Real-Time Atmospheric Phase Fluctuation Correction Using a Phased Array of Widely Separated Antennas: X-Band Results and Ka-Band Progress

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ABSTRACT

NASA is pursuing a demonstration of coherent uplink arraying at 7.145-7.190 GHz (X-band) and 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 used up to three 34m antennas separated by ~250m at the Goldstone Deep Space Communication Complex in California at X-band 7.1 GHz incorporating *real-time correction for tropospheric phase fluctuations*. Such a demonstration can enable NASA to design and establish a high power, high resolution, 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 at both locales, the results of a study to upgrade from a communication to a radar system, and 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 two facilities would complement each other in that different wavelengths have different resolutions and penetration depths. An X/Ka band radar system also has applications for cost effective space domain awareness. 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

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. FIELD RESULTS OF REAL TIME OPEN LOOP DEMONSTRATIONS

Our earlier results were presented in Geldzahler et al. (2015). We focus here on three antenna coherently phased uplink arraying demonstrations. Also, we have a quasi-operational open loop system in that we have beacons from the spacecraft (the telemetry streams). After the phasing (also called calibration), the antennas were slewed to another target for phased uplink commanding. We have accomplished this successfully at Goldstone, and are implementing a similar system with the COTS system at the Kennedy Space Center.

In each of these cases, we have obtained in *practice* the theoretical power increase that comes from the coherent phasing of antennas in the arrays. However, had the phases *not* been close to alignment, the power on target achieved would have been substantially less than theory as seen in Figure 1.

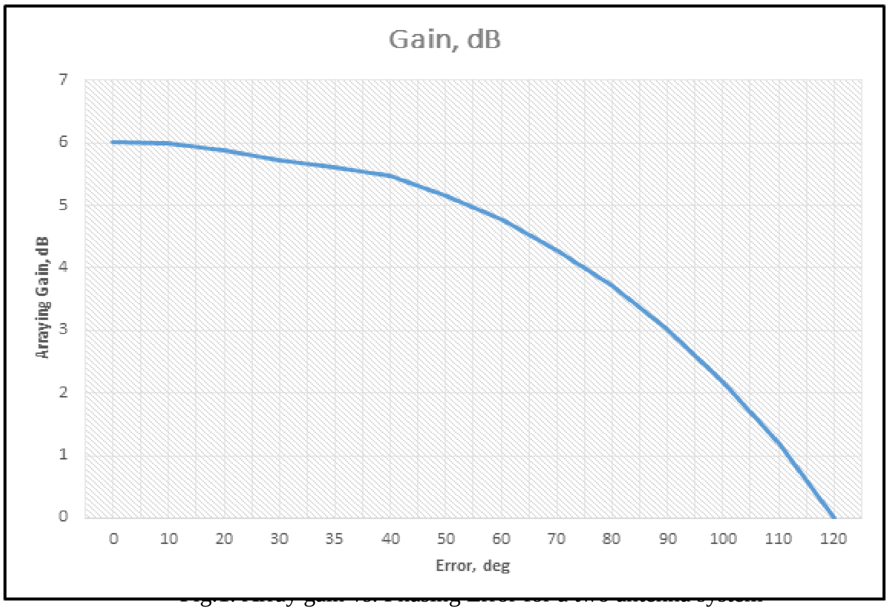

Fig. 1. Gain Diminution as a function of phase error

3a. THREE ANTENNA COHERENT PHASED UPLINK DEMONSTRATION WITH REAL-TIME CORRECTION FOR ATMOSPHERIC PHASE FLUCTUATIONS AT GOLDSTONE

We undertook a demonstration of coherently phasing the three 34m beam waveguide (BWG) antennas at NASA’s Goldstone tracking station to understand if the phased system produced the expected 12 dB increase over a single 34m BWG with a 20 kW transmitter and show that the atmospheric phase fluctuations can be compensated in real time. The results are presented in Figs. 2 and 3.

Figure 2 shows that an 11.3 dB gain was achieved in the 3 antenna array configuration over a single 20kW antenna. The spacecraft command data handling system began saturating above -100 dBm, so Figures 2 and 3 show the spacecraft wideband automatic gain control (AGC) response with a 15-second moving average is slightly less than theory predicts.

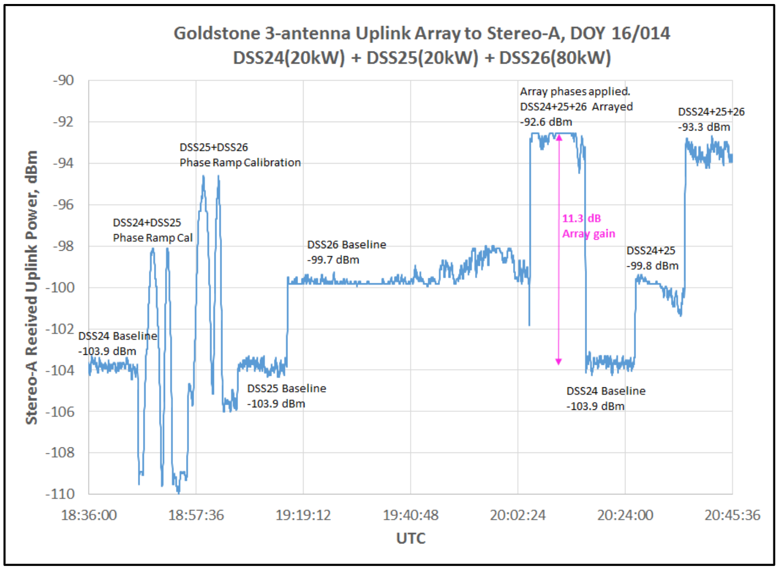

Fig. 2. Demonstration of three 34m element phased uplink array with 20 kW, 20 kW, and 80 kW transmitters. Note, saturation occurred during the phasing so the full 12 dB theoretical increase was not obtained.

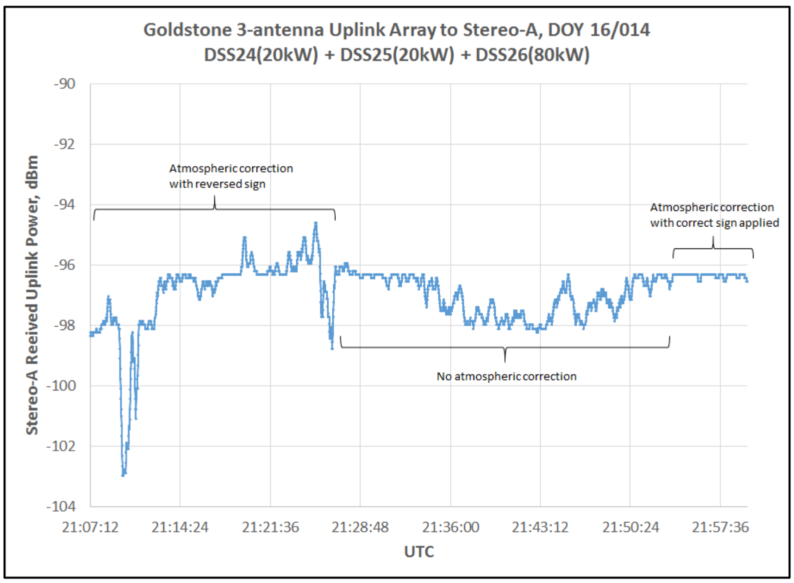

Fig. 3. Demonstration of three 34m element phased uplink array with 20 kW, 20 kW, and 80 kW transmitters and real-time atmospheric phase fluctuations. Note, saturation occurred during the phasing so the full effect of the correction was not obtained.

Going beyond X-band for NASA involves Ka band tracking capabilities. Recall, the range resolution achievable at Ka band is some 2 orders of magnitude finer than possible today using NASA's Goldstone Solar System Radar system. The capabilities for uplink arraying at Ka band do not exist at any of NASA's tracking complexes, so we have stood up a capability demonstration and maturation system using 12m antennas at KSC. Although the previous demonstration of coherent uplink arraying at Ku band undertaken in southern California (D'Addario et al 2009) was successful and gives us encouragement that such techniques will be successful at Ka band, we have no data to bear out our Ka band hypothesis. Furthermore, we have not yet shown how to make uplink arraying at Ka band reliable in an operational sense because we have not previously had the resources to undertake that aspect.

3b. NON-COOPERATIVE TARGETS

The algorithms and techniques for tracking and putting power on a non-cooperative target (i.e. - those with no beacon or telemetry stream) are currently being developed. Our initial results are encouraging, and our goal is to demonstrate this capability by the middle of calendar year 2017.

4. NEXT STEP: KaBOOM: Ka BAND OBJECTS: OBSERVATION AND MONITORING

Fig. 4. 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.

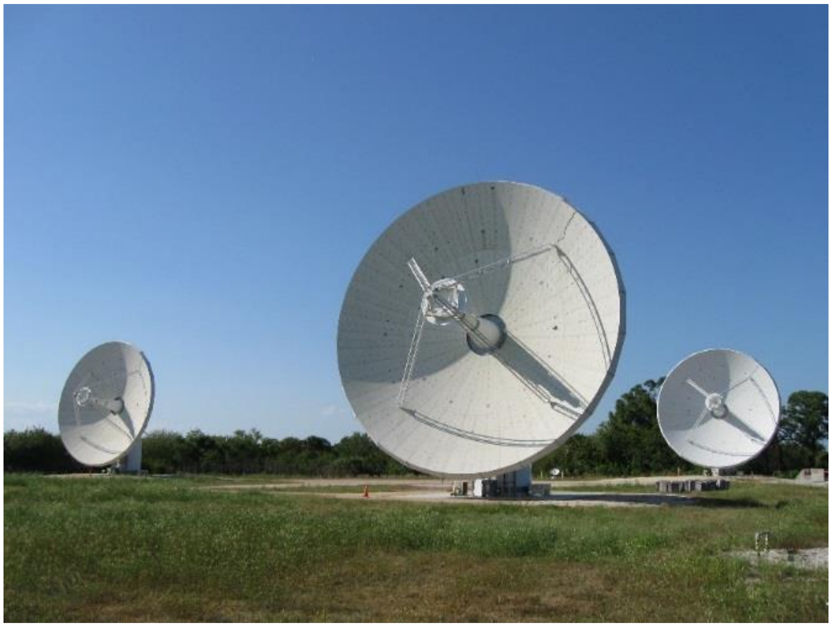

Fig 5. Current array configuration of three 12m reflector antennas at the Kennedy Space Center

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.

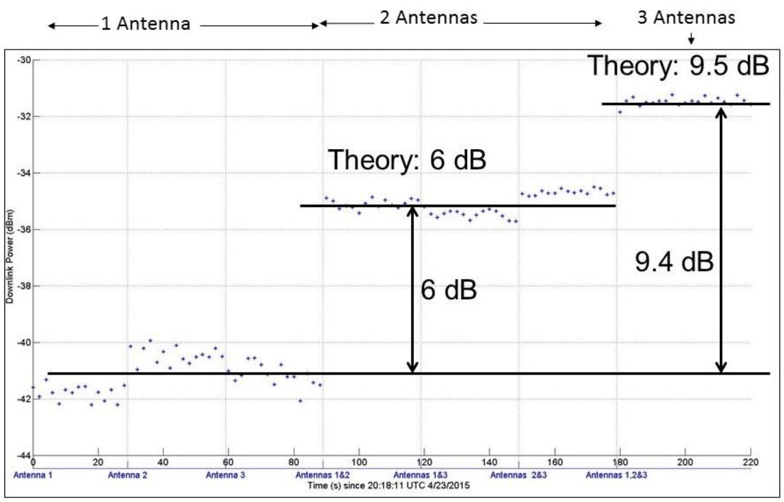

Fig 6. X-band demonstration of the N^2 power increase at the KaBOOM site at the Kennedy Space Center

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.

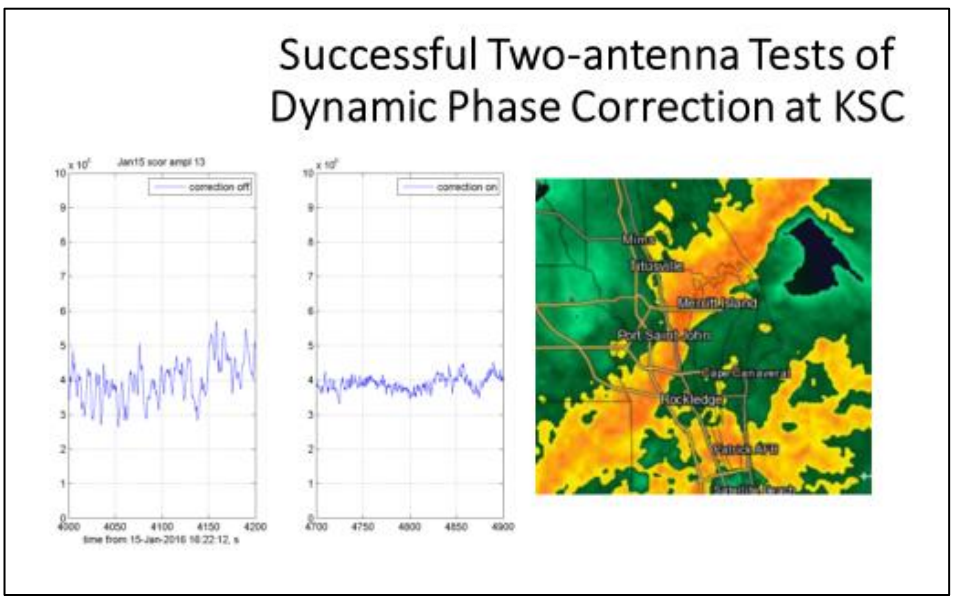

Fig. 7. Demonstration of Real Time Tropospheric Phase Fluctuations under Challenging Weather Conditions

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. 8. 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, 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.

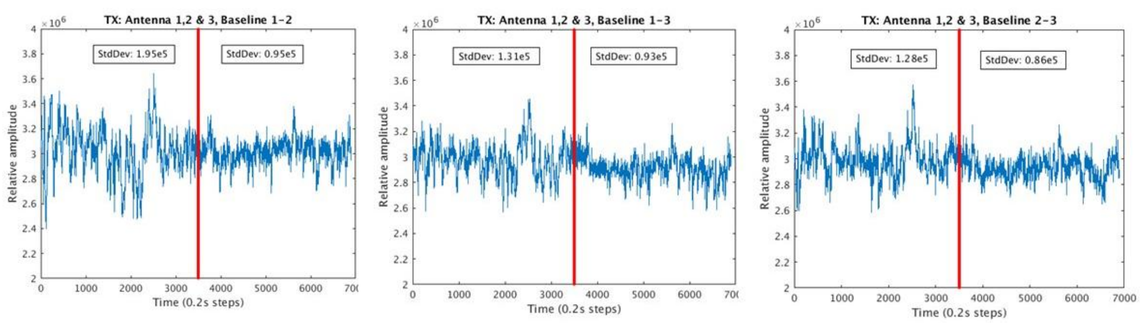

Fig. 8. Real time atmospheric phase fluctuation corrections at 8GHz at the KaBOOM site at the Kennedy Space Center. All three antennas transmitting, the red line indicates where correction was turned on.

5. 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

The target satellite 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.

6. APPLICABILITY TO NASA HUMAN SPACEFLIGHT AND SCIENCE ENDEAVORS

Part of the “flexible path” NASA is embarking on calls for exploration- robotic and crewed- to asteroids. Before a crew is sent to an asteroid, it is most likely, based on past exploration NASA practices that a robotic precursor will be sent to investigate. However, which asteroid will be chosen? If the “wrong” asteroid is chosen, we shall have lost or wasted a decade of time and funding. Hence it is incumbent upon us to select the best target.

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. 9, 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).

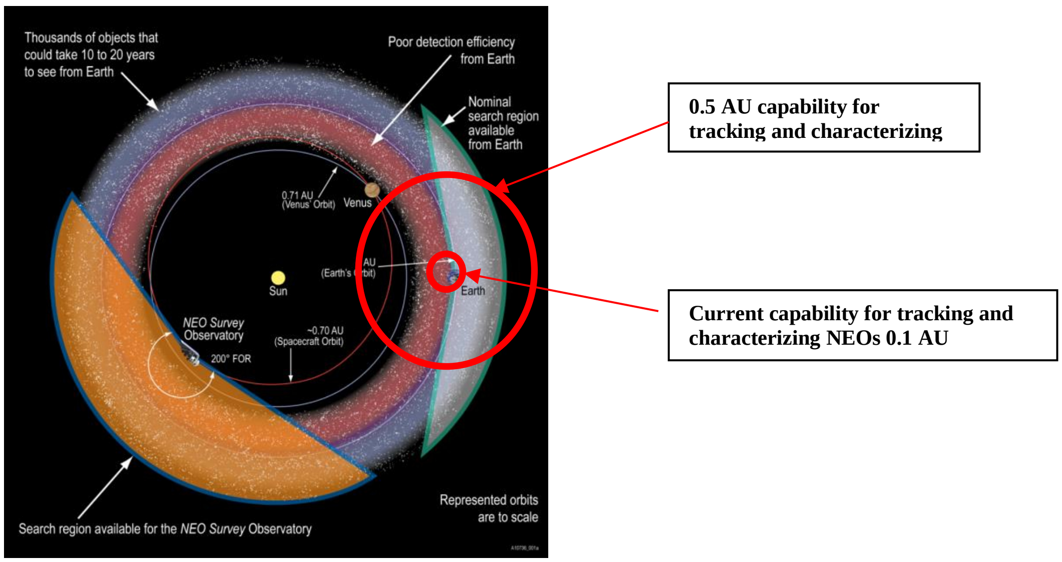

Fig 9. Possibility for a NEO Early Warning System

7. APPLICABILITY TO ORBITAL DEBRIS AND SPACE DOMAIN AWARENESS (SDA)

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.

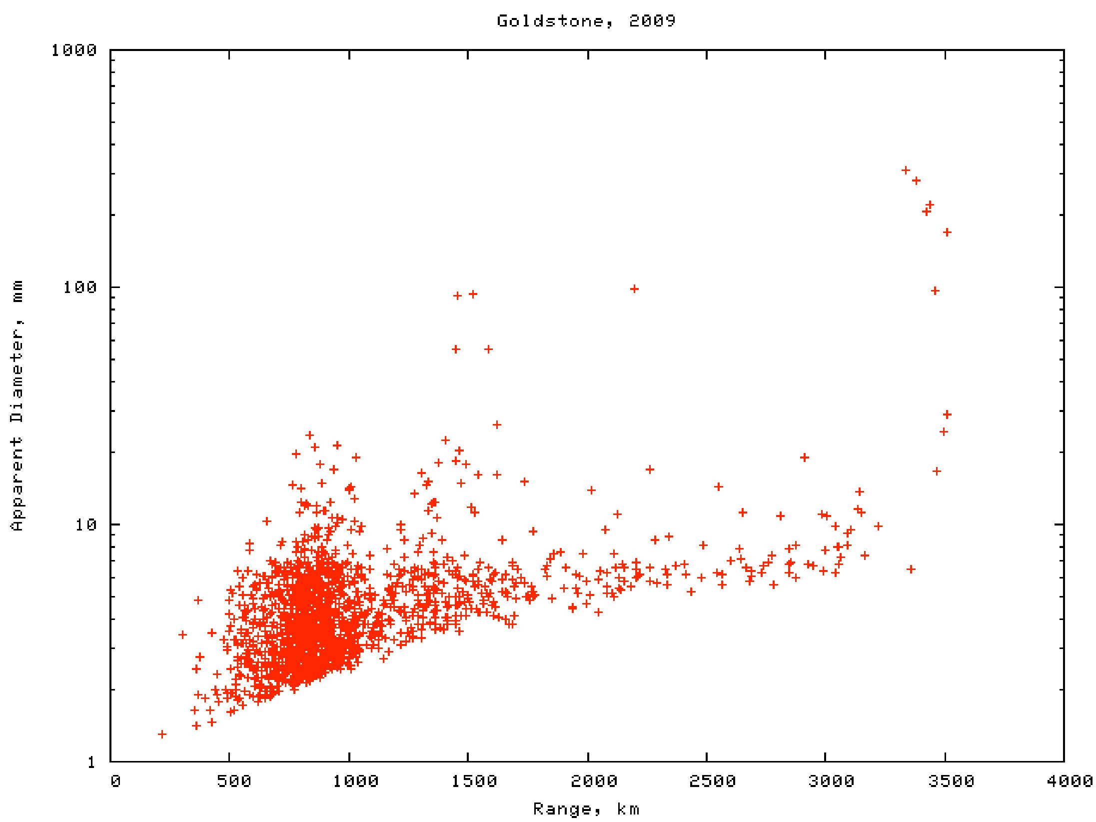

Fig. 10. Goldstone Orbital Debris Radar Apparent Diameters detected in FY2009. Each cross represents an individual particle. The blank part of the diagram near the bottom and toward the right is an artifact of a sensitivity selection effect.

For SDA, the recent GAO report: "SPACE ACQUISITIONS: Development and Oversight Challenges in Delivering Improved Space Situational Awareness Capabilities" (GAO-11-545 May 2011: http://www.gao.gov/new.items/d11545.pdf) summed up the current status: "The United States' growing dependence on space systems for its security and well-being—such as for missile warning; intelligence, surveillance, and reconnaissance; communications; scientific research; weather and climate monitoring; and positioning, navigation, and timing—makes these systems vulnerable to a range of intentional and unintentional threats. These threats range from adversary attacks such as anti-satellite weapons, signal jamming, and cyber attacks, to environmental threats such as harsh temperatures, radiation, and collisions with debris and other man-made or natural objects, which have been increasing rapidly over the past several years."

Detailed simulations of the capabilities of a phased array radar system indicates that current gaps in the following areas of SDA knowledge can be addressed

- **Detect/Track/Identify**: Uncued detection, Unexpected maneuvers
    - Discriminate between closely spaced objects
- **Characterization**: Orbital Debris, Satellite break-ups, collisions
- **Threat Warning and Assessment:** Conjunction assessment, Re-entry prediction

A Ka band system using coherent uplink arraying techniques and bistatic and multistatic radars can meet and probably exceed the goals or, at the very least, compliment a 90 GHz system. Specifically, at Ka-band range resolution of 5 cm and a spatial resolution (using a US-Australia baseline) of ~ 5 cm can be achieved.

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.

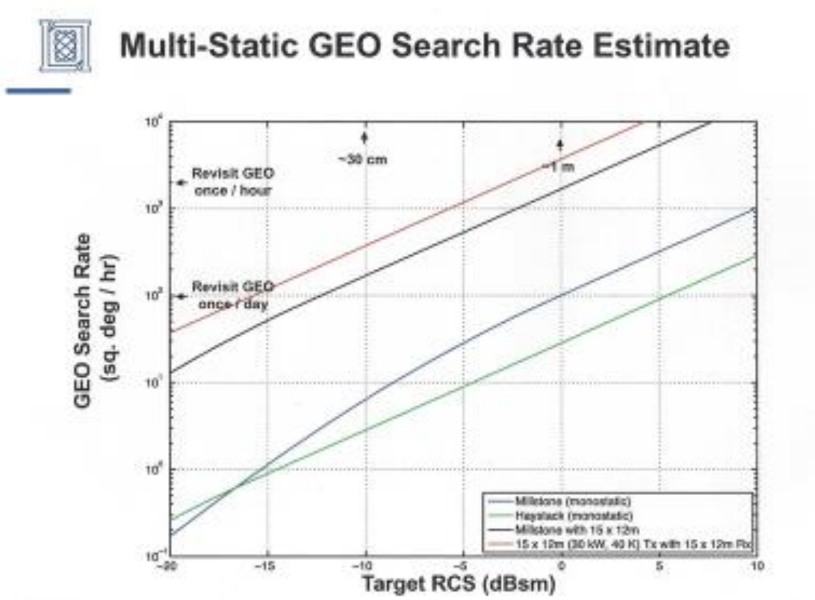

Fig 11. Comparison of current multistatic search rate capabilities with those from an

envisioned phased uplink array. Source: MIT/LL

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.

Figures 12 and 13 show the results of bouncing continuous wave signals off the moon and then capturing them so as to follow the phases through the entire system. There are phase changes when we go from STEREO-Ahead to STEREO-Behind because of location in the sky as well as different frequencies of operation on the two spacecraft. For the pair of antennas designated DSS25/26, the measured phase change after swapping frequencies on 2016DOY049 was -190 deg. Repeating the test on 2016DOY 074, the measured phase change was within 10 degrees of the previous measurement. For the pair of antennas designated DSS24/25, the measured phase change was 39 degrees. The measured phase changes are close to the predicted values (-242 deg and 26 deg, respectively). The repeatability demonstrates the stability of the Goldstone system..

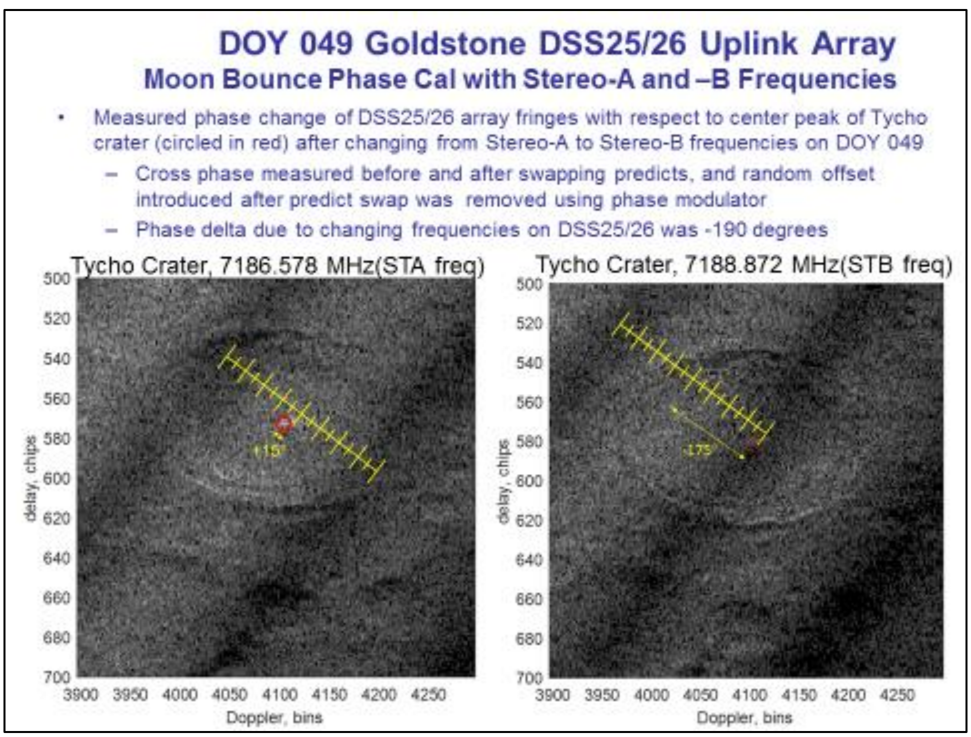

Fig 12. Measured phase change from NASA Deep Space Network antennas DSS 25 and 26 as frequencies were changed to reflect those of Stereo-Ahead and Stereo-Behind

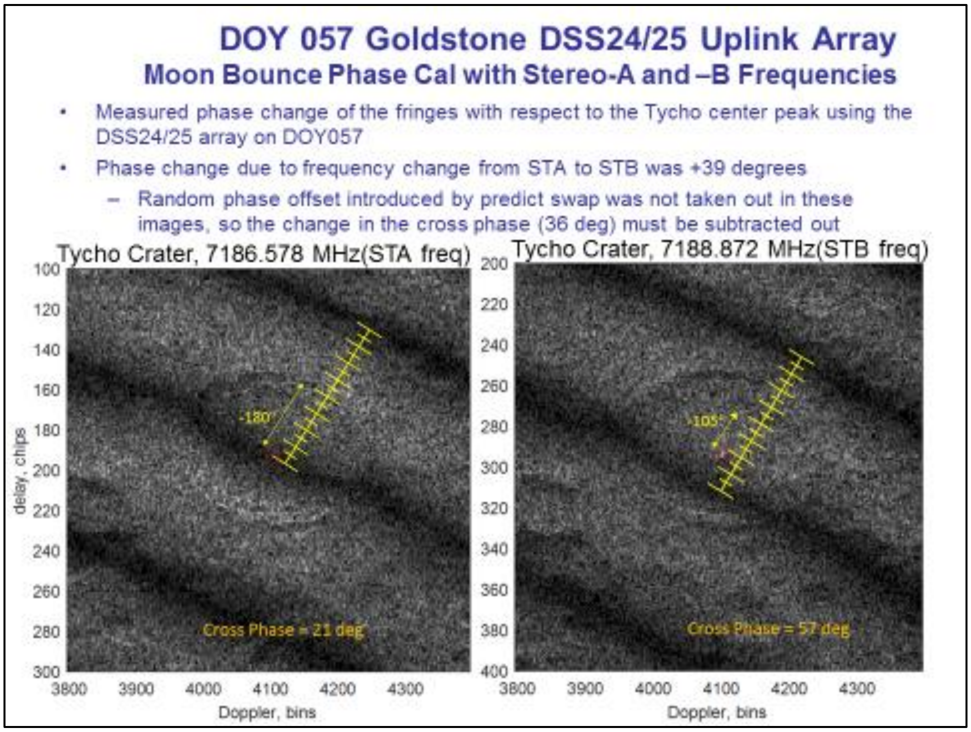

Fig 13. Measured phase change from NASA Deep Space Network antennas DSS 24 and 25 as frequencies were changed to reflect those of Stereo-Ahead and Stereo-Behind

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 14 and 15, 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.

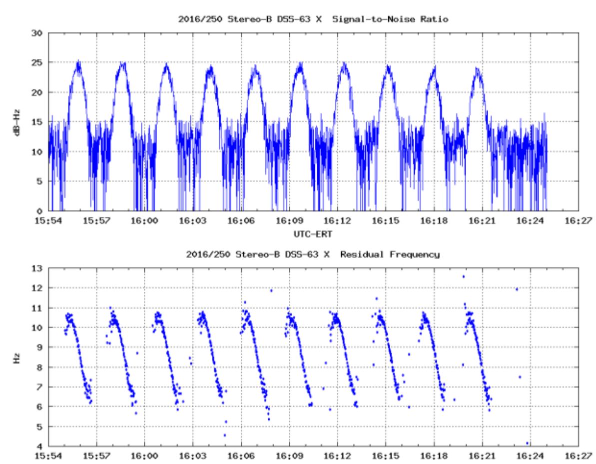

Fig. 14. Signal-to-noise ratio of the received downlink from STEREO-B and the residual frequency rate showing the spin rate. Data from Applied Physics Lab STEREO-B engineering team

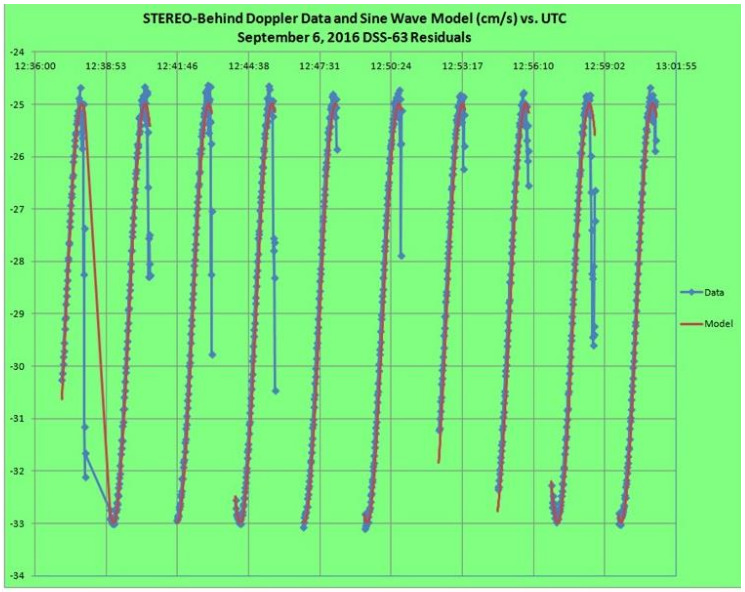

Fig. 15. Sine wave fit to STEREO-B Doppler data. Line-of-sight vs spin axis: 41,1 deg, Period 153,8 minutes, amplitude 4.00 cm/sec, standard deviation of residuals 0.94 cm/sec.

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)

We commissioned a study by the Applied Research Laboratory to suggest manners of achieving a cross-resolution in the 10 cm range at GEO. The result was a multistatic radar coherently phased array of small antennas. A clustered array of antennas for the uplink and a spread system of downlink antennas to be used in a very long baseline interferometer mode to achieve the required cross-resolution.

The results of the APL were validated by the JASONs who performed a summer study to assess a variety of approaches for high-resolution imaging of space objects in geostationary or geosynchronous orbits using ground-based sensors. The JASONs study examined the performance and limitations of a variety of imaging techniques and provided a ranking according to their assessment of overall utility and feasibility. The study examined the top-ranked option - multistatic radar - in considerable detail, addressing issues related to the system architecture, imaging fidelity, signal-to-noise ratio, technological readiness, and construction costs. The report concludes with their findings and recommendations and provides a plan for developing a multistatic radar imaging capability. The top ranked solution was a high-frequency, multistatic system.

MIT/LL has completed a study for on transmogrifying the 3-element space communication system, KaBOOM, to the ground based phased array radar system, KARNAC. Our JPL team is studying as to how to distribute power to a multi-element, 100 antennas, for example, for a high power radar system (see Table 1).

10a. COST EFFECTIVE DEVELOPMENTS

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

Use advanced digital manufacturing processes, we have demonstrated that quality RF parts can be 3D printed, digitally inspected and a final part optimized for NASA use. The X-band feed was printed and met the physical specifications given by NASA, and performance was validated by comparison of performance results of the JPL 2003 machined feed and the 3D printed feed. Examples of 3D printed electronics (Church et al. 2014, Deffenbaugh et al. 2015a) are common but materials characterization at microwave frequencies Deffenbaugh et al. 2016) and advanced 3D printing now allows complete RF/microwave device fabrication (Deffenbaugh et al. 2015b).

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 horn 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 16. X-band RF feed horn produced via additive manufacturing

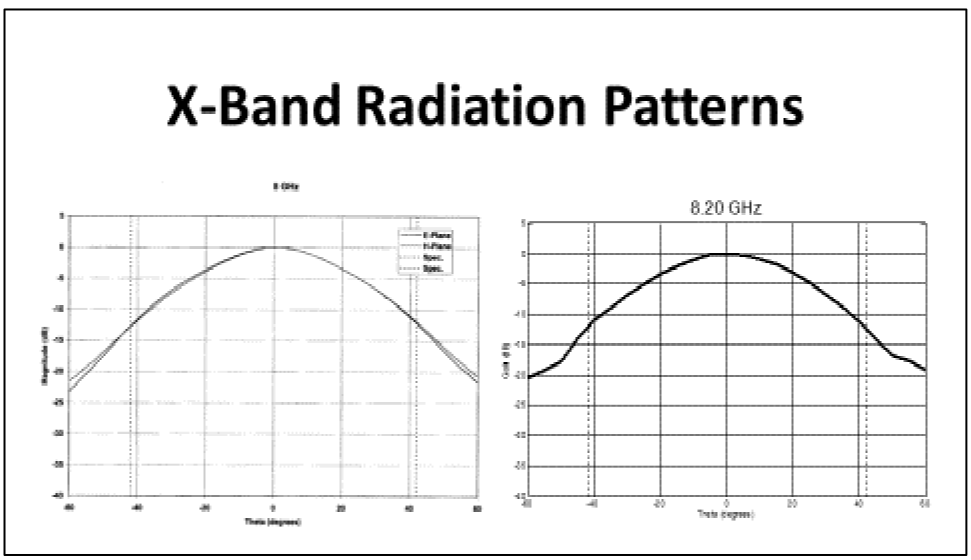

Fig. 17. Comparison of machined (left) and 3D printed (right) RF feed horns

The results of the printed version versus the state of the art CNC version were near identical. This is an important step in validating what many are saying is possible to do with 3D printed electronics. Our next step is the manufacturing of a 30cm RF/optical dish (Figure 16) as a prelude to a 1.5m dish. During this step, we shall flesh our requirements for deposition of other metals to include aluminum. The 30 cm dish is 3D printed using the same nScrypt 3Dn 300 system and then micro-milled, sprayed and heated for silver curing. The 30 cm dish is scheduled to be tested in the next couple of months and then compared to a state of the art fabricated 30 cm dish.

Fig. 18. 3D manufactured 30 cm antenna.

Table 2. Infusion and Implementation of additive manufacturing for space communication and radar systems

3D Printing: Going Forward Plan

Project State	Product	Test/Validation Method	Capability Infusion	Status
Pilot	X/Ka RCP/LCP antenna feed	Antenna groups at JPL and Johnson Space Center	Install and use on new antennas at Kennedy Space Center [KaBOOM[1] (space communication)/ KARNAC[2] (radar) site]	NASA funded; currently getting contract for testing in place
Phase 0	1.5m RF/optical antenna	Proposed rooftop test at Florida Inst. Of Technology by Dr. Sam Durrance [PI, astrophysicist/astronaut]	Low Earth Optical Communications systems [combined with MIT/LL orbiting system]	funding request Approved
Phase I and II, NASA Antenna Manufacture	12m RF/optical antenna	Expand KaBOOM/KARNAC site at Kennedy Space Center	Low cost acquisition of antennas for NEO, orbital debris, and SSA applications	Future program funding pending pilot and validation activity results.
Operational System	Space Object Array Radar (SOAR) system	Rigorous system-level integration & test. Operational readiness review.	Operational, multi-mission, multi-user system	Future program of record pending results of small-scale system.

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. 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 FY17. 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. 19 and 20. The latter also shows many of the collateral and ancillary studies and demonstrations undertaken and planned to enable subsequent steps.

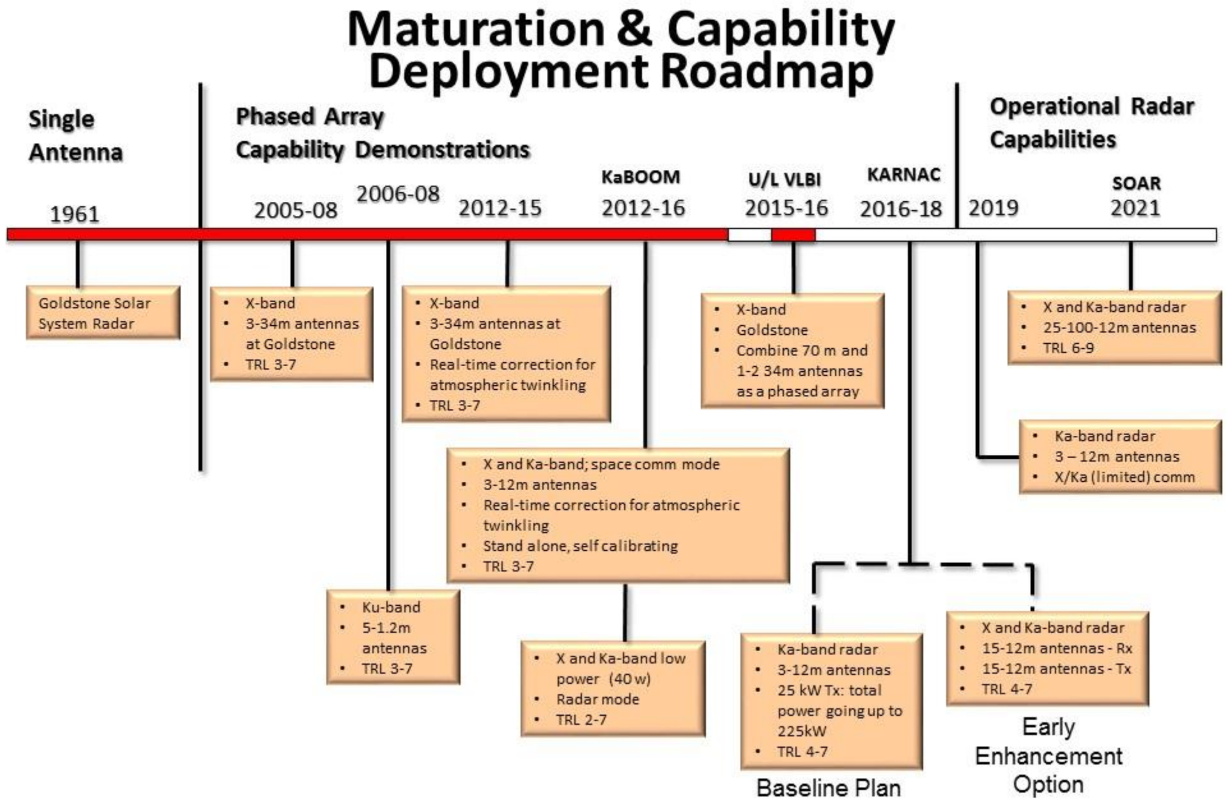

Fig. 19. Maturation and Capability Demonstration Roadmap

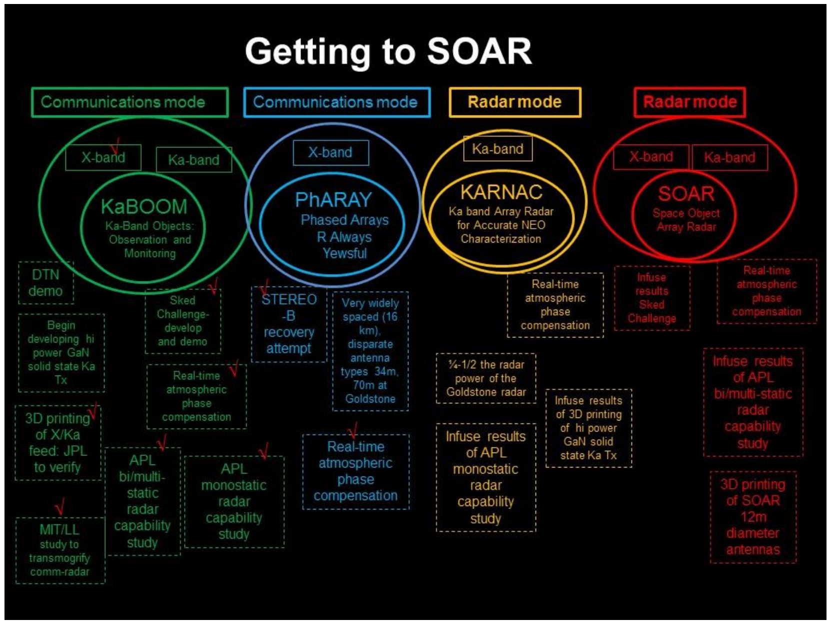

Fig. 20. Evolutionary Approach to a Radar Array. The check marks indicate which of the ancillary studies have been completed

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!

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