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The Effect on Spacecraft Tracking Performance of Using an Array Instead of a Single Dish for Receiving

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This article examines the effect on performance of tracking measurements made using an array-based Deep Space Network (DSN), where the receiving system consists of an array of small antennas instead of a single large dish having equivalent A/T, where A is the effective collecting area for the array signal or a large single dish and T is the system temperature. It describes phasing antennas for generating an array signal to make tracking measurements and then considers various sources of errors affecting the phase of the array signal and how these errors differ from those of a single dish. An examination of each item of single-dish tracking error budgets (range, Doppler, and angular position) shows that for typical tracking applications arraying has very little effect on the phase of the array signal when compared with the signal from a single dish having the same A/T, and therefore arraying has negligible effect on tracking performance as compared with a single dish.

I. Introduction

It has been proposed that the architecture of the Deep Space Network (DSN) for future downlink operations (the receiving system for spacecraft signals) be based on an array of small antennas. This architecture provides flexibility in operations, allows easy future expansion, and is economical to build and operate. However, some concern has been expressed about the tracking performance of an array-based DSN as compared with the tracking performance achieved using large monolithic antennas in the current DSN. Therefore, this article examines whether an array architecture will adversely affect tracking performance as compared with the large single antennas currently used.

Spacecraft range, Doppler, and angular position are the usual tracking measurements made with the DSN. Error budgets for the range, Doppler, and angular position estimates have been developed by the Deep Space Tracking Systems Group at JPL. Because there are a number of parameters that can be varied for making these measurements, tracking error budgets for these data types (range, Doppler, and

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angular position measurements) have been worked out[2] (also see [2,3]) for standard observing conditions in most typical situations. We take these error budgets and examine how various items in the budgets would be affected differently by using an array instead of a single dish to receive (Rx) spacecraft signals.

To understand the effect of using an array instead of a single dish on the performance of spacecraft tracking measurements, the following approach is taken. It is assumed that to generate tracking measurements the combined signal from an array of antennas and a signal from a single dish would be treated in the same way, so here we need to consider only errors in the combined array signal and how they compare with the signal in the case of a single dish. For tracking measurements, the signal-to-noise ratio (SNR) and phase of the signal determine tracking performance. The sensitivity (SNR) in the two cases is assumed to be the same; therefore, to understand how tracking performance would be affected differently, we examine how signal phases would be affected differently in the two cases.

Before examining what happens to the phase of the combined array signal, it's important to understand how signals from various antennas in an array would be combined and what error(s) could be introduced in the process. Therefore, we first consider how phasing of the array would be done for tracking measurements. Then we examine how each component of the tracking error budgets would affect the phase of the combined array signal differently from the case of a single dish. If the phases in the two cases are expected to be affected differently, then we need to consider the amount of the effect. If the effect is substantial, then we should consider its magnitude; otherwise, as the error due to each component for a single dish is known only very approximately (maybe at the ± 50 percent level), for practical purposes we can ignore its impact on tracking performance for using an array instead of a single dish.

We also examine how ranging/Doppler calibration measurements could be done, and the effect on performance, when the transmit (Tx) antenna is different from the receive array antennas. We discuss the case of an array only for receiving and assume a single dish for transmitting the range/Doppler signals.

II. Assumptions

Current conceptual plans for the array-based DSN [1] call for building a sensitivity equivalent to a 70-m antenna (expressed as A/T, where A is the effective collecting area and T is the system temperature) at each of the three DSN sites, using small antennas. It is estimated that using antennas of sizes smaller than 12 m in diameter starts increasing the array cost because of the increased cost of electronics and that, for antennas larger than about 18 m, the cost of the antennas starts dominating the array cost. For a given sensitivity, the cost of an array as a function of antenna size has a broad minimum, and it is in the range of 12 to 18 m in diameter [4]. Spacecraft tracking measurement considerations seem to favor opting for antennas with smaller apertures. This is because smaller antennas have larger primary beams, allowing an increased probability of having a suitable calibration source in the primary beam of the antennas while pointing at the spacecraft in order to make accurate spacecraft tracking measurements. Therefore, we will assume here that the DSN array would use 12-m antennas.

Here we consider the most common situation in the current DSN, which is the use of 34-m antennas for making observations for range, Doppler, and angular position measurements, and we assume a conservative SNR estimate for a tone of 20 dB-Hz for a 34-m antenna making the tracking measurements. Usually accurate tracking observations with a single dish call for stronger signals than this. Further, for comparison of performance for various tracking measurements using an array versus a single dish, we assume the array at each site would have ten 12-m antennas and an A/T that is the equivalent of a DSN 34-m antenna.

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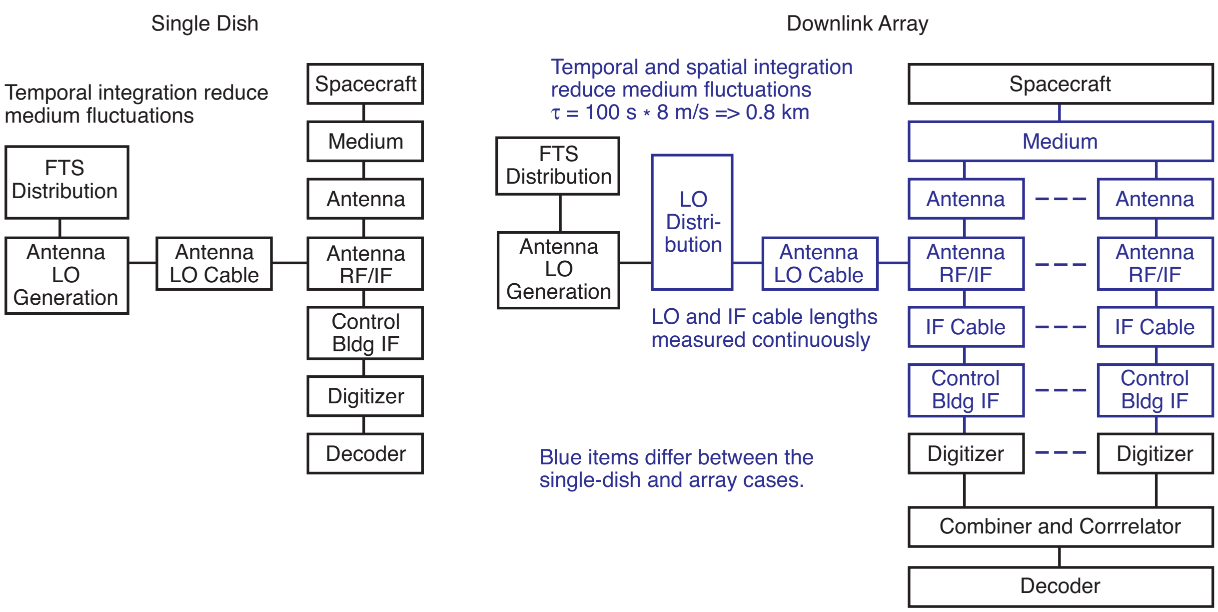
III. Methodology

Before going into the details of the tracking measurements and error budgets, it's useful to examine some of the details of how measurements are made in the two cases and where the signals are affected differently in the two cases. Figure 1 shows the parts of an array that affect signals differently when using a receive array instead of a single dish. The right-hand side of the block diagram shows, in blue, the essential parts of a system that are affected differently in the cases of an array and a single dish. It also notes how the approach intends to keep effects due to these errors small for the proposed DSN Array system [1] when making tracking measurements, as compared with the existing DSN antennas. We expect good phase stability for each antenna of the DSN Array by using modern technologies, simplified electronics, and round-trip path-length measurements for signals to/from each antenna.

Phasing of the array to combine signals from various antennas for the tracking measurements could be achieved by using a signal from one of the antennas as a reference. This would make the phases of all the antennas in the array the same, except for the error due to the SNR of the phase measurement for each baseline (pair of antennas). Of course, there is some delay between the phase measurement and the application of the correction, but this can be kept small for SNR conditions. The phase error for the combined signal from the array of N antennas would be reduced by $\sqrt{(N-1)}$ due to $(N-1)$ baselines and the errors due to the SNR for each baseline being independent. A calculation of SNR for a phase array using one of the antennas as a reference antenna and spacecraft tone signal is given in Fig. 2. The calculations use a conservative tracking measurement observing situation. Essentially,



1. System other than medium, Rx antenna, and electronics.
2. Due to medium, antenna, and electronics.

Message — Parts of an array subsystem that differ from a single dish are much simpler and potentially have smaller errors than those in existing DSN antennas. Also calibrations for arrays are done more easily and rapidly than for a single dish.

1. System other than medium, array antennas, and electronics.
2. Due to medium, array antennas, and electronics.

- Errors common to all antennas — e.g., average atmosphere, local oscillator (LO) generation, etc.
- Antenna dependent — medium and array antennas.
  - Fluctuating medium — spatial and temporal averaging.
  - LO and IF path lengths measured continuously.
  - Simple RF/IF electronics — one frequency conversion, electronics in one package at antenna, and intermediate frequency (IF) gain plus digitizer in control building.

Fig. 1. Sources of tracking errors for a single dish versus an array.

Consider phasing antennas in an array with respect to a reference antenna.

Errors basically depend on reference-antenna variations and the SNR of phasing each antenna.

Estimate the integrated SNR error contribution due to phasing of ten 12-m antennas.

Assuming 20 dB-Hz SNR for the array (34-m equivalent), the SNR for **1 minute** is:

==> 29 dB for the full array.

==> 22 dB for one pair of antennas ==> phase error is 0.36 deg ==> 0.035 mm at X-band.

==> Error due to array phasing is 0.035 mm/$\sqrt{10-1}$) = **0.01 mm** (~0.0002 mm/s — and it's random).

==> Negligible compared to other errors.

Fig. 2. Phase errors for antennas in an array when phasing is done with respect to a reference antenna.

phasing errors for each 12-m antenna pair for a 20 dB-Hz signal (an SNR of 20 dB for a 1-Hz bandwidth) on a 34-m-equivalent antenna is assumed. It would have a 13-dB SNR in a 1-s integration for a baseline of 12-m-diameter antennas in the receive array, and that should be plenty for phasing the array without adversely effecting the array signal phase due to the phasing errors. As indicated in the figure, with a 20 dB-Hz signal on a 34-m-equivalent-sensitivity receiving array, phasing errors while phasing with respect to a reference antenna would be negligible as compared with other errors/uncertainties and could be ignored. In the case of arraying using global phase solutions (determining the phase of one antenna with respect to the combined signal from all the other antennas in the array), the common errors for all the antennas in the array should be like those for a single dish, and the effect of antenna-dependent errors (random from one antenna to the others) would be reduced by $\sqrt{(N)}$.

Next, as shown in Table 1, consider broad categories into which sources of errors could be divided and how their effects on phase errors could differ for the array case as compared with the single-dish case. The sources of errors can be divided broadly into calibration source catalog, propagation, observing geometry, and electronics phase (instrument) stability. As indicated in the table, the sources contributing differently to phase errors for an array signal than for a single dish hardly change the array signal phase when phasing of the array antennas is done with respect to a reference antenna. This is considered in detail below.

It has been suggested that for uplink separate transmit antenna(s) may be used when a receive array of small antennas is employed. To understand the differences in tracking performance due to the use of separate transmit and receive antennas as opposed to the use of a single dish for both transmit and receive, we first look at how range and Doppler calibrations differ in the two cases.

Figure 3 shows a block diagram comparing ranging measurements for an existing DSN 34-m antenna, used as a single dish for both transmit and receive, versus using separate transmitting and receiving antennas, as proposed for the future systems. The left side of the schematic shows a single dish used for both transmitting and receiving, and the right-hand side shows separate antennas being used for transmitting and receiving. Note that only the reference antenna from the receive array is shown. For our discussions, we consider only a single dish for transmitting and only use arraying for downlink. The relative signal path delay between various antennas of the receive array can be made equal, i.e., delay errors between the antennas can be made very small, by calibrating delay and phase values using radio sources. Delay errors between the receive array antennas can be adjusted to <0.1 ns using a broad bandwidth (500 MHz is proposed for the DSN Array) signal from radio sources, and by using phase at the 8.4-GHz band (X-band) this can be made very small.

To calibrate range for separate transmit and receive antennas, there is a cable from the feed on each antenna to the central building whose path length can be measured accurately using a signal from the central place and reflecting it from the antenna end. This can be done fairly accurately [5]. Then the cable of the receive antenna can be used to inject a known signal at the feed input and measure the receive

Table 1. Architectural differences affecting tracking errors—using an array versus a single dish.

Type of error		Single dish	Array—phasing using a global solution	Array—phasing with respect to a reference antenna
Catalog—calibration source position		Common	Common	Common
Propagation	Average	Common	Common	Common
	Fluctuations	Temporal averaging	Temporal + spatial averaging	*Similar to single dish as phase of other antennas servoed with respect to antenna + SNR/sqrt(N-1)*
Geometry	Earth rotation, UT, etc.	Common	Common	Common
	Antenna position	—	Antenna position errors/sqrt(N)	*Like single dish—same point as above + SNR/sqrt(N-1)*
Instrumental	Common all antennas	Common	Common	Common
	Antenna dependent	—	Antenna error/ sqrt(N)	*Same as single dish—same argument as above + SNR/sqrt(N-1)*

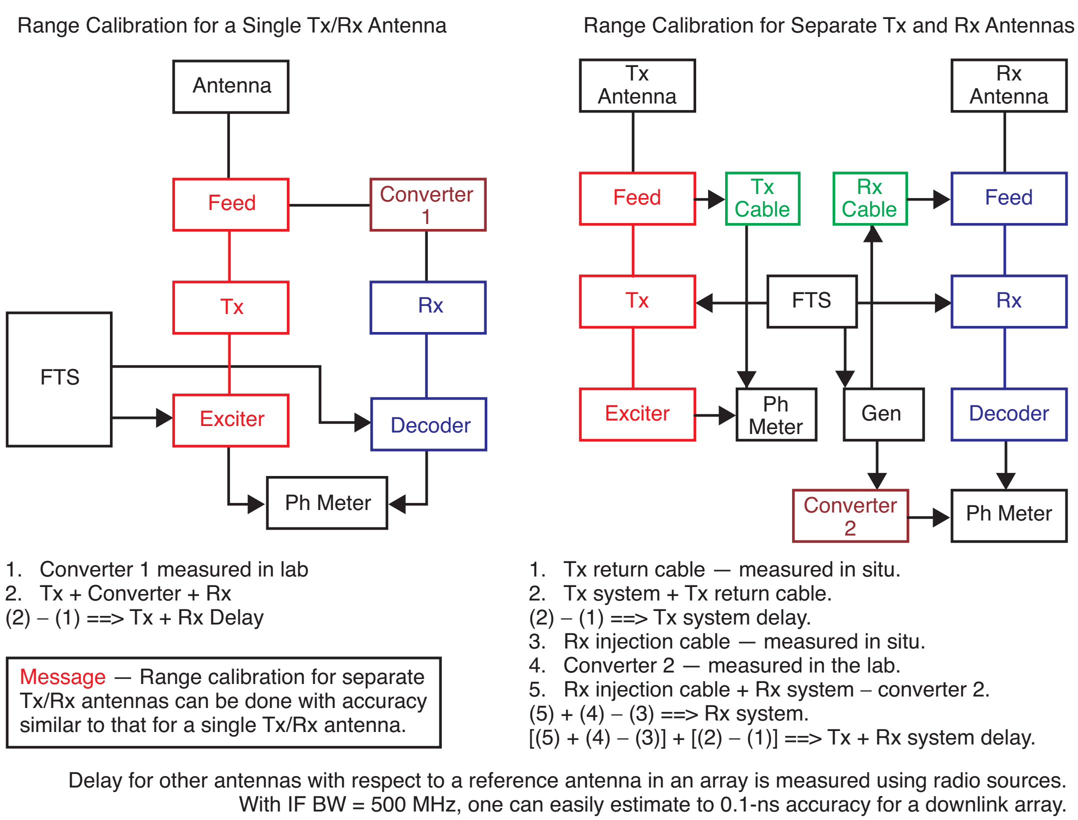


Fig. 3. Range calibration for a single transmit/receive antenna versus separate transmit/receive antennas.

antenna path length. Similarly, the transmit antenna path length can be measured using the cable on the transmit antenna and bringing the transmit signal coupled to the cable. These measurements are done essentially using a approach similar to the one currently used to measure total transmit plus receive antenna path length in present-day DSN systems, except for the following case. When there are separate transmit and receive antennas, we have to add separate cable to each antenna and measure the cable lengths, in addition to measuring the transmit antenna plus its cable and the receive antenna path length plus its cable, and then subtracting the cable lengths from these measurements. Because the path lengths are measured using similar approaches, we expect similar accuracy in the two cases.

IV. Effect of Arraying on Error Budgets for Range, Doppler, and Angular Position Measurements

With the above background, consider range, Doppler, and angular position error budgets for operations with a single dish, given by Border et al. [2], and how these may be affected if an array of antennas with equivalent A/T is used instead of a single dish. On each error budget item, we have added a note showing how the error contribution due to the particular item would be affected differently using an array instead of a single dish for the measurement. It is assumed that array phasing can be done on a 34-m antenna equivalent using a 20 dB-Hz signal from a spacecraft or a 50-mJy radio source, as explained in Fig. 2. The notations on the error budgets shown in Figs. 4 through 6 for range, Doppler, and angular position measurements have the following meaning:

- 1 means the same as a single dish.
- 2 means the same as a single dish except for phasing error due to SNR for each baseline/$\sqrt{(N-1)}$, where N is the number of antennas in the array. As shown in Fig. 2, the effect due to phasing error is negligible for a reasonable signal requirement for making tracking measurements (and this is necessary even for a single dish to make accurate tracking measurements), and therefore it can be ignored.

A. The Range Error Budget

Errors due to spacecraft-related problems, average values of media propagation calibration, Earth orientation parameters, clock, and the ground frequency and timing system (FTS) would have the same effect if the A/T in the two cases (using an array of receive antennas and a single dish for the measurements) were the same (note no. 1). This is because these errors affect the signal phase in the same way in the two cases.

The effects due to fluctuating components of propagation (solar plasma, ionosphere, and troposphere), antenna position, and the antenna mechanical and array electronics would be the same as those of a single dish when the array is phased using a reference antenna (note no. 2).

Ranging calibration could be done as described above (Fig. 3) if separate transmit and receive antennas are used for the receive array, as opposed to the same antenna (a single dish) being used for both transmitting and receiving. Developing suitable procedures would take some effort, but the effect on ranging calibration errors in the two cases should be similar, as schematically indicated in Fig. 3.

B. The Doppler Error Budget

All the error budget items would be affected in similar ways, as in the case of the range error budget.

C. The Angular Position Error Budget

All the error budget items, except dispersive phase, should behave in the same way, as in the case of range and Doppler.

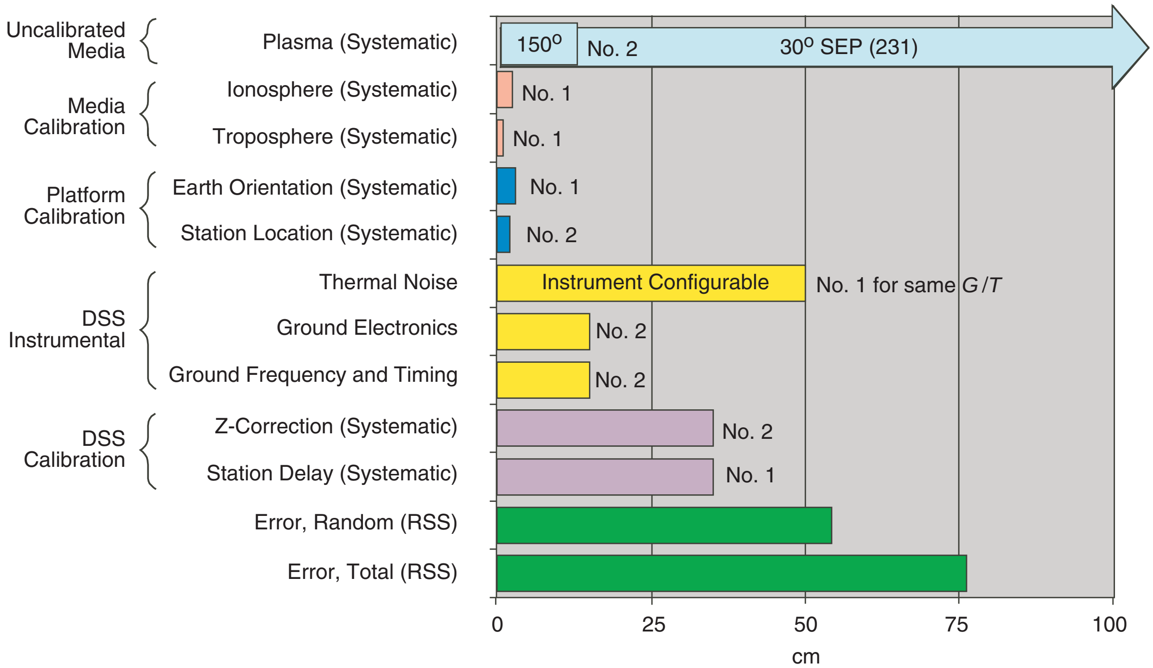


Fig. 4. Effect on the range error budget for arraying antennas as compared to a single large dish (see text for notes 1 and 2).

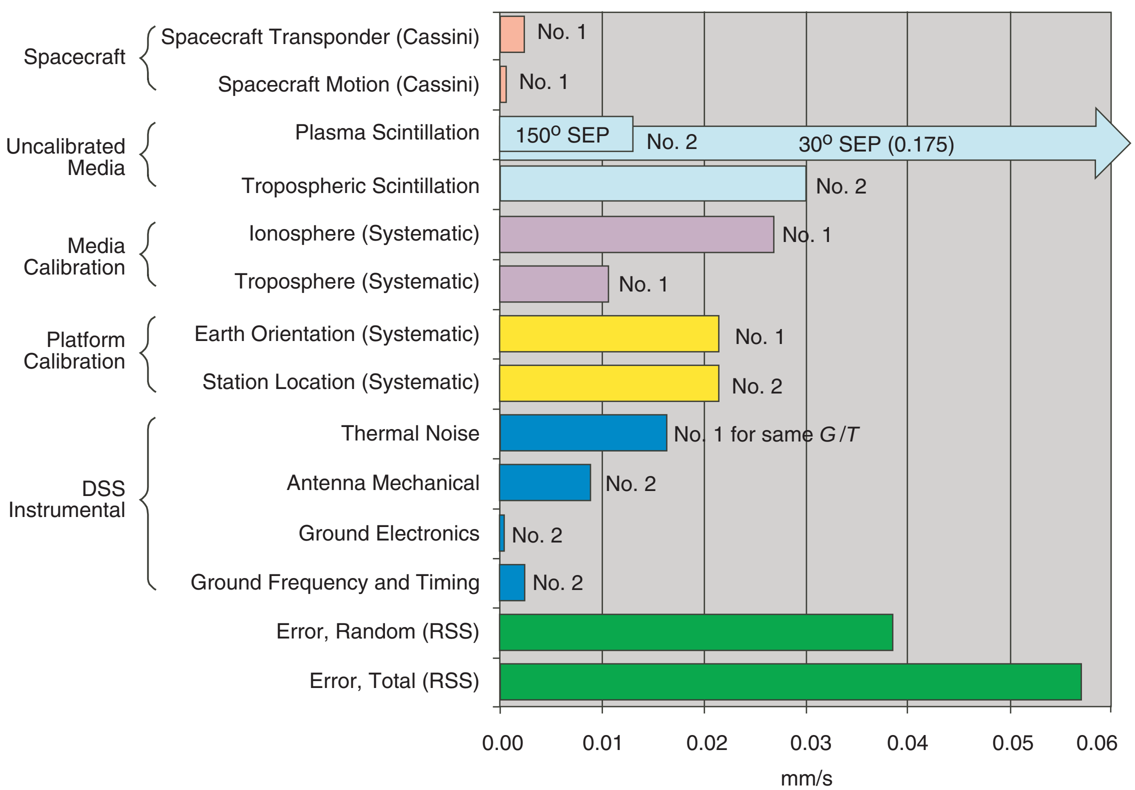


Fig. 5. Effect on the Doppler error budget for arraying antennas as compared to a single large dish (see text for notes 1 and 2).

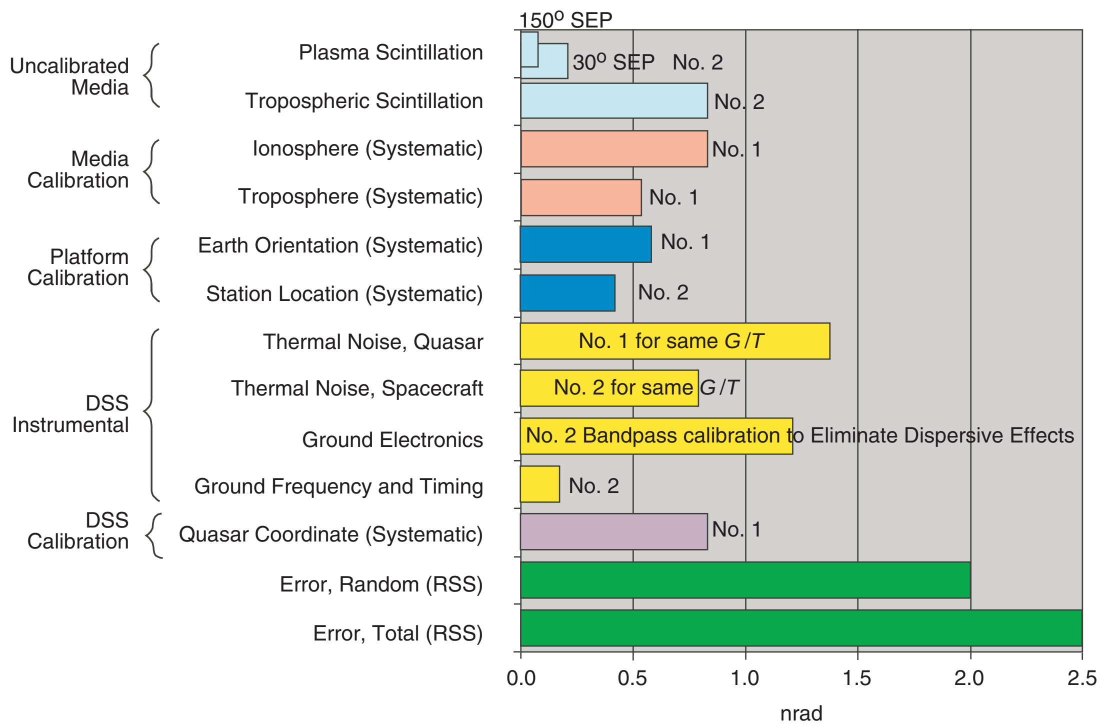


Fig. 6. Effect on the angular position error budget for arraying antennas as compared to a single large dish (see text for notes 1 and 2).

The dispersive component should be smaller in the array case due to each antenna passband being independent and the array signal being the sum of these. Further, we plan to do bandpass calibration, and that should eliminate this effect.

It should be mentioned here that using an array of small antennas of moderate size (say, about 12 m in diameter) makes it possible to have a calibration source(s) with adequate signal strength in the same beam as the spacecraft, especially if the receive array has a size equivalent to the DSN 70-m antennas and uses a calibration signal bandwidth of 500 MHz, as visualized for the proposed DSN Array [1]. This allows simultaneous observation of target (spacecraft) and calibration sources having very small angular separation. Therefore, it would eliminate all of the time-dependent components of angular position calibration errors and drastically reduce other components of the error budget, which are proportional to the angular separation between the target and calibration source. Thus, it would drastically reduce calibration errors for relative angular position measurements and potentially allow very accurate angular position determination (e.g., [6,7]).

V. Conclusion

We expect a negligible effect on the accuracy of spacecraft range, Doppler, and angular position measurements from using an array of receive antennas instead of a single large antenna. However, an array of small antennas of about 12 m in diameter potentially allows the use of same-beam very long baseline interferometry for angular position measurements, which could provide very accurate relative angular position determination.

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