Lower-Cost Architectures for Large Arrays of Small Antennas

Dayton L. Jones
Jet Propulsion Laboratory
Mail Code 138-308
4800 Oak Grove Drive
Pasadena, CA 91109, USA
818-354-7774
dj@sgra.jpl.nasa.gov

Abstract— Future plans for NASA's Deep Space Network (DSN) call for the construction of arrays of small antennas to compliment and eventually replace the existing network of large single antennas. The motivation for this transformation is the need to support much higher downlink data rates in the future, along with the realization that the most cost-effective way to do this is though a large increase in total collecting area on the ground. As currently designed, the DSN arrays will consist of approximately four hundred 12-m diameter antennas at each of three longitudes, operating at X and Ka bands (8 and 32 GHz). A possible near-term option is the construction of large arrays operating at X-band only. Such an array could be built more rapidly and less expensively than an X/Ka band array, and would be able to support the majority of space missions planned for the next 20 years, which will not require bandwidths wider than the 50 MHz X-band allocation. Cost-saving advantages of an X-band only array include the use of COTS antennas much smaller than 12 m in diameter, uncooled receivers, and direct optical transfer of signals from antennas to a central signal processing area.

TABLE OF CONTENTS

1 INTRODUCTION 1
2 CURRENT X/KA-BAND ARRAY DESIGN 2
3 X-BAND FOR FUTURE DEEP SPACE MISSIONS 3
4 AN X-BAND ONLY ARRAY 4
5 COST AND RISK REDUCTIONS 5
6 SIGNAL PROCESSING IMPLICATIONS 6
7 TRADEOFFS 7
8 CONCLUSIONS 7
9 ACKNOWLEDGEMENTS 7
REFERENCES 8
BIOGRAPHY 8

1. INTRODUCTION

The primary purpose of the Deep Space Network (DSN) is to communicate with NASA's planetary science missions. Because of the extreme range of many spacecraft tracked by the DSN, there has always been a high priority placed on achieving the maximum practical sensitivity to allow useful data rates to be obtained. This is particularly important for downlink, since in many cases the scientific return from a mission is directly related to the amount of data that can be transmitted from the spacecraft back to Earth.

The quest for high sensitivity has driven the DSN to construct large diameter antennas and develop extremely low noise amplifiers to place on them. In addition, improvements in error-correcting codes have allowed data to be received at lower SNR levels. However, each of these areas has approached fundamental limits of performance during the past two decades: Significantly larger individual steerable antennas are impractical to construct, receiving system temperatures are dominated by atmospheric and cosmic background noise instead of receiver noise, and code performance is nearing the Shannon limit. Further large improvements in sensitivity require dramatic increases in spacecraft transmitter power and antenna size, or an affordable way to greatly increase the collecting area of ground antennas. A major advantage of increasing the collecting area of ground antennas is that a one-time investment benefits all future missions.

It has been recognized for some time that arrays of small, mass-produced antennas can provide collecting area for much less cost than large single antennas. The main reasons for this are that the cost of a steerable antenna scales as the diameter to a power close to 3, and very low-cost manufacturing techniques such as hydroforming of one-piece reflectors are practical for antennas of several meters and less but not for much larger antennas. As a result, next-generation instruments for radio astronomy that are currently under construction (the Allen Telescope Array or ATA[1]) or planned (the Square Kilometre Array or SKA[2]) are based on large numbers of small antennas operating as arrays. The planned DSN array is also based on this approach. The main goal of the DSN array is to provide more than an order of magnitude increase in sensitivity for telemetry reception than the existing 70-m DSN antennas at both X-band (8 GHz) and Ka-band (32 GHz). Additional goals are increased reliability and flexibility, and reduced operating costs.

0-7803-8870-4/05/$20.00 © 2005 IEEE
IEEEAC paper #1199

[1] For information on the ATA see http://astron.berkeley.edu/ral/ata .
[2] For information on the SKA see http://www.skatelescope.org .

2. Current X/Ka-Band Array Design

The planned DSN array will consist of three clusters, one near each of the current DSN site longitudes. Each cluster will consist of four hundred 12-m diameter parabolic antennas operating at X-band and Ka-band. The antenna clusters will cover an area approximately 2 km in diameter. For details of the current design see, e.g., [2] and [10]. It is likely that smaller clusters of antennas will be used as uplink arrays near each downlink cluster site. However, it is possible that individual larger antennas will continue to be used for uplink; the optimal way to handle uplink is still under study. In some sense this is a less critical issue, given that uplink data rates are generally orders of magnitude lower than downlink rates[1]. The expected cost of the DSN array is in excess of $1B. A significant part of this cost is associated with the requirement that the array operate with high efficiency at the relatively high Ka-band frequency as well as at X-band.

Two 6-m diameter test antennas have been installed at JPL and are being used to quantify the performance of hydroformed reflectors at Ka band. The antennas have a symmetric geometry, as shown in Figure 1. The DSN arrays is planned to have 12-m diameter antennas, which may be scaled-up versions of the hydroformed design or more traditional metal or composite panel antennas. Hydroformed antennas are almost certainly less expensive to manufacture, but it is not yet certain that they can provide adequate performance at Ka-band in a 12-m diameter size. As a backup, a prototype 12-m metal panel antenna has also been ordered by the DSN for evaluation at JPL.

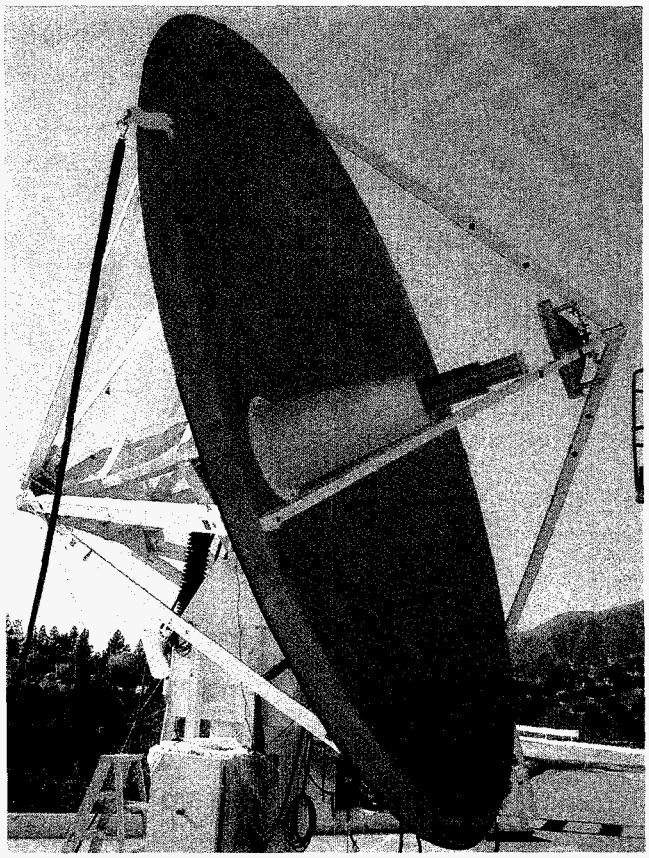


Figure 1. Prototype DSN 6-m Hydroformed Antenna

A small part of one antenna cluster of the planned DSN array is shown in Figure 2. The small separations between adjacent antennas are needed to minimize phase errors between antennas produced by tropospheric water vapor variations at Ka-band [12]. The price of this is some loss of sensitivity due to shadowing at low elevations.

Phasing of any array at Ka-band is a challenge because of the often large and rapidly-varying phase fluctuation imposed by the atmosphere [13]. Phase fluctuations increase with baseline length, so robust array phasing requires a compact configuration of antennas. Robust array phasing at Ka-band also requires that array clusters be located at high, dry sites. This constraint is difficult to satisfy in some regions. Atmospheric phase fluctuations are much smaller at X-band, allowing array phase calibration to be done over longer time scales, using weaker signals, with larger antenna separations, and under less favorable weather conditions.

The DSN array is planned to have two IF signals transported from each antenna, each with a maximum bandwidth of 500 MHz (the width of the deep space downlink allocation at Ka band). The two signals can be any pair of the four possible signals: RCP and LCP polarization at both X-band and Ka-band. Thus, dual-polarization at either X or Ka band or simultaneous single-polarization X and Ka band signals can be provided. The signals are downconverted at the antennas using local oscillators phase locked to a reference signal sent to each antenna from a central signal processing center. Phase coherence is maintained by a two-way fiber optic cable monitoring system, which measures the changes in round-trip phase using a pair of physically adjacent fibers in the same cable.

Telemetry reception requires that signals from the array antennas by added rather than multiplied (cross-correlated). For the planned DSN array this will be done in four identical beamformers, allowing four simultaneous array beams to be pointed anywhere within the antenna primary beam areas. Each beamformer has a maximum bandwidth of about 100 MHz. Determination of the correct delay and phase offsets to apply to each antenna signal will be done with the beamformers using an algorithm like SUMPLE [18] when the spacecraft signal is strong enough. For very weak signal cases, antenna delay and phase corrections can be interpolated from observations of angularly nearby background radio sources. This is a standard technique for calibrating arrays in radio astronomy, and was used at the Very Large Array to receive telemetry from Voyager 2[22]. For this situation and for array testing and monitoring, a cross-correlator with a bandwidth of 500 MHz will be included with each array cluster.

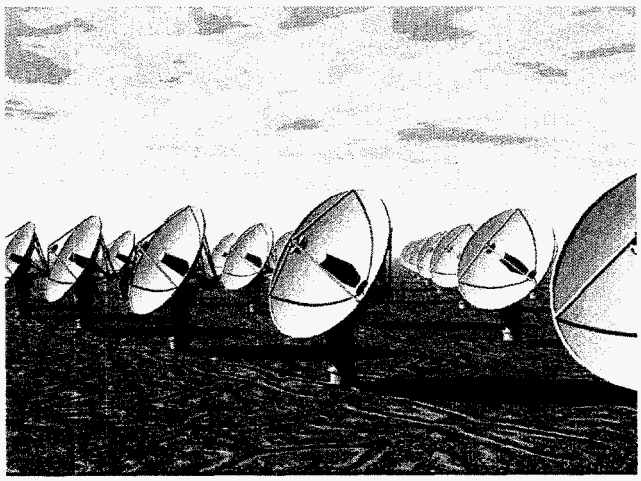


Figure 2. Artist Concept of DSN Array Cluster

3. X-Band for Future Deep Space Missions

A basic premise of this paper is that a large fraction of future mission support could be done with a sensitive array operating at X-band only. If this premise is correct, significant cost saving should be possible by removing the requirement for array operation at Ka-band. But is this premise correct, or at least plausible? To answer this, we need to consider the limitations of X-band and the likely needs of future NASA missions.

The frequency allocation for deep space downlink at X-band is 50 MHz wide. This is often cited as a major reason for using Ka-band to support future missions that require very high downlink data rates. However, a 50 MHz bandwidth is adequate for data rates of at least 25 Mb/s, which is equivalent to several simultaneous video channels. This assumes error correcting coding for the low signal-to-noise (SNR) conditions appropriate for most current deep space missions. The resulting data rates are typically about 0.5 b/s per Hz of bandwidth.

With higher SNR it is possible to get significantly higher data rates from a 50 MHz bandwidth. Equation 1 gives the Nyquist limit for data rate as a function of bandwidth and the number of signal quantization levels:

$$R = 2\,B\log_2(L), \tag{1}$$

where R is the data rate (b/s), B is the bandwidth (Hz), and L is the number of discreet signal levels. For L = 2 (binary modulation) the maximum data rate is 100 Mb/s for a 50 MHz bandwidth. A similar result is found from Equation 2, Shannon's capacity limit for error-free data transmission:

$$R = B\log_2(1+\mathrm{SNR}). \tag{2}$$

Here we see that a data rate of 100 Mb/s is allowed when the SNR is at least 3. Higher SNR allows multi-level modulation techniques and higher data rates within the same RF bandwidth. These equations give upper limits, so we should expect somewhat lower data rates in reality. Nevertheless, a large array could operate in a higher SNR regime much of the time, allowing more data per unit of bandwidth than has been usual for deep space missions. In addition, the total downlink rates can be doubled by using two orthogonal polarizations (assuming that the fundamental constraint is the allowed bandwidth and not the available spacecraft transmitter power).

How many missions in the next two decades will really require higher data rates than this? This is unknown, and probably depends on whether we really mean require or desire. Given the long time scales for proposing, developing, and constructing spacecraft for major planetary missions, it seems unlikely that the next 20 years will see increases in data rates of more than two orders of magnitude. This is approximately the level of increase that can be accommodated within the X-band frequency allocation. A JPL study of future mission telecommunication requirements [1], extrapolated for 20 years, supports the idea that downlink data rates will not exceed a level of tens of Mb/s during that time.

X band is fundamentally more appropriate for telecommunications than Ka band. In fact, based on the physics of signal propagation through the ionosphere and troposphere, X-band is close to optimal from the standpoint of minimizing delay and phase errors that must be monitored and corrected in real time for successful array operation [16]. There are many advantages in terms of operations and reliability if we do not have to fight propagation effects more than necessary.

The real limitation at X-band appears to be the process by which missions are allocated downlink frequencies rather that the total bandwidth that is available. Multiple spacecraft can, in principle, use the full 50 MHz bandwidth at X-band simultaneously as long as they are not located within the same (very small) array beam area. If the instantaneous array sidelobes levels were not low enough to adequately suppress the signals from a spacecraft in a particular direction, active null placement in that direction would provide more than adequate rejection of the signal [21]. Even when multiple spacecraft were within the same array beam (orbiters or landers at the same planet, or a compact constellation of spacecraft, for example), it would be possible for them to share the full 50-MHz bandwidth using time multiplexing if instantaneous bit rate was more important than total data volume. This implies complex scheduling, but that would be a small price to pay for more efficient utilization of the existing downlink frequency allocation.

In general, the allocation of frequencies and bandwidths to individual missions has been done in a way that minimizes the chance of interference between different spacecrarft sig-

nals. This is unquestionably important, but a balance between higher data rates a large fraction of the time in exchange for some loss of data due to interference a small fraction of the time should also be considered.

4. An X-Band Only Array

This paper proposes a DSN array based on the same basic approach as currently planned, but operating only at X-band. This allows the detailed design to be modeled more closely on the very-low-cost design of the Allen Telescope Array[8], which itself will have about 1/4 the sensitivity at X-band of the planned DSN array clusters of four hundred 12-m diameter antennas. The most significant difference is that the total cost of the ATA is expected to be less than $40M.

There are three major reasons for this dramatically lower cost:

- First, the ATA uses 6-m hydroformed antennas designed to operate up to 11.5 GHz, about one third of Ka-band frequencies. This reduces the reflector surface accuracy required, reduces the importance of thermal, gravity, and wind effects, and allows much lighter mounts and drives to be used.

- Second, the ATA uses smaller and lower power cryocoolers. As a result the front end low noise amplifiers are cooled to physical temperatures of about 80K instead of 15K, and the broad-band feed is not cooled, resulting in increased system noise temperatures. The advantages are large reductions in cost, mass, and electrical power (30 times less than for 15K cryocoolers), and an expected large increase in lifetime.

- Third, the ATA does not distribute any stable reference signals to its antennas. There is no frequency downconversion, and consequently no local oscillator, at the antennas; the entire RF band (up to 11.5 GHz) is amplified and modulated onto optical fiber for transmission to a central signal processing bunker. This eliminates the need for a separate fiber cable phase monitoring system. Changes in the delay and phase of the fiber cables are calibrated and removed in the same way as atmospheric and other antenna-based errors are.

Note that all three of these innovations can be applied directly to an X-band only DSN array. In particular, exact copies of the ATA antennas, mounts, and drives would be completely usable, without the need for significant non-recurring engineering costs. The manufacturing cost and on-site construction procedures are already well known.

The offset Gregorian antenna design used for the ATA is shown in Figure 3. This geometry minimizes noise pickup by removing all mechanical structures that scatter radiation from the signal path. Note the low mass of the dish backup structure and mount. Both are considerably less massive than those shown in Figure 1 because of the lower maximum operating frequency (11.5 GHz for the ATA instead of 30-40 GHz for the DSN). Figure 4 shows an ATA antenna with ground shield containing a wideband feed, low-noise amplifier, dewar, and cryocooler. The shield reduces ground pickup by the feed.

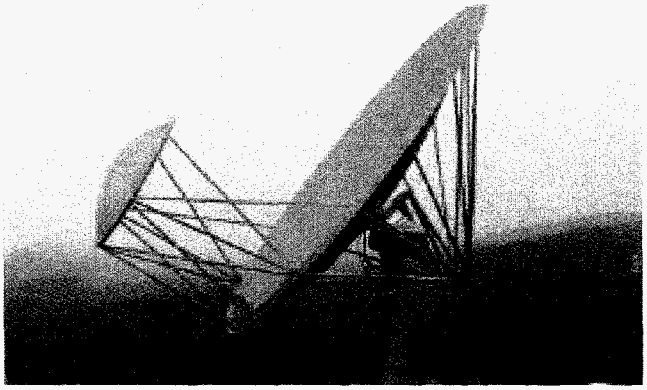


Figure 3. ATA Antenna Structure (photo by S. Shostak)

The first three production ATA antennas have been used for initial testing of the ATA signal path in interferometer mode [7]. The performance of the ATA antennas has been better than expected, particularly the blind pointing which exceeds the specification of 2 arcminutes rms by at least a factor of two[11]. This is more than adequate for operation at 8 GHz. The fiber optic signal path is sufficiently phase stable for operation at frequencies above 8 GHz [9] [17]. This last item is critical for removing the need to distribute local oscillator or other stable reference signals to the antennas. This is a significant simplification. Because the physical size of the ATA is similar to that of a DSN array cluster, the non-recurring-engineering effort devoted to fiber cable phase stability characterization and installation methods is directly applicable to the DSN array case.

Some of the additional ATA antennas that have been constructed recently are shown in Figure 5, and the configuration of the completed ATA is shown in Figure 6. These figures illustrate the relatively compact configuration of the ATA, which is very similar to what is planned for the DSN array clusters.

For a DSN array a different feed and low noise amplifier would be needed, because the ATA design is very broad-band (0.5-11.5 GHz) and this inevitably involves some compromise in performance (noise temperature). The next section discusses low noise amplifier options.

It should be noted that one important limitation of the ATA design is that it cannot be used as an uplink array. Without a way to monitor the fiber cable propagation variations separately there is no way to correctly phase uplink signals between antennas. Consequently uplink with a single antenna or a small dedicated uplink array would be necessary. These are the same options as are already being considered for up-

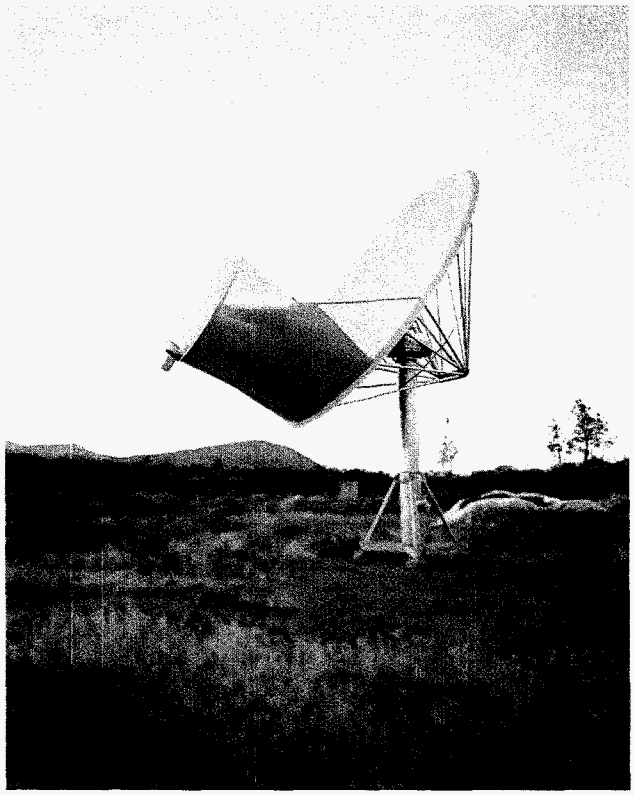


Figure 4. ATA Antenna with Ground Shield

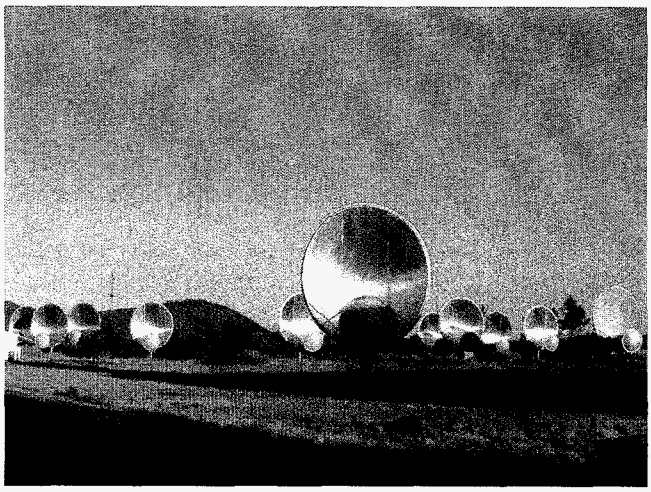


Figure 5. Recently Installed ATA Antennas (photo by R. Forster)

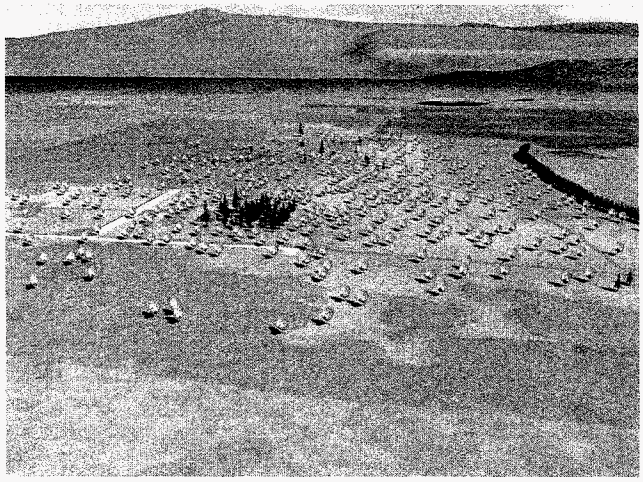


Figure 6. Artist Concept of Completed ATA

link in the current DSN array plan.

5. Cost and Risk Reductions

There are several features of the ATA system design that can be adapted to minimize the cost and development risk of an X-band only DSN array, even if none of the specific ATA hardware designs are used directly. The use of antennas much smaller than 12 meters or even 6 meters in diameter is one example.

Antennas

Table 1 shows representative costs of antennas with diameters between 3 and 12 meters. All of the antennas included here are under construction or are existing commercial products, with the exception of the 12-m hydroformed antenna being considered for the SKA (and the DSN). In this case we have used the detailed design and cost estimates of Schultz[19]. The three smallest diameter antennas listed are commercial off-the-shelf (COTS) products intended for home installation to receive direct satellite broadcast (DBS) television signals. The DBS antenna are all designed to operate up to Ku-band (12 GHz), and thus should work well at X-band.

Note that the cost per square meter of collecting area decreases by nearly an order of magnitude when going from 6-m to 3-m diameter antennas. A likely reason for this is that the DBS antennas are manufactured in very large quantities, while only a few hundred 6-m ATA antennas are being built. This appears to be a good example of mass production driving down the price of an item. It is plausible that there will always be much more demand for smaller diameter antennas than for larger ones. The 12-m antennas are new designs that have not been made in any quantity yet, and they are designed for higher frequency operation, so it is not surprising that their cost per square meter is higher.

The cost estimates in Table 1 include mounts and drives. Some DBS antenna mounts and drives restrict the range of mechanical movement to an azimuth range of about 120 degrees and an elevation range of about 60 degrees. Given that nearly all deep space missions are near the ecliptic plane, full-sky coverage is not essential. The degree to which antenna motion can be restricted depends on the number of array clus-

Table 1. Antenna Cost for Various Diameters

Antenna Diameter & Type	Est. Cost	Cost/m^2
12-m paneled (DSN)	\$ 250 K	\$ 2200 /m^2
12-m hydroformed (SKA)	\$ 150 K	\$ 1300 /m^2
6.1-m hydroformed (ATA)	\$ 30 K	\$ 1000 /m^2
5-m DBS TV antenna (COTS)	\$ 5 K	\$ 270 /m^2
4-m DBS TV antenna (COTS)	\$ 2.8 K	\$ 220 /m^2
3-m DBS TV antenna (COTS)	\$ 1.0 K	\$ 140 /m^2

ter sites, their longitude distribution, and the amount of overlapping coverage required.

Although it is clear than the cost and mass of antenna drive motors and gears will scale with the antenna size, a less obvious issue is the amount of electrical power needed for the antennas drives. For a DSN array based on clusters of hundreds of 12-m antennas the total AC power needed just for moving the antennas is substantial (over a megawatt). This implies a significant power distribution infrastructure and continuing operating costs. For a given total collecting area the number of antennas in a cluster is inversely proportional to the antenna diameter squared. However the mass of each antenna is approximately proportional to volume or diameter cubed, so the total moving mass of all antennas in a cluster is reduced as the antenna diameter decreases. Thus the total power required for the antenna drives is reduced if a larger number of smaller antennas are used.

Receivers

Receivers are an area where a unique design may be warranted, as it is unlikely that any user besides the DSN will have a need for coverage of X-band only. Wide-band systems like the ATA cover X-band, but for the DSN's spacecraft tracking application a wide-band receiving system is not an advantage. Indeed, such a system is susceptible to strong RFI at frequencies far outside the protected deep space downlink frequency allocation. But if we pursue the idea of using antennas much smaller than 12 meters, it follows that our receivers must be much less expensive than the current DSN design since we will need many more of them. The cost of a cooled front end is dominated not by the cost of the low noise amplifier but by the cost of the cryocooler and dewar. Thus, it is the cost of cooling that we need to minimize.

Table 2 lists the noise performance of receivers at different physical temperatures. It is worth noting that uncooled COTS amplifiers for DBS home antennas are available with noise figures of 0.7 dB at Ku-band, corresponding to a noise temperature of about 50 K.

Table 2. Receiver and Total System Temperatures at Various Physical Temperatures

Physical Temp.	Refrig. Type	T_{rcvr}	T_{sys}
4.2 K	J-T exp. nozzle	4 K	18 K
15 K	Sterling cycle	10 K	25 K
80 K	Pulse tube	20 K	40 K
300 K	Uncooled	45 K	80 K

Cryocoolers

We see that in going from the current DSN design of 15K cooling to the ATA design with 80K cooling the system temperature increases by nearly a factor of two. In going to a completely uncooled front end the system temperature increases by more than a factor of 3. This represents a serious reduction is sensitivity. What would we gain in return? Table 3 lists the electrical power required for a number of cryogenic refrigerator types. Not surprisingly, as the physical temperature a refrigerator produces is increased, there is a very large decrease in the input energy required.

Table 3. Power Requirements for Cryocoolers

Refrig. Type	Temp.	Input Power	Lifetime
Gifford-McMahon	15 K	> 1000 W	18,000 hrs
Sterling	40 K	155 W	50,000 hrs
Pulse Tube	80 K	40 W	>80,000 hrs
Uncooled	300 K	0 W	Infinite

For the cryocoolers typically used today on prototype DSN antennas (GB-15 and CTI 350 models operating at physical temperatures of 15K), the power requirements are between 1.2 and 1.8 kW. If similar cryocoolers were used on the 400 antennas of a DSN array cluster, the total electrical load just for cooling would be a significant fraction of a megawatt. This approaches the AC power required for the antenna drives. Of course for larger numbers of smaller antennas this would an even greater issue. Giving up a small amount of performance in system temperature by going from 15K to 40K physical temperature, we reduce the electrical power required by an order of magnitude and simultaneously increase reliability by a factor of almost 3. The Sterling cycle system listed in the table is made by Sunpower and sells for \$2K in quantities of 10,000.

More dramatic power savings are possible by going to the ATA style pulse tube cryocoolers operating at 80K. The input power required for this system is only 40W [14]. The pulse tube technology promises extremely long lifetimes, but this has not yet been verified on the ATA antennas. If we used this type of cooling for an X-band DSN array we would sacrifice a factor of almost 2 in system temperature but would reduce

the electrical power requirements by a factor of about 30 and probably increase the maintenance-free lifetime of the system by a factor of several. The ATA coolers were designed by NIST to be very low cost, and to have a maintenance-free lifetime of at least 10 years.

Signal Transport

The concept of transporting the full RF band from each antenna to a central processing site over fiber optic cables is applicable to an X-band only DSN array. This approach would not be affordable currently for RF frequencies as high as Ka-band. Both the current DSN array design and the ATA use analog modulation of optical fibers, but the DSN design includes phase stable frequency downconverters at each antenna and modulates the optical signal at a relatively low intermediate frequency ($\sim$1 GHz). The ATA modulates the optical signal directly at the RF frequency (up to 11.5 GHz). This would obviously work well for an 8 GHz RF signal.

There are three main advantages of the ATA approach. First, there is the advantage for operations and maintenance of having all of the array electrons (except the initial RF amplifiers) located at a single, shielded, climate controlled location. This minimizes the time and cost associated with debugging and repair, and also makes it straightforward to periodically replace and update equipment made obsolete by Moore's law. The second advantage is in minimizing the complexity of systems at the antennas, where they are exposed to greater environmental stress and are more difficult and expensive to maintain and replace. A final advantage is the removal of a need to actively monitor and compensate for fiber optic cable delay and phase variations. This eliminates one entire monitor and control system, and reduces the number of fibers needed per antenna.

Phasing of the array would include the delay and phase error contribution of the fiber optic cables used for signal transport. In principle this type of error is no different than other antenna-based error, such as the effects of tropospheric propagation, mispointing, or changes in system temperature. All of these antenna-based errors are solved for and removed during the array calibration process. Because the DSN array clusters and the ATA are similar in size, and both operate at X-band, the non-recurring engineering done by the ATA on their signal transport system is directly relevant. This reduces the technical risk to the DSN array for this part of the system.

6. Signal Processing Implications

The most obvious challenge to the "very large numbers of very small antennas" approach for arrays is the dramatic increase in signal processing required. For example, a DSN array cluster with 10,000 small (3-5 m) diameter antennas would have approximately 5×10^7 simultaneous baselines. There are two ways to handle this. First, we could pre-cluster antennas into smaller groups that were compact enough that real-time phase corrections were rarely needed at X-band. These compact sub-arrays would then be treated as single antennas during the full-cluster beamforming or cross-correlation process. Second, we could recognize that we can get by without cross-correlating all possible pairs of antenna and use beamforming architectures whose hardware scales with N instead of N^2. See, for example, the SUMPLE algorithm described by Rogstad[18].

Much work has been done recently on estimating the computing costs, and in particular the scaling of these costs, for the SKA (e.g., [3], [4], [6],[15]). However, almost all of this work has been based on the SKA requirement to produce high quality images of large fields of view. The DSN arrays have no such requirement, which results in a very significant savings in computing resources. For the DSN not only can we get away with signal combining hardware whose cost scales linearly with the number of antennas, but we also need only a small fraction of the bandwidth planned for the SKA. More relevantly, an X-band only array needs only one tenth of the signal processing bandwidth of an X/Ka-band array.

In a recent DSN array cost study by Statman, et al. [20], the cost of signal processing for downlink was estimated at \$20K per antenna. For an array cluster of 400 antennas, this gives a total signal processing cost of \$8M. However, this assumed a maximum bandwidth of 500 MHz. For an X-band only array, the maximum bandwidth need be only 50 MHz. The cost of most hardware for signal processing is likely to scale approximately linearly with bandwidth, so the equivalent signal processing cost for an X-band array would be about \$2K/antenna. This is affordable even for arrays with thousands of antennas.

7. Tradeoffs

The current DSN array is based on 12-meter diameter antennas. This size was chosen to minimize the life-cycle cost of the array, based on a number of assumptions [20]. A critical assumption is the cost of the RF system on each antenna (feed, low-noise amplifier, cryogenics, frequency downconverter, and intermediate frequency amplifiers). In the DSN cost study the RF system was assumed to cost \$100K per antenna, independent of the antenna diameter. This in turn forces the cost minimum to occur at a relatively large antenna diameter.

For the currently planned 400 antennas in a DSN array cluster, the total cost of the antennas will be between \$60M and \$100M (see Table 1), the cost of the RF systems (receivers) will be \$40M, and the cost of signal processing will be \$8M. There are many other costs associated with the entire array (see [20]), but the antenna, RF system, and (for arrays of smaller diameter antennas) signal processing costs dominate so we will concentrate on these three areas.

Now let us consider the costs of using a much larger number of smaller antennas with less expensive RF systems. As a specific example, let us consider an X-band only array using

COTS antennas with diameters of 5, 4, and 3 meters. The current purchase prices for these antennas are about $5K, $2.8K, and $1.0K. To provide the same collecting area as four hundred 12-m antennas, we will need 2300, 3600, and 6400 antennas, respectively. However, we also need to take into account the high system temperatures implied by lower cost RF systems. Let us assume that for 5-m antennas we could use RF systems with low-noise amplifiers (but not feeds) cooled to 80K by ATA-type pulse tube cryocoolers. In this case the system temperature would be about twice that of a DSN feed and amplifier cooled to 15K. Thus, we need twice the total number of antennas, or 4600 in this case. For 4-m antennas we could use a similar RF system or a completely uncooled one. For 3-m antennas probably only uncooled RF systems make sense. For an uncooled feed and amplifier the system temperature will be about 3.2 times higher than for the DSN design, with a corresponding increase in the number of antennas.

Table 4 lists the costs of the 5, 4, and 3-m antenna options, along with the current (paneled) 12-m DSN antenna and the lower cost DSN/SKA hydroformed 12-m antenna design. In the fifth table column, SP is signal processing. This is assumed to be a constant $2K per antenna (see discussion above).

Table 4. Array Cost vs. Antenna Diameter

Dia.	Number	$/Ant.	RF/Ant.	SP Tot.	Total
12-m	400	$250K	$100K	$0.8M	$141M
12-m	400	$150K	$100K	$0.8M	$101M
5-m	4600	$5K	$2K	$9.2M	$41M
4-m	7200	$2.8K	$2K	$14M	$49M
4-m	11,520	$2.8K	$0.5K	$23M	$61M
3-m	20,480	$1.0K	$0.5K	$41M	$72M

It is clear that the 5-m and 4-m COTS antenna options are significantly less expensive than even the hydroformed 12-m option. The smaller diameter options using uncooled RF systems are more expensive because signal processing costs dominate. If Moore's law allows further reductions in signal processing costs, these may become the minimum cost options in the future.

8. Conclusions

An X-band only array could be a viable option for the DSN during the next two decades. This depends entirely on the true need for downlink data rates >> 100 Mb/s from multiple missions during this period. In the longer term, data rates will doubtless continue to increase and Ka-band and/or optical links will be required. However, even then it is likely that X-band will continue to be used as a low risk backup for telecommunications and perhaps for spacecraft navigation. As a result, investment in a near-term X-band only array will continue to be useful beyond the epoch where X-band is able to handle the full downlink data requirements of deep space missions.

For a similar total sensitivity, the approach described here implies a large increase in the total number of antennas in the array compared with 12-m antennas. Nevertheless the total cost should be significantly less because the relatively narrow bandwidth keeps signal processing costs reasonable and the cost per of unit collecting area is reduced by more than an order of magnitude.

9. Acknowledgements

The author thanks T. Cornwell for inspiring this paper by re-emphasizing the case for smaller diameter antennas for the SKA [5]. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the U.S. National Aeronautics and Space Administration.

Technical memos from the SKA[3] and ATA[4] projects and the Inter-Planetary Network (IPN) Progress Reports from JPL[5] have been particularly helpful in this study.

References

[1] D.S. Abraham, "Identifying Future Mission Drivers on the Deep Space Network," *Proc. Space Ops. 2002*, (Houston, TX), Paper T3-64, 1–10, 2002.

[2] D.S. Bagri, "A Proposed Array System for the Deep Space Network," *IPN Progress Report,* **42-157**, 1–16, 2004.

[3] J. Bunton, "SKA Signal Processing Costs", *SKA Memo 65*, 2005.

[4] T.J. Cornwell, "SKA and EVLA Computing Costs for Wide Field Imaging (Revised)," *SKA Memo 49*, 2004.

[5] T. Cornwell, "LNSD Reconsidered – the Big Gulp Option," *SKA Memo 61*, 2005.

[6] T.J. Cornwell, "SKA Computing Costs for a Generic Telescope Model", *SKA Memo 64*, 2005.

[7] D.R. DeBoer and R. Ackermann, "Measurements of the Allen Telescope Array Performance as an Interferometer," *ATA Memo 60*, 2003.

[8] D.R. DeBoer, W.J. Welch, J. Dreher, J. Tarter, L. Blitz, M. Davis, M. Fleming, D. Bock, G. Bower, J. Lugten, G. Girmay-Keleta, L.R. D'Addario, G.R. Harp, R. Ackermann, S. Weinreb, G. Engargiola, D. Thornton, and N. Wadefalk, "The Allen Telescope Array," *Proc. SPIE*, **5489**, 1021–1028, 2004.

[3] Complete copies of Square Kilometre Array memos are available at http://www.skatelescope.org/pages/documents_3.htm .

[4] Complete copies of Allen Telescope Array memos are available at http://astron.berkeley.edu/ral/ata/memos .

[5] Complete copies of IPN Process Reports are available at http://ipnpr.jpl.nasa.gov/tmo/progress_report .

[9] J.W. Dreher, "Phase Stability of ATA Fiber Optic Cables," *ATA Memo 55*, 2003.

[10] M.S. Gatti, "The Deep Space Network Large Array," *IPN Progress Report*, **42-157**, 1–9, 2004.

[11] G.R. Harp, M.C. Fleming, R.A. Ackermann, D.R. DeBoer, and G.C. Bower, "Pointing the ATA Dishes," *ATA Memo 61*, 2003.

[12] D.L. Jones, "Geometric Configuration Constraints for Large Deep Space Network Arrays," *IPN Progress Report*, **42-157**, 1–9, 2004.

[13] S.J. Keihm, A. Tanner, and H. Rosenberger, "Measurements and Calibration of Tropospheric Delay at Goldstone from the Cassini Media Calibration System," *IPN Progress Report*, **42-158**, 1–17, 2004.

[14] J.B. Lugten, R. Radebaugh, and M.A. Lewis, "Low-Cost Cryocoolers for the Allen Telescope Array," *Advances in Cryogenic Engineering*, **49** (*AIP Conf. Proc.*, **710**), 1367–1372, 2004.

[15] C.J. Lonsdale, S.S. Doeleman, and D. Oberoi, "Imaging Strategies and Postprocessing Computing Costs for Large-N SKA Designs," *SKA Memo 54*, 2004.

[16] D.D. Morabito, "Atmospheric-Induced Amplitude and Phase Fluctuations at Ka-Band," *IPN Progress Report*, **42-151**, 1–19, 2002.

[17] D. Plambeck, J. Cartwright, and D. Thornton, "Tests of an ATA Amplifier and Fiberoptic Link," *ATA Memo 54*, 2003.

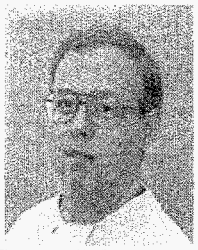
[18] D.H. Rogstad, "The SUMPLE Algorithm for Aligning Arrays of Receiving Radio Antennas: Coherence Achieved with Less Hardware and Lower Combining Loss," *IPN Progress Report*, **42-162**, 1–29, 2005.

[19] R. Schultz, "USSKA Antenna Development," *SKA Memo 63*, 2005.

[20] J.I. Statman, D.S. Bagri, C.S. Yung, S. Weinreb, and B.E. MacNeal, "Optimizing the Antenna Size for the Deep Space Network Array", *IPN Progress Report*, **42-159**, 1–8, 2004.

[21] A.R. Thompson, "Spatial Nulling for Attenuation of Interfering Signals," *SKA Memo 34*, 2003.

[22] J.S. Ulvestad, "Phasing the Antennas of the Very Large Array for Reception of Telemetry From Voyager 2 at Neptune Encounter," *TDA Progress Report*, **42-94**, 257–273, 1988.



Dayton Jones *is a Principal staff member and Supervisor of the Astronomical Measurements Group at the Jet Propulsion Laboratory, Caltech, Pasadena, CA. His research interests include extragalactic astronomy, particularly high resolution imaging using radio interferometry, and the development of the Square Kilometer Array by the international radio astronomy community. He is an author on over 100 papers in the scientific literature. Dr. Jones obtained M.S. degrees in scientific instrumentation from UCSB in 1976 and in astronomy from Cornell University in 1979, and a Ph.D. in astronomy from Cornell University in 1981. He is a member of the International Astronomical Union, American Astronomical Society, International Radio Science Union, Astronomical Society of the Pacific, and Sigma Xi.*