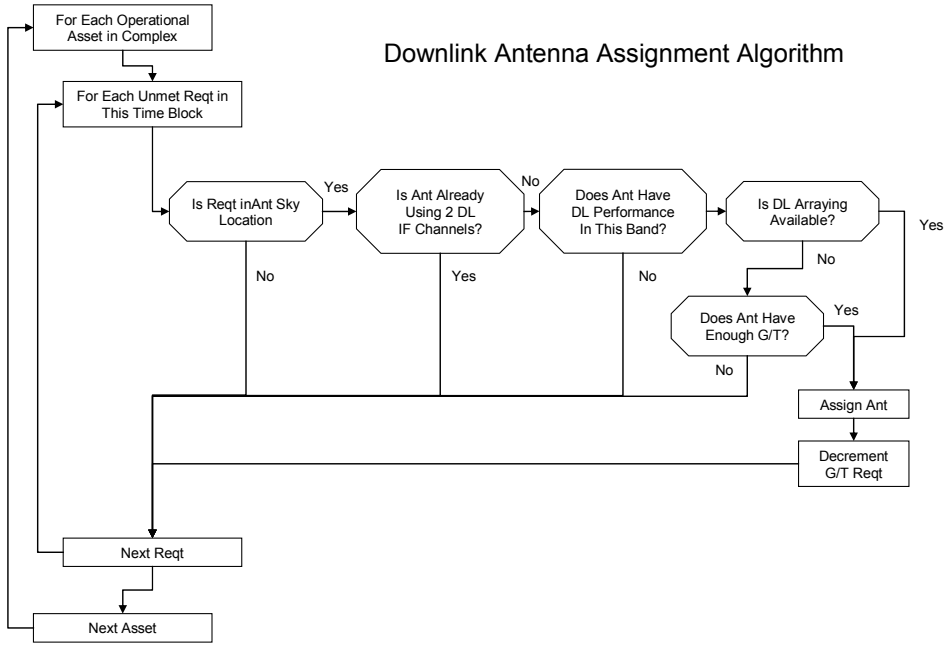


Figure 5: Logical flow diagram of the Antenna Assignment Algorithm.

order to determine an "average" *architecture* based on the entire set of requirements and the construction rules. Average numbers of antennas by type are then determined, as are average costs.

New antennas may be constructed with different characteristics, depending on need. Possible diameters are: 6, 12, 18, 24, 34, 70, 90 and 150m[13]. Downlink S-band (only) receivers are available. Downlink dual-band receivers—X-K26-K32 or X-K32-K38—are also available[14]. Uplink receivers in the S, K26, K32 and K38 bands are available.

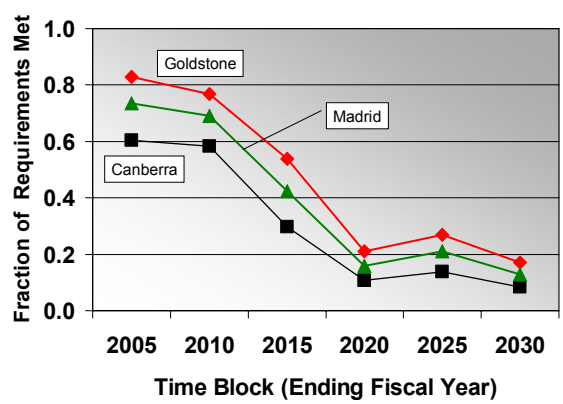
Figure 5 shows the logic flow diagram for the downlink antenna assignment algorithm. The algorithm matches operational antennas with unmet requirements, taking into account sky location, the individual band capabilities of each antenna, and (optionally) downlinks arraying. A similar algorithm is applied to uplink requirements (without uplink arraying.

6. RESULTS

Different DSN architectures are generated by assuming different rules for antenna construction. Many scenarios are possible; three are considered here

No New Antennas

Under these construction rules, DMS requirements are imposed on the DSN, but no new antennas are constructed. The resulting average fraction of uplink and downlink requirements met is shown in Figure 6 as a function of time. The Goldstone complex currently has more antennas than the other complexes, so it will meet more of the future mission requirements. It is clear, though, that no complex will meet more than 20% of the anticipated mission requirements by 2030 if no new antennas are constructed.



.

Figure 6: Average fraction of DMS downlink requirements met assuming no new construction as a function of time for the three existing DSN complexes.

It may seem odd that none of the DSN complexes meet all of the requirements in the current time block (ending FY 05). The figure shows that the Goldstone Complex meets a little more than 80% of its requirements, while the other

5

[13] It is likely that large, efficient K-band antennas (diameter > 70M) are not feasible at reasonable cost. The possibility is included here for completeness.

[14] K-band receivers may be capable of bridging two of the needed K-bands: either K26-K32 or K32-K38. Broad-band receivers bridging all three frequency ranges are probably not feasible.

complexes meet less. Yet, the DSN actually does meet all of its current requirements. Recall that the antenna assignment algorithm used in this study is not actually a scheduling algorithm. It takes no advantage of actual mission timing, synergy or negotiated compromises. The DSN meets all of its commitments through intelligent scheduling; the algorithm used here is a pessimistic approximation of that process. In any case, it is clear that the DSN cannot meet its requirements in the future without additional antennas.

All 34m Diameter Antennas With Downlink Arraying

Under these construction rules, existing antennas are supplemented with new, 34m antennas for uplink and downlink. Downlink arraying of antennas is allowed, beginning in 2015. Figure 7 shows the average number of new 34m antennas needed (for all three complexes) to meet all requirements. A total of 342 antennas would be constructed. The most numerous antenna type is the X-K32-K38 downlink antenna used in large arrays to meet the most demanding downlink requirements. Two-hundred and fifty of these antennas are needed by 2030. The next most numerous antennas are uplink antennas: X-K32-K38 and S-band. Since most missions do not require a large, 34m antenna to meet uplink requirements (see Figure 1), many of the new 34m antennas are used inefficiently; a much smaller antenna would be adequate.

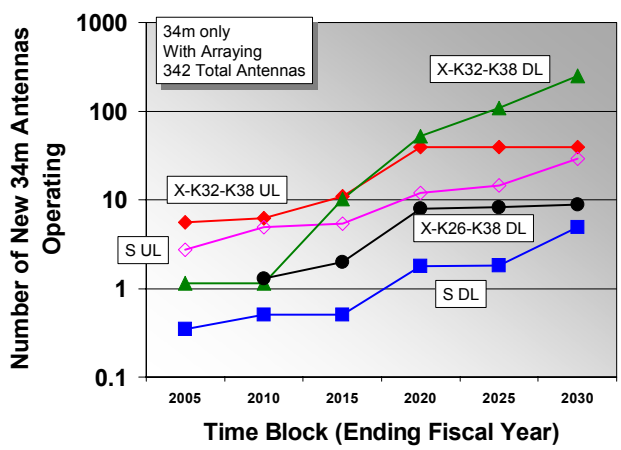


Figure 7: Average number of new 34m antennas needed to meet DMS requirements as a function of time block, by antenna type.

The situation is somewhat different if downlink arraying is not allowed. Only 92 antennas would be constructed; BUT the resulting DSN would not meet all requirements. 95% of uplink requirements would be met, but only 80% of downlink requirements would be met. Individual 34m downlink antennas cannot, by themselves, meet many of the downlink requirements (see Figure 1). If requirements cannot be met, no new antennas are constructed; so the total number of antennas built is much lower, as is the total cost.

Cost as a Function of Antenna Diameter with Arraying

Costs might be lowered by selecting antennas with different diameters. In this approach, all new antennas have the same diameter, D_{new}. Figure 8 shows the average relative construction cost as a function of D_{new}.[15] The dashed curves represent the cost uncertainty due to random selection of mission requirements. A 10% excursion around the minimum at D_{new} = 12m is also shown. Antennas smaller than 12m diameter show sharply increased construction costs because electronics and signal processing costs must be duplicated for each antenna, even though the resulting collecting area and signal are small. Construction costs increase above D_{new} = 12m because larger antennas are relatively more expensive per unit collecting area.

The result is somewhat different when O&M costs are included. The total average relative cost shown in Figure 9 (♦) is just the average relative construction cost (Figure 8) PLUS twenty-five times the annual average relative maintenance cost in 2030[16]. Cost contributions from construction and O&M are roughly equal. As can be seen, the minimum in the cost curve is broader, and moves slightly to the right, to larger antenna diameters. While larger antennas are less efficient to construct, they are more efficient to maintain (per unit area). As a result, total average costs are within 10% of the same value in the range 18m-34m. For reference, the 12m diameter antenna case corresponds to about 1900 new antennas spread among the three complexes.

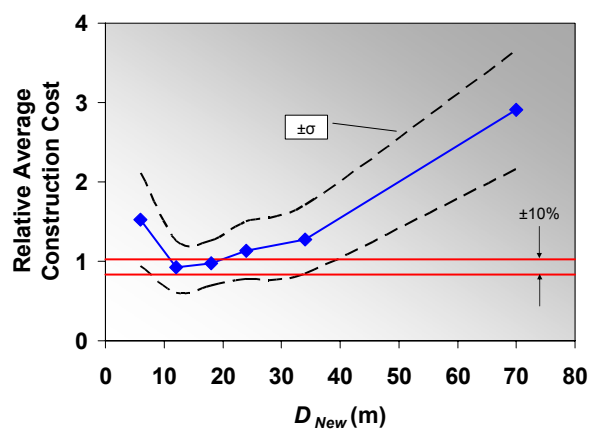


Figure 8: Average relative construction cost for different antenna diameters, D_{new}. The dashed curves represent the standard deviation in cost due to random selection of DMS mission requirements.

[15] Since actual costs are still uncertain and confidential, cost results are reported in relative terms.

[16] The maintenance cost in the last time block is used because is represents maintenance costs of the DSN in its complete form.

The Effect of Mixing Antenna Diameters

The construction rules were changed slightly to allow for a mixture of antenna diameters. The algorithm first attempts to meet each downlink requirement with an individual antennas with diameters up to some maximum value, D_{max}. If the downlink requirements cannot be met with a single antenna, then arrayed antennas of diameter D_{max} are added. In this way, links with small *G/T* requirements are satisfied by single, small antennas while greater numbers of large arrayed antennas are used to meet the more demanding requirements. Individual uplink antennas up to 34m diameter are allowed.

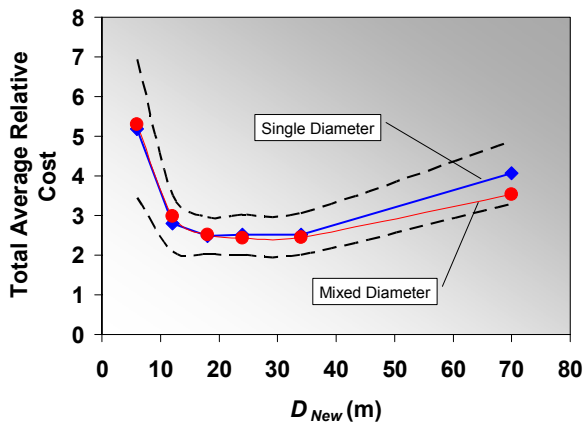


Figure 9: Total average relative full life-cycle cost, including construction and 25 years of maintenance, as a function of new antenna diameter. The dashed curves represent the standard deviation in cost due to random selection of DMS mission requirements.

The resulting total average relative costs for mixed antenna diameters are also shown in Figure 9 (●). As can be seen, the costs for mixed antenna architectures are only slightly lower than for architectures with a single antenna diameter (well within the uncertainty produced by random selection of requirements). The advantage for mixed arrays increases as the maximum allowed diameter increases; but even in the most extreme case considered, 70m antennas, the advantage is still relatively small.

The advantage of using mixed-diameter arrays is small because most new antennas are built to meet the large *G/T* requirements of a few missions. Even if small antennas are available, they cannot meet these requirements by themselves, so large numbers of the largest available antenna are constructed and arrayed. Though the use of smaller antennas to meet the small *G/T* needs of most missions is efficient, this option has little effect on overall cost because costs are dominated by large numbers of arrayed antennas. The simple construction algorithm used in this case may also affect the results; a more intelligent approach to designing mixed arrays may produce a larger advantage.

7. CONCLUSIONS

The Design Mission Set, derived from the SCAWG IMS Database, was used to estimate the number and type of new antennas that may be needed to meet future NASA mission communications needs. Missions, selected at random from the database, were used by the DSN Architecture Analysis Tool to simulate future DSN architectures. Different combinations of new antennas were generated by assuming different construction rules.

If no new antennas are constructed, it is clear that the DSN will meet only a small fraction of future needs by 2030. Downlink arraying is clearly needed to meet the largest *G/T* requirements in this time frame. Most of the new antennas are needed in the K32 and K38 microwave bands to meet the needs of deep space robotic and manned missions.

Antennas with diameters 18m-34m seem to offer the lowest full life-cycle cost (construction plus 25 years of maintenance), though the cost differences are well within the cost uncertainty associated with mission selection. A mix of different antenna diameters should result in lower costs.

8. ACKNOWLEDGEMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

9. REFERENCES

[1] D. S. Abraham, "Future Mission Trends and Their Implications for the Deep Space Network". AIAA Space 2006 Conference, Sept 19-21, 2006, San Jose, California.

[2] Weber, W. J., Cesarone, R. J., Abraham, D. S., Doms, P. E., Doyle, R. J., Edwards, C. D., Hooke, A. J., Lesh, J. R. and Miller, R. B., "Transforming the Deep Space Network into an Interplanetary Network," 2003 International Astronautical Congress, IAC-03-U.4.01, Bremen, Germany, September 29-October 2, 2003

[3] Cesarone, R. J. and Abraham, D. S., "Long-range Planning for the Deep Space Network," AIAA Space 2003 Conference, paper AIAA-2003-6416, AIAA, Long Beach, California, September 23-25, 2003

10. BIOGRAPHIES

Dr. MacNeal received his Bachelor of Arts Degree in Physics in 1974 from Pomona College in Claremont

California, Phi Beta Kappa. Subsequently, he received his M.S. and Ph.D. degrees in Applied Physics in 1977 and 1979 from the California Institute of Technology in Pasadena California. He has conducted research in magnetics, infrared sensors and electromagnetic engineering software for Rockwell International, Litton Data Systems, and MSC Software. He is currently a principal systems engineer at the Jet Propulsion Laboratory in Pasadena, CA.

Doug Abraham is a Senior Engineer within the Architecture and Strategic Planning Office of JPL's Interplanetary Network Directorate. His responsibilities include forecasting future mission requirements and trends, assessing their implications for Deep Space Network evolution, and assisting in the development of the roadmaps and plans needed to guide this evolution. Prior to his current assignment, Doug worked on the Galileo, Ulysses, and Cassini missions, as well as a number of pre-project activities. He began his career as a graduate student intern in the International Space Station Program Office (1988). Doug graduated Magna Cum Laude from Texas A&M University in Physics (1986) and earned an M.S. in Technology and Science Policy, with specialization in technology assessment and electrical engineering, from Georgia Tech (1990).

Robert Cesarone is with the Jet Propulsion Laboratory, California Institute of Technology. He is currently involved in program management, strategy development and long range planning. His activities specifically involve telecommunications and mission operations, including development of architectural options for the Deep Space Network, NASA's network for tracking interplanetary spacecraft. He has held his present position since September 1991 and has been employed at JPL since 1977. Prior to his current assignment he has held a number of positions within the Voyager Navigation Team, in particular that of lead trajectory and maneuver engineer for the Voyager 2 flybys of Uranus and Neptune. Prior to his arrival at JPL, he attended the University of Illinois, where he received a B. S. in Mathematics in 1975 and an M. S. in Aeronautical and Astronautical Engineering in 1977. Mr. Cesarone has authored 50 technical and popular articles covering the Voyager Mission, trajectory design, gravity-assist and space navigation and telecommunications. He is an associate fellow of the American Institute of Aeronautics and Astronautics, a member of the World Space Foundation and a recipient of the NASA Exceptional Service Medal.