Uplink Options for an Array-Centric Deep Space Network[1,2]

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Abstract—The Jet Propulsion Laboratory has begun work on large arrays of small antennas for increasing the receiving capability of the NASA Deep Space Network (DSN). These receive-only arrays promise to be the lowest cost way to meet the downlink needs of future missions. The DSN will also need new uplink capability: a) to provide higher uplink rates to new types of missions, b) to support more spacecraft simultaneously, c) to provide high Effective Isotropic Radiated Power (EIRP) for very distant missions and for spacecraft emergencies, and d) to back up and potentially replace the aging 70-m antennas. This paper discusses various approaches to providing new uplink capability, with the goal of minimizing the overall life cycle cost of the DSN. One proposed way to provide new uplink capability is by uplink arrays of small antennas. This approach has technical challenges, and it needs to be demonstrated that they can be overcome. The second major option is to use 34-m and/or larger antennas for the uplinks. In this option, 34-m antennas might be arrayed to obtain the same or greater EIRP as might be obtained on 70-m antennas. This paper presents a scenario for increasing the overall DSN capacity in several steps. Building blocks are defined that can be used to implement these steps. The key building blocks are 34-m antennas with uplink and downlink, 34-m antennas with receive only, and various array configurations that are equivalent in performance to the 34-m antenna configurations. Making cost estimates for these building blocks will facilitate estimating overall DSN costs for various approaches and levels of capability.

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1. INTRODUCTION

The Interplanetary Network Directorate (IND) at the Jet Propulsion Laboratory (JPL) has a vision of increasing the receiving capability of the NASA Deep Space network (DSN) by a factor of 100 to 500 over the next 20 to 25 years. This is an average rate of roughly 1 dB per year. The mission need for this increased capability has been identified in recent studies [1,2].

The studies also identified a need for new uplink capability, although this need is not as definite as the downlink need. Mission drivers for new uplink capability include the need for higher data rate uplinks, for X-band uplinks with higher Effective Isotropic Radiated Power (EIRP) than is currently provided, and for additional uplinks to support more spacecraft simultaneously. There is also a need to back up and possibly replace the aging 70-m antennas.

For increased downlink capability, both radio frequency (RF) and optical systems are under consideration. It appears likely that both will play a role in the DSN of the future. Due primarily to cost considerations, large arrays of small antennas are the most likely choice for the needed RF capability [3,4].

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For uplinks, RF links almost certainly will be needed even if optical becomes the primary downlink technology. RF uplinks will be needed for situations where the spacecraft cannot point a telescope towards the ground station. These situations include spacecraft emergencies, spacecraft that rotate constantly, and possibly spacecraft that have other reasons that make it impractical or expensive to orient a telescope towards the Earth, such as use of solar electric propulsion.

This paper discusses various approaches to providing new uplink capability, with the goal of minimizing the overall life cycle cost of the DSN. One proposed way to provide new uplink capability is by uplink arrays of small antennas. This approach has technical challenges, and it needs to be demonstrated that they can be overcome. The second major option is to use 34-m and/or larger antennas for the uplinks. In this option, 34-m antennas might be arrayed to obtain the same or greater EIRP as might be obtained on 70-m antennas. This paper presents a scenario for increasing the overall DSN capacity in several steps. Building blocks are defined that can be used to implement these steps. The key building blocks are 34-m antennas with uplink and downlink, 34-m antennas with receive only, and various array configurations that are equivalent in performance to the 34-m antenna configurations. Making cost estimates for these building blocks will facilitate estimating overall DSN costs for various approaches and levels of capability. Preliminary cost estimates are presented.

2. Current DSN Capability

The DSN provides reception for deep space missions at S-band (2.3 GHz) and X-band (8.4 GHz). Use of S-band is declining, and use of Ka-band is increasing, with most current missions using X-band. The DSN currently has 70-m and 34-m antennas. There are also 26-m antennas that are used for near Earth applications, but not for deep space, and we do not discuss these further. There are two types of 34-m antennas, beam waveguide (BWG) and high efficiency (HEF). The BWG antennas receive at Ka-band (32 GHz). It is not decided whether Ka-band will be implemented on the 70-m antennas, on arrays of small antennas, or on both.

There are one 70-m and one 34-m HEF antennas at each of the three DSN complexes, in California (Goldstone), Spain (Madrid) and Australia (Canberra). There are three 34-m BWG antennas at Goldstone, two at Madrid and one at Canberra. There are a total of nine 34-m antennas.

The main performance measure for downlink performance is the ratio of gain to system temperature, G/T. The values of G/T are accurately known for the existing antennas. At X-band, the G/T for a 70-m antenna is somewhat more than four times that of a 34-m antenna. The G/T that would be achieved at Ka-band on a 70-m antenna is not known accurately, partially because it depends on the chosen implementation. However, it is likely to be close to four times the G/T of a 34-m antenna. For the rough calculations in this paper, we assume that the G/T of a 70-m antenna is four times that of a 34-m antenna, for both X- and Ka-bands.

The main uplink frequency band is X-band. There are 20-kW transmitters on all antennas, which means that each antenna can achieve a radiated power of 20 kW (at the feed horn). The 70-m antennas and some of the 34-m antennas also have 20-kW S-band transmitters. For emergencies and other special needs, the 70-m antennas also have 400-kW S-band transmitters. A similar capability at X-band may be needed in the future. Currently, there is only one Ka-band transmitter. This is an 800-W transmitter on a 34-m BWG antenna at Goldstone.

3. Future DSN Array Capability

The DSN capability will be increased as there are mission drivers, and as funds become available. JPL is currently planning for new downlink capability to be implemented as arrays of 12-m diameter antennas. Initial implementations in California (Goldstone), Australia and Spain are anticipated by FY08, FY09 and FY10, respectively. These arrays are planned to have 50 antennas each, with X-band and Ka-band receive capability approximately equivalent to five existing DSN 34-m antennas. This equivalence is based on the following logic. First, it takes eight 12-m antennas to equal the area of a 34-m antenna. Second, the noise temperature of the 12-m antennas will be slightly higher than that of the 34-m antennas, which increases the required number of 12-m antennas to nine. Third, the array will have spare antennas to provide overall system reliability. Overall, we assume that it takes ten 12-m antennas to be equivalent in G/T to one 34-m antenna, and 40 to be equivalent to one 70-m antenna.

Projections for growth of the Array System are of course uncertain. A logical progression might be to grow to 100, then 400, and then 4000 antennas each. At Ka-band, the 4000 antennas would meet the greatest vision of performance 500 times that of today's 70-m antennas at X-band. These progressing levels of DSN array capability are as follows.

Level A: Initial array capability

The initial array receive capability is planned to be equivalent to one 70-m antenna plus one 34-m antenna, at each DSN complex. Even if the performance of the array system is less than predicted, the initial capability will be at least equivalent to one 70-m antenna. Key rationale for this choice is that these arrays will provide complete redundancy for the aging 70-m antennas, and will provide Ka-band performance equivalent to a 70-m antenna, possibly at a lower life cycle cost than implementing this capability on the 70-m antennas.

No new uplink capability is essential to accompany the initial array system. The plan is that the current uplinks will be used. Typically, an existing 34-m antenna will be assigned to provide the uplink for each spacecraft that is tracked by the array. The receive capability of this uplink antenna will typically be added to the array. For example,

one BWG antenna plus 30 array 12-m antennas would be the equivalent of a 70-m antenna, except with lower EIRP.

When the array system is expanded, it will be feasible for the DSN to track more spacecraft simultaneously than at present, and additional uplink capability will be needed. Uplink arrays may be the most cost-effective way to provide this capability. The technical feasibility and costs need to be demonstrated. Therefore, it is proposed that an initial uplink array be demonstrated with a capability at least equivalent to a 34-m antenna, and preferably equivalent to a 70-m antenna, with 20 kW. If the 70-m capability is built, it could be divided into two subarrays each equivalent to 20-kW on a 34-m antenna, and into four subarrays, each equivalent to 4 kW on a 34-m antenna. This initial uplink array would be at only one DSN site, Goldstone.

Note that it is not presupposed that arrays of 12-m antennas will be the uplink of choice for operational implementation. Other options are to use 34-m and 70-m antennas, or arrays of 34-m antennas.

Level B: Enhancement for current and committed missions

The proposed Level B capability would expand the initial capability so as to add the equivalent of the current Goldstone capability to each DSN complex. The added G/T would be at least equivalent to two 70-m antennas, or eight 34-m antennas. This would be operable as one large antenna, as a 70-m equivalent plus four 34-m equivalents, or in other combinations.

The Level B receive capability would significantly enhance the missions that the DSN now supports and those that the DSN has specifically committed to support in the future. There are two limits to telemetry data rate: the received signal power or signal-to-noise ratio (SNR), and the data rate limits of the spacecraft systems. Most current and committed missions are limited by SNR for significant portions of the missions. This is particularly evident for Mars missions, where the SNR changes by roughly an order of magnitude every two years, as the range to the spacecraft changes. A recent study concluded that the proposed Level B capability would enable all current and committed missions to achieve the maximum data rate at all planned spacecraft ranges, as limited by the spacecraft systems, rather than by SNR.

The uplink capability added at each longitude would be the capability of one 70-m antenna plus four 34-m antennas simultaneously, each with 20 kW. This would enable the DSN to support twice as many missions as today, with two-way (uplink and downlink) tracking.

Level C: Enhancement for future missions

For Level C, the envisioned receive capability is ten times that of a 70-m antenna, or 40 times that of a 34-m antenna. The envisioned uplink capability is to have at least ten times the EIRP of a current 70-m antenna, or the equivalent of 200 kW on a 70-m antenna. This envisioned capability still does not presume that uplink arrays will be used, as this 200-kW power level is less than that of one of the two X-band klystrons in the current Goldstone Solar System radar.

Level D: Ultimate vision

The ultimate vision is to fulfill the DSMS vision of increasing the DSN downlink capability by a factor of ten each decade, or an average of 1 dB per year. The ultimate vision for arrays is to have capability equivalent to 100 Ka-band 70-m antennas. The array system would have several clusters of antennas at each longitude, with the sites selected to provide weather diversity for reliable Ka-band operations.

The uplink capability would have sufficient numbers of uplinks to support the required number of missions, and would have the capability to achieve an EIRP equivalent to 1 MW on a 70-m antenna. Note that even this high EIRP does not restrict the approach to uplink arrays. There have been proposals for many years to build a 1-MW X-band capability for radar, by coherently combining the outputs of four 250-kW klystrons.

4. Trade Space and Constraints

The major system parameters to be traded are: antenna size, numbers of antennas, transmitter power and system temperature. The antenna sizes to be considered are 12 m, 34 m and 70 m. Five antenna-size approaches to be considered are:

1. 70-m and 34-m antennas only – today's system expanded
2. 70-m and 34-m antennas for uplinks, with arrays of 12-m antennas for additional receive capability – the initial concept with arrays for receive only
3. 34-m antennas only, arrayed for both uplink and downlink
4. 34-m antennas for uplink, arrayed for high EIRP, plus arrays of 12-m antennas for downlink
5. Arrays of 12-m antennas for both uplink and downlink

In cases where large arrays of 12-m antennas are used for reception, the antennas that provide the uplinks may or may not be used for reception also, added to the array. The choice should be made based upon life cycle cost.

There is a programmatic constraint that the current downlink Array Task must not be dependent on any uplink array work. The downlink Array Task must proceed independent of funding for uplink arraying, and of any decision points for uplink arraying. In the long run, it is acceptable for uplink arraying to impact some details of the downlink array, but the initial Array Task must not be delayed or otherwise negatively impacted by any uplink array work.

5. Basis for Cost Trades

This section presents a basis for performing cost trades.

Uplink Arraying Basic Concepts

To understand what follows, it is necessary to have some basic understanding of the EIRP of uplink arrays. Let us simplify by considering an array of two identical antennas with identical transmitters. The far fields from these antennas are identical. When the antennas are pointed in the same direction, and when the signals align in time delay and phase, the signals in the far fields add in the voltage sense. Since the voltage is twice that of one antenna, the power is four times that of one antenna. Thus the EIRP from an array of two identical antennas is four times that of each antenna, assuming perfect combining.

Generalizing, the EIRP from an array of N identical antennas is N^2 times that of each antenna. Another way to look at this is that the EIRP of one antenna is proportional to the antenna area times the transmitter power, and the EIRP of an array of identical antennas is proportional to the total area of the array times the total transmitter power. This generalizes to unequal antenna sizes, provided that the transmitter power of each antenna is proportional to the antenna area, and that efficiencies are the same for all antennas.

Baseline Building Blocks

Assuming that that uplink arraying is technically feasible, all capability envisioned for the four progressing levels of uplink and downlink capability can be achieved using two "Baseline Building Blocks". These are:

1. A "Full 34-m equivalent", that has G/T equivalent to a current 34-m antenna, and EIRP equivalent to a 34-m antenna with a 20-kW transmitter, and
2. A "Receive-only 34-m equivalent", or "RO 34-m equivalent".

With these building blocks, it takes four 34-m equivalents to achieve the G/T of a 70-m antenna (approximately). Again approximately, it takes two 34-m antennas with 20-kW transmitters to be the equivalent of one 70-m antenna with 20 kW. Thus the uplink and downlink equivalent of a 70-m antenna with 20 kW can be achieved using two Full 34-m equivalents, plus two RO 34-m equivalents. Other uplink and downlink capabilities can be realized similarly.

If uplink arraying is not feasible, then uplinks with EIRP higher than that of a 34-m antenna with 20 kW would require use of 70-m antennas.

Approximate Equivalences

The equivalences of arrays of smaller antennas to one large antenna can only be approximate. Two receiving systems that have the same G/T at zenith, assuming vacuum conditions, will not have the same actual G/T under all conditions of weather and elevation. For example, suppose that one receiving system has twice the gain and twice the vacuum system temperature of a second system. The vacuum G/T is the same for the two systems, but atmospheric noise degrades the second system more than the first system.

Atmospheric Noise — For simplicity, we choose to compare the Ka-band performance of different systems under conditions such that the atmosphere contributes 30 K to the system temperature. At 30 degrees elevation, this is the atmospheric noise that will be exceeded 10 percent of the time at Goldstone (90 percent weather), 30 percent of the time at Madrid, and 50 percent of the time at Canberra.

G/T — We assume that an array of four 34-m DSN antennas have the same G/T as one 70-m antenna. At X-band, the current values of G/T are accurately known, and the performance of the 70-m antenna is slightly better than the array of four 34-m antennas. At Ka-band, however, we do not know the performance as well, because the 34-m receiving systems have not yet been fully implemented, and the 70-m receiving system is in the future, if ever. The assumption that four 34-m antennas is the equivalent of a 70-m antenna seems appropriate, and is good enough for trade studies.

System Temperature — We assume that the reference 34-m BWG antenna has a vacuum system temperature of 27.4 K, which is the value achieved in initial implementations. Laboratory measurements indicate that 23.1 K may be achieved on the implementations that are now in progress. With atmospheric noise of 30 K, the overall system temperature and G/T would be improved by 8 percent, or 0.34 dB.

6. Uplink and Downlink Arrays

In Section 4 we defined a trade space using both large antennas and arrays of smaller 12-m antennas. Because the large antennas are better understood, we concentrate here on arrays of small antennas for both uplink and downlink. We establish possible array configurations that are equivalent to the basic building blocks of RO 34-m equivalents and Full 34-m equivalents.

Receive-only (Downlink) Arrays

For all arrays, we assume use of the 12-m antennas now planned for the initial Array System. At Ka-band, the predicted efficiency is 60 percent, and the planned vacuum system temperature is 30 K. We assume a typical combining loss of 0.5 dB.

The reference 34-m antenna has a vacuum system temperature of 27.4 K, and a G/T of 60.6 dB at 30 degrees elevation, with 30 K of atmospheric noise. It takes an array of nine 12-m antennas to achieve this same G/T. For costing, we plan on ten 12-m antennas to be the equivalent of a RO 34-m antenna, with the tenth antenna a spare to provide high system-level availability.

Uplink Arrays

EIRP — The EIRP of a transmitting antenna is proportional to the area and to the radiated power. Thus, other factors being equal, the ratio of the EIRP of a 12-m antenna with

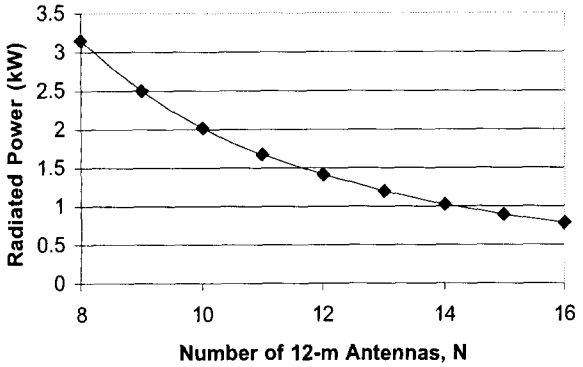
radiated power P, to that of the reference 34-m antenna with radiated power of 20 kW, is

$$\frac{EIRP(12m)}{EIRP(34m)} = \left(\frac{12}{34}\right)^2 \left(\frac{P}{20}\right) \tag{1}$$

We assume that an uplink array will have a typical combining loss of 1 dB, or a factor of 0.8. Without this loss, the EIRP of an array of N identical antennas is N^2 time the EIRP of one antenna. Thus the EIRP of an array of N 12m antennas, compared to a 34-m antenna, is

$$\frac{EIRP(Nx12m)}{EIRP(34m)} = 0.8\left(\frac{12N}{34}\right)^2 \left(\frac{P}{20}\right). \tag{2}$$

Setting this ratio to unity, we can solve for the per-antenna radiated power required for an array of 12-m antennas to have the same EIRP as a 34-m antenna with a 20 kW. The result is shown in Figure 1.



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antennas to have the same EIRP as a 34-m antenna with radiated power of 20 kW.

Radiated Power Level — The radiated power level is one element of the trade space for uplink arrays. Cost is a key consideration, but safety is also a concern. The maximum power that can be radiated from a single 12-m antenna is limited primarily by safety considerations. To meet safety regulations, the flux density at any location must not exceed 5 mw/cm^2, for averaging times of 6 minutes [5]. The calculation of the maximum flux density versus radiated power is quite complicated, and the result is greater than just dividing power by area, because of reinforcement patterns and other effects. The calculation has been done for the 34-m antennas, with a result that the radiated power should not exceed 28 kW. To first order, this result will scale by area to the 12-m antennas, yielding an approximate maximum radiated power of 3.5 kW. This happens to be a very convenient result, because the DSN has used 4-kW X-band transmitters in the past, and the same klystrons could be used at a lower level.

There is another consideration when considering the safe radiated power for an array. This is overlap between the beams of the antennas. To minimize combining losses, and also to minimize costs, it is desirable to locate the array antennas as close to each other as possible without blockage of one antenna by another. At low elevation angles, the beams will be very close to one another, when one antenna beam passes just above an adjacent antenna. If there is a pointing error in one antenna, two beams could overlap at a fairly short distance. Because the transmissions are designed to be phase coherent, there could be places in the overlap where the signals reinforce in the voltage sense, thereby increasing the flux density by a factor of four. At this time, it is not known if this effect will limit the maximum radiated power, or by how much. Controls could be implemented to prevent this situation, such as to detect the impending situation and turn off transmitters appropriately. The average field reinforcement would be a factor of two, not four, and this might be the appropriate limit. Also, aircraft would be extremely unlikely to stay within the beam for more than a few seconds, compared to the 6-min averaging time. Because this situation has not been resolved, and because it is not clear what power level will minimize system cost, it is appropriate to consider systems with different radiated power levels in the trade space.

Uplink–Downlink Arrays

The number of antennas needed in a combined uplink-downlink array, in order to be to a Full 34-m equivalent, is the number required to meet the EIRP, plus any additional receive-only antennas required to achieve the necessary G/T. In most cases, the total number of antennas will greater than the nine required in a downlink-only array, because the system temperature of the transmitting antennas will probably be higher than the 30 K assumed for receive-only antennas.

Suppose the vacuum system temperature of each antenna is T. With the assumed 30 K of atmospheric noise, the system temperature is (T+30) K, compared to 60 K for the receive-only antennas. The G/T of each transmitting antenna is thus lower that that of a receive-only antenna by the factor 60/(T+30). The N uplink antennas contribute to the array a G/T corresponding to 60N/(T+60). Since nine receive only antennas are equivalent to a 34-m antenna, the number of receive-only antennas that must be added to the uplink array to be a Full 34-m equivalent is

$$M = 9 - \left(\frac{60N}{T+30}\right) \tag{3}$$

where M is rounded upwards, and is not less than zero. This equation can be solved for T to get the maximum allowable uplink system temperature in an array of N transmitting antennas and M receive-only antennas. The results are shown in Figure 2.

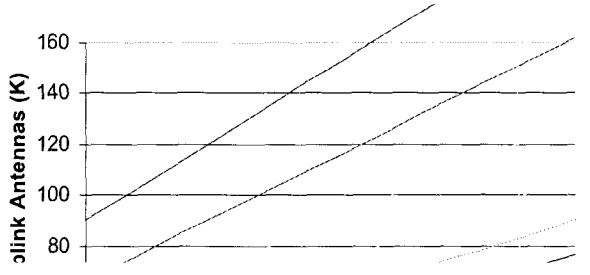

Figure 2. Maximum vacuum system temperature for N uplink antennas, with M receive-only antennas, to be a "Full 34-m equivalent" array.

Cases for Cost Trades – Here we list five specific cases that seem appropriate choices for performing cost trades.

1. 3.2-kW transmitters. This requires eight uplink antennas, and three receive-only antennas if the uplink antennas have T<50 K.
2. 1.6-kW transmitters. This requires 12 uplink antennas, and no receive-only antennas if the uplink antennas have T<50 K.
3. 1.7-kW transmitters. This requires 11 uplink antennas, and no receive-only antennas if the uplink antennas have T<43 K.
4. 0.8-kW transmitters. This requires 16 uplink antennas, and no receive-only antennas if the uplink antennas have T<76 K. Note that if T=50 K, the downlink performance is like 1.33, 34-m antennas.
5. Totally separate uplink and downlink arrays. This requires nine receive-only antennas, plus the number of uplink antennas above for each power level. The uplink antennas will probably need X-band only, room temperature receivers, in order to perform interferometry to accurately determine the antenna locations.

7. System Cost Estimation

We have presented baseline building blocks for large-scale new DSN capability, and we have presented several uplink and downlink array configurations that could be used to construct the building blocks. The main remaining steps to estimate system cost are to estimate the cost of the various elements, and then to compare the results to achieve minimum cost.

For 34-m BWG antennas, it is known what recent antennas cost. However, these antennas include some capability that is necessary in a complete DSN station, but is not necessary in an element of a larger array. Therefore, some engineering is required to define and cost the BWG implementations of the "Full 34-m equivalent" and "RO 34-m equivalent".

For the arrays of 12-m antennas, considerable work is needed to define the system configuration for the uplink arrays, before useful cost estimates can be made.

8. Conclusions

Large arrays of small antennas show promise of being the most economical way to greatly increase the receiving capacity of the NASA Deep Space Network. In addition to new receiving capability, NASA will need new uplink capability to support larger numbers of spacecraft, and more distant spacecraft. Uplink arrays may be the most economical way to achieve this uplink capacity, but the technical feasibility and the cost are not yet known. Other options for uplink capability are to use single very large antennas, or arrays of fairly large antennas, such as the 34-m BWG antennas of the current DSN. This paper has presented baseline building blocks from which any desired capability can be constructed, and some specific configurations of uplink arrays that could satisfy the building blocks. These building blocks can be used in performing system cost trades.

Acknowledgements

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Biography

William J. Hurd *received a B.S.E.E. degree from Clarkson University, Potsdam, New York, in 1961, and the M.S.E.E. and Ph.D.E.E. degrees from the University of Southern California in 1963 and 1967. He is currently a system architect in the Interplanetary Network Directorate of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California. He has been employed at JPL since 1967, and was previously a Member of the Technical Staff at Hughes Aircraft Co., where he was also a Hughes Master's Fellow and a Hughes Doctoral Fellow.*