A Phased Array of Widely Separated Antennas for Space Communication and Planetary Radar

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ABSTRACT

NASA has successfully demonstrated coherent uplink arraying *with real time compensation for atmospheric phase fluctuations* at 7.145-7.190 GHz (X-band) and is pursuing a similar demonstration 30-31 GHz (Ka-band) using three 12m diameter COTS antennas separated by 60m at the Kennedy Space Center in Florida. In addition, we have done the same demonstration with up to three 34m antennas separated by ~250m at the Goldstone Deep Space Communication Complex in California at X-band 7.1 GHz. We have begun to infuse the capability at Goldstone into the Deep Space Network to provide a quasi-operational system. Such a demonstration can enable NASA to design and establish a high power (10 PW) high resolution (<10 cm), 24/7 availability radar system for (a) tracking and characterizing observations of Near Earth Objects (NEOs), (b) tracking, characterizing and determining the statistics of small-scale (≤10cm) orbital debris, (c) incorporating the capability into its space communication and navigation tracking stations for emergency spacecraft commanding in the Ka band era which NASA is entering, and (d) fielding capabilities of interest to other US government agencies. We present herein the results of our phased array uplink combining at near 7.17 and 8.3 GHz using widely separated antennas demonstrations, our moderately successful attempts to rescue the STEREO-B spacecraft (distance 2 astronomical units (185,000,000 miles), the first two attempts at imaging and ranging of near Earth asteroids, and progress in developing telescopes that are fully capable at radio and optical frequencies. And progress toward the implementation of our vision for going forward in implementing a high performance, low lifecycle cost multi-element radar array.
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1. INTRODUCTION

NASA has embarked on a path to implement a high power, higher resolution radar system to better track and characterize NEOs and orbital debris. We are advancing an X/Ka band system (KaBOOM: Ka Band Objects Observation and Monitoring) to supplement the X-band radar at NASA's Goldstone tracking complex in California. The X-band system has been so successful that it is currently being infused into the Deep Space Network as a quasi-operational system much like the current Goldstone Solar System Radar and radio science capabilities. This work describes our path toward demonstrating Ka band coherent uplink arraying with real-time atmospheric compensation using three 12m diameter COTS antennas at the Kennedy Space Center (KSC). Coherent uplink arraying has been successfully demonstrated by two NASA groups: at X band and at Ku band, without atmospheric compensation, and by sending commands to and receiving telemetry from both GEO and deep space satellites. Deep space in NASA terms means a distance greater than 2 million kilometers.

KaBOOM is a Ka band coherent uplink arraying proof of concept demonstration facility being undertaken to allow decisions to be made for implementing a National Radar Facility [large scale array(s)]:

- High power, high resolution radar system
- Space Domain Awareness
- 24/7 availability for NEO and orbital debris tracking and characterization
- Map out radar stealth zones on Mars- help define "no drive" zones for future rovers to avoid the Spirit problem
- Beam sailing propulsion capability

A description and earlier results may be found in Geldzahler et al, (2016).

2. ADVANTAGES OF A MULTIPURPOSE FACILITY EMPLOYING UPLINK ARRAYING TECHNIQUES

- An **array is a more reliable** resource than a single dish. If the 70m is down for any reason, so too is the radar facility. The same is true for the high power klystron tubes used for the radar. At the time of this writing, there are no spare tubes to ensure that a 450 kW radar capability at Goldstone. In addition, the 70m antenna that houses the NASA solar system radar was down for seven months under going depot level maintenance. During that time NASA had NO ground radar capability whatsoever. However, with an array, if any given antenna is taken out for maintenance or is in an anomalous condition, little performance is lost. For example, losing a single antenna out of 25 would be a loss of only 2% of the array downlink capability and only 1% of the uplink capability. Hence, reliability of the array is more resistant and robust to operational "down time" or element failures.
- **Virtually 24/7 availability.** Whereas radar observations on the DSN 70m antenna comprise < 3% of the available antenna time, on a NEO-focused array, some 25-30 times more antenna time could be available and thus 25-30 times the number of sources can be observed in a given year. This will dramatically help NASA reach the goal of tracking and characterizing 90% of NEOs ≥140m by 2020.
- **Spectrum management is not an issue** with the array. Since the high power, coherently combined beam forms ~200 km above the earth, the FAA EIRP limit will not be violated since the transmission from each individual antenna is below the limit thereby obviating the need for a time-consuming coordination among a large number of Agencies.
- The **range resolution** of a radar system is determined by the spectral bandwidth available. At X-band, the International Telecommunications Union has allocation 150 MHz. The Goldstone Solar System Radar uses on 40 MHz of that allocation leading to a range resolution of 375 cm. At Ka band, however, the primary allocation is 2.6 GHz, and with the secondary allocation, a total of 4 GHz bandwidth is available leading to a range resolution of 3.75 cm: two orders of magnitude improvement! In addition, we are exploring means of obtaining 1 cm range resolutions- without going to the highly weather dependent W-band (90 GHz).
- The **angular resolution** of the proposed array in a bistatic or multistatic mode with elements in the western US and in Australia operating at Ka band (33-37 GHz) and used in a radio astrometric mode (measuring to 1/100 of the beam) has an angular resolution of 0.015 milliarcsec; the equivalent of 5 cm at GEO.
- **Scalability.** If still higher resolution or greater sensitivity is desired, additional antenna elements can be added. At roughly $2.0M per antenna element, increased capability can be added quickly and at a low cost.
- **Extensibility** to Ka band. This would be unique to NASA and, in a single-dish equivalent, provide 16 times the angular resolution of the 70m radar system as well as significantly improved range and range-rate measurement.

- **Radio science experiments** are usually conducted by transmitting signals from the spacecraft past/through the target of interest to the ground. However, spacecraft transmitters, ~20W, limit the signal to noise ratio and hence the science results. Using a high power uplink from the ground to the target to the spacecraft and then downlinking the data via telemetry can increase the S/N by ≥ 1000. Science using traditional "downlink" measurement techniques will also be improved due to the higher sensitivity of the array.

3. KaBOOM: Ka BAND OBJECTS: OBSERVATION AND MONITORING

Fig. 1. Overhead shot of the KaBOOM site at the Kennedy Space Center. It is comprised of three 12m diameter antennas. The operations center is seen just to the right of center. Spacing between the antennas is 60m.

Fig. 2. Current array configuration of three 12m reflector antennas at the Kennedy Space Center

The three-antenna element interferometer system at KSC has re-validated previously obtained X-band data but now using COTS equipment rather than the vastly more costly DSN antennas, and establish the overall system baseline performance incorporating lessons learned from an initial implementation. We have done so using satellites with beacons to reassure ourselves that our algorithms are transferable and our hardware is sufficiently stable.

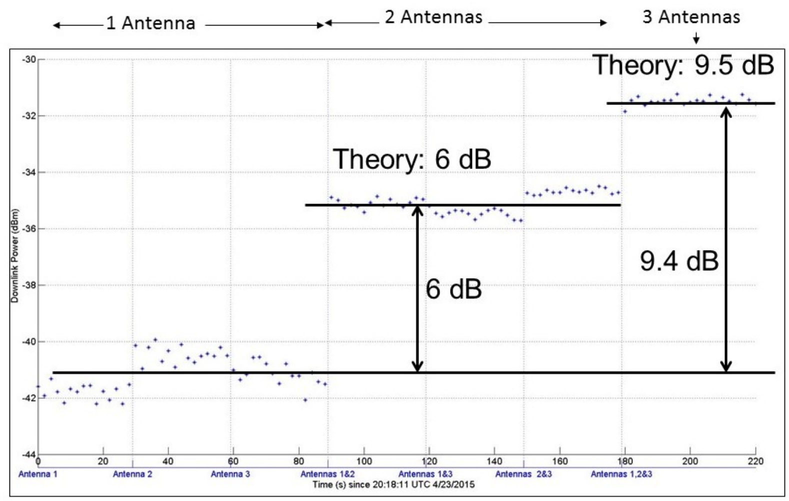


Fig. 3. X-band demonstration of the N^2 power increase at the KaBOOM site at the Kennedy Space Center

Thereafter, we intend to demonstrate coherent uplink arraying with real-time atmospheric fluctuation correction at Ka band; 30-31 GHz. All of these demonstrations involve the interferometer system in a space communications mode.

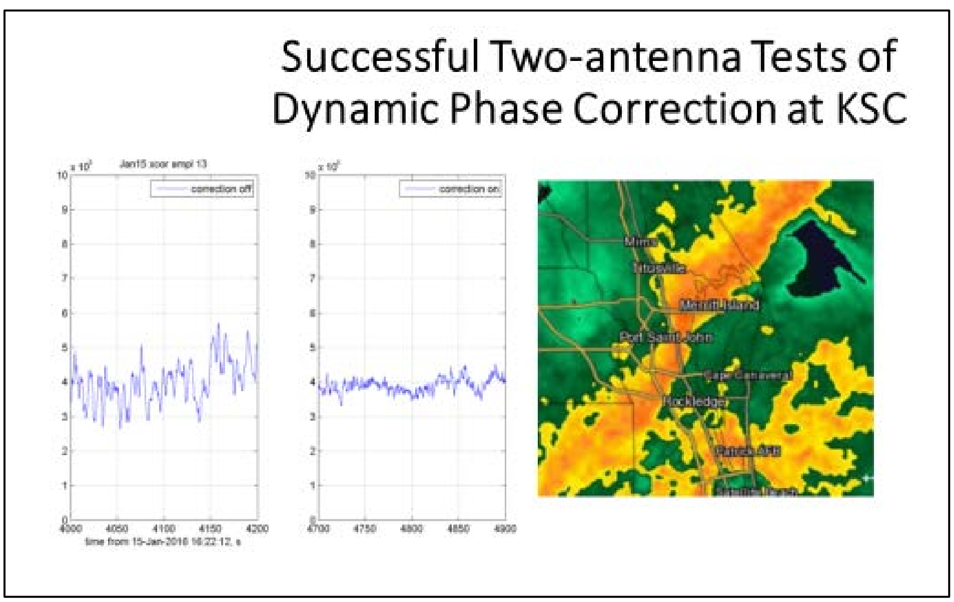


Fig. 4. Demonstration of Real Time Tropospheric Phase Fluctuations under Challenging Weather Conditions

We next undertook to extend our two antenna real time atmospheric phase fluctuation compensation methodology to the full three antenna system at the Kennedy Space Center.

On June 7, 2016, we ran additional open-loop tests of dynamic correction of the transmitted phase for turbulence in the troposphere.

Setup:

Antennas 1, 2 & 3.

Correlation: 0.2 s integrations, fully recorded, corrections applied last 15 minutes of each configuration.

This was again an open-loop test. The idea was to observe the power fluctuations on the downlink at one antenna as well as the phase fluctuations in the cross-correlations so as to see how well correlated they are and whether the cross-correlation phase could be used to correct the uplink phases. The transmitted phase of antenna 3 was offset by –0.25 cycle (= +0.75 cycle) from the alignment phase so as to make the combined power more sensitive to phase fluctuations.

Test sequence:

a. Run phase alignment using downlink power
b. Record for 5 minutes
c. Realign
d. Record for 15 minutes
e. Turn on corrections
f. Record for 15 minutes
g. Realign
h. Record for 15 minutes
i. Turn on corrections
j. Record for 15 minutes

The results of this X-band test are shown in Fig. 5. The results are not as dramatic as seen on the two antenna demonstration

because (a) the atmospheric phase fluctuations are not normally intense at X-band, and (b) the two antenna demonstration was undertaking during a severe thunderstorm storm. Still, <u>we can clearly see a reduction in phase noise in the open loop with our system which is based on legacy hardware and never designed to be phase stable</u>.

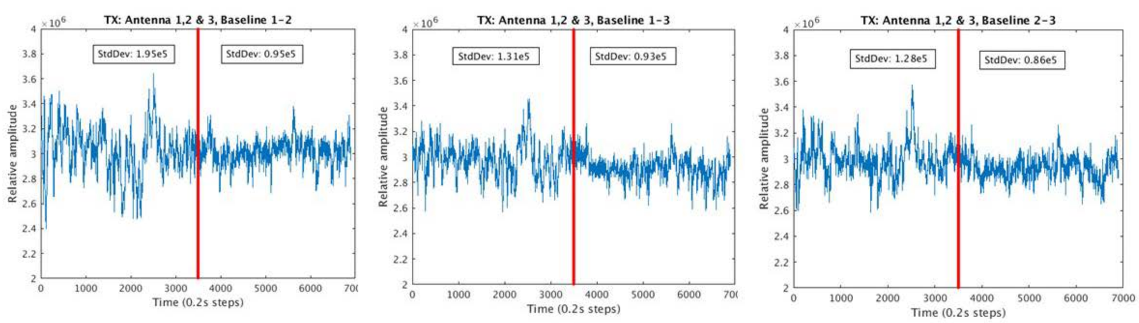


Fig. 5. Real time atmospheric phase fluctuation corrections at 8GHz at the KaBOOM site at the Kennedy Space Center. All three antennas transmitting, the red line indicates where correction was turned on.

We are on track to undertake similar demonstrations in the 30-31 GHz band in late October-through mid-November 2017. That will complete the space communication demonstrations of coherent uplink arraying techniques, and set us on a path for radar modes in the KARNAC phase of our program development.

4. KaBOOM to KARNAC

Following the successful demonstration of real-time atmospheric phase fluctuation correction at Ka band, we shall convert the space communication system at KSC to a Ka band (34-36 GHz) radar system to demonstrate a high power, high resolution radar system (KARNAC: **K**a band **A**rray **R**adar for **N**EO **A**ccurate **C**haracterization). Our initial goal is 10 cm range resolution. If we can obtain Ka band transmitters with a bandwidth of 33-37 GHz, we may be able to attain a 5 cm range resolution. These are theoretical resolutions, and systematic errors etc. may increase these resolutions slightly.

Once KARNAC has successfully demonstrated its target performance and passing of NASA and our partners' funding decision gates, we envision the construction of a larger, multi-element array to increase capability. Table I below shows the potential advantages. It is evident that even with a modest number of antennas (15), there is the possibility of a 100% increase in maximum imaging distance over the current 70m capability and the ability to track objects over a volume more than 8.6 times larger than is current possible. Even a modest system of antennas can provide a substantially greater uplink power than is current available at Ka band. However, this assumes coherent uplink arraying at Ka-band can be successfully accomplished. After the successful demonstration of the initial capability, we shall explore its limitations; i.e. - where does Ka band uplink arraying break down or become ineffective. These data will provide critical data for designing an operational Ka band uplink arraying system. To date, none of the coherent uplink arraying demonstrations using widely separated antennas has failed! This is because time and funding constraints have not allowed any of the teams to test to failure. We plan to rectify this deficiency with KaBOOM. The beauty of an array system is that antennas and transmitters can be deployed as requirements and desirements evolve and as funding becomes available. The totally funding need not be allocated at once.

The advantages of operations at Ka band are enormous: the

- For radar applications, an increased spectral bandwidth allocation of 4 GHz (vs.the 40 MHz with the 7 GHz Goldstone radar) thereby leading to a dramatic increase in spatial and range resolutions (5 cm vs. 400 cm) as well as more power on target (Table I). This is enabled by the newly developed 30 kW Ka band klystrons having a bandwidth of 4 GHz [33-37 GHz]
- For NEOs, Space Domain Awareness, and orbital debris cases, the increased power afforded by uplink arraying radars can help to better characterize objects and can track and characterize objects farther out than current radars (Table I).
- For geolocation applications, measurement of atmospheric fluctuations coupled with other sensor data has the potential to increase the accuracy and precision of ground-based target location.
- For space communication purposes, the wider spectrum allocation (10x wider than at X-band) will allow for more data to be sent at a given time and complements NASA's on-going optical communications efforts.
- For radio science, the 100-1000x increase in possible uplink power will allow for more precise determination of planetary properties.

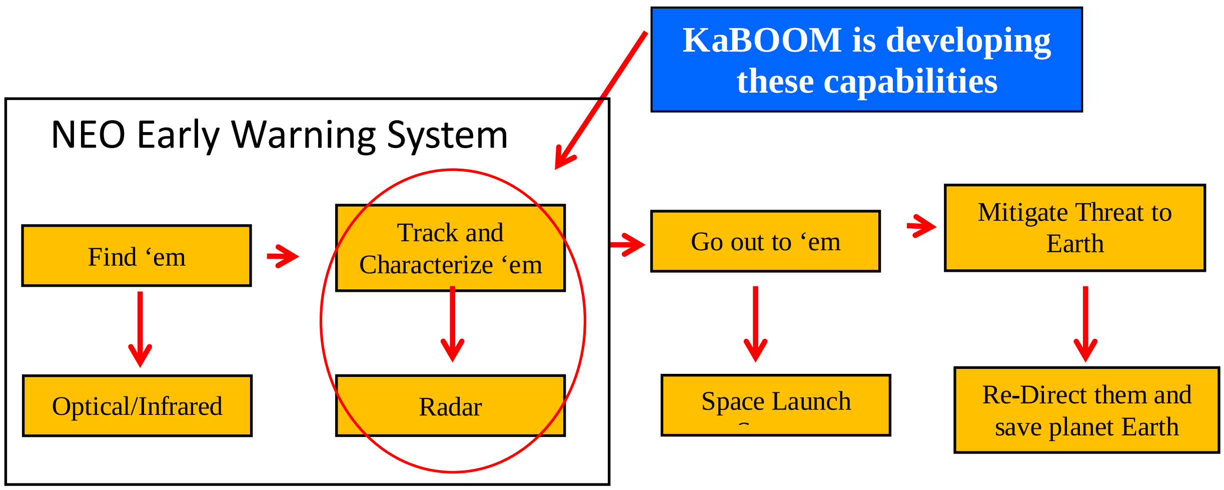
Table I. Comparison of Current and Proposed Systems

Current State of the Art

	# Antennas	Power (TW)	Maximum Distance (AU)
70m; X-band; 460 kW	1	11	0.1
12m; Ka-band; 100 kW; 50% efficiency	1	0.9	0.01
	15	215	0.15
	25	600	0.26
	50	2410	0.37
	100	8650	0.53

One of the target satellites chosen for the Phase 1 Ka band demonstration, WGS 3, has an elevation as seen from KSC of only 10 degrees- meaning an air mass 5.6X greater than that toward the zenith. This constraint of increased attenuation and scintillation coupled with the non-ideal Ka band weather provides a highly challenging environment. Since this is a demonstration for NASA as well as for other partners who may deploy larger systems using these techniques in non-Ka band-pristine locations, we have deliberately chosen a difficult challenge.

5. APPLICABILITY TO PLANETARY DEFENSE



It is well known that radar is an ideal technique to characterize (size, shape, spin, porosity) near earth objects and precisely determine their orbits (up to 5 orders of magnitude more precise than optical determinations). Radar measurements can prevent potential mission targets from being "lost." Many NEOs are lost shortly after discovery using optical techniques. However, radar observations can anchor the orbit of an object for decades or in some cases centuries. Furthermore, higher powers and thus farther distances can be achieved with an arrayed system thereby (a) expanding the search volume for NEOs (a factor of ~150 for an array of 100 antennas), and (b) through characterization, narrow the potential target list thereby reducing the risk of sending a robotic precursor mission to the "wrong" asteroid.

Large arrays with high power transmitters on each antenna could lead to an NEO Early Warning System. In Fig.8, we show the current capability, and what is possible with a large array: extending the area of tracking from 0.1 AU (1 Astronomical Unit is the average Earth-Sun distance, ~ 150M km).

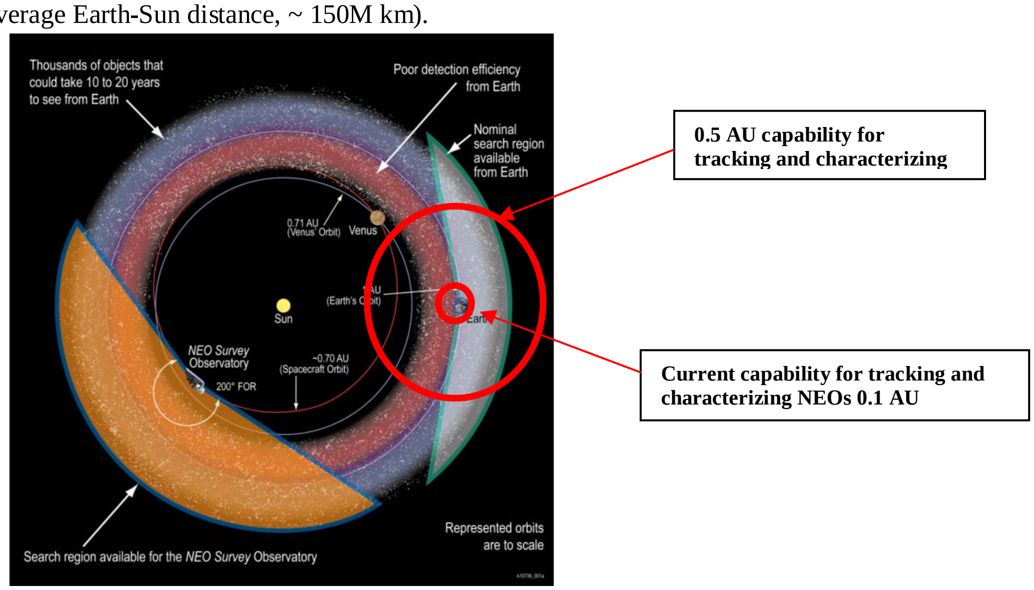


Fig. 6. Possibility for a NEO Early Warning System

6. APPLICABILITY TO ORBITAL DEBRIS

The National Space Policy states the following regarding Orbital Debris remediation (ODR): "For the purpose of minimizing debris and preserving the space environment for the responsible, peaceful, and safe use of all users, the United States Shall:

- "Pursue research and development of technologies and techniques, through the Administrator of the National Aeronautics and Space Administration (NASA) and the Secretary of Defense, to mitigate and remove on-orbit debris, reduce hazards, and increase understanding of the current and future debris environment."

NASA's recognition of the importance of ODR technology coupled with limited resources provides the basis for guidance on ODR investments and activities. In summary:

- NASA related funded and unfunded work should extend only to technology development, not operational systems. NASA has no plans to establish an operational role in ODR.
- NASA will focus efforts in ODR technology development on Technology Readiness Level (TRL) 1-4 concepts.
- Current investments and activities should demonstrate nonduplicative cross-cutting relevance to the technology roadmap areas prioritized in the Agency's Strategic Space Technology Investment Plan.

As time goes on, orbital debris has become and will continue to become an ever increasing source of risk to rocket launches, to the International Space Station, and to government and commercial space assets. Tracking of orbital debris on cm (or even mm) size scales and larger has become concomitantly more imperative. (Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's meteoroid and Orbital Debris Programs," National Research Council report: The National Academies Press at http://www.nap.edu/catalog.php?record_id=13244). Here again, Goldstone has made a contribution- the statistics of the numbers of small particles. The Goldstone 70m antenna can detect individual small particles, but the beam size is far too small to track these particles. The proposed array, with broad primary beam antennas, has the advantage. This type of system can complement and supplement the activities of the Space Fence. However, although NASA's Goldstone antenna can detect individual small (< 1 cm) particles, they are not tracked because the particles move through the very narrow antenna beam (2.2 arcmin) too quickly. Furthermore, that antenna is so busy tracking NASA spacecraft, that little time, perhaps only 100 hours/year, are available for such observations.

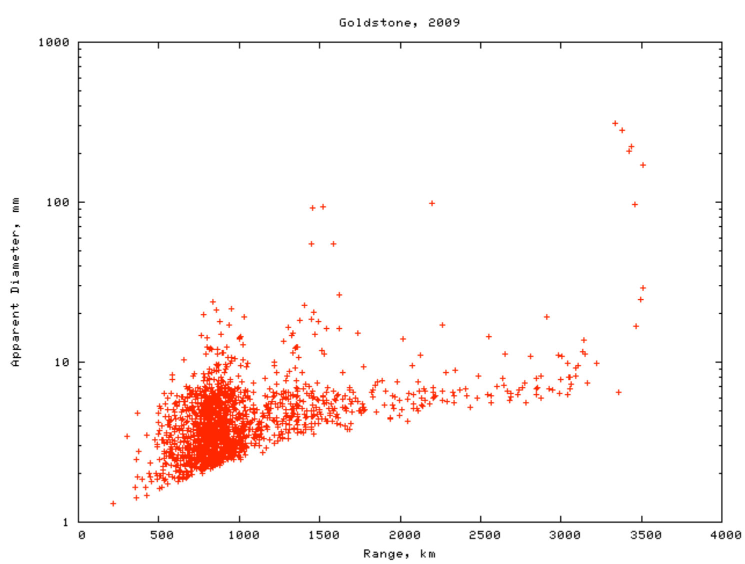


Fig. 7. Goldstone Orbital Debris Radar Apparent Diameters detected in FY2009. Each cross represents an individual particle. The blank part of the diagram near the bottom and toward the right is an artifact of a sensitivity selection effect.

7. ASTEROID IMAGING AND RANGING

The first demonstration of using coherent uplink arraying in a radar mode has been undertaken at the Jet Propulsion Lab (Vilnrotter and Tsao) using two 34m beam wave guide antennas at X-band. Precise calibration of Array Radar antenna phase required, and the phase calibration can be accomplished via the "Moon-Bounce" method. In addition, closed-loop phase control was required to maintain phase calibration since temperature variations and equipment instabilities degrade coherence. The proposed array radar approach provides simultaneous projection of OD **velocity vectors** onto **three independent baselines,** thus enabling trajectory determination from a single Array Radar observation!

In brief, three 34m BWG antennas with 20 kW transmitters at 7.18 GHz were available. The array spanned ~ 500 meters with antenna null-to-null beamwidths ~ 170 mdegs and spacings: DSS-24 – DSS-25 baseline ~ 23 mdegs and DSS-24 – DSS-26 baseline ~ 15 mdegs. For a single antenna: EIRP of 34m antenna, 20 kW transmitter; two antenna array: peak EIRP of 34m antenna, 80 kW transmitter; three antenna array: peak EIRP of 34m antenna, 180 kW transmitter. CAVEAT: Simultaneous multi-frequency/multi-baseline operation remains to be shown. This would enable processing of simultaneous echoes from different baselines.

The results of our initial phased array radar tests with the Goldstone 34m antennas were presented in Figure 12 of Geldzahler et al. (2014). Fig.11 shows the predicted two order of magnitude increase in speed of a GEO search even for a modest sized (15 Tx, `15 Rx) array.

7a. ASTEROID 2007 WV4: IMAGING AND RANGING

On 31 May and 1 June 2017, we observed asteroid 2007 WV4 using three 34m diameter beam waveguide antennas at NASA's Goldstone Deep Space Network tracking station.

Here are the circumstances of the close approach of 2007 WV4.

- It is in a very elliptical and highly inclined orbit about the Sun.
- It approaches our planet from south of the ecliptic and from the direction of the Sun.
- It is literally not visible to our ground-based optical telescopes right now as it is in the daytime sky and will only become visible to them at a high declination in the night sky in a couple of days after this close approach to the Earth.
- Radar is the only way to observe it at this time

Properties

- Diameter: 900m
- Optical albedo: 0.045➔ dark object
- The 2017 encounter is the closest by this asteroid for at least the last 400 years
- Classifies as a potentially hazardous object

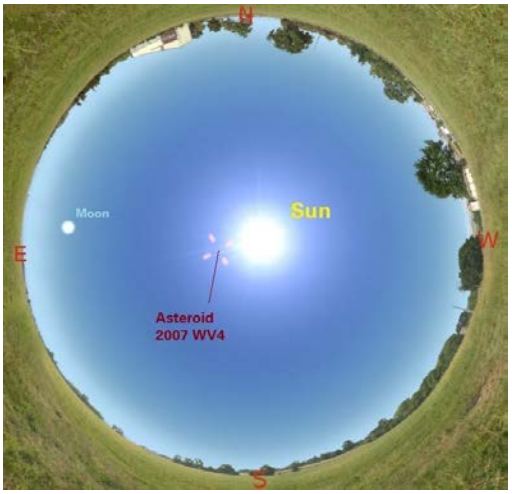


Fig. 8. Sun-2007WV4-Earth Orientation on 31 May-1June 2017

- Doppler-delay image of 2007 WV4 asteroid taken using Goldstone uplink array on DOY 151-152
- Uplink array using three 34-m BWG antennas (DSS24/25/26 transmitters @ 20kW/20kW/80kW)
- Receive station was single 34-m BWG antenna (DSS13)
- Image formed using 1 μs chips (150-m resolution in range) and 300 second integration

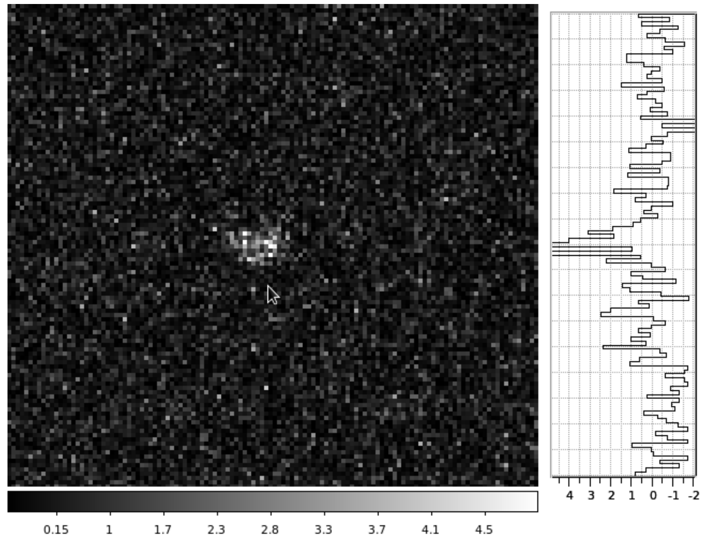


Fig. 9. 2007 WV4 Asteroid Doppler-delay Image using the Goldstone Uplink Array

We also attempted ranging measurements of near Earth asteroid 2007 WV4. The raw delay was measured from the time the PN code was generated at SPC-10 to when the PN echo from asteroid was recorded at DSS-14 (70m antenna). The range estimate to 2007 WV4 asteroid was computed by subtracting the ground delay from the raw range delay measurement. There was some uncertainty due to the calibration of the delay from the SPC-10 uplink exciter to DSS-25 transmit antenna, and from the DSS-13 receive antenna to DSS-14 digital recorder.

SPC-10 to DSS-25 delay is ~71.5 μs (based on prior measurement in different configuration)
DSS-13 to DSS-14 delay is ~155 μs (no calibration; estimated from physical distance)

Using the uplink array on 2017DOY152, the range measurement from 2007 WV4 to DSS-25 was about 3.19237 x 10^6 km ±50 km.

7b. ASTEROID 3122 FLORENCE: IMAGING AND RANGING

On 31 August – 2 September, we observed asteroid 3122 Florence using three 34m diameter beam waveguide antennas at NASA's Goldstone Deep Space Network tracking station as uplink array and DSS13 as the downlink antenna..

Radar images of asteroid 3122 Florence obtained at NASA's Goldstone Deep Space Communications Complex between August 29 and September 1 using the Solar System Radar on the 70m antenna have revealed that

- The asteroid has two small moons
- Confirmed that main asteroid Florence's is about 4.5 km (2.8 miles) in size.
- The sizes of the two moons are not yet well known, but they are probably between 100 - 300 meters (300-1000 feet) across.
- Florence is only the third triple asteroid known in the near-Earth population out of more than 16,400 that have been discovered to date.
- All three near-Earth asteroid triples have been discovered with radar observations and Florence is the first seen since two moons were discovered around asteroid 1994 CC in June 2009.

The radar images also provide our first close-up view of Florence itself.

- 3122 Florence is fairly round,
- it has a ridge along its equator,

- at least one large crater
- two large flat regions
- numerous other small-scale topographic features.

The images also confirm that Florence rotates once every 2.4 hours, a result that was determined previously from optical measurements of the asteroid's brightness variations.

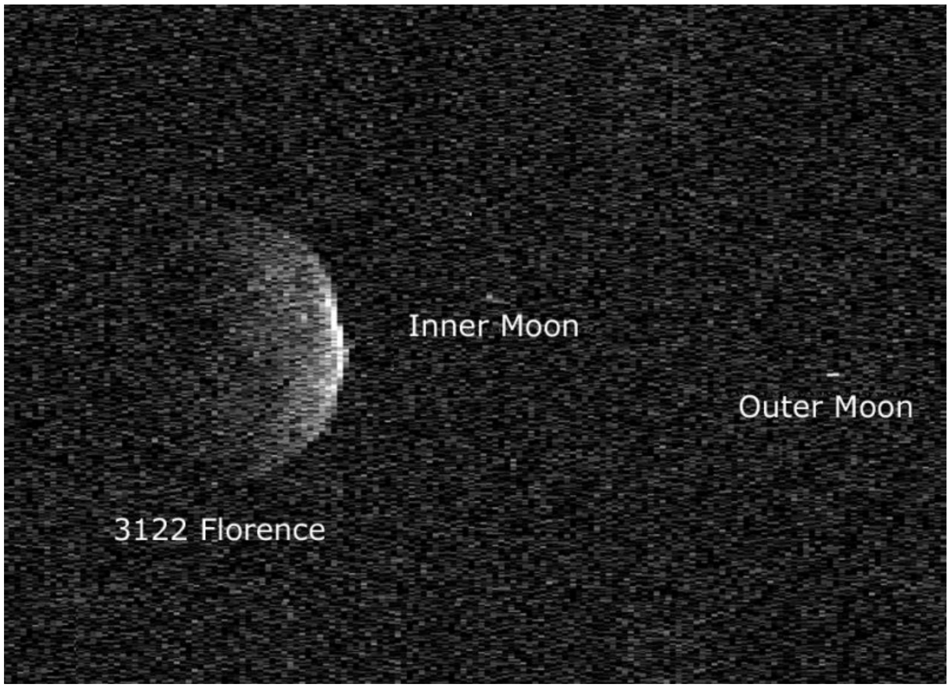


Fig. 10. 3122 Florence Asteroid Doppler-delay Image using the Goldstone 70m antenna. Resolution of 75 meters, the moons are only a few pixels in extent and do not reveal any detail.

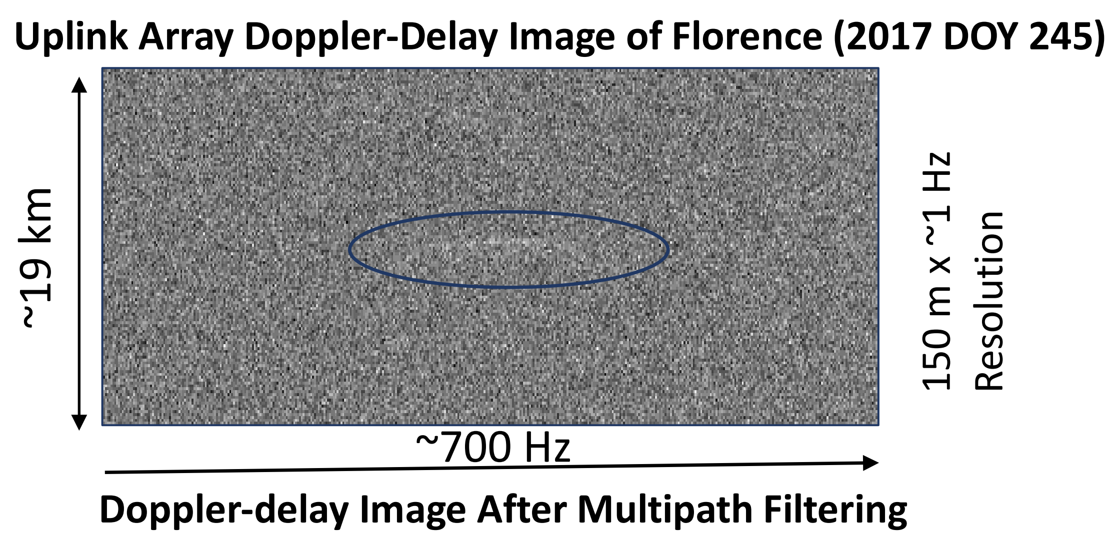


Fig. 11. 3122 Florence Asteroid Doppler-delay Image using the Goldstone Uplink Array

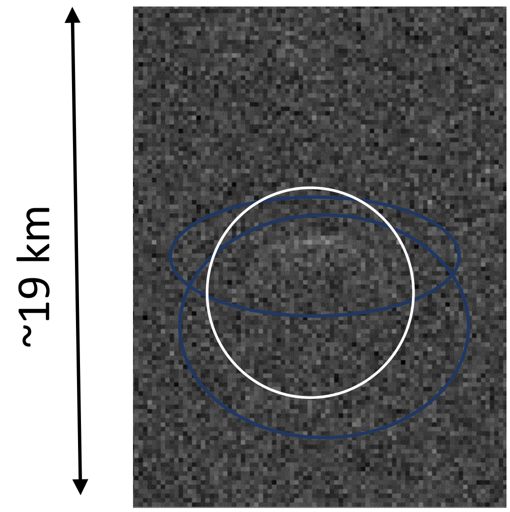


Fig 12. 3122 Florence Asteroid Doppler-delay Image using the Goldstone Uplink Array (enhanced)

Figures 11 and 12 were derived from an uplink array configured using three 34-m antennas at Goldstone at 8 GHz

- DSS24 with 20 kW transmitter (TXR)
- DSS25 with 20 kW TXR
- DSS26 with 80 kW TXR

The receive station was single 34-m antenna at DSS13. The image was formed using 1 μs chips (150-m resolution in range). Unfortunately, we experienced strong multipath interference at DSS-13 from the transmitting stations during the uplink array observations which resulted in increased background noise in the image. Some filtering of the multipath interference was possible, but it was limited by the multipath frequency overlap with the desired echo

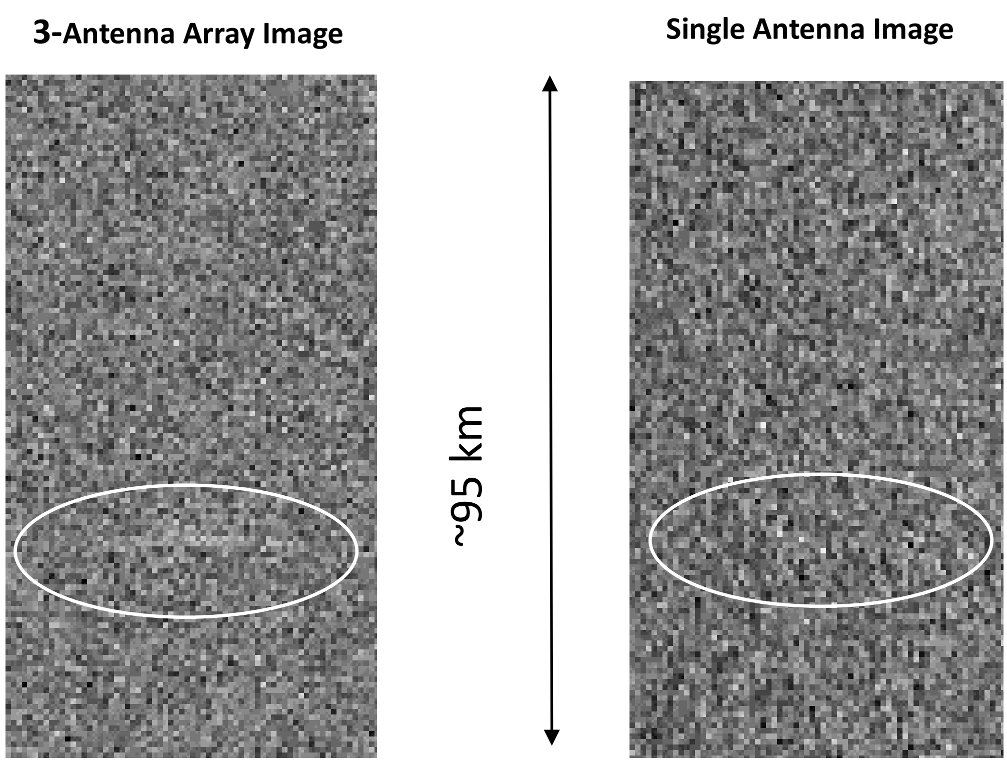


Fig.13. 3-antenna Uplink Array vs. Single Antenna Comparison: Florence Images (750m x 2Hz Res)

The images on the right show the SNR improvement provided by the 3-antenna array (20/20/80 kW) over a single antenna (80 kW). They were generated using identical integration times on 2017 DOY 244. The array provides theoretical 6 dB increase in uplink EIRP compared to single DSS-26 antenna with 80kW transmitter. Compared yo 2007 WV4 (see above), the echo from Florence was expected to be slightly weaker despite being a larger asteroid. The closest distance from Earth for Florence during the observation was approximately 18.5 lunar distances, while 2007 WV4 was at 8 lunar distances during the 2017 DOY 151/152 track

We also attempted ranging measurements of near Earth asteroid 3122 Florence. Improved calibration of the ground path delays in uplink array at Goldstone resulted in more accurate range measurements

- Round-trip delays from SPC-10 to each transmit antenna was measured using modulated 1K PPS signal from FTS (DSN Frequency and Timing Subsystem)
- The same measurement was repeated for the DSS-13 to DSS-14 delay

Range estimate to Florence asteroid was computed by subtracting the calibrated ground delay from the raw range delay measurement, and dividing by 2 to find the one-way range. The raw range delay was determined by correlating received echo with the transmit signal.

The measured two-way delay to Florence after removal of calibrated ground delay was 47.180517 seconds (04:24 UTC DOY 244).

Using the uplink array on 2017 DOY 245, corresponding one-way range is 7,072,171 km ±15 km. The uncertainty is mostly due to the low SNR of the recorded echo at DSS-13.

8. RECOVERY OF NON-COMMUNICATING SATELLITES

NASA's STEREO BEHIND was lost on October 1, 2014. All contingency operations up until Aug 22, 2016 using the 70m antennas with 20 kW transmitters were unsuccessful. STEREO-B finally did phone home on August 22, 2016. **We have *reconnected with* but not yet *recovered* the spacecraft**. We have previously phased up the three 34m antennas at NASA's Goldstone tracking station in the Mojave Desert to try and jam a set of emergency commands in through a backlobe or a side lobe. We may have to do so again as the spacecraft orientation continues to be increasingly unfavorable for "normal" communications.

Two of the three 34m BWGs at Goldstone have 20 kW transmitters while the third has an 80 kW transmitter. When coherently phased, the combined power is 16 times that of a single 34m antenna and four times that of the 70m antenna. We have, albeit unsuccessfully, attempted recovery operations with the phased uplink array on a monthly basis since March 2016, and after negotiation with the Heliophysics Division at NASA HQ shall continue to do so through June 2017.

At the time we normally get the 3-34m antennas at Goldstone, they were unavailable for uplink arraying, so the Deep Space Network 70m antenna was used and successfully contacted STEREO-B! The carrier signal locked, and we now understand the orientation, spin rate, and spin precession rate of the spacecraft and we also know the battery has been damaged: 2 of 11 cells are dead. Recovery operations are underway to slow the spacecraft sufficiently for the star tracker to capture stars thereby allowing us to orient the solar panels to sun-point.. As seen in Figures 10 and 11, the signal from STEREO-B varies periodically every 1.7 minutes with a peak to peak amplitude of 11 dB. This is a reconnection with the spacecraft, not yet a recovery. Further attempts at recovery are underway with the DSN 70m to slow the spin rate and capture telemetry, etc. The uplink arraying team has another run on September 22-23, 2016.

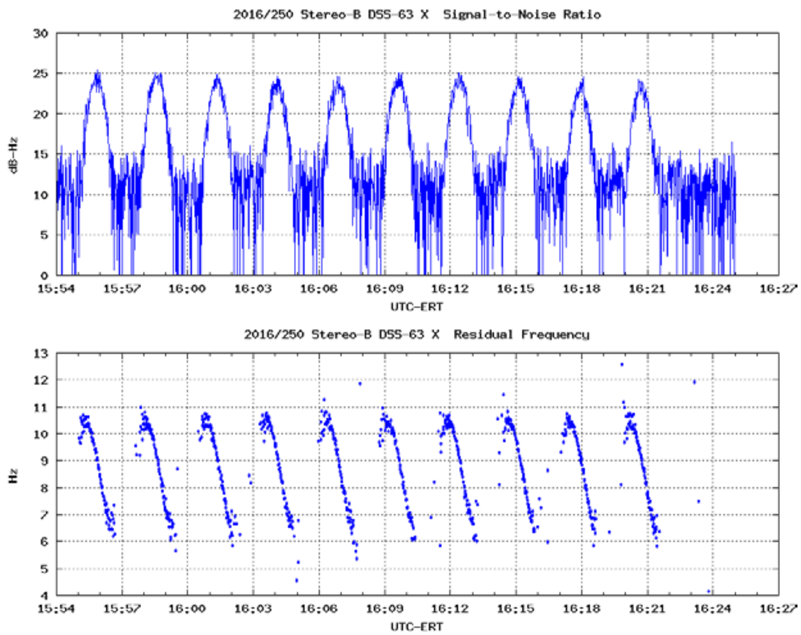


Fig. 14. Signal-to-noise ratio of the received downlink from STEREO-B and the residual frequency rate showing the spin rate. Data from Applied Physics Lab STEREO-B engineering team

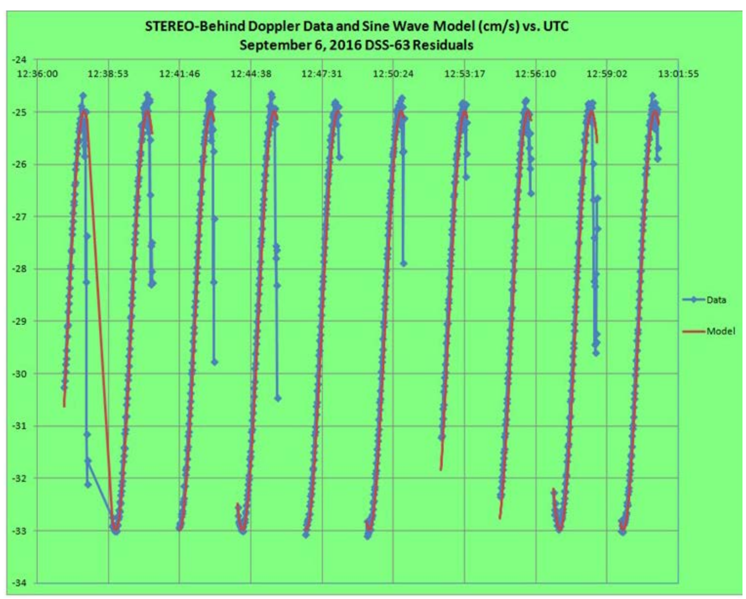


Fig. 15. Sine wave fit to STEREO-B Doppler data. Line-of-sight vs spin axis: 41,1 deg, Period 153,8 minutes, amplitude 4.00 cm/sec, standard deviation of residuals 0.94 cm/sec.

9. GOING FORWARD PLANS

As of this writing, only KaBOOM is funded. The near term steps for the effort at Kennedy Space Center are demonstrations of:

1. X-band- communication mode:
    a. Self-calibrating, stand-alone system
    b. Real-time atmospheric phase fluctuation compensation (non-cooperative target)
2. Ka-band- communication mode:
    a. Demonstration of the N^2 effect
    b. Real-time atmospheric phase fluctuation compensation (cooperative target)
    c. Self-calibrating, stand-alone system
    d. Real-time atmospheric phase fluctuation compensation (non-cooperative target)
    e. Low power Ka band bistatic radar
    f. Determination of where the coherent phasing breaks down
3. Transmogrify KaBOOM space communication system to the KARNAC high power radar system

We have made a detailed cost estimates for replacing the communication mode system in KaBOOM with a purely Ka band radar system. The transformation from KaBOOM to KARNAC - Plan A- has been jump started by our obtaining three surplus Ka band TWTs (34-36 GHz spectral response, each 30 kW peak power).

KARNAC has the potential to transmit half the power (225 kW) as the Goldstone radar system (450 kW) albeit with a range resolution of 10 cm as opposed to the 400 cm at Goldstone.

10. GETTING TO SPACE OBJECT ARRAY RADAR (SOAR)

The key to implementing and operating a multi-element array such as soar is keeping down the life cycle costs. We have wonderful examples is the VLA and VLBA (operated by NSF/AUI). To reduce the costs still further, our immediate goals are to use additive manufacturing techniques for manufacturing 12m class antennas- either monolithic structures or a combination of small dishes to achieve the desired aperture diameter.. For NASA purposes, we want these antenna to perform at both RF and optical frequencies. The latter desirements is derived from two objectives: RF- SOAR, and optical because NASA studies indicate that to undertake optical communications from Mars at conjunction, a 12m class optical light bucket is the key. For optical comm, a wavelength of 1550 nm is the specification. However, our goal is to make a 12m dish or its equivalent capable of imaging in the visible. Our specification is $\lambda/10$ with a stretch goal of $\lambda/20$.

A second development we are pursuing is the development of solid state transmitters with a 50% efficiency with an eye to replace the currently used TWTA's which are much less efficient. We plan to begin with a prototype of a 100W transmitter in the 33-37 GHz range, and from there determine what developments are need for multi-kW transmitters. The 100W Tx could have additional application for use on NASA spacecraft for deep space missions- if we can demonstrate a lower size, weight and power than the currently used tube-based communication systems.

10b. ADDITIVE MANUFACTURING- FIRST STEPS

The intended use for the feed horn and the follow on Ka band feed is to fit on arrays of small diameter antennas. The printed feed h12orn is a carbon composite operational in the 8-9 GHz range with some 10-12 dB gain. The component was precision printed using a 3D printer, nScrypt 3Dn 300 with a thermoplastic extruder, nFD™. A high precision micro-mill was used to increase the smoothness along the critical walls within the feed horn and then sprayed with a thick film silver conductor. The part is then temperature cycled to 70 °C to cure the silver paste. The measured temperature range in a cooled receiver is -263 to -258 °C (10 to 15 K). Temperature cycling of the 3D printed horns was performed from -197 °C to +70 °C (77 K to 343 K) by dipping in liquid nitrogen at least three times with 60 minute dwells by with no observable cracking or other degradation. Environmental testing is increasingly becoming important as 3D printing is used in a wider range of environments. In addition to the 3D printed version of the feed horn, we also fabricated one using the traditional CNC from an aluminum block. This aids in validating the 3D printed version by providing a gold standard to compare against. Our initial results are given below:

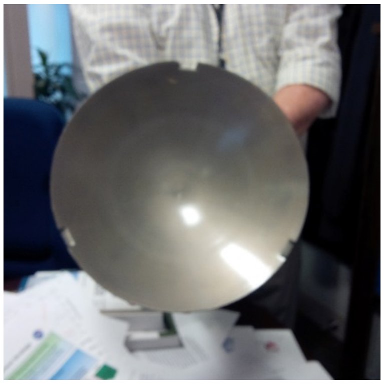
 

Fig. 16A and B. 3D manufactured 30 cm RF/Optical antenna. First attempt; second attempt

The challenges of printing a 300 millimeter dish that is optically polished and more than 90% reflective are significant. Printing a dish using a layer by layer approach implies many large, as compared to optical wavelength, features. Removing those features using sanding and polishing is trivial if the printed object is flat. If the printed object is parabolic then it is critical to precisely follow the shape during sanding and polishing. Maintaining the parabolic shape during polishing is challenging and this requires maintaining even pressure throughout the sanding process. The first prints for the dish were done using standard additive manufacturing on a 3 axis nScrypt 3Dn series printer. A 3D CAD model and then a slicer program to break up the dish into many layers is used. Each layer is printed normal to the bed. After many layers, the object begins to take shape and the parabolic shape will have a stair step feature. This stair step effect is minimized by reducing the layer by thickness. If each layer is 100 microns, this leaves a 100 micron stair step. The dish in Figure 16A used traditional, orthogonal to the bed printing. Polishing used standard polishing equipment with the machine polishing orthogonal to the bed. This means the center portion of the dish is polished with a 1" diameter sander and the entire 1" diameter touches the dish. As the polisher moves upward to accommodate the slope of the parabola, the edge of the sander is polishing. This presents new features in the sanding process induced by the sanding method. A coating was then applied to add a smoothing feature, then dried and sprayed again with a silver flake material from DuPont.

An improved process was done in all areas of printing, polishing and slivering. The dish was printed in a true 3D manner using a 6 axis nScrypt 3Dn series printer with the nozzle printing horizontal to the shape of the parabola. Horizontal to the shape of the parabola is a 90 degree shift at the center from the bed and then the angle changes as the parabola begins to take shape. This approach removes the stair step effect and it also speeds up the prints by a factor of 10. The end result is a ridge effect. The ridges are around 50 microns and this is still very large as compared to optical wavelengths. The ridges are then sanded using the 6 axis approach. The polisher moves normal to the surface of the parabola, not normal to the bed. This puts the 1" sander near flat in all areas of the dish. The ridges are challenging to remove and takes significant sanding. In addition, the printed holders which the dish is connected to induces a slight bulge. After multiple coatings using a polymer and silver chemistry, the surface becomes very smooth, near optical quality smoothness. There are some grooving features that still need to be resolved and some contouring on the bulging the needs to be optimized. The results to date are a highly reflective solid coating of silver on a parabolic dish as shown in Figure 16B.

The next steps are to eliminate the bulges, increase the rigidity of the backing and optimize the polishing motion. The motion is a complex 6 axis routine that can very slightly warp the dish if all is not perfect. To aid in that perfection, the polisher is being equipped with a pressure sensor and real time feedback and minimal motion to allow a constant pressure at all times. In addition to this, it is important to understand the printing characteristics; a few noted attributes of the printing characteristics are defined by the motion of the system, the dispensing of the material and the nozzle size. These impose variations as compared to CAD models. To accommodate this, the printing system and printed results must be studied and quantified and then put back into the printing process. This is known as design to manufacture rules. The result is a near perfect print with a near perfect smooth surface.

The ultimate goal of 12 meter prints will take design to manufacture rules and will also need more material studies. The material used to print this round is a carbon loaded polymer. As the prints get bigger, these polymers can warp during printing; this can be quantified and accounted for. It will be important to account for the CTE of the diverse materials and optimize those materials for specific operating conditions.

11. NOTIONAL ARRAY GOING FORWARD PLAN

The teams have made fine progress toward bringing out the risk and demonstrating the techniques required for a successful, reliable, low-cost operational phased array radar system of widely separated antennas. Our X-band demonstrations are nearly complete, and only more work in making the system even more phase stabile is needed and will be completed in FY17.

We await permission to use the WGS system at Ka band to test put the next phase. We do have permission to use a recently launched satellite during the 26 Oct-16 Nov 2017 calibration period. However, the Ka band demonstrations are not necessary to begin the design of a multi-element array phased uplink system. We know that we can simplify the complexity of our initial design, and this is work also to be accomplished in FY18. As we acquire new antennas, we shall undertake the implementation of this design as a baseline system for the high power, high resolution radar system. The high level view of our vision is presented in Fig. 17 and 18. The latter also shows many of the collateral and ancillary studies and demonstrations undertaken and planned to enable subsequent steps.

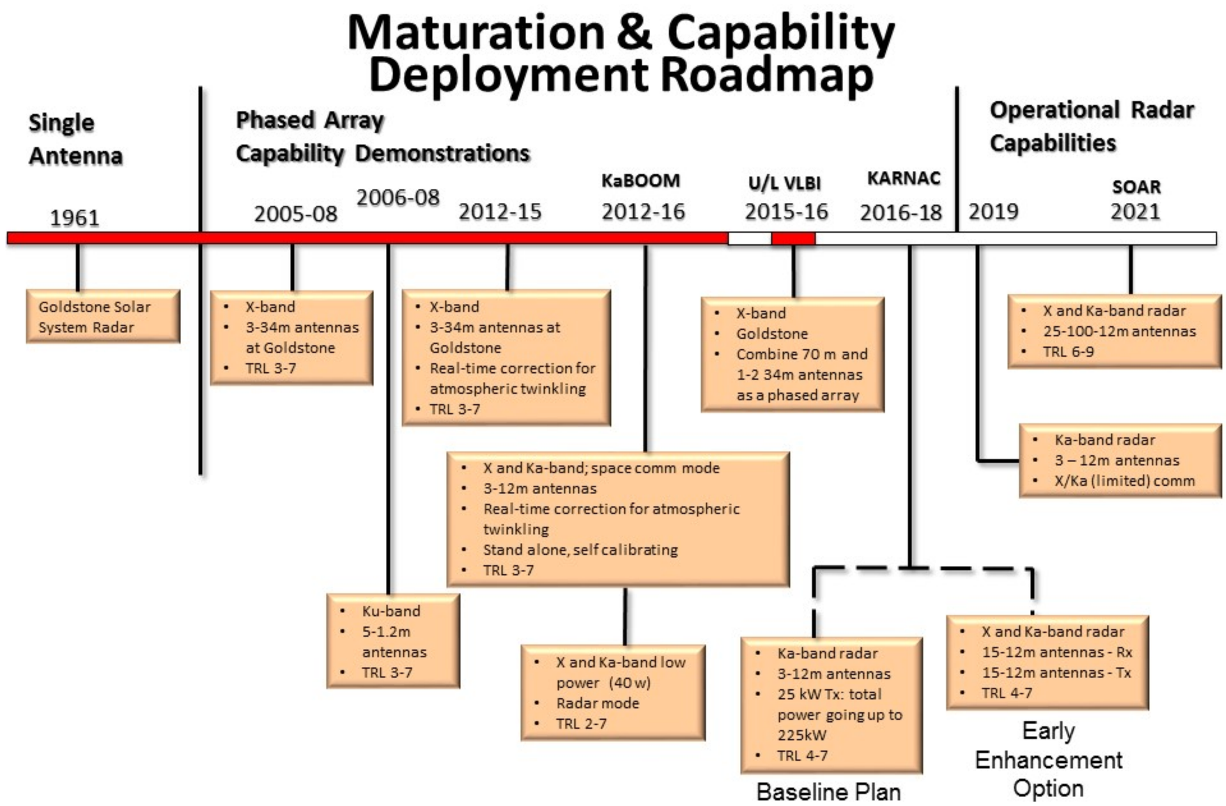


Fig. 17. Maturation and Capability Demonstration Roadmap

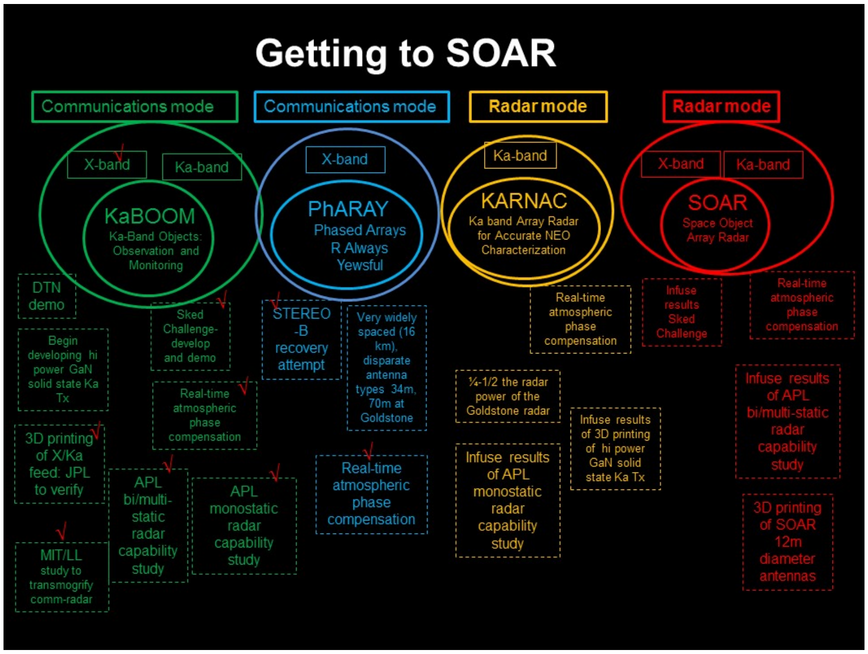


Fig. 18. Evolutionary Approach to a Radar Array. The check marks indicate which of the ancillary studies have been completed

12. CONCLUSIONS

We have the funding in place for a demonstration of uplink arraying at Ka band with real-time compensation for atmospheric fluctuations. We started at X-band in a space communications mode, next repeating the demonstration but at Ka band (30-31 GHz), and finally demonstrate Ka band radar capabilities. Our colleagues at MIT/LL are completing a study to estimate the hardware required and cost to transform our space communication system to a high power radar Ka band system. In addition, our colleagues at the Applied Physics Laboratory, who previously completed a study for us on the capabilities of a large monostatic Ka band radar system, are completing of a multistatic radar system capabilities. When a myriad of folks said “You’ll NEVER be able to send commands to a space craft via a coherently phased uplink array,” the teams just went ahead and successfully overcame all the challenges. The teams have never been phased by having to follow the phases through all the phases of the demonstration, thereby accomplishing what NASA does so well: Doing the “impossible” every day. NASA hard!

13. ACKNOWLEDGEMENTS

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REFERENCES

Church, K., Chen, X., Goldfarb, J. M., Perkowski, C. W., and LeBlanc, S. 2014, "Advanced Printing for Microelectronic Packaging," IPC Proceedings, Avail. http://www.circuitinsight.com/programs/54211.html.

D’Addario, L., Proctor, R., Trinh,* J., Sigman, E., and Yamamoto, C. 2009 “Uplink Array Demonstration with

Ground-Based Calibration" http://ipnpr.jpl.nasa.gov/progress_report/42-176/176D.pdf

Deffenbaugh, P. I., Newton, M., Church, K. H. 2015a, "Digital Manufacturing for Electrically Functional Satlet Structures," IMAPS, International Symposium on Microelectronics, Orlando, Florida, pp. 210-215, Issue 1, Fall 2015.

Deffenbaugh, P.I., Weller, T.M., and Church, K.H. 2015b, "Fabrication and Microwave Characterization of 3-D Printed Transmission Lines," in IEEE Microwave and Wireless Components Letters, vol. 25, no. 12, pp. 823-825, Dec. 2015.

Deffenbaugh, P. I., Stramel, D., and Church, K. H. 2016, "Increasing the Reliability of 3D Printing a Wi-Fi Sensor Device," IMAPS Conference, Pasadena, CA, Oct. 11, 2016.

Geldzahler, B., "Coherent Uplink Arraying Techniques for Next Generation Space Communications and Planetary Radar Systems," SPIE Defense, Security + Sensing, 2011.

Geldzahler, B., "Coherent Uplink Arraying: A Self-Calibrating, Nearly Stand-Alone System," Military Sensing Symposium/Broad Area Maritime Surveillance, 2011.

Geldzahler, B. et al. 2014, "Field Demonstration of Coherent Uplink from a Phased Array of Widely Separated Antennas: Steps toward A Verifiable Real-Time Atmospheric Phase Fluctuation Correction for a High Resolution Radar System" AMOS Conference.

Geldzahler, B et al., 2016, "Real Time Atmospheric Phase Fluctuation Correction Using a Phased Array of Widely Separated Antennas: X Band Results and Ka Band Progress," AMOS Conference

Vilnrotter, V., Lee, D., Cornish, T., Tsao, P., PaaI, L. and Jamnejad, V. IEEE A&E SYSTEMS MAGAZINE, MAY 2010

Vilnrotter, V., Tsao, P., Lee, D., Cornish, T., Jao, J., Slade, M., Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, March 2011