System Concepts for Transmit Arrays of Parabolic Antennas for Deep Space Uplinks[1,2]

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Abstract—Phased arrays of parabolic antennas are a potentially lower-cost way to provide uplink transmission to distant spacecraft, compared to the 34-m and 70-m antennas now used by the NASA Deep Space Network. A large transmit array could provide very high EIRP when needed for spacecraft emergencies, such as the equivalent of 1 MW radiated from a 70-m antenna. Cost-effectiveness is realized by dividing the array into smaller arrays to provide routine support to many spacecraft simultaneously. The antennas might be as small as 12-m in diameter, with as many as 100 antennas covering an area of 0.5 km to 1 km in extent. Such arrays present significant technical challenges in phase alignment, which must be maintained at close to 1 mm. The concept requires a very stable system with accurately known antenna phase center locations. The system is first calibrated by transmitting from all antennas, and observing the signals at a target located in the far fields of the individual antennas. The antennas are then pointed to the operational targets, with the signal phases and time delays set to reinforce in the target directions. This requires accurate knowledge of the target directions and calculation of the required phases. The system must be phase-stable for all directions and over the time between calibrations, which is desired to be at least one day. In this paper, a system concept is presented, the major error sources are identified, a rough error budget is established, and key elements of the system are discussed. A calibration method is recommended which uses satellites as radar targets. The performance goal is to achieve a combining loss of less than 0.2 dB in good weather, and of less than 1 dB in all but extremely bad weather.

TABLE OF CONTENTS

1. INTRODUCTION 1
2. SYSTEM AND OPERATIONS CONCEPTS 2
3. PHASE CALIBRATION 3
4. SYSTEM DESIGN 4
5. ERROR SOURCES AND FEASIBILITY 6
6. CONCLUDING REMARKS 7
7. ACKNOWLEDGEMENTS 7
8. REFERENCES 7
9. BIOGRAPHY 7

1. INTRODUCTION

The NASA Deep Space Network (DSN) has three Deep Space Communications Complexes located at Goldstone, California; Madrid, Spain; and Canberra, Australia. Each complex provides X-band uplink signals to distant spacecraft using 20-kW transmitters on 34-m and 70-m diameter antennas. The 70-m antenna at Goldstone also transmits 500-kW at X-band for the Goldstone Solar System Radar, but this transmitter cannot support spacecraft uplinks because it operates at a different X-band frequency. All three 70-m antennas also have 400-kW S-band transmitters, but use of S-band for deep space communications is being phased out in favor of X-band uplinks and X-and Ka-band downlinks.

Motivation for Transmit Arrays

In the future, the DSN needs higher Effective Isotropic Radiated Power (EIRP) at X-band than is now provided by the 20-kW transmitters on the 70-m antennas. This is required to support the much higher uplink data rates for future Mars missions, and to provide command links into very low gain antennas at Jupiter and Saturn distances. The low gain antennas situations arise in spacecraft

[1] 0-7803-8870-4/05/$20.00© 2005 IEEE
[2] IEEEAC paper #1316, Version 2, Updated November 12, 2004

emergencies, and for orbiters and landers on the moons of these planets.

The future DSN also needs much greater receiving capability and, at the same time, needs to reduce operations costs. The planned approach is to develop large arrays of 12-m receiving antennas. One way to reduce the operations costs is to retire the aging 70-m antennas, which will require extensive refurbishment if their lifetimes are to be extended. It may also be desirable to retire the 34-m antennas.

Transmit arrays of small antennas have the potential to provide the needed EIRP at reduced cost [1]. One efficiency is that the same transmit arrays could provide very high EIRP, and also could provide many simultaneous uplinks to support multiple missions. A second efficiency arises from the synergy with the large receiving array, especially if the same antenna size and design is used as for the receive antennas. A third consideration is safety. When very high power is used on one 70-m antenna, the maximum safe flux densities for humans and for aircraft are exceeded. It is therefore necessary to coordinate with other agencies to assure that no aircraft or personnel are in areas where the safe limits are exceeded. This would not be necessary with transmit arrays, because the flux density from each antenna is lower that the safety limits. A system that does not require interagency coordination improves operational flexibility and reduces costs.

Transmit Array Concept

The basic concept of a transmit array of large antennas is much like that of any phased array transmitting system. A concept diagram is shown in Figure 1.

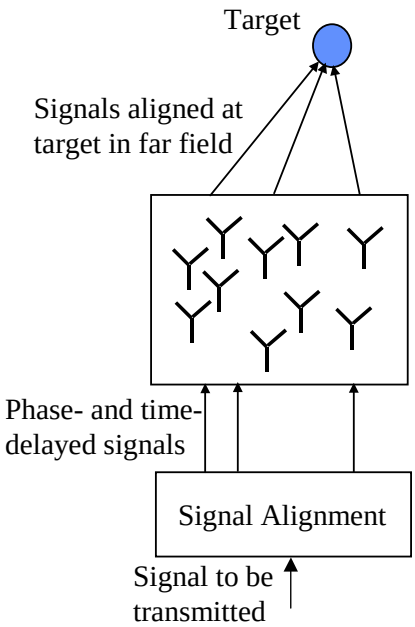

Figure 1 – Transmit Array Concept

The signals from the various antennas must be transmitted with proper phase and time delay so that the signals reinforce at the target. The steps to accomplish this are: 1) build a very stable system, 2) calibrate the system using a calibration target at an accurately known position in the far fields of the individual antennas, 3) for the operational target, calculate the required phase and time delays for each antenna so that the signals will reinforce at the target, and 4) generate the signals with the required alignments.

Background and Challenges

A limited form of transmit arraying using two large parabolic antennas was demonstrated by JPL in 1994 [2]. This demonstration was a radar system. Pulse streams were transmitted from the two antennas, with the pulse times offset so that the pulses did not overlap at the target, an Earth orbiting satellite. The echoes were received by one antenna, and the phase offsets between corresponding pulses were measured. The phase at one antenna was then adjusted in a closed-loop fashion to align the phases. After phase alignment was achieved, the pulses were overlapped in time, so that the signals reinforced at the target. This system worked well as long as closed-loop phase control was maintained. The system did not work well in an open loop mode, even after initially achieving phase lock. Two reasons for this are that the satellite orbits were not known with sufficient accuracy, and that the system phase stability was not adequate. The demonstration objectives were met, however, as this system was intended to work in a closed-loop manner.

For deep space uplinks, the spacecrafts receiving the uplinks are much too distant to be used as radar targets for closed-loop phasing. Conceptually, the transponders on the spacecraft might be used to return the differential phase information from the various transmitting antennas. But this does not work in the critical application of transmitting to a spacecraft that is in an emergency situation. Therefore, for deep space communications, it is necessary to align the uplink phases in an open-loop manner, after system calibration.

2. System and Operations Concepts

A block diagram showing the system concept is presented in Figure 2. The calibration method shown uses a radar target in Earth orbit. Other possibilities that have been considered are discussed briefly in Section 3.

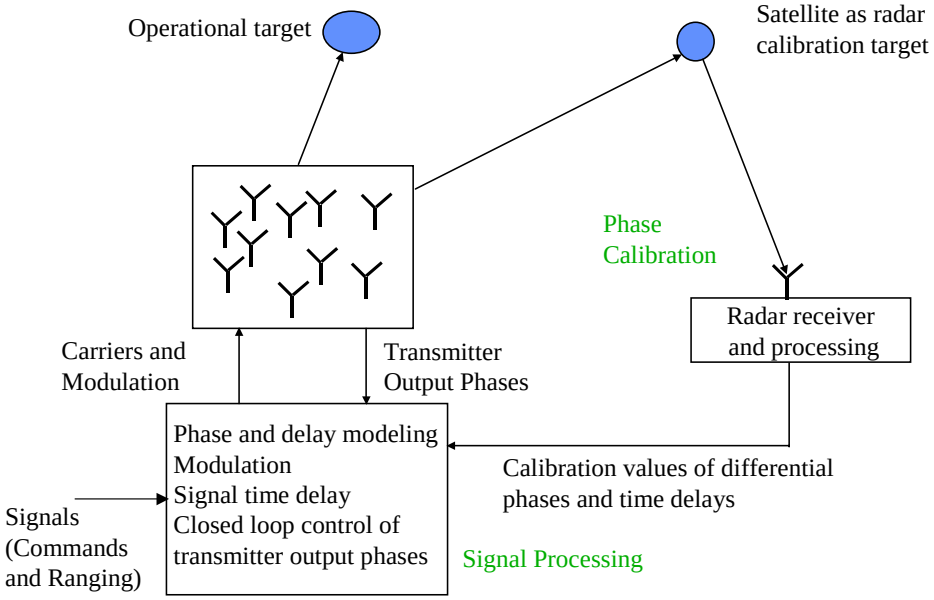

Figure 2 – System Simplified Block Diagram

There are three major operational steps. First, the locations of the antenna phase centers are calibrated using Connected Element Interferometry (CEI); these measurements are updated as necessary, which might be monthly or quarterly. Second, the system phase offsets are calibrated using a satellite as a radar target; it is a goal that this is necessary no more often than daily. Third, the desired signals are radiated to the operational targets, with proper time-and phase-delays for each antenna.

CEI is the short-baseline analogy to Very Long Baseline Interferometry (VLBI). Both of these techniques receive the radio signals from distant radio sources and compare the signals to extract the differential time delays between pairs of antennas, and their derivatives. Besides the baseline lengths, the distinguishing characteristic is that VLBI systems have independent local oscillators for each antenna, whereas CEI systems have one common local oscillator, and hence connected elements. To perform the CEI measurements, each antenna in the transmit array has a receiving system similar to that of a receive array, except that system temperature is not critical. Many CEI observations are done using targets in many different directions. The target directions are very well known, because they have been previously determined by VLBI observations. Sufficient measurements are made to solve for the differential locations of the antenna phase centers. If necessary, the motions of the phase centers with elevation and azimuth are modeled, and the parameters of the models are estimated.

The phase calibration by radar is discussed in Section 3. The real time operation and the system design are discussed in Section 4.

3. PHASE CALIBRATION

The phase offsets of the signals from each antenna are calibrated by observing the phases as received at a target in the far fields of the individual antennas. The location of the target must be known accurately, and the phases are measured differentially.

Several options were considered for the observation target:

1) A spacecraft target that measures the phases, or that observes the amplitude of the combined signal and provides feedback to the array so that the amplitude can be maximized.

2) A spacecraft that relays the phases to an Earth receiver via the spacecraft transponder.

3) A calibration receiver or relay mounted on a tower in the far fields of the antennas.

4) An Earth satellite used as a radar target to reflect the signals to a receiver on the ground.

The baseline approach selected is the radar approach. The spacecraft transponder method may be useful as a demonstration, but is probably not practical as an

operational system due to scheduling constraints and the need to have cooperation of the target spacecraft flight project. The tower may be a viable option, but there are concerns about ground multi path, and about the feasibility of locating towers on hills of appropriate height and distance from the array.

Radar Target Considerations

For radar to be a feasible method, there must be a sufficient number of targets available, these targets must have adequate and stable radar cross sections, such as provided by spheres of appropriate size, and the targets must have known or knowable orbits.

Preliminary investigations indicate that a sufficient number of targets are available with good radar characteristics. The main problem is that the orbital predictions are not sufficiently accurate to achieve accurate phase calibration. For example, at a range of 1000 km, and for an array baseline of 0.5 km, an orbit error of 1 m would cause a phase calibration error of 0.5 mm (1m * 0.5 km / 1000 km). As discussed in Section 5, the required phasing accuracy is approximately 1 mm, with a budget for each error source on the order of 0.3 mm. Furthermore, the orbital predictions are not nearly as good as 1 m. This means that measurements of the orbits are required.

Measuring the Orbit

Two methods are under consideration for measuring the orbit. The CEI Phase Calibration Method is shown in Figure 3.

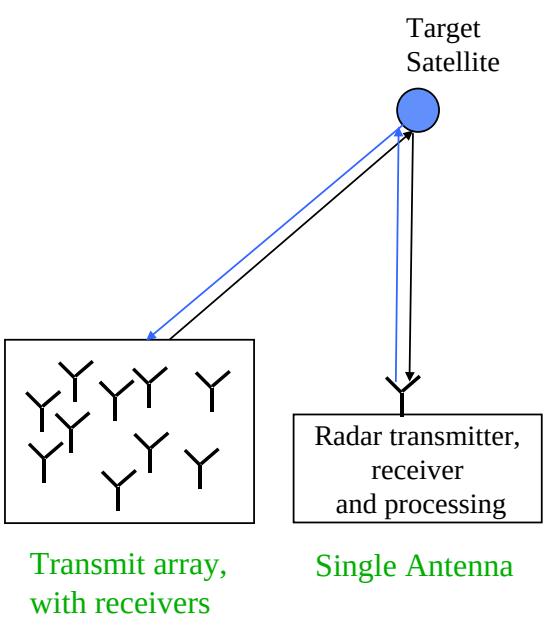

Figure 3. CEI Phase Calibration Method

All (or at least several) of the array antennas must have receive capability on the transmit frequency band, which complicates the microwave system design. To measure the target location, one or more antennas radiate to the target, and the receiving antennas receive the reflected signal. The target thus becomes a radio source for CEI, and CEI methods are used to solve for the target location versus time. Then all transmitters radiate to the target, and one antenna receives the reflected signals. The differential phases can now be accurately calibrated, using knowledge of the target position from the previous step. Note that the two steps can be performed simultaneously rather than sequentially, so that system calibration can be done almost instantaneously.

The second method is the Orbital Solution Phase Calibration Method, shown in Figure 4. One begins with the best possible predictions of the satellite orbit. The transmit array radiates to the target for all or a large part of one pass of the target, and the reflected signals are observed by the radar receiver. The differential phases and time delays for the multiple signals are measured versus time. These measurements are used to perform a simultaneous solution for the parameters of the target orbit and the offsets in the transmitted phases. This method has significant cost advantages because it is not necessary for multiple antennas to be able to receive at the transmitting frequency. Analysis is underway to determine the feasibility and accuracy of this method.

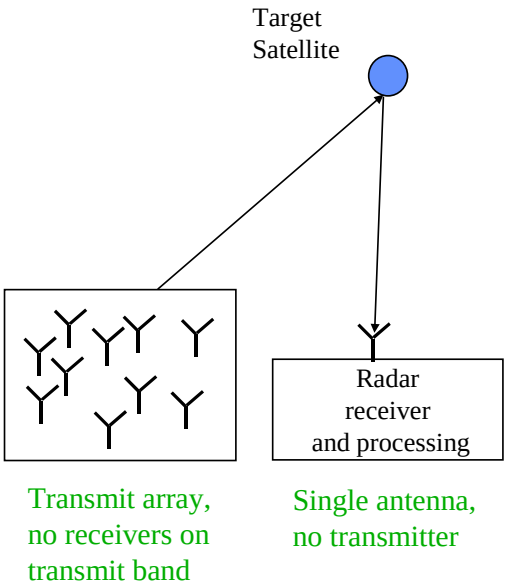

Figure 4. Orbital Solution Phase Calibration Method

4. System Design

This section discusses three key aspects of the system design.

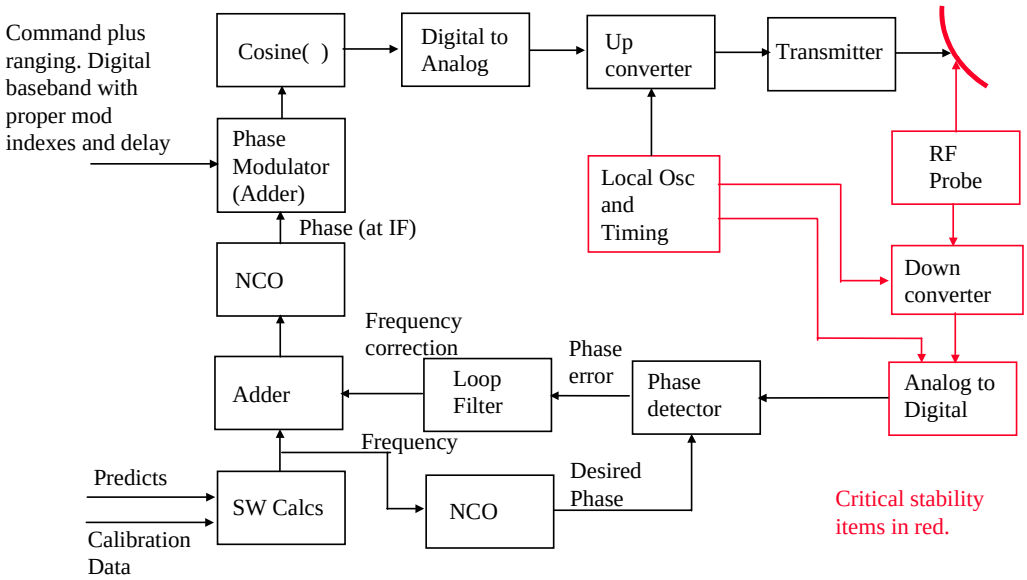

Figure 5. Phase Control Loop

Phase Control Loop

Figure 5 shows a conceptual block diagram of the phase control loop. The phase that needs to be controlled for each antenna is the radiated phase in the far field. To minimize phase errors due to system instability, it is important to control the phase at a point representing the far field. The most representative point is at the output of the transmitter, and just before the feed. Points on the surface of the antenna do not appear to be as good, because any one point on the antenna does not represent the entire wave front. The system uses an RF probe to continuously observe the signal at a point close to the input of the feed.

The desired phase is generated in a numerically controlled oscillator (NCO), based upon predictions of the target location and previous calibration data. The RF probe signal is down-converted and physically brought to a phase detector located close to the NCO that generates the desired phase. A phase locked loop (PLL) controls the uplink signal phase to agree with the desired phase. The system elements that require extreme stability are shown in red in Figure 5. These are the RF probe, the local oscillator, the down converter, the cabling or fiber optic link that brings the signal from the RF probe to the point where it is digitized, the cabling that brings the LO signal to the digitizer, and the Analog-to-digital converter.

The components in the uplink signal path need only be sufficiently stable that the PLL can track out their instabilities. These components include a NCO whose phase is controlled by the PLL, a digital adder that adds the signal modulation phase to the NCO carrier phase, a conversion from phase to cosine of phase, a digital to analog converter, an up converter, and the transmitter.

Signal Time Alignment

Figure 6 shows the time alignment of the signals from the various antennas. Command and ranging signals are input to the array signal processing, either in analog or digital form. If necessary, they are converted to high rate digital signals. The command and ranging signals are each multiplied by the correct modulation indexes, and the results are summed to obtain the desired signal modulation phase for each sample time. Meanwhile, the predictions and the calibration data are used to calculate the required delay value for each antenna, for each point in time. Digital delay lines delay the signal appropriately for each antenna. The resulting wideband digital baseband signals are applied to the output of the uplink NCOs in the phase control loops.

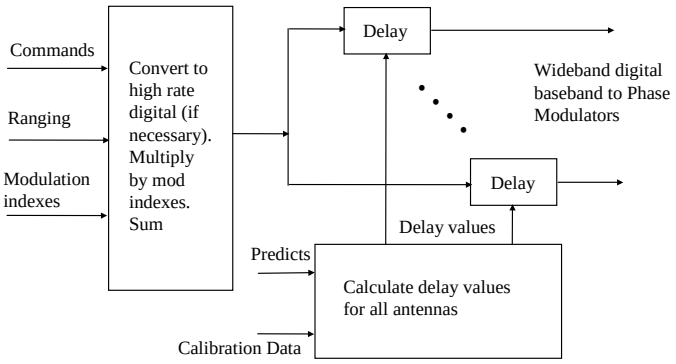

Figure 6. Signal Time Alignment

Radar Calibration Processing

The radar calibration signal processing is shown in Figure 7. The transmit array radiates mutually orthogonal signals from the antennas. Although various signal sets could be used, a probable choice is a set of orthogonal codes. The system generates the proper signal for each antenna. Each signal is applied to one of the delay lines shown in Figure 6, and the signals are delayed as for normal operations.

To measure the phase errors at the target, it is desired that these phase errors be as constant as feasible. Therefore, the same uplink phase modeling and control is used as for the operational scenario, using the best previous values for system phase calibration.

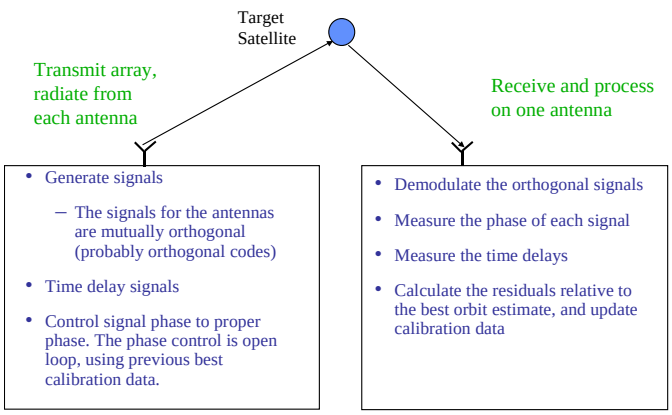

Figure 7. Radar Calibration Processing

The signals from all the antennas are reflected by the target, and received by one receiving antenna. Conceptually, the receiving antenna may or may not be one of the transmitting antennas. In practice, it is probably a separate antenna with receive-only capability, located some distance from the transmit array so as to minimize interference. Regardless of the location of the receiving antenna, the downlink path is the same for all uplink signals, so that the differential phases are preserved. The processing demodulates the signal, separates the orthogonal signals from each transmitter, and measures the differential phases and perhaps time delays. The residuals are calculated relative to the predicted target orbit. If the Orbital Solution Phase Calibration Method is used, there is a simultaneous solution for the updated orbit and the system phase errors. If the CEI Phase Calibration Method is used, the phase errors are calculated relative to the targets positions determined from the CEI measurements.

5. Error Sources and Feasibility

Allowable Phase Error

The loss in the signal combining depends on the accuracy in aligning the signal phases from the group of antennas. Previous work [2] has shown that the loss in EIRP is approximately 0.2 dB for rms phase errors of 11 degrees, and 1 dB for rms phase errors of 25 degrees. At the DSN X-band uplink frequency of 7.19 GHz, the wavelength is 4.17 cm, and a phase errors of 11 degrees corresponds to a time delays of 3.8 ps and a distance of 1.27 mm.

Combining loss is an important parameter, because achieving a certain EIRP takes more antennas as the combining loss increases. Cost trades need to be done to choose the best design point. A major complication is the error due to atmospheric delays. This error is highly dependent on the weather and on antenna spacing. As an initial approach, we have chosen to set a goal of 0.2-dB loss in good weather, and not more than 1-dB loss except possibly in very bad weather. This means that the system losses outside of atmospheric delays should be less than 0.2 dB.

There will be a number of contributors to the phase error. Just to scope the magnitude of the allowable errors, suppose that there are 16 error sources, that we allocate an equal error to each source, and that the errors add in a rss sense. In units of distance, the 0.2-dB loss corresponds to an rss error of 1.27 mm, so each error source must be less than one-fourth of this, or about 0.3 mm, 1 ps or 2.7 degrees. A more-specific error budget is discussed by Amoozegar [3,4].

Error Analogy to Connected Element Interferometry

Many of the key error sources for transmit arraying are similar to corresponding error sources in CEI. The problem of aligning the transmit phases is analogous to solving for the phase offsets in CEI. The key common error sources for the two techniques are: 1) System mechanical stability and knowledge of the antenna phase center locations versus elevation and azimuth, 2) System electronic stability, and 3) Differential signal delays in the propagation paths, dominated by the atmosphere.

There are three error sources that are unique to transmit arraying. These are: 1) Electronic stability of the transmitter system rather than the receiving system of interferometers, 2) System calibration using a far-field signal source, and 3) Error in maintaining calibration for a day or longer between calibrations. Methods to achieve the required accuracy for the first two of these error sources are discussed in Section 4. This leaves the CEI errors sources, and the need to maintain stability for a day or longer.

In transmit arraying, we point the antennas to a calibration target, measure the phase offsets at the target, and calculate the required phase corrections. Some time later, we point the antennas to the desired operational target, apply the required calibration corrections and the phase adjustments due to the different target direction, and transmit. There is an analogous scenario in CEI. Suppose in CEI we point the antennas to one radio source and calculate the phase errors with respect to a model. Then, some time later, we point the antennas to another radio source in a different direction, applying the phase corrections from the first observation and the phase adjustments due to different target direction. We now measure the differential phases. These phase errors are analogous to the errors in the transmit array scenario.

A series of CEI experiments is being run to help determine the feasibility of meeting the transmit array phasing goals [5]. These experiments use the three 34-m beam waveguide antennas at Goldstone, California, designated DSS 24, 25 and 26. The few-hundred-meter separation between these antennas is representative of the possible extent of a transmit array of smaller antennas, so that atmospheric effects are similar.

Preliminary results are available for the first few experiments. Between DSS 25 and DSS 26, the experiments achieved rms phase residuals from approximately 0.7 mm on a cold winter night, to 1 to 2 mm on summer nights. Poorer results were obtained for baselines involving DSS 24, because DSS 24 has a less stable frequency distribution system than the other antennas. It is planned to upgrade this system to enable better results and accurate three-baseline closure. Further tests are planned to establish the performance under different atmospheric conditions, and to separate the key error sources of atmosphere, electronic stability and mechanical stability.

Overall, the initial CEI results indicate that there is a strong likelihood that the phasing performance required for transmit arraying can be achieved.

6. CONCLUDING REMARKS

Transmit arraying is a promising approach to achieve very high EIRP for deep space communications without using extremely large antennas and extremely high-power transmitters. The required system calibration and stability are very challenging. Conceptual approaches and high-level designs have been presented to meet these challenges. In addition, CEI experiments are being conducted to assess the achievable performance, and preliminary results are encouraging. Detailed analysis, system design and realistic demonstrations are required to definitively establish feasibility.

7. ACKNOWLEDGEMENTS

The research described in this publication was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The author thanks the many people at JPL who are contributing to transmit arraying concepts, and especially Christopher Jacobs for the results on connected element interferometry.

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9. BIOGRAPHY

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