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Pros and Cons of Using Arrays of Small Antennas versus Large Single-Dish Antennas for the Deep Space Network

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This article describes briefly the pros and cons of using arrays of small antennas instead of large single-dish antennas for spacecraft telemetry, command, and tracking (TT&C), communications and navigation (C&N), and science support that the Deep Space Network (DSN) normally provides. We consider functionality and performance aspects, mainly for TT&C, though we also consider science. We only briefly comment on the cost aspects that seem to favor arrays of small antennas over large single antennas, at least for receiving (downlinks).

I. Introduction

The Deep Space Network (DSN) antennas of the National Aeronautics and Space Administration (NASA), especially the 70-m antennas, which provide most of the collecting area, are getting older and are becoming less reliable than desired. Further, it is difficult for the 70-m antennas to provide reliable operation at 32 GHz (Ka-band), where there is a 500-MHz-wide spectrum allocation compared to only 50 MHz at 8 GHz (X-band). In the future there may be a need for support for more deep-space missions, and also a need for increasing data rates from these missions. This means there may be a need for more sensitivity (A/T, where A is antenna effective collecting area and T is system temperature) at both X- and Ka- space communication bands. Therefore, it may be necessary not only to replace the aging antennas but also to increase the sensitivity (A/T) of the DSN.

Because the cost for large antennas increases as $d^{2.7}$ (where d is dish diameter) [1], the cost of building large antennas increases much faster than the effective collecting area, and there is hardly any possibility of using mass production techniques to lower the antenna cost since there is only a limited market for very large antennas. On the other hand, the commercial communications market has driven improvements in technology that have enabled low-cost, small (<~ 10 m in diameter) antennas to be mass produced, thus reducing their cost considerably. The consumer market is driving continuous improvements in both receivers and digital electronics, so their reliability has become very good and cost has continued to decrease. These advances raise the interesting possibility of using arrays of small antennas for the DSN. The NASA Space Communication Architecture Working Group (SCAWG), which examined the question of architecture for the future ground-based communications

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and navigation (C&N) system for NASA, recommended an architecture based on arrays of small antennas to replace existing old large antennas and for any future expansion in the ground capabilities of the C&N system [2]. This is because arrays promise higher reliability, better utilization of resources, more flexibility in operations, and lower overall cost than large single antennas. Therefore, it becomes interesting to examine the pros and cons of using arrays of small antennas versus large single dishes in terms of functionality, performance, and overall cost.

II. Cost Considerations for Receiving (Downlink)

Cost is considered only briefly because addressing it in detail involves a lot of complexity. The cost depends on assumptions about technologies, amount of A/T, how operations are run, etc. We do not have models that can accurately predict the cost of either large single antennas or array systems over a wide range of parameter space. One can do a parametric cost study to figure out the cost of arrays, but there are simply too many variables and not enough data to draw direct conclusions, except general trends based on experience. It may be possible to do some cost analysis for specific plans and assumptions, but that may not be very useful for a general discussion.

In general, the larger the A/T required, the lower the cost per unit sensitivity (A/T) using the array approach because mass production techniques can be employed. On the other hand, the cost of large single antennas increases with increasing size of the antenna as $d^{2.7}$. If the cost of development (nonrecurring expense, NRE) is not included, and the cost of only construction and operations/maintenance is considered, it has been shown that receive arrays of small antennas (including electronics) are less expensive than an equivalent A/T using large single antennas;[1] e.g., for construction cost see [3], for maintenance see [4]. The cost for operations should be similar for the two systems, except debugging, fault finding, and calibration in general should be easier for arrays because far more data consistency tests are possible.

At some point when more A/T is required, it becomes difficult to build very large antennas, and arraying of a few large antennas to get a very large A/T has problems of high sidelobes for the synthesized array beam. This is because there are only a few antennas forming the array and root mean square (RMS) sidelobes for a synthesized array beam are generally only about a factor of N (where N is number of antennas in the array) smaller than the main response. Sidelobe levels are important when multiple spacecraft are being tracked simultaneously by multiple beams, because the sidelobes determine the level of cross-talk between signals in different beams.

III. Cost Considerations for Transmitting (Uplink)

The cost considerations for uplinks are more complex because they involve optimizing the size of antennas, transmit amplifiers, and equivalent isotropic radiated power (EIRP) of the

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[1] "DSN Array Life Cycle Cost Study," Ball Aerospace, May 2004 (proprietary/restricted); Bruce MacNeal, "Cost Analysis of Ball Study Results," personal communication, Jet Propulsion Laboratory, Pasadena, California, June 2004.

array at the same time. The EIRP for an array is given by N^2 times EIRP of an individual antenna (where N is the number of transmit antennas), so the number and size of antennas and the size of power amplifiers will depend on the array EIRP. However, it appears that for a reasonable range of parameters, the cost of construction and maintenance should be lower for using an array approach than using single large antennas.[2]

IV. Major Pros and Cons for TT&C, Science Support, and General Considerations

We describe major pros and cons of using arrays of small antennas versus large single dishes for the DSN, a ground segment of NASA's space communication and navigation system. In Table 1, we limit ourselves essentially to technical aspects of the main functions and performance as related to TT&C services, mission science support, and other science support that the DSN provides normally, and a few general aspects. We do not explicitly consider cost for the reasons described previously.

Table 1. Pros and cons of arrays of small antennas versus single large antennas.

Pros	Cons
Telemetry	
• Flexibility in matching capacity to requirements allows better utilization of resources. • Higher reliability: trading reliability of mechanical systems (big antennas) with more electronics. Electronics in general has much higher reliability, requires less maintenance, is easier to monitor, and can be quickly replaced compared to mechanical hardware. • Failure of one or a few small antennas causes graceful degradation in sensitivity or can be compensated by adding from spares/lower priority tasks or maintenance/calibration pool. • It is possible to use the same spectrum for multiple spacecraft in the same array antenna beam simultaneously, as long as multiple spacecraft are not in the same synthesized array beam. This may require a radio frequency interference (RFI) nulling approach to realize the full advantage. • RFI excision using nulling approach is possible. • Lost spacecraft search easier due to wider field of view of the individual antennas making up the array. • Easier to expand (A/T) capacity. • Lower system temperature for a synthesized beam, especially when the synthesized beam is near a planet but not looking at the disc of the planet. The array antennas have a large field of view and therefore the increase in the system temperature for the individual antennas is small compared to monolithic large antennas (see Appendix). Also, the filling factor for a synthesized array beam is small, so the increase in the system temperature when pointed at a planet is smaller than for a	• More electronics and number of things to control, though they are automated. • Phasing, especially in bad weather at Ka-band on weak sources, is more complex and may have combining losses, which will increase with the severity of the weather. Phasing can be done using radio sources within the antenna beam if there is enough sensitivity to monitor a suitable source(s) in the beam. • Effective sensitivity (system noise temperature for the signal detection) for array will depend on the instantaneous synthesized beam and all the sources in it. Therefore, the system temperature for a spacecraft signal will vary as the spacecraft goes around a planet or the array projected baselines change. However, these variations are predictable. Single dish antennas are also susceptible to variations in system temperature due to planetary emission in the antenna beam.

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[2] Larry D'Addario, "Cost Models for Transmit Array," personal communication, Jet Propulsion Laboratory, Pasadena, California.

Table 1. Pros and cons of arrays of small antennas versus single large antennas (continued).

Pros	Cons
Telemetry — continued	
single large antenna. For example, the noise contribution from the planetary disc in some cases is about an order of magnitude more for a 34-m antenna versus an array of 10-m antennas. • The array antennas have a wider field of view. Therefore, the possibility of having suitable calibration radio source(s) in the antenna beam increases with decreasing the array antenna size and the same overall A/T. This can be used to make array phase calibrations while observing a weak spacecraft signal.	
Command (uplink)	
• It is possible to use solid-state transmitters for arrays instead of vacuum tubes needed for high power transmitters used on large single antennas. This allows larger transmitter bandwidth, increases reliability, and reduces maintenance. • Total array EIRP = N^2 * EIRP of each array antenna. This implies that the array EIRP increases rapidly with the number of antennas in the array, and can become extremely large. • Easier maintenance without interrupting normal operations is possible with proper planning because few antennas can be taken out at a time for service/maintenance.	• Phasing and maintaining phasing of the uplink arrays needs to be developed. • Instantaneous larger sky coverage for uplink signals with single large antennas compared with arrays allows better chances of commanding a lost or malfunctioning spacecraft, but steering an uplink signal in different directions may be easier for an array. This is because arrays allow electronic steering over the wider beam of the array antennas, and also smaller antennas of an array can be generally moved faster than large antennas. The relative merit of the faster steering of the uplink beam depends on the fraction of time spent in moving antennas to the total time.
Tracking	
• With the use of smaller antennas for arrays, it is easier to switch rapidly between observations of calibration sources and spacecraft for high-accuracy angular position observations, e.g., delta differential one-way ranging (ΔDOR) observations. This is useful to reduce calibration errors and improve the angular measurement accuracy [5,6]. • The use of small antennas for arrays increases the probability of having a suitable calibration source in the same beam as the spacecraft [7]. Thus, same-beam interferometry (SBI) becomes practical, which may be capable of providing the ultimate in relative angular position accuracy with respect to nearby calibration source(s). (A summary of the error sources affecting angular position accuracy and how SBI will help is in preparation.[3]) • Accurate Earth-orientation parameters and radio source catalogs for ΔDOR become easier because more frequent measurements will be possible using one or a few of the antennas from an array at each Deep Space Communications Complex (DSCC).	• It has been suggested that range calibration using separate receive and transmit arrays can be done and there are no adverse effects of arraying on tracking performance [8]. However, the technique needs to be developed for practical use, especially if at least one of the antennas in the system doesn't have both transmitting and receiving capabilities. If one of the antennas in the system has both receive and transmit, then one can phase all the antennas in transmit and receive arrays using this antenna as a reference, and then use range calibration of this antenna to determine the range of a spacecraft, as is done now for DSN ranging [9].

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[3] D. S. Bagri, "Measuring Angular Position of a Weak Radio Source Using the Deep Space Network: For Use as a Calibrator to Determine Accurate Angular Position of a Spacecraft," in preparation.

Table 1. Pros and cons of arrays of small antennas versus single large antennas (continued).

Pros	Cons
Science/mission support/enhancement	
• Some mission science and some of the other science may be easier or possible only with arrays, especially when interferometer visibility data (cross-correlations of signals from antennas) can be used. Many science observations are harder or not possible with single-dish instruments (e.g., accurate angular positions of sources, or measurement of the flux densities of weak compact radio sources). This is because arrays provide much higher angular resolution and greatly enhanced sensitivity for signal detection.	• Signal-to-noise ratio (SNR) for arrays is reduced compared to single dish of equivalent *A/T* due to loss of coherence in the signal combining, although generally this is small compared with the effects of receiver gain variations, tropospheric fluctuations, and RFI at a single dish.
General	
• Most calibrations and/or tests can be done on a non-interference basis, using a few antennas at a time. This allows easier initial debugging and integration of the system, and regular calibration using radio sources. • Easier maintenance without interrupting normal operations is possible with proper planning, as a few antennas can be taken out at a time for service/maintenance. The rest of the system can remain available. This should also allow the maintenance staff to be used more efficiently. • Keeping only a few percent of array antennas as spares allows flexible maintenance, calibration, and optimized matching of resources with requirements. • Architecture based on using separate transmit and receive antennas becomes economically desirable when arraying is considered. This allows the use of efficient strategies, e.g., —Physical separation between transmit and receive arrays simplifies antenna electronics because of reduced isolation requirements for receive system in the transmit frequency band. —Different antenna sizes for transmit and receive antennas, separately optimized. —Different numbers of antennas for transmit and receive arrays. —Transmit antennas looking at a target only when required, independent of receive/downlink. —Possibility of using one transmit array at a DSCC and time multiplexing transmissions to multiple targets spacecraft at a low duty cycle but higher data rate; this utilizes the fact that total array EIRP = N^2 * EIRP of each array antenna, but requires spacecraft to accept uplink data in high-data-rate bursts. • Arrays allow increasing the system sensitivity to very large values, essentially without any limit, by adding more antennas in the system, with	• Control software is more complex but has been done for other arrays. • There is considerable experience in universities and other laboratories around the world in building and efficiently operating receive arrays, but there is no experience in using transmit arrays (except for phased-array radar, which has only limited relevance).

continued

Table 1. Pros and cons of arrays of small antennas versus single large antennas (continued).

Pros	Cons
General — continued	
only linear increase in the cost with sensitivity. This would allow building simpler and less expensive communications equipment on spacecraft. As a ground communications system is a multimission capability, this has the effect of reducing communications cost of the space segment of most missions, when arrays with large enough sensitivity (*A/T*) become available for routine operations. This is unlike the case of single large antennas where the cost increases much more rapidly than the antenna sensitivity (because cost $\propto d^{2.7}$, as described earlier), and beyond a certain point it may not be possible to increase the sensitivity because of the technology limits on the size of the large antennas (currently about 100 m in diameter).	

V. Summary and Conclusion

Basically, large single antennas and arrays of small antennas, perhaps in the range of 6 to 18 m in diameter, are the two architectures that have been considered for deep space communications and tracking. Each of these architectures has its advantages and limitations, especially when it comes to science.

From functionality and performance considerations, the array architecture has many advantages for telemetry and tracking. Some of these are: observing multiple spacecraft simultaneously using the same RF spectrum, same-beam interferometry that can enable very accurate angular tracking of spacecraft, potentially lower system temperatures while observing target(s) near planets, and nulling of RFI. Also, there are operational advantages of using an array architecture, such as matching resource allocations to capacity requirements, higher reliability, flexibility in scheduling, ease of calibration and maintenance, fewer spares required, and ease of future expansion. Though it requires more complicated software to control and monitor the array systems compared with that needed for large single antennas, it is done routinely for many instruments (arrays) successfully (e.g., see [10,11]), so this shouldn't be a cause for concern if we are willing to learn from others' experience.

A question arises about the array combining loss due to atmospheric variations affecting the phasing of the array when array antennas have to be spread out to avoid shadowing at low elevations. The optimum size of the array should be part of a configuration study, but from practical considerations it may be desirable to use an array size of 1 to 2 km in diameter. When the array can be continuously phased on the signal from a source in the beam (normally the spacecraft signal), the phasing loss will be negligible. Even when in-beam phasing is not possible and periodic phasing with other calibration sources is necessary, the combining loss due to atmospheric fluctuations for a 1-km array extent should be generally (about

95 percent of the time) less than a few percent at X-band, and less than about a decibel (rms phase fluctuations less than 0.6 radian) at Ka-band for most reasonable sites (e.g., see [12]). Also, generally one can keep the phase variations of the array antennas small by using nearby antennas of the array instead of more distant antennas when the source signal is weak and/or weather is not likely to be good, and thereby keep the combining losses due to tropospheric variations low.

The technology for downlink arrays has been around for a long time. Arrays have been considered for space communications in the past (e.g., see [13]), but more recent technology advancements have made arrays more reliable and cost effective, and technology advances with time make the array approach ever more attractive for space communications. How to build and operate receive arrays is well understood, and many arrays are operated economically with high reliability (e.g., see [10,11]). On the other hand, the phasing of uplink arrays and how an array will perform is not understood well, and needs to be established.

A direct cost comparison for arrays of small antennas versus large single dishes is difficult, except for general trends based on experience, unless a specific implementation is considered. The life cycle cost considerations by a group of independent consultants, based on some general requirements, seem to favor arrays over large single dishes.

In conclusion, there are substantial advantages in using arrays of small antennas instead of large single antennas to receive (downlinks) for telemetry and tracking services, but some development work is necessary before arrays can be employed for uplinks to spacecraft. For mission science support and other science applications, arrays of small antennas have advantages in some cases but may be limited in others compared with large single antennas. This is especially true if the arrays are designed mainly from the TT&C considerations.

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Appendix

System Temperature Increase due to Planets for a 34-m Antenna, a 70-m Antenna, and an Array of 10-m Antennas, and the Increase in Data Rate for an Array Over a Large Antenna with the Same Effective Collecting Area

We describe the system temperature increase due to planets for a 34-m antenna, a 70-m antenna, and an array of 10-m antennas, and the increase in data rate for an array over a large antenna with the same effective collecting area.

As long as the angular size of the disc of a planet is much smaller than the beam of a single dish or instantaneous (synthesized) beam of an array of small antennas, the contribution to the system temperature due to the brightness temperature of the planetary disc is the same for the two systems. When the size of the array beam becomes similar or smaller than the planetary disc, the noise contribution for the array is less than that for a single dish. This is because the part of the planetary disc that is outside the synthesized beam doesn't contribute to the array output.

To estimate a rough magnitude of the effect, we make some simplifying assumptions. We assume that the gain of the array in the direction of the main peak of the synthesized beam is constant over the synthesized beam half-power beamwidth (HPBW), and zero in other directions. In the same way, for a single dish the gain for all directions within the main beam is constant, and zero outside it. Also we assume that the array beamwidth is given by observing wavelength divided by the array size projected in the direction of the source, and in the single-dish case, the beamwidth is given by the wavelength divided by the diameter of the antenna. It should be noted that the projected size of the array is foreshortened by roughly the cosine of the angle from the zenith (e.g., at 60 deg zenith angle, a 1-km circular array would have a projected extent of 1 km by 1 km *cos 60 deg or 0.5 km). This affects the size and shape of the synthesized array beam, but the total array collecting area, and therefore the array sensitivity, remains constant until antenna shadowing occurs at low elevations.

The contribution of a planetary disc to the system temperature for a single dish is assumed to be equal to the fraction of the antenna beam covered by the planet multiplied by the disc brightness temperature for the planet. The contribution of a planet to the noise in an array, when the array synthesized beam is equal to or smaller than the planet's angular size, is roughly equal to the disc brightness temperature multiplied by the array filling factor (fraction of the total array area covered by antennas). For a given total array collecting area, the filling factor is directly proportional to the solid angle of the synthesized beam. Higher angular resolution implies a smaller filling factor.

We assume the planetary disc is made up of a number of very compact (essentially point) sources. When the array is phased, the phase of all the antennas will be equal for the sources within the synthesized beam, and therefore the signals from all the antennas for these sources would coherently add. However, signals from other sources outside of the synthesized beam would have different phases at different antennas depending on the baseline, and for a large number of antennas the array output signal for these sources would sum to essentially zero. Thus, the array signal contribution would only include sources within the synthesized beam direction.

This can be expressed mathematically in the following way. The noise contribution T_n from the disc of a planet for both a single dish and an array can be written as

$$T_n = T_b \, \Omega \, A_e / \lambda^2$$

where

T_b is the brightness temperature of the planet.

A_e is the effective area of the antenna (or total collecting area for an array).

λ is the wavelength.

$\Omega = \min(\Omega_p, \Omega_b)$.

Ω_p is the solid angle subtended by the planet.

Ω_b is the solid angle of the beam.

The array beam can be expressed as $\left(\lambda^2 / \text{Array size projected in the source direction}\right)$.

Here, array size refers to the physical extent of the region in which the array antennas are located, not to the array collecting area.

When the array beam is smaller than the planetary disc $(\Omega_b < \Omega_p)$, we get

$$\begin{aligned} T_n &= T_b \, \Omega \, A_e/\lambda^2 = T_b \, \Omega_b A_e/\lambda^2 \\ &= T_b \left(\lambda^2 / \text{Array size projected in the source direction}\right) A_e/\lambda^2 \\ &= T_b \left(A_e / \text{Array size projected in the source direction}\right) \end{aligned}$$

The term $\left(A_e / \text{Array size projected in the source direction}\right)$ is the same as array filling factor (defined as effective collecting area divided by projected area of the overall array looking in the source direction). Therefore, when the array beam is smaller than the planetary disc, the noise contribution from the planet to the array is

$$T_n = T_b * \text{Array filling factor}$$

The noise contributions to the system temperature for various planets at closest and farthest distance from Earth for 34-m antennas, 70-m antennas, and arrays of 10-m antennas are shown in Table A-1. Arrays with equivalent total effective collecting area to a 34-m or 70-m antenna are considered at X-band and Ka-band. Table A-1 applies for array synthesized beams up to the size of the planet. Here, we have used 10-m antennas as an example to give an idea of contribution to system temperature for the arrays using small antennas. Also, for simplicity, and to get a rough idea of approximate numbers for system temperature values, we have ignored effects of atmospheric attenuation, antenna efficiency, etc.

In Table A-1, for each planet, the first row shows the noise contribution due to the part of the planet seen by the array synthesized beam, the second row shows the noise contribution from the planet to each antenna of the array, and the third row shows the total noise contribution from the planet in the array signal. Only the values for cells in the table that are interesting have been calculated. Values of the angular sizes for planets at minimum and maximum distances from Earth are taken from http://wikipedia.com. Brightness temperatures of the planets are taken from [A-1] and the references in it.

Table A-1. Approximate system temperature values for the array of 10-m antennas having equivalent effective collecting area of a 34-m antenna or a 70-m antenna, and having projected size in the direction of the source equal to a circle of diameter 300 m.

Planet	Diameter looking from Earth, arcsec		Disc temp, K	Array beam for projected size 300 m diameter, arcsec		Noise due to planet for 0.3-km array with 34-m antenna equiv effective area				Noise due to planet for 0.3-km array with 70-m antenna equiv effective area			
						X-band		Ka-band		X-band		Ka-band	
	Max dist	Min dist		X-band	Ka-band	Max dist	Min dist	Max dist	Min dist	Max dist	Min dist	Max dist	Min dist
Mercury	5	13	437	25	6.6				5.6				5.6
10-m single-dish contribution, K									1.8				1.8
Total array noise, K									7.4				7.4
Venus	10	66	466	25	6.6		6.0	6.0	6.0		6.0	6.0	6.0
10-m single-dish contribution, K							3.6	1.1	48.4		3.6	1.1	48.4
Total array noise, K						0.1	9.5	7.1	54.4		9.5	7.1	54.4
Mars	4	25	194	25	6.6		2.5		2.5		2.5		2.5
10-m single-dish contribution, K							0.2		2.9		0.2		2.9
Total array noise, K							2.7		5.4		2.7		5.4
Jupiter	30	49	152	25	6.6	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
10-m single-dish contribution, K						0.2	0.6	3.3	8.7	0.2	0.6	3.3	8.7
Total array noise, K						2.2	2.6	5.2	10.7	2.2	2.6	5.2	10.7
Saturn	15	20	150	25	6.6		3	3	3		3	3	3
10-m single-dish contribution, K							0.2	0.8	2.3		0.2	0.8	2.2
Total array noise, K							3.2	3.8	5.2		3.2	3.8	5.2

Estimates of the ratio of data rate for an array of 10-m antennas versus a single dish, when the array beam is smaller than the planetary disc, are shown in Table A-2. Here, the array is assumed to cover a projected circular area with a diameter of 300 m. For comparing the data rates for the two systems, we assume that there is no atmosphere and the system temperature, excluding contribution due to the planetary disc, for both the array and the single-dish systems is 20 K at X-band and 40 K at Ka-band. Also, data rate is assumed to be inversely proportional to the total system noise (temperature). In Table A-2, the array consists of 10-m antennas having the equivalent effective collecting area of a 34-m antenna or a 70-m antenna, and the array size is a 300-m-diameter circle projected in the direction of the source. (Values of total array effective noise due to planet are from Table A-1).

Table A-2. Ratio of data rate for array to single dish when the array beam is smaller than the planet size. Data rate is assumed to be inversely proportional to the total system noise (temperature).

	34-m antenna temp on planet, noise from planet,* data rate ratio‡				70-m antenna temp on planet, noise from planet,** data rate ratio‡			
	X-band		Ka-band		X-band		Ka-band	
Planet Earth–Planet distance:	Max	Min	Max	Min	Max	Min	Max	Min
Mercury								
Large antenna noise from planet	0.2	1.5	3.0	20.4	0.9	6.3	13.0	87.6
Array noise from planet				7.4				7.4
Data rate ratio for array vs. a large single antenna				1.3				2.7
Venus								
Large antenna noise from planet	0.9	41.0	12.9	466.0	4.0	175.0	51.0	466.0
Array noise from planet		9.5	7.1	54.4		9.5	7.1	54.4
Data rate ratio for array vs. a large single antenna		2.1	1.1	5.4		6.6	1.9	5.4
Mars								
Large antenna noise from planet	0.1	2.5	0.8	33.3	0.3	10.4	3.7	144.0
Array noise from planet		2.7		5.4		2.7		5.4
Data rate ratio for array vs. a large single antenna		1.0		1.6		1.3		4.1
Jupiter								
Large antenna noise from planet	2.8	7.4	38.0	101.0	11.7	31.3	150.0	150.0
Array noise from planet	2.2	2.6	5.2	10.7	2.2	2.6	5.2	10.7
Data rate ratio for array vs. a large single antenna	1.0	1.2	1.4	2.8	1.4	2.3	4.2	3.8
Saturn								
Large antenna noise from planet	0.7	1.9	9.4	26.0	2.9	8.0	37.0	111.0
Array noise from planet		3.2	3.8	5.2		3.2	3.8	5.2
Data rate ratio for array vs. a large single antenna		1.0	1.1	1.5		1.2	1.8	3.3

* For 10-m antenna array with 34-m antenna equivalent area

** For 10-m antenna array with 70-m antenna equivalent area

‡ For array vs. large antenna

From the results in Table A-2, we can summarize the increase in data rate (by percentage) at maximum and minimum Earth-planet distance when an array is used relative to a single dish with the same effective collecting area, and the array has projected size of 300-m-diameter circle in the direction of the source. As before, we assume that the system temperature for both systems without contribution from the planet is 20 K at X-band and 40 K at Ka-band, and the data rate is proportional to SNR. Results are shown in Table A-3.

Table A-3. Increase (in percentage) in data rate for an array of 10-m antennas with projected array size of 300 m diameter in the direction of the source and having an equivalent effective collecting area of 34-m and 70-m antennas.

	Delta data increase for the array compared with 34-m antenna, percent				Delta data increase for the array compared with 70-m antenna, percent			
	X-band		Ka-band		X-band		Ka-band	
	At Earth–planet distance							
Planet	Max	Min	Max	Min	Max	Min	Max	Min
Mercury				30				170
Venus		110	10	440		560	90	440
Mars				60		30		310
Jupiter		20	40	180	40	130	320	280
Saturn			10	50		20	80	230

Reference

[A-1] A. Greves, H. Steppe, D. Graham,, and C. J. Schalinski, “Disk Brightness Temperature of the Planets at 43 GHz,” *Astron. Astrophys.*, vol. 286, pp. 654–658, 1994.