Uplink Arraying Next Steps

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To improve the uplink capability of the Deep Space Network (DSN), NASA has sponsored two experimental campaigns at JPL to demonstrate the feasibility of uplink arraying for communication applications at X-band (about 7.1 GHz). These two efforts have made significant progress in demonstrating the uplink arraying concept and in advancing our understanding of the associated error budget. These efforts, which are near conclusion, have focused primarily on demonstrating the feasibility of uplink arraying for communications applications.

This article examines the use of uplink arraying for applications other than routine communications. Among the topics investigated are features and characteristics such as the array bandwidth, atmospheric calibration, array phase and amplitude stability, array blink pointing, and array delay calibration. Applications investigated in this article include radiometric tracking, radio science, solar system radar, and emergency communications. No insurmountable obstacles are identified in this study for the application of uplink arraying to non-communications services. A number of studies are recommended to eliminate risk in the application of uplink arraying to non-communications services.

I. Introduction

Funded by NASA, the Deep Space Network (DSN) Advanced Development Program supports efforts that improve DSN performance in order to meet the future needs of deep-space and planetary missions. One such effort is to develop cost-effective alternatives for maintaining and increasing DSN uplink capacity in the event that DSN 70-m antennas are retired or that more capability is desired than the DSN 70-m assets can presently provide. The Advanced Development Program is developing an 80-kW uplink capability for the beam-waveguide (BWG) antennas that will enable them to back up the 70-m antennas and eventually exceed the 70-m antenna capability at about 7.1 GHz [1]. This program is also developing uplink arraying capabilities that not only can back up the 70-m antennas but also can exceed their capacity [2]. The objective of this article is to briefly describe the current (end of Fiscal Year 2008) status and examine the next steps in uplink arraying. This article only considers X-band applications.

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II. Current Status

Presently, the effort for uplink arraying development is focused on feasibility demonstration. The goal is to prove, via field demonstration, that uplink arraying of separate antennas (as in a sparse array) is possible and that it can be implemented in a low-cost fashion. Another goal of the present activity is to achieve a better understanding of the error sources and their contribution to arraying loss.

The current phase of uplink arraying development, which includes two parallel efforts, is near completion. In one, five 1.2-m antennas are arrayed to demonstrate low-cost arraying feasibility. This effort is known as the Small-Scale Demonstration. In the other, three Goldstone Deep Space Communications Complex 34-m BWG assets are arrayed to demonstrate the arraying of DSN large antennas.

It is important to note that the present development effort is focused on showing that the basic idea of uplink arraying works and that the results do not have a sufficiently high level of readiness to be provided for infusion. Phase II of uplink arraying development will advance the readiness for infusion to a level suitable for future operational use by addressing, among other things, robustness and cost issues. Phase II can begin in Fiscal Year 2009 or Fiscal Year 2010.

A. The Small-Scale Demonstration

The Small-Scale Demonstration has successfully demonstrated uplink arraying for communications applications. It consisted of five 1.2-m antennas that transmitted signals to a commercial geostationary satellite at 14 GHz. All four steps of uplink arraying have been successfully and repeatedly demonstrated:[1]

(1) The antennas were calibrated using terrestrial calibration receivers.

(2) After initial calibration, the antennas were pointed to a geostationary commercial communication satellite.

(3) Single-tone and modulated signals were transmitted with the array in the direction of the satellite and were successfully relayed back to the ground.

(4) Phase alignment was maintained without recalibration over the satellite's small (0.1 deg) but significant diurnal motion.

Antenna phases maintained alignment for several days without a need for recalibration. The resulting loss was less than 1 dB averaged over several tests. The error budget in the Appendix provides a conservative estimate of the loss: 0.91 dB. All the above steps were executed via remote control. The final report on this effort is expected to be published in October 2008.

[1] L. D'Addario, R. Proctor, J. Trinh, E. Sigman, and C. Yamamoto, "Uplink Array Demonstration With Ground-Based Calibration," *The Interplanetary Network Progress Report*, Jet Propulsion Laboratory, Pasadena, California, in preparation.

Arraying loss is defined as the ratio of the ideal effective isotropic radiated power (EIRP) to the measured EIRP. Ideal EIRP can be achieved if the phase alignment among array elements has no error.

B. Uplink Arraying of Goldstone 34-m Antennas

Using a deep-space probe called EPOXI (an acronym formed from EPOCh and DIXI: Extrasolar Planetary Observation and Characterization and Deep Impact Extended Investigation), a recent uplink demonstration has shown considerable progress in the arraying of three Goldstone 34-m antennas at X-band. This effort is near completion and is expected to successfully complete in Fiscal Year 2009 [3]. To date, it has been shown that the three-element array can be calibrated using the EPOXI automatic gain control subsystem and that the calibrated phases were kept in alignment for more than 5 hours. During the EPOXI experiment, the spacecraft was tracked over a large portion of the sky with the elevation angle varying in the 30- to 60-deg range. During the experiment, both continuous-wave (CW) and modulated signals, at about 7.1 GHz, were transmitted and were successfully received by EPOXI. The observed arraying loss was smaller than 1 dB.

The major issue remaining is first to calibrate antenna phases using the Moon bounce technique [4] and then to point to the spacecraft while maintaining calibration. Prior tests of the Moon bounce approach have shown promise, and therefore it is expected that this work will successfully conclude in Fiscal Year 2009.

III. Applications Beyond Communications

The current effort that is near conclusion has focused primarily on demonstrating the feasibility of uplink arraying for communications applications. There is also interest in the community to extend the work to include other applications, such as radiometric tracking, solar system radar, radio science, and emergency communications. Therefore, applications above and beyond routine communications need to be examined, and the utility of uplink arrays for such applications needs to be demonstrated via field experiments.

It should be noted that many design considerations are the same for arrays and for single antennas. It is, therefore, only necessary to deal with array-specific features and limitations. The rest of this section mainly examines array-specific topics and their potential impacts on the desired applications. Specifically, the following question will be addressed: What characteristics of uplink arrays are different from a single antenna, and what is the impact of these differences on different applications?

In the following subsections, we will examine certain features of arraying that may impact services of interest to us.

A. Array Bandwidth

In uplink arraying, the phases of array elements (carrier phase) are aligned to maximize power in the direction of the desired spacecraft. Although the alignment of the array element carrier phases constitutes the main challenge in uplink arraying, the transmitted data also have to be aligned for successful data transmission. Data timing alignment is easier than carrier phase alignment because the data rate is much lower than the carrier frequency of 7.1 GHz. To achieve good data alignment, the root-mean-squared (rms) timing difference between array elements should be small compared to the bit time. For example, if the array is transmitting a data rate of 1 Msps, with a symbol time of 1 μs, the array timing alignment error should not exceed 0.1 μs. Table 1 shows the relationship between the 3-dB bandwidth and the timing alignment error of an uplink array.

Table 1. Array bandwidth and timing error.

Differential Timing Alignment (Distance)	3-dB Bandwidth	Approximate Data Rate That Can Be Supported	Examples
100 ns (32 m)	2.5 MHz	1 Msps	EPOXI Uplink Array Experiment
10 ns (3.2 m)	25 MHz	10 Msps	Small-Scale Demonstration
1 ns (0.32 m)	250 MHz	100 Msps	Potential future array

Similar to phase alignment, timing alignment can be achieved via initial calibration of the individual array antennas. However, due to the much lower stability requirement, the required frequency of timing calibration will be much lower than phase calibration (for example, phase calibration may need to be repeated once a week, while time calibration may be repeated once a month).

In our two demonstrations, because the transmitted data rates were low, the cable lengths and electronics that determine the timing at each antenna proved to be sufficiently well matched that the alignments were adequate without adjustment. Furthermore, the antennas were close enough together that no timing adjustment was needed as a function of direction in the sky.

For example, the small-scale array transmitted at rates of tens of kilobits per second without a need for calibration. In this demonstration, time alignment between the array elements is a few tens of nanoseconds (for all directions) without calibration. Hence, the array has an inherent bandwidth of about 10 MHz. A simple calibration of array element delays can greatly increase this bandwidth.

The Goldstone 34-m antenna array demonstration transmits at rates about 2 kbps or lower because spacecraft transponders cannot handle higher rates. Again, it is possible to calibrate the individual antennas for any reasonable requirement. For example, at X-band, deep-space bandwidth allocation is 45 MHz, and the array can easily be calibrated to handle this bandwidth.

It should be noted that for the array to be able to transmit at a high (wideband) data rate, the array electronics must also be designed as wideband systems.

In the above analysis, the atmospheric effect has been ignored because such effects are wideband. It is safe to assume that at and about X-band, the atmosphere is frequency insensitive (flat response) over many hundreds of megahertz [5].[2]

In summary, by utilizing a wideband design together with time delay calibration, an uplink array can easily transmit wideband signals exceeding 100 MHz. Clearly, any wideband transmission should be limited to the allocated bandwidth approved by regulatory bodies.

B. Tropospheric Calibration

Since radio waves travel more slowly in the atmosphere than the vacuum, a signal propagating through the atmosphere experiences a delay. The dry component of the delay at Goldstone is about 2 m, whereas the wet component is several centimeters with large diurnal and seasonal variations. The DSN uses a GPS-based approach to calibrate the atmospheric wet delay [6]. This calibration has an accuracy of about 1 cm at zenith. Note that it is customary to specify "delay" as the distance that light travels for a given time delay.

The GPS approach provides tropospheric delay estimates that are good for the whole complex — all antennas use the same data [6]. Hence, the GPS-based calibration approach can also be used for an array because this approach is not antenna specific.

On rare occasions, mainly for high-quality radio science measurements, water-vapor radiometry is used for enhanced atmospheric calibration. Reference [7] provides an example of data taken at Goldstone using water-vapor radiometry. The objective of the media calibration study in [7] was to show that media calibration using water-vapor radiometers can allow signal Allen standard deviation of 3×10^{-15} on time scales of 1,000 to 10,000 s. Furthermore, atmospheric delay was calibrated to a fraction of 1 mm (rms). In one demonstration, two antennas separated by 20 km were calibrated to have an rms differential delay of 0.4 mm.

The calibration is most effective if the water-vapor radiometer samples, as closely as possible, the same slant path as that of the DSN signal. The impact of a spatial offset between the water-vapor radiometer and the DSN antenna has been studied in some detail [8]. In one set of tests, whereas the calibration delay error is only 0.3 mm at an integration time of 100 s for a 17-m separation distance, this error grows to nearly 0.6 mm at 100 m distance (6-deg elevation angle). At a 100-s time interval, the Allen standard deviation is 6×10^{-15} for a distance of 17 m versus 1.2×10^{-14} at 100 m. For the above reasons, the DSN common practice is to reduce the distance between the dish antenna and the radiometer, preferably below 50 m. Clearly, some minimum distance is required to prevent shadowing between the antenna and the radiometer. It is worth noting that tropospheric calibration may be

[2] Although this article only addresses X-band uplink arraying, it should be noted that the atmospheric response is also frequency insensitive at the Ka-band region of the spectrum (~34 GHz) for many hundreds of megahertz.

further enhanced by future development of co-pointing water-vapor radiometers that can be installed on the antenna subreflector [9].

In principle, the media calibration technique discussed above can also be employed for uplink arrays to ensure a high level of phase stability using water-vapor radiometers. However, as noted earlier [8], media calibration quality degrades with distance between the radiometer and the antenna under calibration. Thus, it is important that the water-vapor radiometer be placed near the array elements for satisfactory results. Therefore, depending on the array size, more than one radiometer may become necessary to calibrate the media in order to meet the distance requirement (i.e., the distance between the radiometer and the antenna that is being calibrated). The exact number of radiometers depends on the array size and its configuration.

It has also been suggested that, due to the averaging effect among the array antennas, only the reference antenna needs to be calibrated (assuming that the reference antenna is nearly in the center of the array). The atmosphere will add additional differential delays to the other array elements that are likely to cancel each other out in an approximate sense.[3]

In summary, the main tool for media calibration at DSN sites is GPS based, and this approach can be used for uplink arrays without modification. However, for the rare occasions where extreme accuracy is required, a study is necessary to determine the number of radiometers for an array. Some of the questions that need to be answered are the following: What is the best strategy for calibrating the media for an uplink array using radiometers? Is more than one radiometer necessary to calibrate the medium above an array? How should water-vapor radiometers be sited with respect to the array in order to minimize the atmospheric-induced signal distortions?

C. Array Phase Stability

Among different applications that may use uplink arraying, radiometric tracking, and radio science are the most demanding of signal phase stability. The phase variations of an observed signal transmitted by an uplink system (single antenna or an array) are mainly due to the contributors shown in Table 2.

Table 2. Potential contributors to phase instability in an uplink system.

	Contributor to Phase Instability
1	Phase noise of the signal source
2	Changes in electrical length of signal distribution lines
3	Changes in phase shift through active electronic devices
4	Variations in path delay caused by the atmosphere

DSN complexes use hydrogen maser technology as the signal source with very low phase noise. The performance of the maser source exceeds the requirements set forth by most

[3] Larry D'Addario, personal communication, Jet Propulsion Laboratory, Pasadena, California, August 2008.

radio science and tracking applications.[4] Because an uplink array would use a similar signal source to the one used by a single antenna, it can be concluded that the first contributor in Table 2 will not adversely affect phase stability of an array any more than it would affect a single antenna. Therefore, the first entry in Table 2 can be ruled out as a major source of signal phase degradation.

Long-term instabilities can also originate when the signal pathlength changes due to thermal and mechanical stress. We divide this into two parts: transfer of the master reference oscillator's signal to the array site (in case the oscillator is remotely located, as it is at DSN complexes), and signal distribution within the array. At DSN complexes, careful design and implementation of the signal distribution lines (e.g., thermally isolating or burying fiber-optic cables sufficiently deep) result in a differential path delay spread of about 10 ps over a diurnal thermal cycle [10].[5] Since thermal cycles are diurnal in nature, the imposed phase variation is of a very slow-changing type, i.e., long time constant. For this reason, the DSN's single antennas (i.e., 34-m and 70-m assets) are usually not adversely affected by thermal issues when performing radio science and tracking operations over averaging intervals of a day. Within the array, the distribution must be at least as precise in order to maintain phase alignment among the antennas. The Small-Scale Demonstration has shown that subpicosecond stability is achievable via a low-cost, actively stabilized system.[6] Therefore, the second entry of Table 2 is also ruled out as a major source of phase degradation over a day.

Active electronic components can add phase noise and phase instability for an array as well as a single antenna. For an array, both the architecture and the detailed design of the electronics are selected to minimize these contributions. If the phase alignment among the array elements is maintained, then the phase of the combined signal at the target will also be stable. Both our demonstrations (the Small-Scale Demonstration and the arraying of Goldstone antennas) have shown that the electronics contribution to the phase error is small. The error budget in the Appendix assigns less than 6 deg of phase variation due to arraying. Similar to the single-antenna case, these variations are small in magnitude with a slowly changing characteristic (long time constant). Hence, the third entry in Table 2 is dismissed as a significant source of phase instability.

The impact of the atmosphere on array signals was discussed in the previous section.

D. Uplink Array Power Stability

Uplink arrays are likely to experience a small and slowly changing power fluctuation due to thermal effects. Thermal changes will cause small phase drifts between array elements. The phase change between array elements manifests itself as a change in the apparent array power. However, these power changes are small and slow. The level of the change is an array design parameter. For example, the two field demonstrations described in Section II observed power fluctuations smaller than 1 dB.

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[4] *Frequency and Timing Subsystem Functional Requirements Document (FTS FRD)*, DSMS No. 834-168, (internal document), Jet Propulsion Laboratory, Pasadena, California, January 4, 2007.

[5] This level of stability was also observed during the EPOXI experiment [3].

[6] Larry D'Addario, personal communication, Jet Propulsion Laboratory, Pasadena, California, August 2008.

There might also be contributions to the array power variation due to power fluctuations of individual antenna elements. In practice, assuming that the array elements are using saturated power amplifiers, individual elements will exhibit little, if any, radiated power variation.

For radio science applications, one of the observables is signal amplitude with a 0.1 dB stability requirement.[7] Because the amplitude variations of uplink arrays are very slow, they can be filtered out via post-processing. Thus, an uplink array should be able to meet short-term amplitude stability requirements of radio science observations. The slow-varying assumption of signal amplitude needs to be verified. Signal amplitude variations are mainly due to the atmospheric fluctuations, mechanical and thermal changes in signal distribution cables, and thermal changes in the electronics. These three contributors to amplitude instability have different levels of intensity and have different temporal dependences.

E. Array Delay Calibration

Absolute delay calibration (also known as station delay calibration) is necessary for ranging and radar applications. The suitability of uplink arrays for station delay calibration needs to be investigated [11]. Station delay calibration is a well-developed technique when single antennas are used [12].

Ranging can be performed by using the same antenna to transmit and to receive (two-way coherent ranging) or using two separate antenna systems for uplink and downlink (three-way ranging). In two-way ranging where a single antenna is used, a waveform is sent up the chain to near the antenna feed and then it is captured and returned via the downlink chain after frequency translation [12]. This process provides for the calibration of the cables and antenna electronics for range measurements. Presently, the DSN conducts ranging observations that vary in accuracy from less than 1 m to more than 2 m, depending on the observation averaging time, Sun–Earth–probe angle, signal-to-noise ratio, and a few other parameters. In Reference [13], a range error budget example, for coherent two-way ranging, is given with a total rms error of 75 cm, where 35 cm is allotted to station delay calibration.

In three-way ranging, where uplink and downlink antennas are in two different complexes, ranging accuracy is worse than in two-way ranging because of clock timing differences between the two complexes (two different clocks).[8] In three-way ranging, if the uplink and downlink stations are in the same complex, there will be no loss due to timing difference between the clocks because both systems will use the same clock (three-way coherent). However, calibrating the uplink and downlink paths is somewhat more complex than two-way ranging, resulting in a degradation of the ranging performance, albeit by a small amount [11].

Presently, it is not clear if, in a future array configuration, uplink and downlink systems will be the same or separate.

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[7] Sami Asmar, personal communication, Jet Propulsion Laboratory, Pasadena, California, August 2008.

[8] *Frequency and Timing Subsystem Functional Requirements Document (FTS FRD)*, DSMS No. 834-168, (internal document), Jet Propulsion Laboratory, Pasadena, California, January 4, 2007.

Station delay calibration in an uplink array can take advantage of the fact that the timing error between the array elements is kept small to allow wideband communications; see Subsection III.A. Typically, the rms delay error between the array elements is less than 1 ns. To get the information needed for station delay calibration, it is then sufficient to measure the delay from the ranging instrument to one of the array antennas (reference antenna). Using a wideband ranging signal, the delay calibration of the reference antenna can be done very accurately. Presently, the DSN uses a 1-MHz ranging tone [14] to achieve accuracy in the 1-m range [13]. An uplink array can use a ranging signal with much higher frequency, e.g., 10 MHz, hence drastically reducing the station delay calibration error. It is noted that the effective station delay calibration error is the root sum square (RSS) of the rms timing error of array elements with respect to the reference antenna and the calibration rms error of the reference antenna.

When comparing the array ranging accuracy to single-antenna accuracy, we also have to account for the added error due to the difference between three-way coherent ranging and two-way coherent ranging.

The atmosphere also adds a delay uncertainty among array elements. This uncertainty depends mainly on the following parameters: location of the array, the size of the array, and the performance of media calibration. As discussed in Subsection III.B, Reference [9] indicates that atmospheric differential delay calibration error can be reduced below 1 mm with good media calibration. The error budget in the appendix allocates 2.1 mm to this effect for an operational system. Therefore, the additional atmospheric uncertainty associated with an uplink array is very small compared to the total station calibration uncertainty of 35 cm, as reported in [13].

In summary, it seems that uplink array station delay calibration has the potential to provide the same (or better) accuracy as the existing DSN ranging. However, this claim is in need of substantiation via further analysis, development, and testing. Moreover, field tests are required to fully characterize array-based ranging.

It is noteworthy that a new development known as the *space clock* may reduce the need for two-way ranging in the future [15]. This technology claims onboard long-term frequency stability of 10^{-15}. The integration of the space clock with an ultrastable oscillator delivers both short-term and long-term performances approaching that of the hydrogen maser. Hence, in principle, the space clock may enable future missions to conduct one-way tracking (downlink only).

F. Blind-Pointing of Uplink Arrays

For uplink applications at X-band, the DSN 34-m and 70-m antennas are routinely blind-pointed to deep-space targets with a small pointing error [16]. To achieve this, the following parameters need to be known:

(a) The location of the target spacecraft;

(b) The location of each antenna on the Earth; and

(c) The location of Earth, including how its geographical coordinates (in which the antenna position is given) are tilted with respect to the coordinate system in which the spacecraft position is given.

For (b) and (c), there is a wide body of knowledge, and it is safe to assume that the required accuracy can be achieved. For (a), we are dependent on prior tracking of the spacecraft. An array requires a more accurate spacecraft position than a single dish due to its narrower beamwidth. However, for deep-space targets, the angular position can typically be predicted with accuracy better than 0.1 mdeg [17], which is much smaller than the beamwidth of a large array. *Note: the larger the array size, the smaller the beamwidth. For example, an X-band array of size 0.6 km has a beamwidth of 4 mdeg, which is at least 40 times larger than the DSN tracking accuracy.*

Since the desired direction is known with sufficient accuracy, then blind-pointing means making the actual beam direction agree with the desired direction without the assistance of any real-time feedback. There are two parts to this: pointing the individual antennas and pointing the array beam. The design of reflector antennas up to 100 m that point to much better than their beamwidths is a well-known technology for all wavelengths of interest to NASA, so antenna pointing need not be considered further. Pointing of the array beam is equivalent to aligning the carrier phases at the target and is controlled by the array's phase error budget. Using the Small-Scale Demonstration, we have already shown that the phase error budget easily allows for the array beam pointing with the desired level of accuracy.[9] For larger arrays, an experiment on June 27, 2008, using the EPOXI spacecraft demonstrated successful pointing when three 34-m antennas (DSS-24, DSS-25, and DSS-26) were arrayed with an array physical dimension of about 250 m [3].

IV. Services Beyond Routine Communications

In the following sections, we examine the use of uplink arraying for radio science, radiometric tracking, solar system radar, and emergency communications.

A. Radio Science

Accurate radio science measurements require good phase and amplitude stability and good atmospheric calibration. As discussed earlier, the phase stability of an uplink array is similar to a single antenna. However, when water-vapor radiometers are employed, a media calibration approach for uplink arrays needs to be developed and its performance demonstrated.

For radio science applications, the short-term amplitude stability requirement is 0.1 dB.[10] As discussed in Subsection III.D, the amplitude variations of uplink arrays are very slow; hence,

[9] L. D'Addario, R. Proctor, J. Trinh, E. Sigman, and C. Yamamoto, "Uplink Array Demonstration With Ground-Based Calibration," *The Interplanetary Network Progress Report*, Jet Propulsion Laboratory, Pasadena, California, in preparation.

[10] Sami Asmar, personal communication, Jet Propulsion Laboratory, Pasadena, California, August 2008.

they can be filtered out via post-processing. Radio science requirements apply to time periods of seconds to minutes, whereas array amplitude stability has a time constant of tens of minutes or longer. Thus, an uplink array should be able to meet short-term amplitude stability requirement of radio science observations. The slow-varying assumption of signal amplitude needs to be verified. Signal amplitude variations are mainly due to the atmospheric fluctuations, thermal changes in signal distribution cables, and thermal changes in the electronics. These three contributors to amplitude instability have different levels of intensity and have different temporal dependences.

B. Radiometric Tracking

Doppler. The requirement for accurate Doppler measurements for an array is the same as for a single-antenna system. An accurate Doppler measurement requires good phase stability, as detailed in Subsection III.C. The potential sources of phase degradation are listed in Table 2. In summary, the following are necessary for good Doppler measurement:

(1) Highly stable signal source,

(2) Low noise signal distribution,

(3) Stable electronics, and

(4) Good media calibration.

As discussed in Subsection III.C, the above requirements for good Doppler measurement are the same as for the single-antenna case.

Range. Requirements for good range measurements are the same as for single antennas: an accurate station delay measurement. This subject has been discussed in detail in Subsection III.E.

C. Solar System Radar Transmission Using an Uplink Array

The radar application, due to its R^4 loss characteristic, requires very high EIRP levels. Since uplink arraying promises a low-cost way of delivering high EIRP values, it is potentially attractive for solar system radar activities. A casual examination of radar requirements does not raise any technological flags against the use of uplink arraying for radar applications. Indeed, the current effort for uplink arraying of Goldstone 34-m antennas (see Subsection II.B) uses radar imaging of the Moon for the initial calibration of the 34-m antennas [4]. Figure 1 shows examples of these images generated using three 34-m antennas deployed in single, double, and triple configurations. In this figure, the radar signal bandwidth is 200 kHz, resulting in a resolution of about 750 m.

The current DSN radar signal bandwidth is 40 MHz. This bandwidth can easily be accommodated by uplink arrays; see Subsection III.A. NASA is interested in increasing radar bandwidth to 150 MHz for better resolution — current Goldstone Solar System Radar resolution is about 3.5 m; a bandwidth increase to 150 MHz will improve resolution to 1 m, assuming

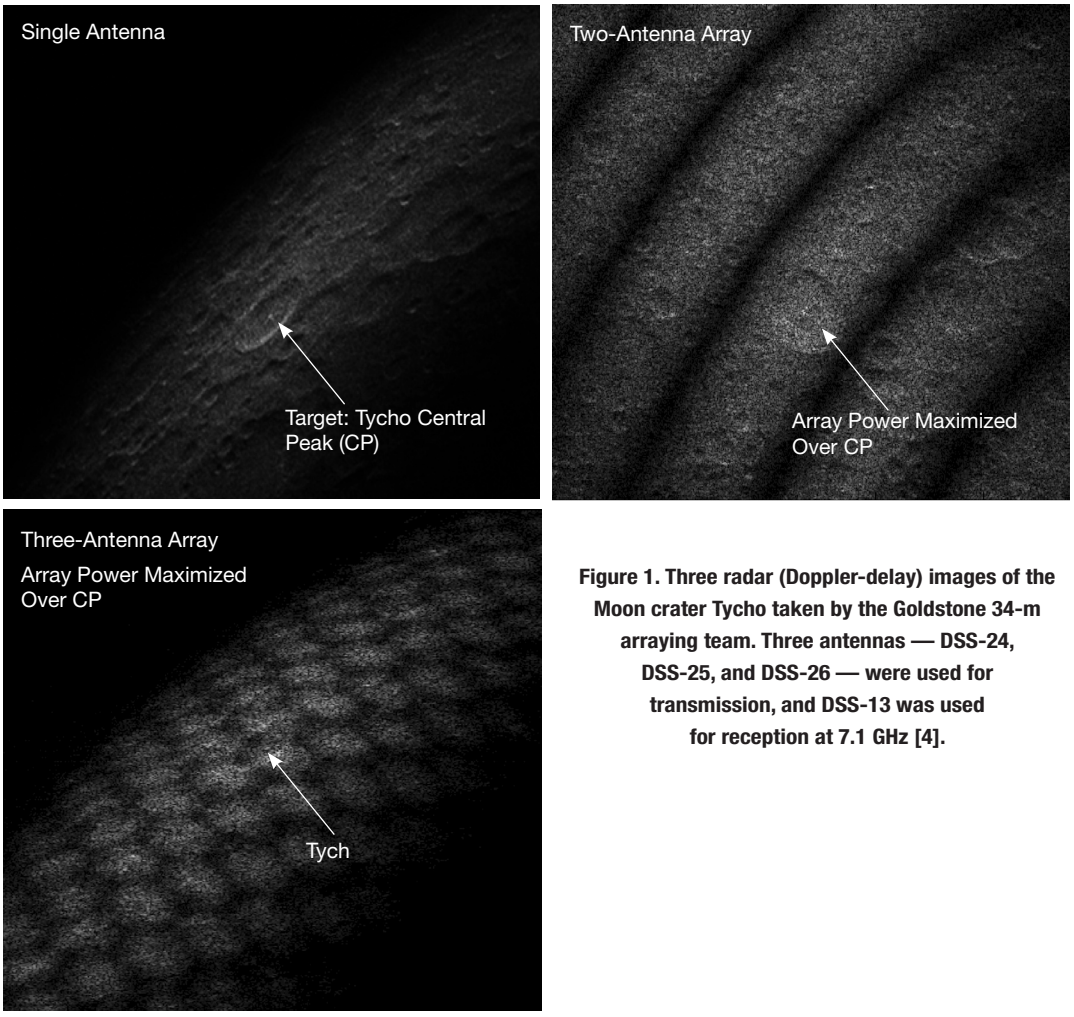

Figure 1. Three radar (Doppler-delay) images of the Moon crater Tycho taken by the Goldstone 34-m arraying team. Three antennas — DSS-24, DSS-25, and DSS-26 — were used for transmission, and DSS-13 was used for reception at 7.1 GHz [4].

adequate signal-to-noise ratio. As discussed in Subsection III.A, uplink arraying is capable of wideband operations. The current obstacle to increasing Goldstone Solar System Radar bandwidth is in the bandwidth limitation of the high-power (250-kW) klystron; uplink arraying can potentially solve this problem by drastically reducing the power requirement of the amplifier.

There are no stringent phase or amplitude requirements that uplink arraying cannot meet for radar applications.[11] Knowledge of instrumentation delays (station delay) is required as part of radar measurements. However, radar calibration requirements are less demanding than ranging and radio science requirements. Goldstone Solar System Radar often uses separate transmit and receive antennas. Therefore, radar measurements that originate with an uplink array and terminate in a separate antenna or downlink antenna array do not pose a calibration problem for the solar system radar.[12] It should be also noted that arraying, unlike a single antenna, creates fringes at the target (see Figure 1). However, these fringes do not seem to limit the application of uplink arraying to radar.[13]

[11] Martin Slade and Joseph Jao, personal communication, Jet Propulsion Laboratory, Pasadena, California, August 2008.

[12] Martin Slade and Joseph Jao, ibid.

[13] Martin Slade and Joseph Jao, ibid.

Presently, solar system radar operates at 8.6 GHz using only the 70-m Goldstone antenna. It may be prohibitively expensive to design the uplink array to support 8.6-GHz transmissions as well as 7.1-GHz transmissions using the existing DSN assets. The most economical solution might be to conduct solar system radar operations at 7.1 GHz. However, for the array to operate as a radar transmitter in the 7.1-GHz band, regulatory issues need to be addressed. Also, out-of-band interference generated by a 7.1-GHz radar signal should be investigated to make sure interference will not hamper other users operating at nearby frequencies.

Lastly, if an uplink array is used as the Goldstone Solar System Radar transmitter, the receive-end of the link needs to be specified. Presently, Goldstone communications antennas cannot receive in the transmit band of 7.1 GHz. Perhaps this can be remedied by adding 7.1-GHz reception capability to one (or more) of the Goldstone antennas, or such receivers can be added to the Very Large Array (VLA).

It is important to note that, for a newly developed array that does not necessarily utilize the existing DSN large antennas, the array can be designed with radar as a requirement. In this case, the design may allow for multiband operations. Such a system can cost-effectively provide communications services at the communication band of 7.1 GHz and radar services at the radar band of 8.6 GHz.

In summary, uplink arraying in principle seems to be capable of radar transmissions; however, the issues discussed above need to be addressed before an operational system can emerge.

D. Emergency Communications Using an Uplink Array

The common practice with deep-space probes is that, upon the detection of a serious anomaly, the spacecraft places itself into "safe mode." Although the "safing" process varies from spacecraft to spacecraft, generally the following three steps are executed:

(1) All instruments are turned off, or placed on standby,

(2) Solar panels are oriented toward the Sun, and

(3) The high-gain antenna is pointed towards Earth.

The last step, antenna pointing, varies from mission to mission. For example, distant missions may point their antenna to the Sun rather than Earth, and some missions may use the low-gain antenna for safing.

In the safe mode, the probe transmits at a low rate, typically 40 bps. This allows the flight team to monitor the health of the spacecraft while the DSN tracks the spacecraft. After the analysis of the situation, the flight team generates scripts to command the spacecraft to take action to get out of safe mode; the DSN radiates the commands.

The emergency commands can be transmitted via a single antenna or an uplink array. It seems that both options provide the same performance assuming they both generate the same level of EIRP. However, for outer planet missions, if the low-gain antenna is used during safe mode, an array may be more desirable because of the possibility of generating higher levels of EIRP.

A less-frequent scenario occurs when the probe in the safe mode is not able to transmit. There can be various reasons for this scenario: the flight team may not be able to turn on the onboard transmitter, the spacecraft might be tumbling, or some other reason. In this case, the common practice is for the flight team to generate emergency scripts to command the spacecraft to take corrective action. The DSN radiates the command to a position based on the last known state of the probe.

A concern may arise that over the course of several days the spacecraft may drift away from its last known position due to inaccurate trajectory predicts. This can happen, for example, if a trajectory correction was scheduled to be executed about the time that the spacecraft assumed safe mode, in which case the flight team would be uncertain whether the trajectory correction was correctly executed. For distant locations — i.e., Mars and beyond — it is highly unlikely that the lost spacecraft can drift outside the narrow beam of the 70-m antenna or even the narrower beam of an uplink array. Note that, for example, an array with a physical dimension of 350 m has a beamwidth that is $\frac{350}{70} = 5$ times smaller than the DSN 70-m antenna, and this difference is 25 times for the beam solid angle. *Note: In this example, 350 m is the array physical extension and not its aperture size.*

However, if the above situation occurs in earlier stages of the flight when the spacecraft is relatively close to Earth, the possibility of the lost spacecraft straying out of the uplink beam increases. In this case, the uplink system should scan around the position based on the last known state of the spacecraft. Hence, a single antenna with its larger beamwidth may find the lost probe faster than an uplink array with smaller beamwidth, assuming the same EIRP for both systems. But uplink arrays can potentially provide much higher EIRP than single antennas. Higher EIRP means that less time is required to pause at each location for command transmission. Hence, the uplink array search performance, depending on its EIRP level, may approach a single antenna's performance. It should be noted that the search for a lost spacecraft requires sequential transmissions in directions near a position based on the last known state of the spacecraft. Each transmission will require a finite dwell time for receiver synchronization and signal acquisition.

A potential advantage of uplink arraying for commanding a lost spacecraft is that, for small changes in the beam direction, the array can implement the search electronically whereas scanning with a single antenna must be performed mechanically. Electronic scanning is faster than the mechanical one.

Based on the above discussion, it appears that an uplink array is suitable for emergency commanding. However, it is also recommended that the emergency performance of uplink arraying be further investigated and its performance fully characterized for different emergency scenarios as well as different array sizes and power levels.

Figure 2 shows a report generated by the Magellan flight team describing a real-life safing scenario.

Public Information Office
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For Immediate Release
November 23, 1990

The Magellan spacecraft mapping Venus with its imaging radar went into a safe mode at 7:11 p.m. PST Friday, according to a Magellan Project spokesman at NASA's Jet Propulsion Laboratory.

The spokesman said that the spacecraft shut down its high-rate telemetry to Earth, turned off its radar, and halted the stored mapping sequence when an onboard computer detected errors in an uplink command sequence. Those errors were attributed to the ground control computers that create the uplink sequences.

The spacecraft's computer system went into a safe mode with the high-gain antenna pointed to Earth. Communication with the spacecraft was not lost and flight controllers said that three mapping orbits would be lost before mapping of the Venus surface resumes early Saturday.

It was the second loss of mapping incident in eight days. The Magellan signal was lost for 40 minutes on Nov. 15. There were two earlier losses of signal in August.

Figure 2. An example of a real safing event.

V. Summary

No insurmountable obstacles were identified in this study for the application of uplink arraying to non-communications services. The following studies are recommended before uplink arrays are used for non-communications services:

(1) Develop a procedure for precise calibration of the atmosphere above uplink arrays when water vapor radiometers are used.

(2) Develop a procedure for station delay calibration of uplink arrays.

(3) Examine the impact of array power variations on radio science.

(4) Characterize array emergency communications for a lost spacecraft.

(5) Further investigate array application for the radar service:

- Examine the cost impact of employing the available DSN assets for radar, including regulatory issues.
- Examine the impact of array fringes on the radar service.
- Examine new designs with dual band (communications and radar) capability.

(6) Conduct array field demonstration of radio science, radiometric tracking, and radar services.

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Appendix

Uplink Array Phase Alignment Error Budget

Table A-1. Uplink array phases alignment error budget.

	Small-Scale Demo at 14.5 GHz			Operational Array at 7.19 GHz		
Item Description	Value	Units	Effective val. rad	Value	Units	Effective val. rad
Noise in calibration measurement[1]	0.02	rad	0.02	0.02	rad	0.02
Knowledge of cal. rcvr. positions[2]	1.4	mm	0.16	0.25	mm	0.04
Knowledge of antenna positions[2]	0.5	mm	0. 15	0.25	mm	0. 04
Pointing errors during calibration	0.25	beam	0. 05	0.1	beam	0. 01
Multipath interference during calibration			0. 30			0. 10
Errors in near-field correction[3]			0. 05			0. 05
Refractive index error[4]	25	ppm	0. 11	11	ppm	0. 17
Electronics drift after calibration[5]			0. 10			0. 10
Mechanical changes after calibration[6]	0.1	mm	0. 03	0.1	mm	0. 02
Phase shifter inaccuracy[7]			0. 20		beam	0. 05
Pointing errors on target	0.25	beam	0. 05	0.1	mm	0. 01
Atmosphere to target[8]	0.08	mm	0. 02	2.1	mm	0. 32
RSS, rad			0. 46			0. 40
EIRP loss, dB			–0. 91			–0. 68

[1] Includes effects of other antenna signals, receiver noise, and atmospheric turbulence.

[2] Operational array will have improved initial survey for antennas and receivers, and sensors to measure receiver movement.

[3] Near-field correction error assumed to be 10 percent of actual.

[4] Local measurements of air pressure, temperature, and dew point are used. Accuracies 5 mbar and 2 deg C for Small-Scale Demo, 5 mbar and 1.5 deg C for operational.

[5] Electronics drift: new architecture for both arrays, 8 hours after cal., based on experience with demo.

[6] Mechanical: Guess based on experience. Mainly wind and thermal. Demo worse for wind due to weak mounts, better for thermal due to smaller dishes.

[7] Phase shifters: Operational array will use custom-designed phase shifters integrated with RF electronics.

[8] Atmosphere: Operational array is worse because of its larger extent. Value is for 98th percentile weather at 20-deg elevation angle, based on VLA data.

Small-Scale Demo array:
1.2-m antennas, 16 m extent, 14 m max. cal. path distance, 3.5 d min. cal. elevation.
Operational array:
6.0-m antennas, 600 m extent, 102 m max. cal. path difference, 5.3 d min. cal. elevation.