Pros and Cons of using Arrays of Small Antennas versus Large Single Dish Antennas for Deep Space Network

D. S. Bagri
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
818-393-4317
Durgadas.S.Bagri@jpl.nasa.gov

Abstract— This paper briefly describes 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. It considers functionality and performance aspects, mainly for TT&C, though it also considers science. It only briefly comments on the cost aspects that seem to favor arrays of small antennas over large single antennas, at least for receiving (downlinks) [1, 2, 3].

TABLE OF CONTENTS

1. INTRODUCTION

Reason for this study - Deep Space Network (DSN) antennas of the National Aeronautics and Space Administration (NASA), especially the 70m antennas, which provide most of the collecting area, are getting older and less reliable than desired. Further, it is difficult for the 70m 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). It has been pointed out that in the future there will be a need for supporting more deep space missions, and increasing data rates from these missions. This means there will be a need for more sensitivity (A/T, here A is antenna effective collecting area, and T is system temperature) at both X and Ka space communication bands. Therefore, it may not only be necessary to replace the aging antennas but also to increase the sensitivity (A/T) of the DSN.

As the cost for large antennas increases as $d^{2.7}$ (here d is dish diameter) [1], so 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 as there is only a limited market for very large antennas. On the other hand, the commercial communications market has driven improvements in technology that has enabled low cost, small size (<~ 10m 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. Also the Space Communication Architecture Working Group (SCAWG) of NASA, which examined the question of architecture for the future ground based communications and navigation (C&N) system for NASA, recommended an architecture based on arrays of small antennas to replace existing old large single dish 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 dish 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.

2. 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 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 plan and assumptions but that may not be very useful for a general discussion.

1———————————
[1] 978-1-4244-2622-5/09/$25.00 ©2009 IEEE
[2] IEEEAC paper #1573, Version 3, Updated December 09, 2008
[3] The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with National Aeronautics and Space Administration.

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 (non recurring 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[4]; 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 RMS (root mean square) 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.

3. COST CONSIDERATIONS FOR TRANSMITTING (UPLINK)

The cost considerations for uplinks are more complex because they involve optimizing the size of antennas, transmit amplifiers, and EIRP (equivalent isotropic radiated power) of the array at the same time. The EIRP for an array is given by N^2 times EIRP of an individual antenna (here 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, using separate transmit and receive arrays, the cost of construction and maintenance should be lower for using array approach than using single large antennas for both transmit and receive[5].

4. 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 Deep Space Network (DSN), a ground segment of the space communication and navigation system of NASA. In what follows we limit ourselves essentially to technical aspects of the main functions and performance, as related with telemetry, tracking and command (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.

5. SUMMARY AND CONCLUSION

Basically, large single antennas and arrays of small antennas, perhaps in the range of 6-18 m diameter, are the two architectures which 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 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 to large single antennas, it is done routinely for many instruments (arrays) successfully (e.g. see [11], [12]), 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 1-2 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 combing loss due to atmospheric fluctuations for a 1 km array extent should be generally (about 95% 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 [13]). 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.

2

[4] DSN Array Life Cycle Cost Study prepared by Ball Aerospace, May 2004 (Proprietary/ restricted); Bruce MacNeal, "Cost Analysis of Ball Study Results", JPL Internal Memo, Jun 2004, Private communication.

[5] Larry D'Addario – Private Communication

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 [14]), but more recent

Table 1 Pros and Cons of using arrays of small antennas versus large single dishes

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. • 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 radio frequency interference (RFI) nulling approach to realize the full advantage. • RFI excision using nulling approach 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 disk 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 using monolithic large antennas (see Appendix 1). 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 single large antenna. For example, the noise contribution from the planetary disc in some cases is about an order of magnitude more for a 34m antenna versus an array of 10m antennas. • The array antennas have a wider field of view. 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.	• More electronics and number of things to control, though they are automated. • Phasing, especially in bad weather at Ka-band on weak sources, 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 it 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.
Command (Uplink) -	
• Its 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 = N2 * 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 as few antennas can be taken out at a time for service/maintenance.	• Phasing & maintaining phasing of the uplink arrays needs to be developed. • Instantaneous larger sky coverage for uplink signals with single large antennas than 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

Pros	Cons
	antennas. The relative merit of the faster steering the uplink beam depends on 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-DOR (delta differential one-way ranging) 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). (For a summary of the error sources affecting angular position accuracy and how SBI will help, see [8]). • Accurate earth orientation parameters and radio source catalogs for delta-DOR becomes easier because more frequent measurements will be possible using one or a few of the antennas from an array at each complex.	• 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 [9]. 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 [10].
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 due to the fact that 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 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. o Physical separation between transmit and receive arrays simplifies antenna electronics because of reduced isolation requirements for receive system in the transmit frequency band.	• Control software 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 using transmit arrays (except for phased array radar, which has only limited relevance).

Pros	Cons
○ 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 complex 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 = N2 * EIRP of each array antenna, but requires spacecrafts 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 only linear increase in the cost with sensitivity. This would allow building simpler and less expensive communication equipment on spacecraft. As ground communication system is a multi mission capability, this has effect of reducing communication cost of space segment of most missions, when arrays with large enough sensitivity (A/T) become available for routine operations. This is unlike in the case of single large antennas where the cost increases much more rapidly than the antenna sensitivity (because cost ∝ d2.7, as described earlier), and beyond 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 100m diameter). ○	

technology advancements have made arrays more reliable and cost effective, and technology advances with time keep making the array approach ever more attractive for space communications. How to build and operate receive arrays are well understood, and many arrays are operated economically with high reliability (e.g. see [11], [12]). On the other hand, the phasing of uplink arrays and how it will perform in routine operations is not understood well, and needs to be established, though some progress has been made in this more recently[6].

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.

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.

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.

APPENDIX 1 – SYSTEM TEMPERATURE INCREASE DUE TO PLANETS FOR A 34M ANTENNA, A 70M ANTENNA, AND AN ARRAY OF 10M ANTENNAS, AND 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 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 beam width is given by observing wavelength divided by the array

5

6 Larry D'Addario – Private Communication and recent Technology presentations

size projected in the direction of the source, and in the single dish case the beam width is given by the wavelength divided by diameter of the antenna. It should be noted that the projected size of the array is foreshortened by roughly cosine of the angle from the zenith (e.g., at 60 deg zenith angle a 1km circular array would have a projected extent of 1 km by 1km *cos 60deg 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 synthesized beam of the array 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.

Table A1 – Approximate system temperature values for the array of 10m 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. 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. The values for cells in the table that are interesting have only been calculated. Values of the angular sizes for planets at minimum and maximum distances from earth are taken from Wikipedia web archive. Brightness temperatures of the planets are taken from [15] and the references in it.

Planet	Dia looking from earth (arcsec)		Disc Temp (K)	Array beam for projected size 300 m diameter		Noise due to planet for 0.3 km array with 34m Antenna equivalent effective area				Noise due to planet for 0.3 km array with 70m Antenna equivalent effective area			
	Max dist	Min dist		X-band	Ka-band	X-band		Ka-band		X-band		Ka-band	
	arcsec	arcsec	(K)	arcsec	arcesc	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
	10m 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
	10m 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
	10m 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
	10m 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
	10m single dish contribution (K)→						0.2	0.8	2.2		0.2	0.8	2.2
	Total array noise (K) →						3.2	3.8	5.2		3.2	3.8	5.2

Lets 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. But signals from other sources outside of the synthesized beam would have different phases at different antennas depending on 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 single dish and array can be written as

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

Here 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, and

Ω_b is the solid angle of the beam.

The array beam can be expressed as (λ^2/Array size projected in the source direction). Here array size refers to the physical extent of the region in which the array antennas are located, not to the array collecting area.

Table A2 - 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). Here the array consists of 10m antennas having the equivalent effective collecting area of a 34m antenna or a 70m 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 A1).

		34m Antenna Temp on planet, noise from planet for 10m ant array with 34 m ant equivalent area, and data rate ratio for the array versus single large antenna				70m Antenna Temp on planet, noise from planet for 10m ant array with 70 m ant equivalent area, and data rate ratio for the array versus single large antenna			
Planet		X-band		Ka-band		X-band		Ka-band	
	Earth-Planet distance →	Max	Min	Max	Min	Max	Min	Max	Min
Mercury	Large ant 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 versus a large single antenna				1.3				2.7
Venus	Large ant 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 versus a large single antenna		2.1	1.1	5.4		6.6	1.9	5.4
Mars	Large ant 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 versus a large single antenna		1.0		1.6		1.3		4.1
Jupiter	Large ant 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 versus a large single antenna	1.0	1.2	1.4	2.8	1.4	2.3	4.2	3.8
Saturn	Large ant 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 versus a large single antenna		1.0	1.1	1.5		1.2	1.8	3.3

Table A3 – Increase (in percentage) in data rate for an array of 10m antennas with projected array size of 300 m diameter in the direction of the source and having an equivalent effective collecting area as 34 m and 70 m antennas.

Planet ⇓	Delta data increase for the array compared with 34m Antenna (%)				Delta data increase for the array compared with 70m Antenna (%)			
	X-band		Ka-band		X-band		Ka-band	
At earth-planet distance ➔	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

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

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

$= T_b$ (λ^2/Array size projected in the source direction) A_e / λ^2

$= T_b$ (A_e /Array size projected in the source direction)

The term (A_e /Array size projected in the sourcedirection) is same as array filling factor (defined as effective collecting area divided by projected area of the over all 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 contribution to the system temperature for various planets at closest and farthest distance from Earth for 34m antennas, 70m antennas, and arrays of 10m antennas are shown in Table A1. Arrays with equivalent total effective collecting area to a 34m or 70m antenna are considered, at X-band and Ka-bands. Table A1 applies for array synthesized beams up to the size of the planet. Here, we have used 10m 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. Estimates of the ratio of data rate for an array of 10m antennas versus a single dish, when the array beam is smaller than the planetary disc, are shown in table A2. Here the array is assumed to cover a projected circular area with a diameter of 300m. For comparing the data rates for the two systems we are assuming that there is no atmosphere and the system temperature, excluding contribution due to the planetary disk, for both the array and the single dish systems is 20K at X-band and 40K at Ka-band.

From the results in table A2, 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 20K at X-band and 40K at Ka-band, and the data rate is proportional to SNR. The results are shown in Table A3

ACKNOWLEDGEMENTS

I thank Larry D'Addario, and Yuhsyen Shen for helpful discussions, and Dayton Jones for helpful comments on the draft of this paper.

REFERENCES

[1] P. Blacksmith and A. C. Schell, "A Comparison of Three Antenna Techniques in terms of cost versus performance", in Design & Construction of Large Steerable Aerials; (for satellite communication, radio astronomy and radar), pp135-139, 1966.

[2] Space Communication Architecture Working Group (SCAWG) - Final Report, "NASA Space Communication and Navigation Architecture Recommendations for 2005-2030", 15 May 2006, pp 80-99.

[3] Sander Weinreb, "Very Large Microwave Arrays for Radio Astronomy and Space Communications," *IEEE MTTS Workshop*, Long Beach, CA, June 17, 2005.

[4] B. MacNeal, " A Parametric Cost Modeling System for the Analysis of DSN Array Costs", IND Sec. 960 Note Series No. 17, https://ind-lib.jpl.nasa.gov/docushare/dsweb/Get/Document-18152/+ParametricCost+Model.doc

[5] D. S. Bagri and W.A. Majid, "Estimating Accurate Relative Spacecraft Angular Position from Deep Space Network Very Long Baseline Interferometry Phases Using X-Band Telemetry or Differential One-Way Ranging Tones", IPN Progress Report 42-172, February 15, 2008.

[6] W. A. Majid and D. S. Bagri, "Precision Relative Astrometry with the Deep Space Network", IPN Progress Report 42-172, February 15, 2008.

[7] W. Majid and D. Bagri, "In-Beam Phase Referencing with the Deep Space Network Array", IPN Progress Report 42-169, May 15, 2007.

[8] D. S. Bagri, "Measuring angular position of a weak radio source using Deep Space Network - for use as a calibrator to determine accurate angular position of a spacecraft", in preparation.

[9] D. S. Bagri, "The Effect on Spacecraft Tracking Performance of Using an Array Instead of a Single Dish for Receiving", IPN Progress Report 42-172, Feb 2008.

[10] DSMS Telecommunications Link Design Handbook (810-005) - http://deepspace.jpl.nasa.gov/dsndocs/810-005

[11] P. J. Napier, A. R. Thompson, and R.D. Ekers, "The Very Large Array: Design and Performance of a Modern Synthesis Radio Telescope", Proceedings of the IEEE, Vol.71, 1295-1320, 1983.

[12] P. J. Napier, D. S. Bagri, B. G. Clark, A. E. E. Rogers, J. D. Romney, A. R. Thompson, and R. C. Walker, "The Very Long Baseline Array," Proceedings of the IEEE, Vol. 82, pp. 658-672, 1994.

[13] D. S. Bagri, "The Effect of Atmospheric Phase Fluctuations on Uplink Arraying," IPN Progress Report 42-157, pp. 1-7, May 15, 2004.

[14] G. M. Resch, T. A. Cwik, V. Jamnejad, R. T. Logan, R. B. Miller and D. H. Rogstad, "Synthesis of a Large Communications Aperture Using Small Antennas", JPL Publication 94-15, Jet Propulsion Laboratory, Pasadena, CA, July 1, 1994.

[15] 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.

BIOGRAPHY

Durgadas S. Bagri joined the Jet Propulsion Laboratory (JPL) in Pasadena, California, in 2000. At JPL he has been working on the system engineering for the DSN Array and on the improvements in measurement accuracy of tracking data for deep space navigation. He received his Ph. D. in 1975, working at Tata Institute of Fundamental Research, India, in the area of radio astronomy instrumentation. He worked as an electronics engineer from 1976-78 and 1983-85, and as a system engineer from 1985-2000 for the Very Large Array and Very Long Baseline Array of the National Radio Astronomy Observatory in the U.S.A.