Optimizing the Antenna Size for the Deep Space Network Array

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JPL, in conjunction with NASA Headquarters (Code SE), is conducting a feasibility study for a Deep Space Network Array. The DSN Array will have a gain-to-noise temperature ratio (G/T) that is equivalent to ten times the G/T of the 70-m antenna subnet at ∼8.4 GHz (X-band) by arraying a large number of small antennas. (At ∼32 GHz (Ka-band), the G/T is four times higher!). Similarly, the DSN Array achieves the flux density of several 20-kW X-band transmitters by arraying smaller transmitters on smaller antennas. The life-cycle cost (LCC) of the DSN Array, including development, installation, and operations, will vary depending on the antenna size.

This article updates prior work by Weinreb and MacNeal on optimizing the antenna size for the downlink, and adds a similar study for the uplink antennas. The basic methodology is to compute the antenna-related LCC as a function of antenna diameter and select the antenna diameters that minimize the LCC. The antenna-related LCC is approximated by the sum of the recurring engineering (RE) cost for the antenna-related components and the operations and maintenance (O&M) costs for the antenna part of the DSN Array for 20 years, assuming that the RE is amortized over 20 years as well. To compute the full DSN Array LCC, one has to add the non-recurring engineering (NRE) and the non-antenna RE and O&M costs. The key result is that, for downlink, the selected antenna size is 12 m and, for uplink, the selected antenna size is around 34 m.

I. Introduction

JPL, in conjunction with NASA Headquarters (Code SE), is conducting a feasibility study for a Deep Space Network Array.[6] The DSN Array will have a gain-to-noise temperature ratio (G/T) that is

[1] Microwave Array Project Office.

[2] Tracking Systems and Applications Section.

[3] Communications Ground Systems Section.

[4] Microwave Systems Section.

[5] Mission Systems Concepts Section.

[6] D. Bagri and J. Statman, *Concept of Operations for the Deep Space Array-Based Network*, Rev C, 900-001 (internal document), Jet Propulsion Laboratory, Pasadena, California, June 18, 2004.

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equivalent to ten times the G/T of the 70-m antenna subnet at ~8.4 GHz (X-band) by arraying a large number of small antennas. (At ~32 GHz (Ka-band), the G/T is four times higher!). Similarly, the DSN Array achieves the flux density of several 20-kW X-band transmitters by arraying smaller transmitters on smaller antennas. The life-cycle-cost (LCC) of the DSN Array, including development, installation, and operations, will vary depending on the antenna size.

This article updates prior work by Weinreb[7] and MacNeal [1] on optimizing the antenna size for the downlink, and adds a similar study for the uplink antennas.

The basic methodology of this article is to compute the antenna-related LCC as a function of antenna diameter (as shown in Fig. 1) and select the antenna diameters that minimize the LCC. The antenna-related LCC is approximated by the sum of the recurring engineering (RE) cost for the antenna-related components and the operations and maintenance (O&M) costs for the antenna part of the DSN Array for 20 years, assuming that the RE is amortized over 20 years as well. To compute the full DSN Array LCC, one has to add the non-recurring engineering (NRE) and the non-antenna RE and O&M costs.

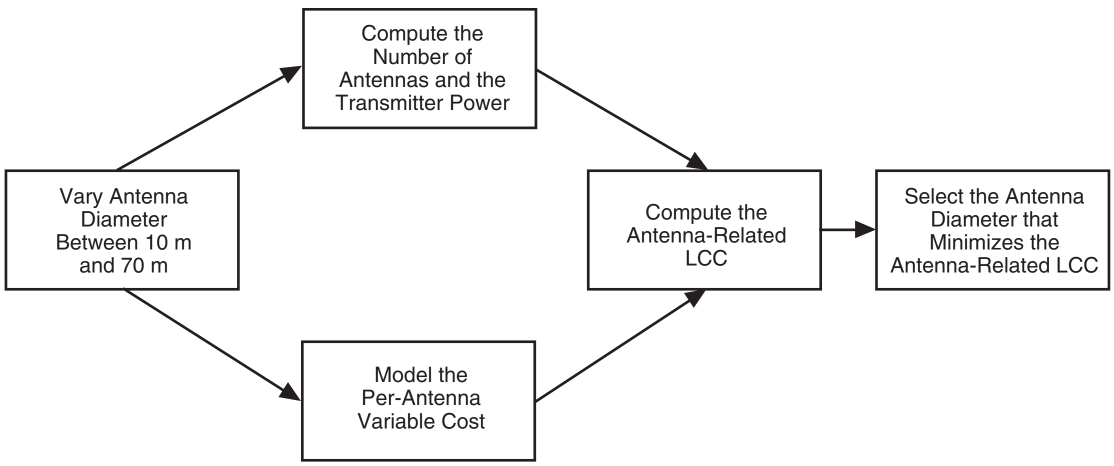

Fig. 1. Study methodology.

II. Models for the Cost Components

To conduct the study, we identified 11 antenna-related LCC components. The components are listed below, along with the model of the dependence between their per-antenna cost and the antenna diameter.

(1) *Power and foundation.* These are the costs of the electrical substations, switching equipment, power distribution circuits, and antenna foundation. The per-antenna costs are identical for uplink and downlink antennas. For a 10-m antenna, the per-antenna costs are $2K ($2,000) for power and $20K for the foundation, and they are proportional to the square of the antenna diameter.

(2) *Frequency and timing signals (FTS).* This is the cost of distributing the frequency references and timing signals from a single source to the antennas, including trenching, fiber-optic distribution, and signal stabilization. The per-antenna cost is the same for uplink and downlink antennas, $10K, and is invariant with the antenna diameter.

[7] S. Weinreb, "Optimum Antenna Diameter for an Array of Hydroformed Antennas," JPL Interoffice Memorandum (internal document), Jet Propulsion Laboratory, Pasadena, California, January 5, 2003.

(3) *Liquid nitrogen (N_2), water, and TV.* These are the costs for distribution of liquid nitrogen, water for fire protection, and surveillance TV. The cost is the same for uplink and downlink, \$2K for N_2 distribution, \$1.5K for water for fire protection, and \$0.5K for TV surveillance, invariant with the antenna diameter.

(4) *Heating, ventilation, and air conditioning (HVAC).* This is the cost of distributing (and generating, if required) the heating, ventilation, and air conditioning needed by the antennas. The per-antenna cost for uplink is \$375K (driven by the chilled-water requirements), and for downlink it is \$7K, invariant with the antenna diameter. Additional savings may be achieved by using the same chilled-water plant to supply multiple antennas. Also, the modeling here is based on water-cooled transmitters. At low power levels, there are potential cost savings by switching to air-cooled or even solid-state transmitters.

(5) *Roads and trenching.* This is the cost of the secondary/local end roads from main site roads to the individual antennas and of the trenching for cables. The cost is the same for uplink and downlink antennas, \$5K for roads and \$5K for trenching, invariant with the antenna diameter.

(6) *Antenna mechanical.* This is the cost of the stationary and moving parts of the antenna, including the control mechanisms. We have modeled the per-antenna cost as proportional to $d^{2.7}$, where d is the antenna diameter. The cost for uplink antennas is modeled as 90 percent of the cost of downlink antennas of the same diameter. This is because the uplink antennas must meet the same phase center stability requirements, but more permissive requirements for surface accuracy and pointing accuracy, as the downlink antennas.

(7) *Antenna feed/low-noise amplifier (LNA)/electronics.* This is the cost of the feed system, low-noise amplifiers, and downconversion to intermediate frequency (IF). The per-antenna cost is \$100K for downlink and \$70K for uplink, invariant of the antenna diameter. The unit difference is driven by the fact that the unit for the uplink antenna does not require Ka-band capability and may use less sensitive equipment.

(8) *Transmitter.* This is the cost of the transmitter subsystem, including the power amplifier, specialized power (e.g., motor generator), and heat exchanger. We have assumed that per-antenna flux density is kept constant (i.e., P_T/d^2 is constant, where P_T is the power of each transmitter and d is the antenna diameter). The cost of the transmitter system in millions of dollars (\$M) is modeled as $0.1 + 0.3\sqrt{P}$, where P is the transmitter power in kilowatts.

(9) *Arraying equipment.* This is the cost of the correlation and combining equipment to create an arrayed signal. The per-antenna cost for downlink is \$20K, and for the uplink it is 100K, invariant with antenna diameter. The per-antenna uplink cost is higher because of the need to accommodate additional function (radar cross-correlation and phase control) and the lower production volume. There is additional uplink cost for the radar antenna that is not included here because it is independent of the antenna diameter.

(10) *O&M—mechanical.* This is the cost of O&M for the mechanical parts of the system. We have modeled the *total* cost for downlink as 14 full-time equivalents (FTEs) plus \$1M, based on the Ball study.[8] For the uplink, the model for the total cost (incremental) is 3 FTEs plus \$0.5M.

(11) *O&M—microwave and electronics.* This is the cost of O&M for the microwave and electronic parts of the system. We have modeled the *total* cost for downlink as 10 FTEs plus \$1M, based on the Ball study. For the uplink, the model for the total cost (incremental) is 6 FTEs plus \$0.5M.

[8] *Executive Management Board (EMB) Review*, (internal document), Jet Propulsion Laboratory, Pasadena, California, June 2004.

Figure 2 shows the normalized variation in these cost components with the antenna diameter. The Appendix shows the actual values. To validate the costs, we have matched them with various quotes, primarily those from the previous cost study [1], and the Ball System reliability, maintainability, availability (RMA) study.[9]

III. Downlink and Uplink Cost Models

The total antenna-related LCC for the downlink is shown in Fig. 3. Additional modeling assumptions were as follows:

(1) G/T is derived assuming that antenna gain (G) is proportional to d^2 and antenna system noise temperature (T) is fixed.

(2) There is modest (∼0.5 dB) arraying loss. To get the required G/T, we add 12 percent more antennas.

The antenna-related LCC for the uplink is shown in Fig. 4. Additional modeling assumptions were as follows:

(1) The overall flux density is that equivalent to having four 28-kW transmitters on four 34-m antennas. At X-band, 28 kW on a 34-m antenna is the level that can be radiated safely without coordination. For other antenna diameters, the per-antenna flux density is kept constant (i.e., P_T/d^2 is constant, where P_T is the power of each transmitter and d is the antenna diameter), maintaining uplink operations without coordination.

(2) There is moderate (∼1.0 dB) arraying loss. To get the required flux density, we add 25 percent more antennas.

(3) Each antenna has a minimally cooled receive system for calibration and self-location.

IV. LCC Uncertainty

The focus of this analysis was on the variation of the LCC components with antenna diameter. At the same time, each LCC component carries some uncertainty. Uncertainty will be treated by first assigning to each element an expected cost, a best-case cost (A), and a worst-case cost (B). These three inputs

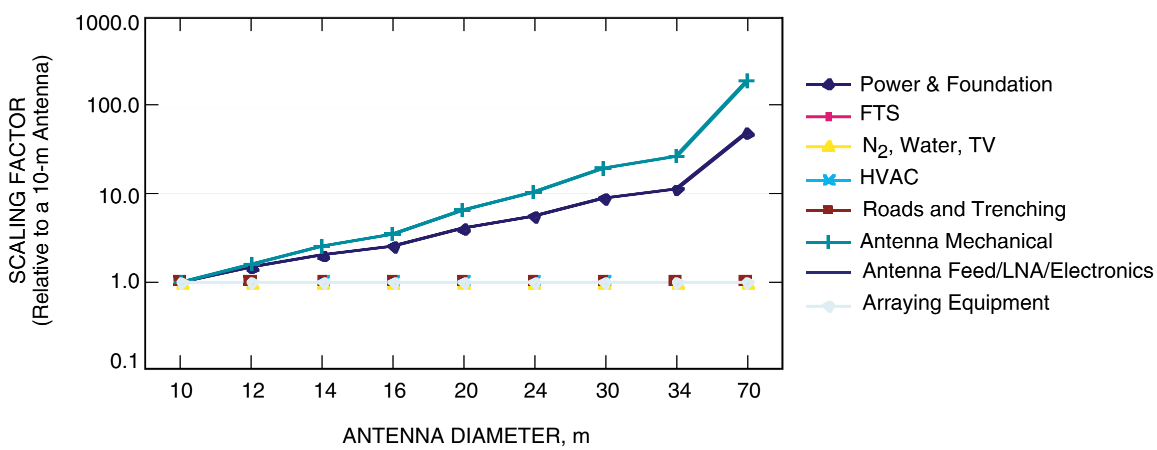

Fig. 2. Scaling factors for the cost components.

[9] Ibid.

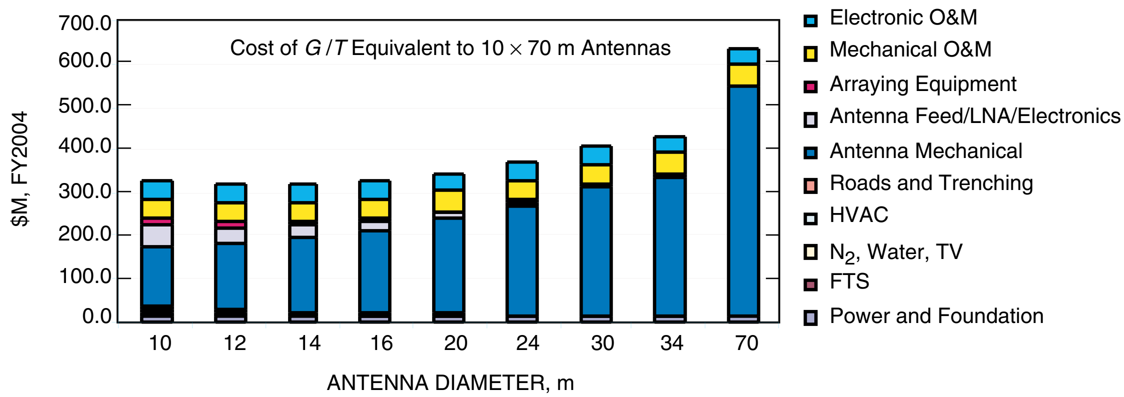

Fig. 3. Antenna-related LCC for downlink.

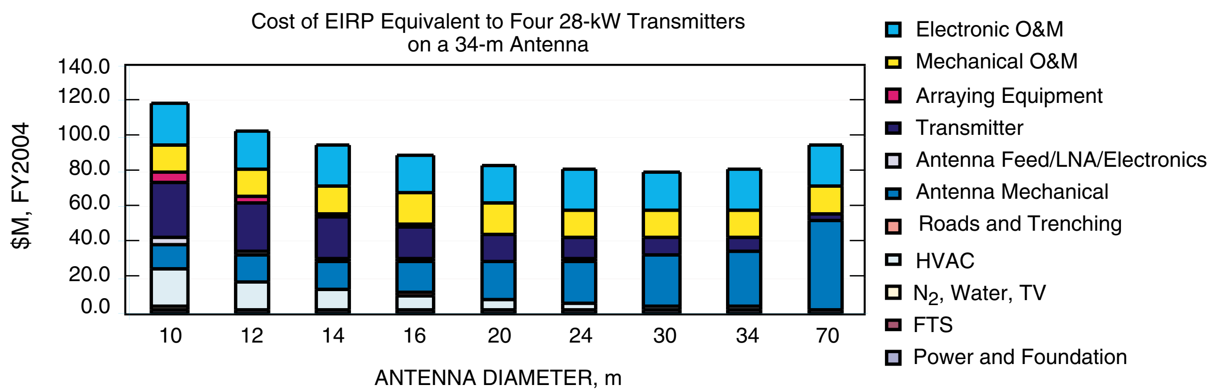

Fig. 4. Antenna-related LCC for uplink.

will specify a cost distribution, shown schematically in Fig. 5. The distribution uses a quadratic curve to describe the cost probability below the expected value. This reflects the likelihood of achieving a cost below the expected value, but does not allow costs below A, the best case value. The distribution uses a longer exponential tail above the expected value to describe the likelihood that costs might increase well above the expected value. The asymmetry of the distribution produces a mean cost somewhat above the expected cost, depending on the choices for A and B.

Once the cost distribution is defined for each cost element, Monte Carlo analysis will be used to accumulate cost distributions at various levels of the work breakdown structure (WBS). Several thousand random samples will be drawn from each cost component and added together, according to the WBS structure. The results will be "rolled-up" costs, each with its own statistical distribution. The distribution at each WBS level will then be analyzed to determine mean cost and uncertainty. As costs are accumulated, the distributions will tend to a Gaussian distribution with uncertainties somewhat less than the uncertainties of the components (due to the Central Limit Theorem).

This type of cost uncertainty analysis will immediately identify WBS elements that are (1) large and (2) uncertain. These particular elements represent high cost risk. Steps will then be taken to formulate risk reduction strategies that may include different technologies, different acquisition strategies, etc. With focused, steady effort, the overall cost risk will decrease as the DSN Array program approaches implementation.

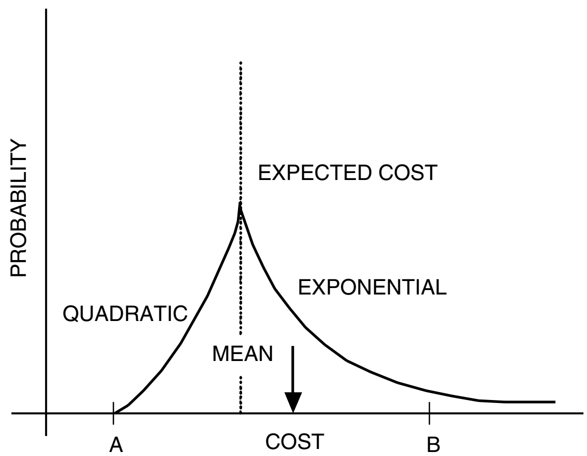

Fig. 5. Schematic diagram of a typical cost uncertainty distribution function.

V. Summary

For downlink, the LCC indicates a rather shallow minimum between 10 m and 16 m. We also must consider two additional effects:

(1) Smaller antennas have wider beams, making it more likely that a radio source is in the beam and, thus, alignment and navigation goals are easier to meet.

(2) With a trend of reduction in the cost of electronics, and the lack of a similar trend for the cost of mechanical subsystems, the minimum is likely to shift toward smaller antennas.

Given the LCC data and the above observations, we have selected the downlink antenna diameter as 12 m.

For uplink, the LCC indicates a rather shallow minimum between 24 m and 34 m. Combining this with the relatively low technology readiness level (TRL) of uplink arraying, and the experience we have with 34-m antennas, we have selected 34 m as the uplink antenna diameter.

Because of the shallowness of the LCC curves, these values are not likely to change significantly as the costs are refined, but we expect to update the LCC periodically, as costs are better understood.

Acknowledgments

We would like to acknowledge the input and discussions from William Hurd on the uplink array, Mark Gatti on the cost modeling, and Barry Geldzahler of NASA Headquarters on the navigation aspects of the DSN Array and the impact of the antenna diameter on navigation support.

Reference

[1] B. E. MacNeal, "Parametric Cost Analysis of NASA's DSN Array," SpaceOps 2004, Montreal, Canada, May 2004.

Appendix
Data for the Optimization Study

The tables below summarize the data used in selecting the optimal antenna size. Table A-1 shows the relative cost of the LCC component as a function of antenna diameter. Tables A-2 and A-3 show the component and total LCC costs for the downlink and uplink antennas, respectively.

Table A-1. Ratios, relative to a 10-m antenna.

LCC component	Antenna diameter, m								
	10	12	14	16	20	24	30	34	70
Power and foundation	1.0	1.4	2.0	2.6	4.0	5.8	9.0	11.6	49.0
FTS	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
N_2, water, TV	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
HVAC	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Roads and trenching	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Antenna mechanical	1.0	1.6	2.5	3.6	6.5	10.6	19.4	27.2	191.3
Antenna feed/LNA/ electronics	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Arraying equipment	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table A-2. Downlink antennas.

LCC component	RE, 10 m, \$M	Antenna diameter, m								
		10	12	14	16	20	24	30	34	70
No. of antennas to get equivalent of 10 70-m antennas	—	548.8	381.1	280.0	214.4	137.2	95.3	61.0	47.5	11.2
Power and foundation	0.022	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
FTS	0.020	11.0	7.6	5.6	4.3	2.7	1.9	1.2	0.9	0.2
N_2, water, TV	0.004	2.2	1.5	1.1	0.9	0.5	0.4	0.2	0.2	0.0
HVAC	0.007	3.8	2.7	2.0	1.5	1.0	0.7	0.4	0.3	0.1
Roads and trenching	0.010	5.5	3.8	2.8	2.1	1.4	1.0	0.6	0.5	0.1
Antenna mechanical	0.250	137.2	155.9	173.6	190.7	222.9	253.2	296.0	323.1	535.7
Antenna feed/LNA/ electronics	0.100	54.9	38.1	28.0	21.4	13.7	9.5	6.1	4.7	1.1
Arraying equipment	0.020	11.0	7.6	5.6	4.3	2.7	1.9	1.2	0.9	0.2
Mechanical O&M	0.010	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0
Electronic O&M	0.010	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
Total	—	325.6	317.3	318.8	325.2	345.0	368.6	405.9	430.9	637.6

Table A-3. Uplink antennas.

LCC component	RE, 10 m, $M	Antenna diameter, m								
		10	12	14	16	20	24	30	34	70
Power per transmitter	—	2.4	3.5	4.7	6.2	9.7	13.9	21.8	28.0	118.5
No. of antennas to get the EIRP	—	57.6	40.0	29.4	22.5	14.4	10.0	6.4	5.0	1.2
Power and foundation	0.022	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
FTS	0.020	1.2	0.8	0.6	0.4	0.3	0.2	0.1	0.1	0.0
N_2, water, TV	0.004	0.2	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0
HVAC	0.375	21.6	15.0	11.0	8.4	5.4	3.7	2.4	1.9	0.4
Roads and trenching	0.010	0.6	0.4	0.3	0.2	0.1	0.1	0.1	0.0	0.0
Antenna mechanical	0.225	13.0	14.7	16.4	18.0	21.0	23.9	28.0	30.5	50.6
Antenna feed/LNA/ electronics	0.070	4.0	2.8	2.1	1.6	1.0	0.7	0.4	0.3	0.1
Transmitter	—	32.6	26.4	22.1	19.0	14.9	12.2	9.6	8.4	4.0
Arraying equipment	0.100	5.8	4.0	2.9	2.2	1.4	1.0	0.6	0.5	0.1
Mechanical O&M	—	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Electronic O&M	—	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0	22.0
Total	—	118.2	103.5	94.8	89.3	83.5	81.2	80.5	81.1	94.5