Large Phased Array Radar Using Networked Small Parabolic Reflectors

Farid Amoozegar

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
(818) 354 -7428
Farid.Amoozegar@jpl.nasa.gov

Abstract— Multifunction phased array systems with radar, telecom, and imaging applications have already been established for flat plate phased arrays of dipoles, or waveguides. In this paper the design trades and candidate options for combining the radar and telecom functions of the deep space network (DSN) into a single large transmit array of small parabolic reflectors will be discussed. In particular the effect of combing the radar and telecom functions on the sizes of individual antenna apertures and the corresponding spacing between the antenna elements of the array will be analyzed. A heterogeneous architecture for the DSN large transmit array is proposed to meet the radar and telecom requirements while considering the budget, scheduling, and strategic planning constrains.

TABLE OF CONTENTS

1. INTRODUCTION

In recent years, various options have been proposed at the Jet Propulsion Laboratory (JPL) to replace the large antennas of the deep space network (DSN) due to aging and rapid increase in power and aperture requirements within the next three decades. One option is to use a large flat plate phased array antenna consisting of dipoles, or waveguides while another option is to use a large phased array of small parabolic reflectors [1-3]. There are several functions performed by the DSN, i.e., telecom, radar, radio astronomy, and radio science. Phased array antenna systems have originally been developed for radar multi-target tracking. Due to the flexibilities offered by phased array systems, however, the imaging and telecom applications were also considered in recent years. Today, many phased array antenna systems consisting of dipoles or waveguides exist with apertures as large as 60m [4]. The primary concern with phased array systems consisting of dipoles, or waveguides, however, is the cost and complexity. As the required power and aperture of the phased array antennas increase, blind spots begin to limit the power and aperture. The blind spots act like short circuits in certain view angles, which could cause serious fire hazards in high power scenarios, typical for deep space applications [5]. On the other hand, using large phased array of small parabolic reflectors has great challenges, particularly when all elements are simultaneously transmitting. Therefore, it has been proposed to separate transmit and receive arrays of parabolic reflectors in order to simplify the design and lower the cost [1]. Traditionally, a large transmit array of parabolic reflectors has been called the Uplink Array, which is based on the fact that the most essential requirement of the large transmit array is to provide emergency uplink to a spacecraft in deep space.

The objective of this paper is to compare the telecom array with the radar array in terms of phase calibration, power, and aperture. The intent is to identify the architecture options of the large transmit array of parabolic reflectors when radar functions are also included together with the uplink telecom functions. In Section 2 of this paper, after a brief description of the Gold Stone Solar System Radar (GSSR), the primary requirements of the radar array is outlined followed by discussions on calibration issues and the importance of the pulse repetition frequency (PRF) as the most critical design parameter. Then, after the differences of the telecom and radar arrays are established, the role of beamforming, which is the major advantage of any phased array antenna system, will be discussed in relation to phase calibration. In Section 3, a heterogeneous architecture is proposed as a method of combining the radar and uplink telecom functions, with budget and DNS upgrade schedule constraints taken into consideration. The paper will be summarized in Section 4 with some conclusions on the method of planning the power and aperture. Note that, throughout this paper, the telecom array and the Uplink Array terms are used interchangeably with the assumption that the receive array of reflectors is a separate array, which is dedicated to the downlink telecom function as well as imaging applications of DSN and is therefore, not the subject of discussion in this paper.

2. SOLAR SYSTEM RADAR ARRAY

One of the major national assets within the Deep Space Network (DSN) is the Goldstone Solar System Radar (GSSR), which is the largest of its kind in the world. GSSR primarily consists of a 70m antenna with a 500-kW transmitter. GSSR provides images of Mercury, Venus, Mars, the satellites of Jupiter and Saturn, the Moon, and asteroids and comets. The 70m antenna has different high power transmitters for telecom and radar applications. Therefore, the eventual decommissioning of the 70m antenna would result in loss of a major national asset unless it gets replaced with an alternate large aperture antenna with high power transmit capability.

In 1990, GSSR was used in conjunction with other 34m antennas to form high resolution radar images of the Moon, using delay-Doppler techniques. Today, much of the radar techniques developed in 1990 are being augmented and utilized at JPL in a new effort lead by Dr. Victor Vilnrotter [6, 7] to array two of the 34m antennas transmitting simultaneously and receiving the combined echo from the Moon with a third 34m antenna. All three antennas are located at a few hundred meters away form each other, which makes the phase alignment quite a challenge. The delay-Doppler method is used to form interferograms, which contain precise relative array phase information for each antenna in transmit mode. In other words, the Moon is being used as a target to correct for the transmitters' phase differential between the two transmitting antennas that form the 2-element array in this case [8]. The GSSR is a national asset, and provides superior coverage and resolution compared to the Arecibo facility. Successful demonstration of 34m transmit arraying could pave the road for a new arrayed version of GSSR as the 70m antenna is decommissioned due to aging. The array could consist of antenna sizes other than 34m. However, the principles would stay the same. In the remainder of this section, various aspects of the radar array, as well as the primary differences of the telecom and radar array will be discussed.

Advanced Radar Applications for Lunar Coverage

Large aperture phased array radars such as Pave Paw, Cobra Dane, and Patriot, etc., have long been utilized for detection and tracking of satellites and ballistics missiles with slant ranges up to several thousand miles with range accuracies in the order of 1-10m. In a previous paper [9] we discussed the recent requirements and challenges facing a phased array system dedicated to Lunar coverage in terms of signal design and antenna requirements to perform detection, identification, and tracking of simultaneous moving targets on the Lunar surface. Currently, the GSSR does not use the Moon as the target for its calibration. However, as discussed in [9] the phased array of parabolic reflectors for Lunar applications would require a minimum of 12m aperture size for telecom and radar functions. Further investigation [9] also revealed that up to 18m diameter antennas will be required if the antennas are to be used for Lunar navigation in conjunction with other telecom functions. Therefore, the antenna element size in the future large transmit array of reflectors is driven primarily by radar calibration requirements as well as the navigation requirements rather than merely by telecom requirements. Moreover, as will be discussed in the following sub-sections, the formation of multiple beams in the transmit direction helps providing additional degrees of freedom in controlling, and or reducing the differential phase errors. Utilization of the radar calibration techniques through beamforming, and augmentation of the transmit array to include other new Lunar applications will take the telecom array several steps closer to also becoming a radar array. Therefore, it would be interesting to know what additional steps would be necessary to upgrade the telecom array (Uplink Array) to a radar array. In other words, what aperture size, power per element, and element spacing could be used in order to replace the GSSR with a large transmit array of small parabolic reflectors given that new Lunar applications are also considered.

Similarities of Radar and Telecomm Array

Since the Uplink Array was primarily considered based on closing the command link to a troubled spacecraft in deep space, other functions of the DSN, particularly radar, and radio science have not been addressed as of yet. However, the study of various methods for Uplink Array phase calibration revealed some of the key advantages of radar techniques [10]. Some examples of the similarity in requirements of telecom and radar array are the delay-Doppler capabilities and the radar-like signaling, such as binary phase coded signals with digital pseudo-random sequence. The pulse compression nature of such signals provides significant protection against radio interference. The inclusion of an additional radar signal, which is at a slightly higher frequency than the telecom signal, would require some RF switching capability added to all or portions of the array. With the noise-like signaling with CDMA format, radar array technology would also benefit from recent developments of wireless sensor networks in terms of resolving schedule conflicts, smooth hand-over scenarios between the sub-arrays, and phase calibration techniques using the on-board spacecraft receivers.

Array and the Effective Isotropic Radiated Power (EIRP)

The gain of the 70m antenna at S-band is 62.7 dB, while at X-band the gain is about 72.9 dB. The existing high power X-band transmitter for the GSSR with 70m antenna is 500 kW, while only a 20 kW transmitter is used for uplink telecom applications at X-band. Considering the emergency uplink requirement, and the GSSR high power requirements, the total required EIRP for the DSN would be within the range of .7 TW to 9.7 TW [11]. The EIRP requirement for emergency uplink is still under investigation at JPL. However, the GSSR total EIRP is currently 9.7 TW, which is greater than the telecom requirements. Therefore, since the GSSR generally operates at the higher EIRP, if the radar array is to be combined with the telecom array, the power and aperture would be driven by the radar requirements. The EIRP for an individual 12m (4 kW) antenna at X-band is about 92.86 dBW. Ignoring the combining loss for the array, the corresponding number of elements for radar would be about 71, and 20 for the telecom. Alternatively, for a 4m aperture size and 1kW of power per element, the corresponding number of elements would be about 426 for radar and 118 for the telecom. If we were to use 15m (4 kW) elements, the corresponding number of elements for 70m equivalent EIRP at X-band for radar and telecom array would be 57, and 16, whereas for 15m (6 kW) it would be 47, and 13 respectively.

Therefore, the only reason to separate the radar and telecom array apertures would be the difference in cost of a few RF switches and frequency converters. The Master clock, transmitter modulator, Exciter requirements, and signal distribution network would be the same. The microwave component technology at X-band is mature enough and the cost of a dozen RF switches, and frequency converters don't seem to be a critical decision factor for separating the radar and telecom arrays. Although a comprehensive trade study for the radar versus telecom array has not been conducted yet, depending on the cost and complexity of the additional RF electronics for radar array, the optimal aperture size might shift upwards towards 15m (6 kW). Alternatively it may dictate a heterogeneous array of 34m, 15m and 12m apertures (Section 3). If the radar and telecom array are separated, much of the concepts in calibration, operation, interference handling, and back end signal processing would have to be duplicated. In other words, if we were to build a radar array, we would need a larger aperture, e.g., 15m, than what is needed for the telecom array, and other requirements and techniques will be almost identical.

Effects of Radar Array Element Aperture on Calibration

One approach to identify the trade between power and aperture is to start with the target size when the radar technique is used for calibration. The minimum target size, whether it is for point targets, or extended targets (e.g., Moon) will determine the minimum aperture size as well. The size of the calibration target is perhaps the most important factor in Uplink Array phase calibration with radar technique, since it sets the requirements for the signal amplitude, integration time, and the periods of calibration. Several system parameters (e.g., transmitter power, antenna gain, maximum duty cycle, false alarm rate, system noise temperature, sampling intervals, integration time and coherence length of the transmitted signal, and minimum detectable power) have to be taken into consideration along with possible measurement errors before the optimal size of the calibration target can be estimated, which then determines the target cost, orbital accuracy, mass, and RF electronics that can be incorporated.

To give an example of the effect of target size, consider the Rayleigh approximation that is valid when the target diameter is $d < \lambda/5$ while the optical region begins when $d > 10\lambda$. Therefore, the target size for X-band falls within the range $d > 10\lambda$ (e.g., 30-40 cm), and if we use a sphere with no aspect angle changes, a non-fluctuating target can be assumed at LEO orbit altitudes (500km). If GPS sensors can provide 1m target position uncertainty for targets within 30cm-40cm in diameter, then even a 1 m-deg pointing error would correspond to ~ 8m offset at 500 km, which could miss the calibration target if the target is as small as 40 cm. Knowing the measurement error covariance that can be tolerated together with the size of the target that provides sufficient signal-to-noise ratio help completing the search in available target catalogs on the Moon, or other in-orbit targets. Most cataloged targets of opportunities in the near earth orbits are identified by their size, followed by the accuracies of their range, velocity, and acceleration. Note that the range, velocity, and acceleration errors map onto the phase error. When dealing with Lunar targets, depending on whether a specular, or diffuse target is used, additional constraints such as multi-path, sidelobe levels for clutter rejection, baseline decorrelation, target control points, maximum allowable delay and Doppler spread, and aliasing would have to be considered. Discussion of Lunar target requirements for phase calibration of radar and telecom array is beyond the scope of this paper, and would be discussed in a future paper.

We already discussed in a previous paper [1] that the key cost driver of the Uplink Array is the transmitter. The most important factors that identify the cost of a transmitter are the following, 1) average power and efficiency, 2) peak power and duty cycle it can tolerate, 3) phase stability. Obviously, in the trade of power for aperture one is more limited by the transmitter power, since the phase stability of transmitters become harder as the power increases due to thermal issues. Therefore, we can further reduce the key cost factors to one number, which is the average power of the transmitter. So, a good start for the entire end-to-end error analysis and determination of the target characteristics is to pick an average power level for the individual transmitters. The size of the individual array antenna element will then be a matter of calculation of power density limits that are safe to operate without causing any microwave power hazard or interference to the neighborhood channels, or to the flying nearby targets. Therefore, before identifying the next most important factor for the Uplink Array design, i.e., element spacing, and other secondary characteristics of the Uplink Array, one has to know the intervals of time needed for the calibration, i.e., calibration time windows, which all depend on target size. Since we have already assumed that we know the transmitter average power, then the maximum phase stability, and coherence length of transmitter signal can be identified, and we would know how often we need to calibrate. That is, the intervals of time between calibration instants as well as the integration time during the calibration can be identified. Therefore, the most critical factor in phase calibration is the target (pixel) size that can lead us to a stable and repeatable calibration. This in turn indicates that the most critical task begins with target radar cross-section, which leads us to the target size of interest. The best place to start the target size determination is with the smallest detectable size when the array is in radar detection mode. This limit is basically equal to the limit of the background noise power level after integration at the receiver IF filter. The receiver integration time, and sampling time (number of samples N_s within the integration window) will be known based on the IF filter bandwidth (sampling), and transmitter maximum coherent length t_{int}. After integration of N_s samples per N_E elements the received signal power from the target will be obtained from the following relation,

$$N_E^{LC} P_{re} N_s^2 = kTB_W N_s N_E$$

Where T and B_w are the system noise temperature and bandwidth. Note in the above equation, the left side is the signal power after coherent integration (added in voltage) while the right side represents the noise power after integration, which adds in power. In the above equation, for simplicity, it was assumed that the noise variances for all receiver elements are identical. Note also that the element power P_{re} on the left side is further multiplied by the number of antennas used to receive the signal, which is raised to a power LC (level of coherence). The level of coherence is an indication of how perfectly the element-to-element integration can take place, i.e., $1 < LC < 2$. After solving for the minimum detectable antenna element power P_{re} and plugging in the radar equation we can get the minimum required target size, and obtain the power aperture product.

Radar Array and Telecom Array Element Spacing

The pointing requirements and antenna element spacing of a radar array are also somewhat different from the telecom array. This is primarily due to different methods of tracking for radar and telecom applications. As mentioned before, the telecom array is calibrated in detection mode only. In other words, we do not need to track the target while calibrating the telecom array. Instead, we assign targets in various directions and use a large enough target to obtain adequate signal-to-noise ratio in the shortest time possible. The final signal-to-noise ratio in terms of total pulse energy (E) that intercepts the target is simply a multiplication of the signal power to noise ratio by the total dwell time, or the integration time t_{int}. The integration, or dwell time, on the other hand, depends on the search volume, which in turn depends on whether all the elements are operated in a coherent array mode or independently, or in groups (sub-array). If the search solid angle is represented by Ω then for a linear array with a baseline of length D, and antenna effective aperture area A, the integration time is given as the following relation [12],

$$t_{\text{int}} = \left[\frac{\Omega}{\lambda^2 / D\sqrt{A}} \right]^{-1}$$

Alternatively if the search volume is shared by N_{TR} of transmit/receive (T/R) array elements the integration time will be modified accordingly as follows,

$$t_{\text{int}} = \left[\frac{\Omega / N_{TR}}{\lambda^2 / A} \right]^{-1}$$

Now, assuming all T/R array elements have identical characteristics, a figure of merit for selection of the array mode versus independent element operation mode is the ratio of the array SNR in coherent mode to the array SNR in independent mode, which can be expressed as follows [12],

$$\frac{(E/N)_{distibuted}}{(E/N)_{independent}} = \frac{\sqrt{A}}{D} N_{TR}^2 = \frac{\sqrt{A}}{d} \times \frac{N_{TR}^2}{(N_{TR} - 1)}$$

Where D stands for the maximum length of the array and d is the spacing between the array elements of aperture size A. According to this relation, the element spacing Δ for the radar array would be the following

$$\Delta \geq \sqrt{A} \times N_{TR}^2 / (N_{TR} - 1)$$

Furthermore, assuming the number of elements is much larger than 10, the above criteria simplifies to the following,

$$\Delta \geq \sqrt{A} \times N_{TR}$$

Therefore, it is better to operate the radar array elements independently for the search mode and use the elements in phase coherent mode for tracking while calibrating the radar array. Based on this relation, for a radar array that operates in phase coherent mode (i.e., array mode), the element spacing is somewhat larger than for a telecom array, which is calibrated in detection mode. The pay off for the radar array is very high, particularly in light of the discussions above and the many common needed functions. Much of the techniques, as well as hardware electronics of the telecom and radar array are the same. The hybrid architecture concept of SAR (Synthetic Aperture Radar) and GPS for integrated Lunar surface positioning and navigation was also discussed in [9] where other potential benefits of joint optimization of radar and telecom arrays using the Moon as a calibration target were introduced. Furthermore, the scaleable high EIRP feature of radar array with multitudes of baselines will mitigate the requirements for deep space probes in many applications. The other operational scenario of combined radar and telecom array is the multi-mission support and network synchronization of widely separated spacecraft, particularly those needing synchronization for single image or single science events. Therefore, array calibration in various modes of operation needs to be studied so that the optimal mode of operation for array calibration can be identified.

Radar Array Pulse Repetition Frequency (PRF)

The objective of this section is to make best use of radar literature to address *PRF* issues of the array when operating in pulsed radar mode. Figure 1 illustrates the situation for pulses hitting the target at the same time. Note that when the array is in pulsed radar mode, if the element-to-element time delay and the pulse intervals for each element signal are not carefully selected, then some power is lost due to timing error. The problem is that the power loss due to the inappropriate *PRF* would be fluctuating, and is very hard to separate it from the variations caused by differential phase error. In any case, when using more than one transmitting element, each element is transmitting a series of pulses, therefore, the choice for pulse repetition frequency and the pulse duration becomes even more critical. On the one hand, the pulse integration shall provide sufficient power level for calibration, and on the other hand each pulse series emerging from each element shall coincide with the other pulse series with a high probability to avoid loss of power efficiency.

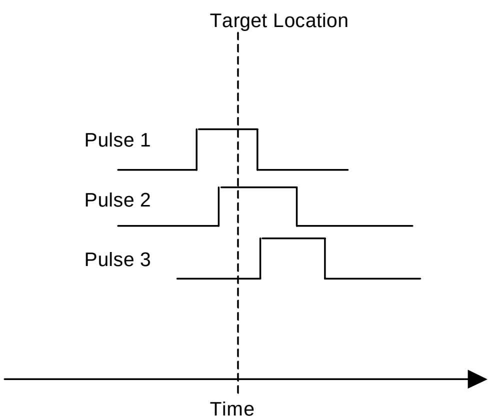

Figure-1 Radar pulse overlap maximization

Different cases may be considered for *PRF* and pulse duration for array elements. One important case is when the individual elements are pointing to the same calibration target with various *PRF*s and various pulse durations. Furthermore, let τ_k represent the pulse duration for each element with corresponding pulse intervals T_k then, it can be shown [13] that the probability P_r of two or more pulses to coincide for *n* consecutive pulse intervals is as follows,

$$P_r = 1 - \prod_{k=1}^{n} q_k - \sum_{k=1}^{n}\left(\frac{p_k}{q_k} \times \prod_{j=1}^{n} q_j\right)$$

Where $p_k = \tau_k / T_k$, refer to the probability of occurrence of a pulse at a particular point in space, and $q_k = 1 - p_k$ is the probability of nonoccurrence. Note that, the underlying assumption in these two cases 1& 2, is that the beams for all elements coincide at the target position, otherwise a separate formula is derived in [13] for cases when beams are crossed by the target at different times with different beam widths and different beam sweeping periods for each element. Regardless of which case is used, the mean time between the pulse coincidences (MTBC) is set by the minimum pulse duration of the elements, i.e., $MTBC = \tau_{\min} / P_r$. These relations become important when treating the array in radar mode, particularly when using ranging and command signals to the spacecraft while trying to avoid range ambiguities, phase drifts, and time delay differences among array elements.

Beamforming Effects of Phase and Amplitude Errors

The generalized pattern of a linear array with random element locations can be represented by [14],

$$f(Sin\theta) = \sum_{i=1}^{N} A_i \exp\left[-2\pi j Sin\theta (i-1) d / \lambda)\right]$$
$$Sin\theta = k\lambda / Nd, \quad -N/2 + 1 \le k \le N/2$$
$$f_k = \sum_{i=1}^{N-1} A_i \exp\left[-2\pi\, jki / N\right], \quad k = 0, N-1$$

Where *d* is the mean distance between elements and λ is the wavelength of the transmitted signal, and θ is the off-boresight angle and f_k is the discrete Fourier transform of the general pattern. Now, if the radar signal is chirped at the rate of $\alpha = 2\pi B/T$, where *B* is the signal modulation bandwidth and *T* is the pulse duration, then the delayed radar echo at the receiver after beating with local oscillator will be

$$x_d = Cos(\omega_d t + \theta_d), \quad t_d \le T$$
$$\omega_d = \alpha\, t_d, \quad and \quad \theta_d = \omega_o\, t_d - \frac{1}{2}\alpha\, t_d^2$$

Note that in radar applications we would like to preserve the phase and amplitude changes caused by the target features, and only want to correct for the unwanted clock jitters, and nonlinear tracking errors due to array anomalies, which generally will be range dependent. As the target moves and its range varies, the target echo gets an additional shift from its nominal center frequency bin $\omega_n = 2\pi n/T$ where *n* corresponds to the number of FFT bins for frequency estimates. The moving target would have a new frequency ω_d so the FFT signal will have an additional shift as the target moves which is given by the following, i.e.,

$$\varphi_d = (\omega_d - \omega_n)\frac{T}{2}$$

This means that the phase difference will be a function of range, which in turn means it is a function of beam direction as opposed to delays introduced by cables. The cable delays and angle of arrival delays are easier to remove, since cable lengths and angle of arrivals are easier to identify than range. For an array of baseline *D* the phase shift components in the FFT bins due to the angle of arrival delay at each element, and cable delay could be represented by φ_{ai} and φ_{ci} which are given by [14]

$$\varphi_{ai} = \pm \frac{2\pi BDSin\theta}{4c}, \quad \varphi_{ci} = \pm \frac{2\pi BD}{4c'}$$

Where the c, and c' in the denominators correspond to the speed of light in air, and in cable medium respectively. In the above relations it is assumed that the reference delay is taken at the center of the array. Generalizing the above phase shift components for target delays seen by different antenna elements introduces time of arrival delay t_i , i.e.,

$$t_d = t_D + t_i, \quad i = 1, N$$

Then the corresponding frequency and phase variations for each element can be represented by the following relations;

$$\omega_i = \alpha t_i$$

$$\theta_i = \omega_o t_i - \omega_i (t_D + \frac{1}{2} t_i) \approx -\omega_i t_D$$

$$\varphi_i = \frac{\omega_i T}{2}$$

Note that the largest phase error is due to the range difference, i.e., φ_i. The amplitude and phase errors are manifested in terms of beam broadening, which is normally caused by amplitude errors, and skew, and rising of the sidelobe levels while filling the nulls. According to [14] the cable errors normally cause a skew in the array pattern with beam broadening. The phase correction can be applied either prior to or after the beamforming. If phase errors are removed prior to beamforming the array pattern will have broader main beam, and higher sidelobe levels. The second approach is to apply a frequency shift to the spectrum of each receiver by the amount of ω_i prior to ranging. In this approach the beamforming will be applied to signals at the same frequency in each receiver [14]. The phase correction in the second method is implemented by multiplying each sample of the received waveform by exp $(-j\omega_i t)$ prior to the Fast Fourier Transform (FFT). This will remove the φ_i error, which is induced by FFT process. The remaining phase error, i.e., the $\omega_i t_D$ can be removed by the first method. It is important to note that in both of the methods indicated above, the correction has to take place for each steering direction, which is not always possible, as in situations where multiple beams are formed by taking the FFT of the receiver outputs across the aperture, and the corrections are valid only for the central beam. For delay-Doppler radar the corrections have to take place for each coherent integration period, therefore data volume reduction would be quite a challenge [9]. To summarize this section, one difference of radar array and the telecom array is the handling of beamforming, and the type of corrections required, which in turn depends on the application. So far, the telecom array has not been considering beamforming, i.e., only one combined beam is assumed for the entire array. That may not necessarily be the simplest approach, however. One big advantage of multiple beams for the array is that not only it helps nullifying the interference and helps complying with safety codes, but it also allows the usage of adaptive algorithms to carefully shape the appropriate beam for calibration. In other words, while PN sequencing method randomizes the RF phase differential error in time domain, the usage of beamforming in the calibration process helps spreading the phase error in various beams in spatial domain. In doing so, the primary beam could be shaped according to an adaptive beamforming algorithm, which in the radar community is referred to as phase conjugation algorithm [8]. Adaptive beamforming could greatly simplify calibration when using extended targets particularly when the target is composed of many uneven scatterers of various sizes and distributions.

3. HETEROGENEOUS ARCHITECTURE

There are quite a number of reasons that motivate the large transmit array architecture migration towards a heterogeneous one as opposed to the fixed 12m element size that has been traditionally considered for the array antenna element size at JPL. For the transmit array the aggregate total EIRP at each complex is N^2GP. Each antenna size could only tolerate a certain range of power amplifiers due to stability requirements as well as calibration SNR requirements. That is, from a system design perspective, i.e., scheduling, cost, calibration, and inclusion of radar and radio science applications it is better to consider various antenna element sizes. It is hard to envision the efficient utilization of a homogeneous array. That is, a uniform antenna size for all the applications, for all complexes at all times is not necessarily the most cost effective approach to DSN array design. In other words, even if there were no radar applications considered for the array, the budgeting, scheduling, and dynamic range of G/T requirements calls for heterogeneous element sizing. The element size distribution could range anywhere from 4m to 34m. We now discuss various reasons why we need a heterogeneous architecture if the radar array functions are to be combined with the uplink telecom and navigation functions of the transmit array. It may be argued that the operational requirements of the array for the heterogeneous architecture may be a major draw back. However, in a separate paper [1] we discussed some of the trade offs of the front end and the back end signal processing with FPGA technology which could relax the computational and software aspects of the array requirements extensively. Therefore, when discussing heterogeneous architectures, the impact on the operation complexity and software related issues are negligible when compared with a homogenous array and, therefore, can be ignored for all practical purposes.

Advantages of 4m Aperture

Aperture size of 4m was proposed in [15] with power per aperture up to 150W, and element spacing of 20m. The proposed architecture in [15] does not apply to radar array though, since the tower-based method of calibration is used with a fixed receiver that collects array signal, and sends a feedback from the tower to the control center for correction. Note that, since radar techniques for calibration are not used in [15], a miniature scale prototype model has to be built together with several highly stable towers before making any further conclusions about the feasibility of the method. Note also that the range and Doppler calibration are not possible with the tower method due to the fixed location of the target receiver. In other words, while in the radar calibration technique the challenge is only to find the target size and its orbit dynamics, for the tower-based method the challenge is not only the tower stability, but also generalization of the phase error signal of a set of fixed tower geometry to the rapidly changing geometry of the array-to-spacecraft in the real-world scenarios. The 4m aperture would also completely rule out any high EIRP application of the existing DSN, such as radar and emergency uplink beyond 1 TW.

There are several advantages for the radar techniques and the use of higher aperture sizes in excess of 12m, e.g., 15m, 18m, or even 34m over the tower-based method, which is constrained to 4m aperture only. First, when using radar techniques, one can look for available targets, such as the Moon and use the existing DSN assets to study the array feasibility, and if radar calibration techniques work, the concepts can easily be extended to spacecraft methods, since the geometrical conditions vary in the same way. Using the tower-based method, on the other hand, rules out advanced radar applications as well as other new applications proposed for the integrated Lunar communications and navigation. One has to overly simplify the DSN functions and its core capability to a large extent when using 4m, or smaller aperture dimensions.

According to [15] the miniature scale for the array of 4m antennas consists of 1-1.2 m diameter antennas with 1W amplifiers, and 18m towers that carry four calibration receivers. The advantage of this scalable model is that it could be extended to a real network of 4m array with end-to-end system design while the disadvantage is that it is not inclusive of the higher EIRP requirements of GSSR, neither the emergency uplink. One advantage of the proposed model in [15] is that it uses many of signaling and synchronization schemes, such as PN-sequencing, that are necessary to realize a large array anyway. However, the main problem with this approach is the basic underlying assumption, which is a linear relationship between the miniature scale and the real array. The linearity assumption is only true for small apertures, and low power per element. It is also assumed in [15] that the antenna phase centers are already stabilized and aligned so that the phase errors due to antenna movements in various directions could be ignored. This is a highly risky assumption, since there is absolutely no guarantee for the mechanical phase stability of the transmit array at the time of calibration in various directions.

Advantages of 12m-18m Aperture

There are two main classes of radar targets for calibrating the array, i.e., the near field, and the far field targets. The need for the far field target for the calibration of phased array has already been discussed [1]. The far field target for the array at X-band, and Ka-band frequencies with a baseline of 1km falls well beyond 60, 000 km, and 230, 000 km. The target ephemeris needs to be known within ~1km [9]. Obviously, the Moon is the only far field target that satisfies the requirements for being used as the Uplink Array calibration target. Given the power density limits per aperture by FCC, the lower limit of SNR for Lunar applications would be just about 12m although a safer requirement is 18m to relax the signal design requirements, e.g., peak power per pulse. From navigation point of view, which is beyond the scope of this paper, 18m is a more favorable size [9].

Advantages of 15m Aperture

The advantages of the 15m on transmit side was discussed in the previous section. There are also several advantages for the receive array if 15m is used. First, it covers the wider choice of calibrators, and provides better signal-to-noise ratio on the calibrator. Secondly, it gives a good sensitivity for the sources being studied, particularly for longer baselines. It is also crucial for interferometric array applications to keep the number of antennas small. Larger antennas help in pointing requirements. That is, for precise pointing we generally need 1/10, or 1/30 of the beam width while the signal-to-noise ratio on a pointing measurement with an array is proportional to $D^2 N^{1/2}$ with N elements of diameter D. Hence, to achieve the pointing requirements it is more advantageous to have fewer large dishes than to have many smaller antennas. The aperture diameter of 15m seems to be the compromising size for all applications if we were to use a homogeneous architecture for transmit and receive arrays.

Advantages of 34m Aperture

There are several advantages for the 34m element size for the array. For one thing, most of the current large DSN antennas are 34m in diameter. Secondly, most of the experimental efforts at JPL with the array concept have been based on using the existing 34m antennas simply because they are available. Some of the hardware limitations of 34m antennas could make the 34m arraying somewhat costly. Although recent efforts at JPL revealed that arraying the 34m antennas at Goldstone in transmit mode is indeed feasible [16]. On the receive side, as mentioned in the first section, the 34m antennas have already been used operationally, while on the transmit side they have been researched and upgraded to some extent for experiments for the Moon bounce experiment [6]. Any additional success of the 34m array demonstration would not only prove that the telecom array (Uplink Array) is feasible, but also provides a lot of insight for the radar array, which is the subject of this paper. The only disadvantage of the array of two 34m antennas is the lack of flexibility to incorporate the upgrades and modular increase of the array. However, initial trend seems to be in favor of continuing the array effort with 34m while shifting to sizes 12m, 15m, or 18m as the array evolves, hopefully, to a larger one over the years to come.

4. SUMMARY & CONCLUSION

Rapid technological changes in recent years, and the corresponding budget fluctuations as well as large dynamic range of requirements have been causing a lot of uncertainty in design of big systems that span a relatively long period of time, e.g., over a decade. This is particularly true for such large systems as DSN with a highly sophisticated global network, which takes multiple organizations to redesign it, and then it takes many more years, e.g., three decades, to deploy it while requirements keep changing rapidly as well. This trend triggers the evolving network architecture concept, which fits well with the array nature. Distributed array radar (DAR) of small parabolic reflectors have been considered in the past, however, not for distances to the Moon and beyond. Generally, the large aperture phased array systems with power, and aperture suitable for Lunar ranges could be envisioned with conventional array methodologies, i.e., flat plate array configurations [17]. However, design of a large aperture radar that starts at Lunar ranges and then grows in aperture size to cover the outer space to the edge of solar system, as does the GSSR, requires careful design strategies.

It was briefly discussed in this paper that the target requirements for calibration and testing of the large radar array would require usage of the Moon, or similar far field targets in the solar system. It was also discussed that even if just the telecom functions are considered for the transmit array, different antenna sizes will be required at various stages of time over the three decade period. This is not necessarily due to technical reasons only, rather, it could be due to budget constrains, or mission requirements. And, if a multi-function DSN array is desired, the move towards heterogeneous array architecture would be even more practical due to additional differences in design and calibration requirements for radar, and navigation functions of the array. The remaining question is then to identify the optimal transmit array size distribution per year per DSN complex based on two critical assumptions 1) the existing core DSN capabilities are preserved with all its functions, i.e., radar, radio science, radio astronomy, telecom and tracking, etc., 2) array deployment is to be adaptive with budget fluctuations, technological changes, as well as mission requirements over the next few decades.

REFERENCES

[1] F. Amoozegar, Leslie Paal, James Layland, Robert Cesarone, Vahraz Jamnejad, Arnold Silva, Dave Losh, Bruce Conroy and Tim Cornish, "Uplink Array System of Antennas for the Deep Space Network", 2004 IEEE Aerospace Conference, Big Sky, Montana, March 6-13, 2003, paper number 1254

[2] V. Janmenjad, T. Cwick, G. Resch, " Cost and Reliability Study for a Large array of Small Reflector Antennas for JPL/NASA Deep Space Network (DSN)", IEEE 1993, Aerospace Applications Conference Digest, February, 1993.

[3] V. Jamnejad, J. Huang, " A Study of Phased Array Antennas for NASA's Deep Space Network, " Antenna Applications Symposium, Allerton Park, Monticello, Illinois, September 19-21, 2001.

[4] Frederick Daum, and Robert Fitzgerald, "Decoupled Kalman Filters for Phased Array Radar Tracking", IEEE Transaction on Automatic Control, Vol. AC-28, NO. 3, March 1983

[5] K. Sarabandi, F. Amoozegar, "A Study of Array-of-Phased Arrays for Large Aperture Synthesis for Deep Space Applications & Rover-Based Missions, Technical report, Jet Propulsion Laboratory, March 29, 2006

[6] V. Vilnrotter, R. Mukai, D. Lee, " Uplink Array Calibration via Far-Field Power Maximization, " IPN Progress report, 42-164, Jet Propulsion Laboratory, February 15, 2006

[7] F. Davarian, V. Vilnrotter, " Uplink arraying for the Interplanetary Network, " Proceedings of the 24th AIAA International Communications Satellite systems Conference (ICSSC), San Diego, June 13, 2006

[8]F. Wang, F. Amoozegar, K. Sarabandi, "Ground Array Calibrations", Proceeedings of IEEE International Geoscience and Remote Sensing Symposium, Seoul, Korea, July 24-29, 2005

[9] F. Amoozegar, "Applications and operation Concepts of Large Transmit Phased Array of Parabolic Reflectors", 2006 IEEE Aerospace Conference, Big Sky, Montana, March 4-11, 2006

[10] W. Hurd, "System Concepts for Transmit Arrays of Parabolic Antennas for Deep Space Applications", 2005 IEEE Aerospace Conference, Big Sky, Montana, March 5-12, 2005

[11] DSMS Telecommunications Link design Handbook, TMOD No. 910-005, Jet propulsion laboratory

[12] R. Heimiller, et. al, " Distributed Array Radar", IEEE Trasnsaction on AE, Vol. AES-19, NO. 6, November 1983

[13] G. TA. Demos, M. S. Weprin, " Probability of Pulse Coincidence in a Multiple Radar Environment", Correspondence, 1983, IEEE Transactions on AES, Vol. AES-19, NO. 4, July 1983

[14] M.L. Lees, "Digital Beamforming Calibration for FMCW Radar", IEEE AES, Vol. AES-25, NO. 2, March 1989

[15] L. D'Addario, " Options for Uplink Array", technical report, Jet propulsion Laboratory, June 1, 2005

[16]V. Vilnrotter, MGS Uplink Array experiment summary, DOY057, 0000-0800 UTC, technical news brief, Jet Propulsion Laboratory, February 2006

[17]F. Amoozegar, Vahraz Jamnejad, and Robert Cesarone, "Prospects for Tracking Spacecraft within 2 Million Km of Earth with Phased Array Antennas", IEEE International Symposium on Phased Array Systems and Technology, October 14-17, 2003