Coherent Uplink Arraying Techniques for Next Generation Space Communications and Planetary Radar Systems

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ABSTRACT

For several years, NASA has been pursuing demonstrations and development of coherent uplink arraying techniques for the next generation space communications and planetary radar systems. In addition radio science experiments would benefit with a 1000 times increase in signal to noise over current systems. I shall describe the three methods of uplink arraying NASA has pursued, all successful, and share the vision for going forward from laboratory demonstrations to the proposed implementation and deployment of a dedicated multi-purpose facility to infuse an amalgam of these methods into a system that enhances NASA's missions.

Keywords: antenna arrays, atmospheric fluctuations, coherent uplink, coherent forward link

1. INTRODUCTION

For the past decade, NASA has been investigating ways to replacing the aging 70m antennas of the Deep Space Network (DSN). Furthermore, as more NASA spacecraft communicate at Ka band, high efficiency dishes will be required. To address these requirements, arrays of small [~12m] diameter dishes were proposed, but the question arose as to how uplink would be accomplished in an array era. Over the last 7 years, we have funded 3 teams, 2 at the Jet Propulsion Laboratory (JPL) and one at the Harris Corporation in Melbourne FL, to demonstrate the feasibility of uplink arraying. We started at X-band to limit effects of atmospheric fluctuations, but a demo at Ku band was also undertaken. The demos had major aspects in common: (1) each had to phase up, aka calibrate, the signals to a fraction of a wavelength although each demo accomplished this by different means and (2) the systems are all carefully modeled as to antenna characteristics, phase noise throughout the system (i.e.- up/down converters, cables, fiber, etc) All of the demos have been successful, some more so than others, but there is no doubt that coherent uplink arraying can be reliably implemented in a low cost, low maintenance mode.

2. THE NEED FOR UPLINK ARRAYING

NASA has several major needs for uplink arraying: (1) planetary protection- tracking and characterization (size, shape, spin, surface roughness) of near Earth objects (NEOs), (2) Improved detection/tracking of small (≤1-10cm) orbital debris particles, (3) rapidly available high power emergency uplink capability for spacecraft emergencies, (4) radio science experiments (tomography of planetary atmospheres, general relativity tests, mass determinations, occultations, surface scattering, etc). The NASA Authorization Act 0f 2008 directs NASA to catalog 90% of NEOs > 140m in size. The Goldstone radar on the 70m antenna is available only 2-3% of the time due to spacecraft tracking obligations and is further limited by the high power density of the beam since the transmitter is 450 kW.

Tracking of orbital debris particles less than 10cm is size is difficult. Where high resolution is possible, the antennas beam is too small for accurate tracking; statistics of small particles is obtained. In those facilities where particle tracking is possible, the resolution is lacking.

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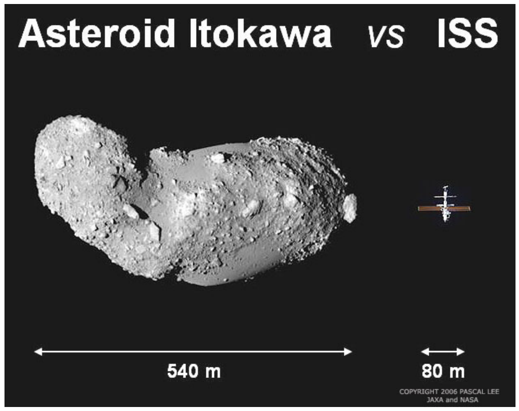


Fig 1. Relative sizes of asteroid Itokawa and the International Space Station

3. ADVANTAGES OF A MULTIPURPOSE FACILITY EMPLOYING UPLINK ARRAYING TECHNIQUES

- The **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. 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, availability of the array is more assured 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 purpose 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 beam forms ~200 km above the earth, the FAA EIRP limit will not be violated obviating the need for a time-consuming coordination among a large number of Agencies.
- The **angular resolution** of the proposed array is 4 times better than that of the 70m antenna at Goldstone. With antenna spacings of 60m, an effective diameter of ~300m can be achieved- imagine a 5x5 antenna array. Increased angular resolution can help characterize NEOs in unprecedented detail.
- **Scalability.** If still higher resolution or greater sensitivity is desired, additional antenna elements can be added. At roughly $1M per antenna element, increased capability can be added at a low cost.
- **Extensibility** to Ka band. This would be unique to NASA and 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 (ala New Horizons) 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.

4. UPLINK ARRAYING DEMONSTRATED

Three successful demonstrations of coherent uplink arraying have been conducted:

- NASA/JPL: moon bounce calibration method. This demo was done at X-band using 3- 34m beam waveguide antennas. There is demonstrated capability of planetary radar and sending of modulated [BPSK] commands at 2 kbps (the DSN standard rate) to deep space [1-5M km]. First steps have been taken toward demonstrating ranging/Doppler capabilities and having an operational closed loop feedback system ensuring instant availability

- NASA/JPL: calibration receivers on nearby towers method. This demo was done at Ku band using 5-1.2m antennas. Modulated [BPSK] signals were sent to geostationary communication satellites
- NASA and Harris Corporation: local closed-loop phase control calibration method. This demo was done at X-band using 3 low cost 12m antennas. Modulated (2MHz bandwidth BPSK, and QPSK, 2Mbps rate ½ Viterbi) signals were sent to geostationary satellites. When a satellite beacon or background quasar was present in the primary beam of the antennas, real time compensation for atmospheric fluctuations was demonstrated.

4.1 MOON BOUNCE METHOD - UPLINK TO EPOXI

This demonstration, at X-band, was undertaken at JPL by the team led by Vic Vilnrotter. They demonstrated conclusively that coherently combined uplink array signals sent to NASA's EPOXI spacecraft were successfully received: 5 sets of 10 NO-OP commands were uplinked at maximum rate (2 kbps), and all 50 NO-OP commands were received and acknowledged by EPOXI. Furthermore, the on-board coherent lock accumulator automatic gain control readings showed that (1) the theoretically expected array gains were demonstrated- nominally 4X gain for 2-antenna array, 9X gain for 3-antenna array, (2) the array phasing remained stable throughout the demo - 5hrs 25mins, (3) two different, independently derived frequency predict sets that were used each yielded results leading to stable array operations above 30 degs elevation. Finally, a quick demo of "Nearby-Spacecraft" phase-calibration was demonstrated successfully.

Fig. 2. DSN 3-34m beam waveguide antennas at the NASA tracking station in Goldstone, CA

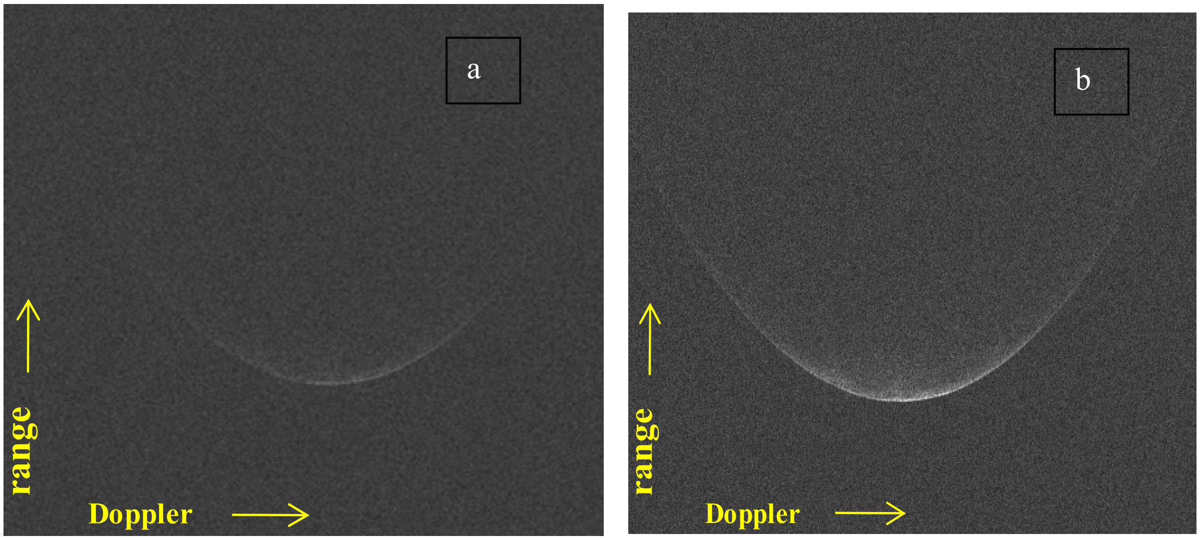


Fig 3. Doppler-delay images of Venus, taken on DOY-297, GSSR processing: a) single 34m antenna illumination; b) 2-34m antenna phased-array illumination, showing greatly improved image quality.

4.2 CALIBRATION RECEIVERS ON NEARBY TOWERS METHOD

This demonstration, at Ku-band, was undertaken near JPL by the team led by Larry D'Addario. They demonstrated conclusively that coherently combined uplink array signals sent to several commercial geostationary satellites were successfully received, that the bit error rate even for this non-optimized system approached the theoretical limit, and that the system was phase stable for almost 3 weeks.

Fig 4. 5 1.2m Ku-band antennas

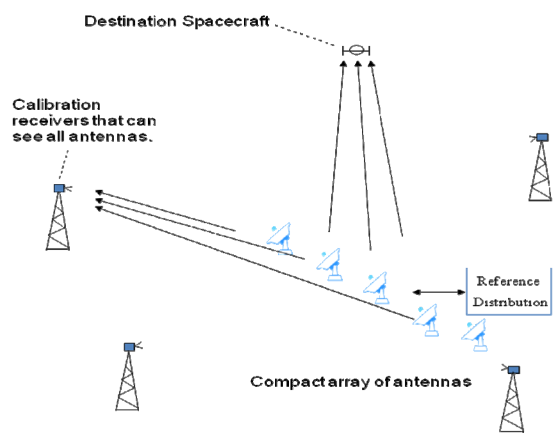
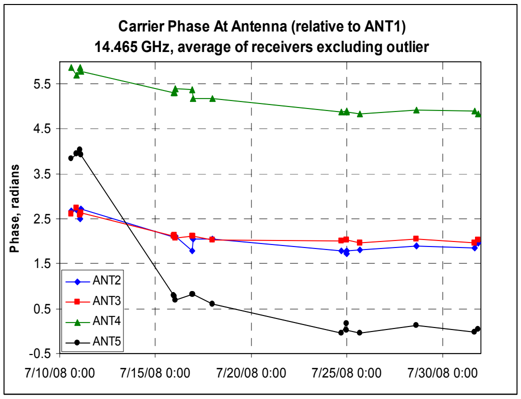


Fig. 5: System Concept

The procedure for the Towers calibration method is as follows: (1) Point all antennas to a calibration receiver, each transmitting a unique pseudo-random code. (2) Receiver measures each antenna's carrier phase, all simultaneously. (3) Repeat for each cal. receiver. (4) Use all data to solve for antenna phase and delay offsets, for errors in receiver positions, and for index of refraction, and (5) Point to target spacecraft. Apply measured phase and delay offset at each antenna.



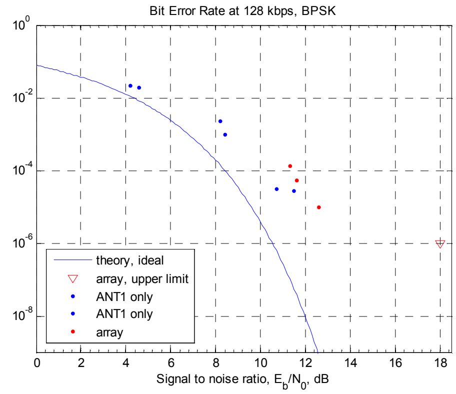


Fig. 6: System stability

Fig 7. Bit error rate. Measured vs. Theoretical

4.3 LOCAL CLOSED-LOOP PHASE CONTROL CALIBRATION METHOD

This demonstration, at Ku-band, was undertaken in Melbourne FL at the Harris Corporation by the team led by G. Patrick Martin and Kathy Minear. They too demonstrated conclusively that coherently combined uplink array signals can be achieved using a model-based uplink arraying method that does not require external calibration targets due to a continually self-calibrating circuit control thereby yielding instant availability of the system. Furthermore, they demonstrated that if there is a reference source such as a beacon on the uplink target satellite or a background celestial source (e.g.- a quasar), then the system can compensate in real time for atmospheric fluctuations- providing that both the target source and reference source are in the primary beam of each antenna of the array. This group too demonstrated the theoretical benefits in EIRP for uplink combining, namely 6 dB power enhancement for doubling of antenna elements and 9.5 dB for an array of 3 antennas. Also, demonstrated were the theoretical benefits in G/T for downlink combining. The major downside to this demonstration is that NASA was not given access to the algorithms so we have not been able to verify whether the techniques demonstrated represent simply a point solution or whether they are applicable in general.

Fig 8. Array of Three 12m Reflector Antennas on a Scalene Lattice

5. ERROR SOURCES IN UPLINK ARRAYING

There are three principal error contributors in any coherent uplink arraying system, the first two must be addressed by any uplink arraying method whereas the need for the third may be location specific:

- Circuitry variation between the point where a signal is phased for transmission and the location from which that signal is radiated or received

- Imprecise knowledge of the geometrical location of each Antenna Reference Point (ARP), usually the intersection of azimuth and elevation axes, and the relationship of a particular antenna's phase center to the ARP
- Uncompensated differential propagation phase variation due to tropospheric effects

At X and Ku-bands, compensating for the atmospheric fluctuations as clearly not necessary since all commands etc were received on the target spacecraft. It is not clear whether or not at Ka band, real time atmospheric compensation techniques are urgent, vital, or merely nice to have.

5.1 CIRCUITRY

In general, typical circuitry phase errors include not just the fiber optic transmission lines, but also those inherent to or generated by/within the up-converters, filters, fiber optic transmitters and receivers, and power amplifiers. All of these components are temperature sensitive and time variable. In Fig. 9, the phase variations easily seen on the left hand side of the plot derive from the air conditioner cycling in the ops center! The largest phase variations occurred when the air conditioner was turned off during a weekend.

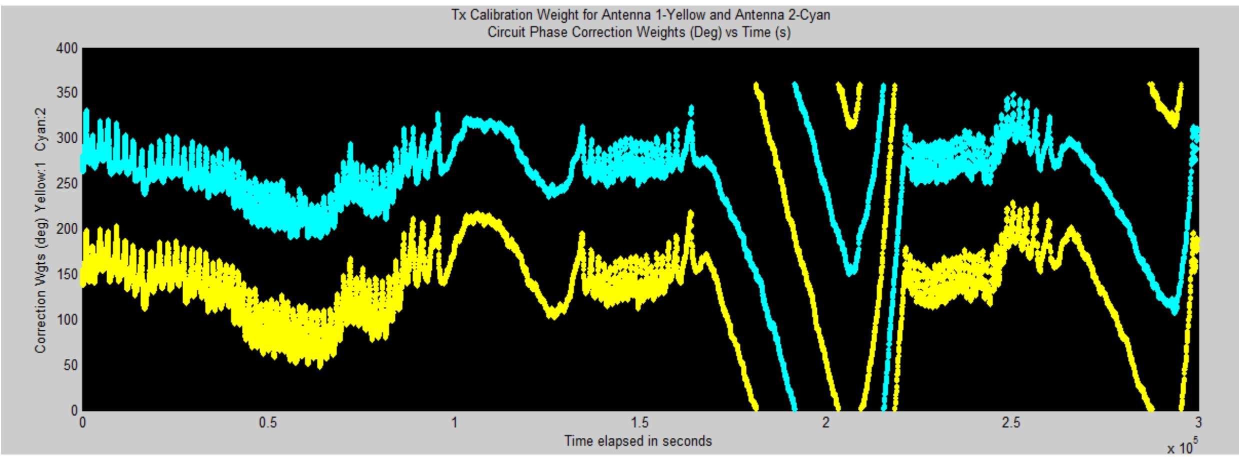


Fig. 9. Phase Changes in Paths to Assembly 1 and 2 during Closed Loop Circuit Control Experiment. Total extent is slightly more than 83 hours.

Circuitry variation over time and temperature is the dominant error in beam formation at X-Band, and distributing precisely phased signals to the antenna elements becomes increasingly difficult as separation and frequency increase. Note that effective arraying requires that circuit phase error contribution to the total error budget be held to no more than about 10° peak, implying tolerable variation less than a few parts per million.

5.2 ANTENNA REFERENCE POINTS

In general, it may be extremely difficult to determine accurately and continually update the positions of widely spaced antenna elements. In the case of large reflector antennas in fixed installations such determination can usually be achieved with very high precision.

Consider for instance, the NRAO VLBA (National Radio Astronomy Observatory, Very Long Baseline Array) or multiple 34m BWG reflectors at Goldstone. The mechanical accuracy and stability required for achieving high gain and precise pointing in turn ensures a very stable ARP.

Once determined using a variety of means, such as laser surveying and/or interferometry of known stellar objects or spacecraft, the ARP tends to be constant barring significant geological disturbance such as earthquakes or hurricanes.

5.3 ATMOSPHERIC FLUCTUATIONS

Coherently arrayed uplink signals that were uncompensated for tropospheric propagation were expected to be almost negligible at X-band except at low elevation or during extreme weather conditions. This is true as verified by the X-band demonstrations at Goldstone. However, in the humid environment of Florida, the troposphere introduces significant variation at 30º elevation and below.

Again, Ku-band coherent uplink arraying demonstrations near Pasadena CA showed negligible effects of the atmosphere. However, in principle, the atmospheric effects at Ka band are expected to be about four times larger than at X-band and twice as dramatic a at Ku band, so significant variation may be expected at any elevation- even in dry, desert air. Still, we are moving toward obtaining data at Ka band to understand fully the magnitude of the atmospheric fluctuation effects on coherent uplink arrayed signals at Ka band.

6. ERROR CORRECTION TECHNIQUES

This section is based on the local closed-loop phase control calibration method. See D'Addario et al for a similar detailed discussion using the tower method of phasing up the antennas. This approach applies a continual closed loop circuit phase control to all transmit and receive pathway circuitry, including transmission lines, frequency converters, filters, power amplifier, feed with polarizer and diplexer, and the antenna itself.

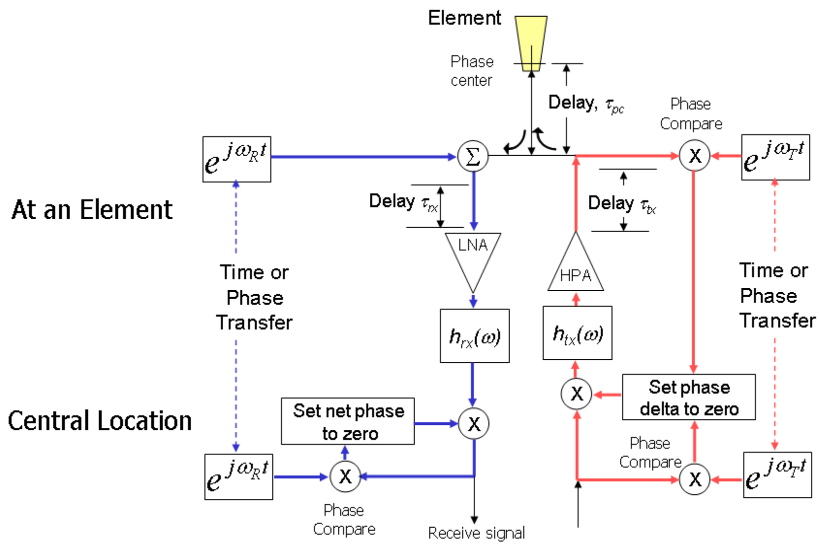


Fig. 10. Closed Loop Circuit Compensation

By closing a loop on the entire pathway, there is no unknown phase coefficient. The array is always ready for transmit at the carrier frequency and does not rely on limited calibration target availability or pointing away to a calibration target. Using a complex envelope paradigm, the beam is formed at the carrier frequency using controlled phase, so time delay adjustment occurs at baseband (zero frequency) with no impact on carrier phase shift.

In most systems, time delay accuracy must satisfy both carrier phase precision and information content alignment. Since the carrier phase is unaffected, then, in principle, for Ka band, coarse control to nanoseconds or hundreds of picoseconds conveniently realized through digital processing is sufficient versus analog femtosecond precision that would be required for traditional methods. For systems like the DSN, time transfer, as has been demonstrated, works quite well. For more widely separated systems, as in a very long baseline interferometry applications, the phase transfer method may be superior.

In this experimental setup, the receive pathways should be placed under closed-loop control in order to accomplish precision interferometry (although this has not been demonstrated), precise range and range-rate measurements (again, this has not been demonstrated), precision ARP refinement, and to achieve tropospheric propagation error mitigation using known location angularly nearby sources.

In essence, all of the uplink array implementations rely on feedback loops. Assume a precise phase reference at widely separated physical locations. One can use either two-way time transfer or the Harris Corp's phase transfer method. At a point including as much circuitry as feasible, a sample of the signal being transmitted is compared with the remote phase reference. Thus, any phase deviation can be attributed to circuit variability. A weighting device in the transmit pathway applies the measured correction, forcing the entire pathway to a net zero phase shift between generation point and transmission.

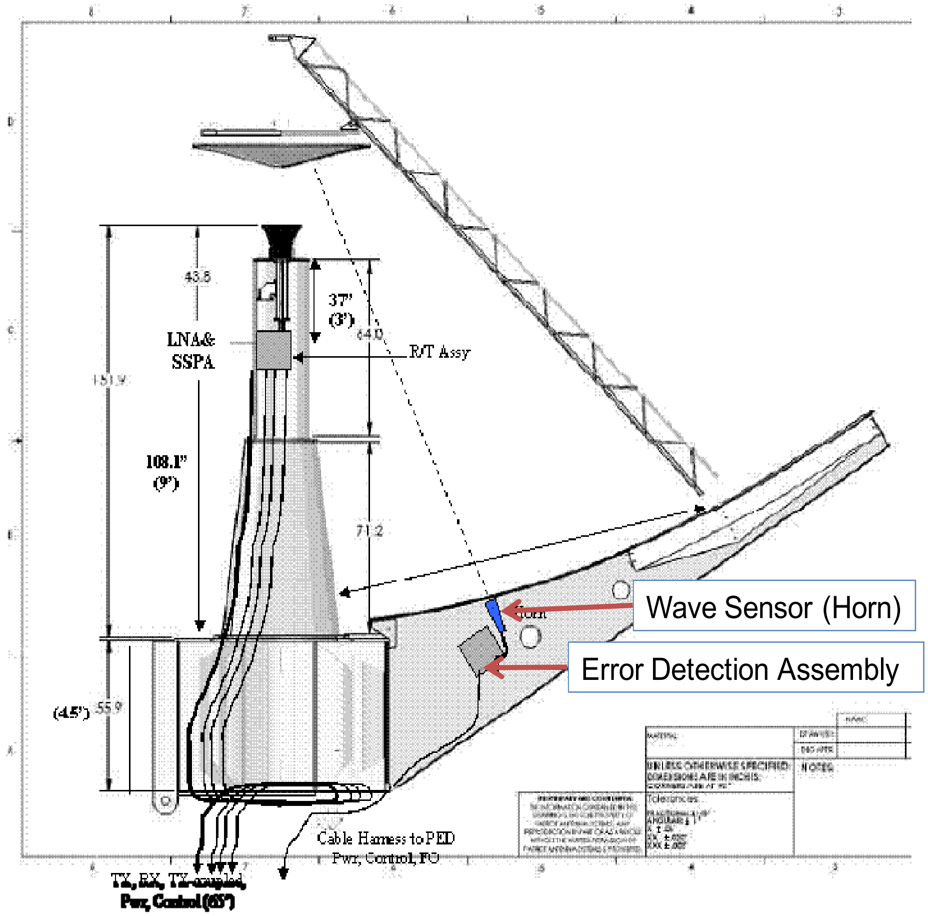


Fig. 11. Circuit Feedback Sensor on Reflector Surface

In the NASA experiment in Florida., the feedback point was located on the reflector surface, thus including all temperature sensitive feed components and internal reflector variation. The feedback point is the last accessible physical point before the wave leaves the reflector. As the reflector and its components expand and contract due to temperature changes, the circuit path length change is sensed and corrected. Hence, all of the unknown circuit phase errors can be sensed and controlled, making the antenna ready for instantaneous, blind pointing transmit operation.

7. RESULTS

7.1 CLOSED LOOP CIRCUIT CONTROL EXPERIMENT

In order to achieve a coherent beam for uplink, the phase errors around the circuit should be as small as possible. In the case of the demonstration in Florida, our goal was to achieve a peak-to-peak phase variation of no more than 10^o and an rms phase variation of no more than 3^o. After accounting for some less than optimum hardware, both goals were achieved and indeed surpassed. Figure 12 shows the phase stability of the closed loop system over an 83+ hour run.

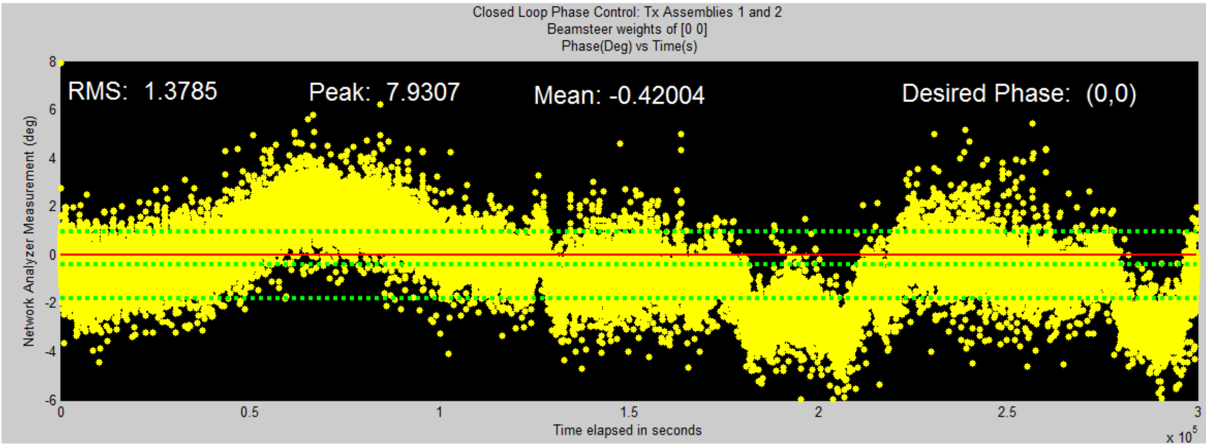


Fig. 12. Results for Closed Loop Circuit Control using Transmit Error Detection Assemblies.

7.2 GEOMETRICAL MODELING OF THE ANTENNAS

Errors arising from array element and geometrical position and orientation are the second major source of differential phase error when forming the uplink beam. These error sources were modeled as inputs to the uplink beamforming phase differential calculations. Each reflector comprising the array is described by a table of parameters beginning with its ARP latitude, longitude and elevation. These coordinates were determined initially with surveying methods using a laser rangefinder and theodolite establishing location relative to a nominal surveyed site reference good to within a fraction of a millimeter. Next, using the calibrated receive capability, observations of known emitters allowed adaptation of the geometry model through solution for each ARP, resulting in refinement of the initial location

The reflector geometry table parameters also include values for typical errors: gravity distortions (the antennas are not homologous), azimuth axis tilt, and RF axis offset from the mechanical elevation axis. While we expected that these array geometry parameters were highly stable, but they were continually refined and tracked. The array geometry, reflector orientation, imperfections, etc., are parametric values in an overall model of the array. These parameters in association with the model establish a basis for determining all beamforming weight settings, thus a model based form of calibration. By sensing and refining these parameters continually, the model was adapted to current conditions.

7.3 BEAM FORMING ERROR MITIGATION

Since the transmitted wave emerges from the antenna phase center and not the ARP, beamforming errors can occur if one uses the ARP without accounting for positional variation between these locations. For example, some of the potential error sources include differences in manufacturing tolerances between antennas, uncompensated thermal distortions of the dishes due to irregular heating/cooling of the surfaces and antenna back-structures, differences in feed to reflector distance or reflector focal length, and optical misalignment.

To compensate and account for these and similar errors sources, antenna element and array modeling of the geometrical factors addressed during the demonstration are shown in Fig. 13.

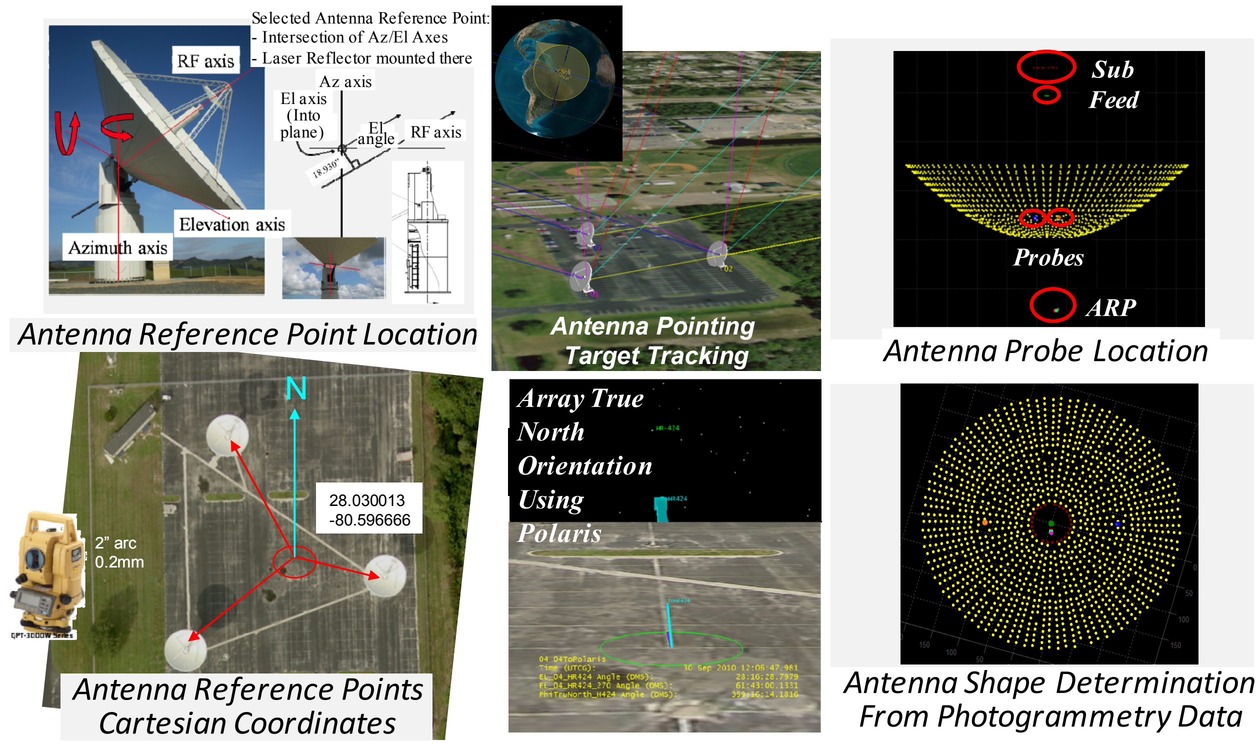


Fig. 13. Relationships between each element’s antenna reference point, sensor probes, and focus and the array’s true north orientation

The time delay is calculated from the antenna focal point, i.e. –the phase center, and this requires precise modeling the antenna surface and the relationship of surface points to the ARP. Next, photogrammetry, with wraparound observations was required to locate precisely all the points of interest, some of which were behind the reflector. Finally, mathematical modeling using optimization techniques was used to determine the geometrical relationships among the ARP, probes, and focus. Without such careful modeling relating the ARP to the antenna’s phase center, significant phase errors might have resulted thereby requiring still further means of calibration.

7.4 TROPOSPHERIC FLUCTUATION PHASE ERROR CORRECTION RF ADAPTIVE OPTICS

The tropospheric contribution to phase errors can be significant and are certainly unpredictable as evidenced by water vapor radiometer measurements. However, there is no apparent linkage between meteorological data and the observed phase fluctuations. Thus, ground-level measurements are not accurate indicators of what is occurring higher in the atmosphere Developing an all encompassing, universal model to predict the phase stability of a particular site would be extremely difficult. Furthermore, if the longest baseline of the array is even a few kilometers in extent, different weather conditions above individual array elements would make precise modeling of atmospheric phase fluctuations of the array as a whole an extraordinary challenge.

A simpler solution is to develop a real-time atmospheric compensation algorithm just as the optical astronomers do using a sodium laser to get an artificial “star” in the telescope field of view simultaneously with the object of interest. The algorithm developed for the closed loop uplink arraying demo, the RF analog of the well known adaptive optics methodology was successfully used to mitigate in real-time the varying atmospheric fluctuations. The algorithm handles the general case where each dish-to-target path may be looking at different columns of atmosphere due to the wide spacing of the elements.

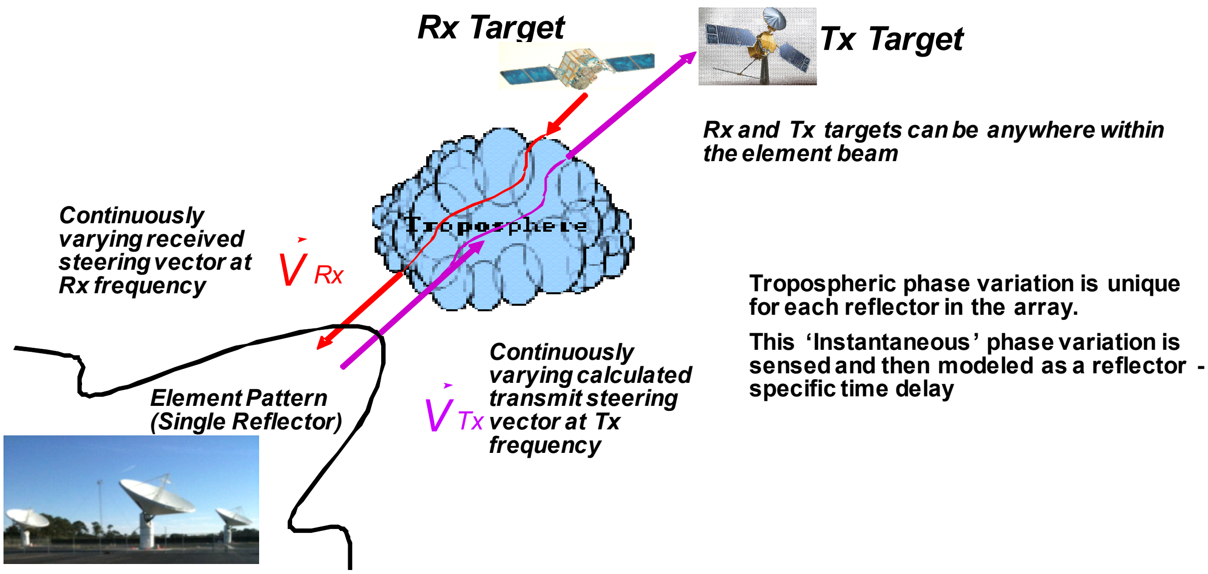


Fig. 14. Pictorial Representation of Tropospheric Fluctuation Phase Error Correction via RF Adaptive Optics

Real time propagation variations were mitigated by using a signal from a source of known angular position preferably within the primary beam is received through the tropospheric variation. Since the closed loop receive circuit control was in operation, variations in the received steering vector from the modeled vector measure the magnitude of the tropospheric phase contribution in the direction of the received signal. If the antenna beam width is small, then tropospheric variation toward the Tx target will be essentially the same as to the receive target. Since the effect due to tropospheric variation, mainly due to water vapor and turbulence, is one of frequency independent time delay, then the total differential delay obtained from model and measured receive variation was able to be applied to calculations of the steering vector for the transmit direction. Any known astrometric source may be used for this purpose, such as another satellite, quasar or supernova remnant.

8. MEASURED RESULTS OF REAL TIME ATMOSPHERIC COMPENSATION

Since the proof resides in measured data, first we show the results of the expected EIRP gain from a coherently phased uplink array.

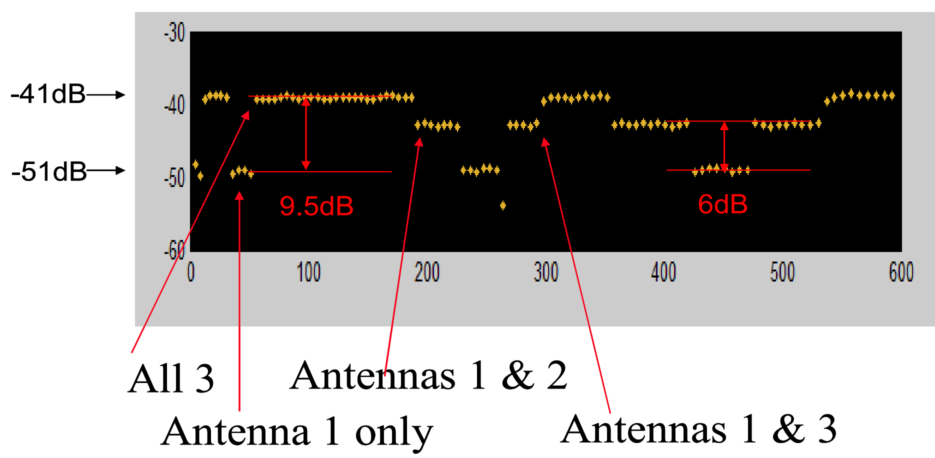


Fig. 15. Measured EIRP increase for three arrayed 12m antennas through target satellite

We were not satisfied testing the algorithms and demonstrating coherent uplink arraying in clear, relatively dry (for Florida!) air. Fortunately, Tropical Depression 16, later upgraded to Tropical Storm Nicole, provided a marvelous opportunity to excel.

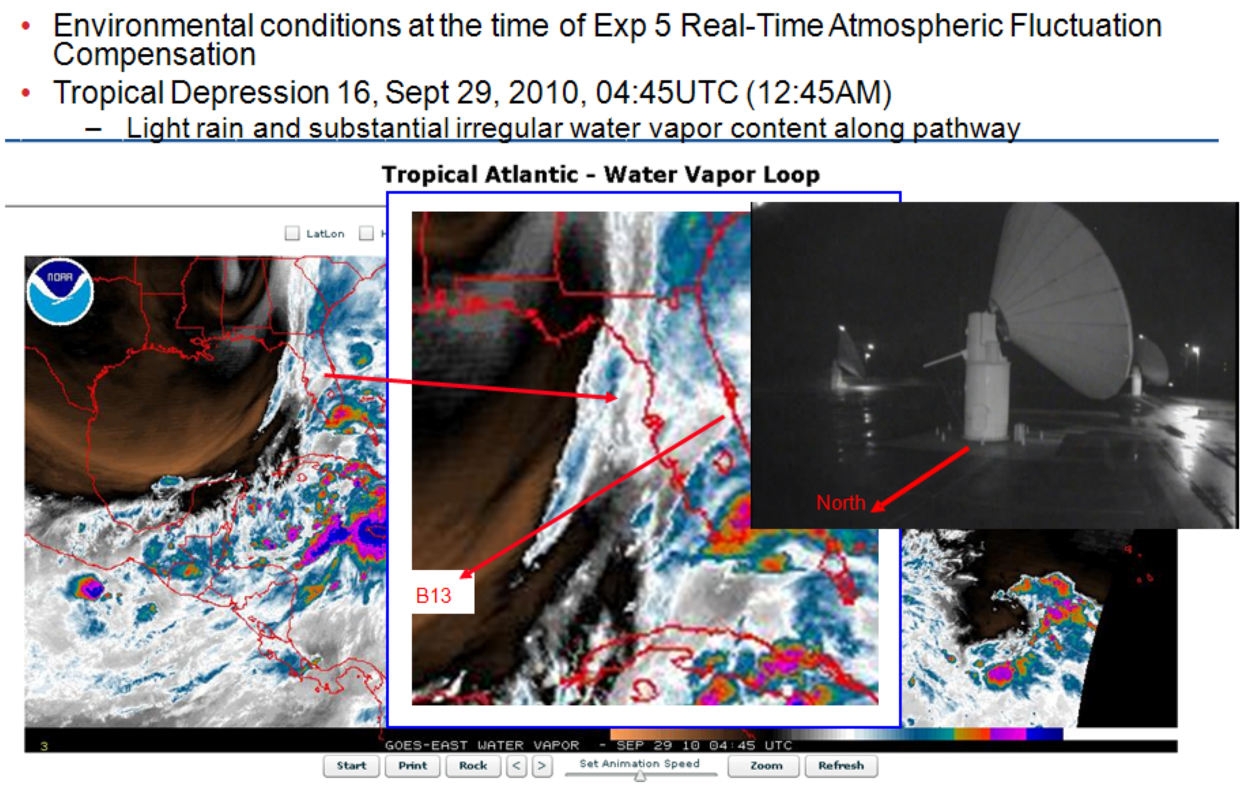


Fig. 16. Conditions of a robust test of real-time atmospheric fluctuation compensation coherent uplink arraying

Under these conditions, Fig. 17. Shows the phase fluctuations with and without the real-time atmospheric fluctuation algorithm noted in the figure as "instant return."

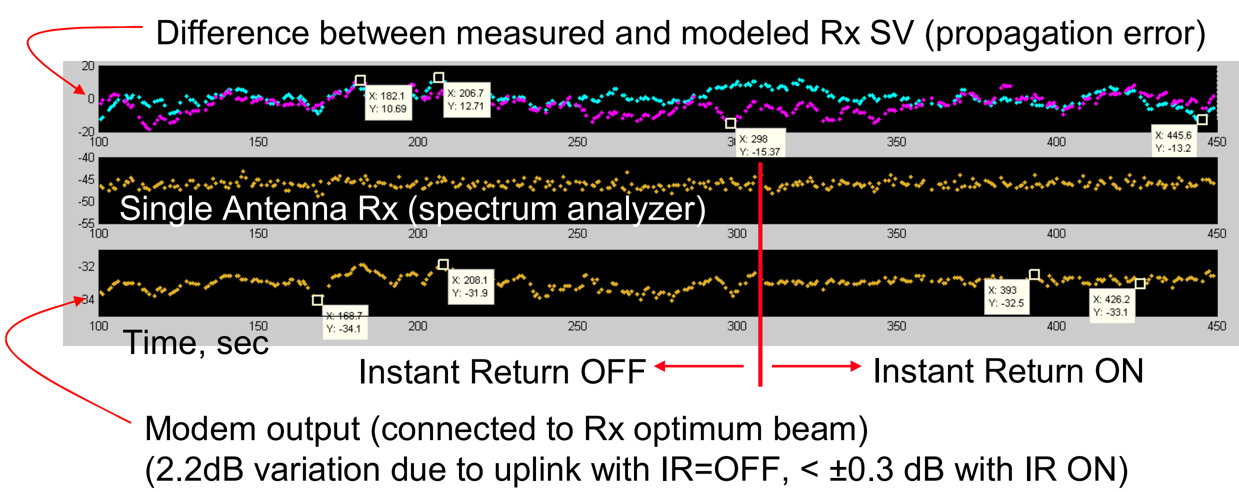


Fig. 17. Demonstration of ~ order of magnitude decrease in phase fluctuations using RF using the compensation algorithm

With the demonstration of real-time atmospheric fluctuation compensation, we have almost closed the chapter on uplink arraying demos at X-band. Further capabilities under study at JPL are Doppler range and range rate measurements.

9, NEXT STEPS: A PERSONAL VIEW

Going beyond X-band for NASA involves Ka band tracking capabilities. Although the demonstration of coherent uplink arraying at Ku band has been successful and gives us encouragement that such techniques will be successful at Ka band, we have no data to bear out that hypothesis. Furthermore, we have not yet shown how to make uplink arraying reliable in an operational sense because we have not had the resources to undertake that aspect. The next three paragraphs describe the author's personal vision. It has not yet been endorsed or funded by NASA, but represents a sequence of next logical steps should arrayed uplink be deemed a high enough priority.

Should those resources become available, the next step we are contemplating is a demonstration of coherent uplink arraying at Ka band (26-40 GHz). The advantages of going to Ka band for satellite communications are that it affords a broader spectrum allocation thus providing an opportunity to acquire more data via satellite communications. Furthermore, going to Ka band will help alleviate spectrum crowding. Right now, with a 50 MHz wide spectrum allocation at X-band, any deep space spacecraft gets some 5-7 MHz allocated to it. At Ka band, the spectrum allocation is 500 MHz wide so an order of magnitude increase per spacecraft is not unreasonable to expect. For radar applications, we anticipate that going to Ka band should yield higher resolution and more power on target. Finally, for spacecraft navigation, we anticipate gaining a factor of about 30 in precision for Doppler ranging; 4x from the wavelength difference and 16x due to the wavelength squared nature of interplanetary matter scattering effects and assuming 50% efficiency.

We also need to determine whether or not real time atmospheric fluctuation compensation at Ka band is urgent, vital, or just nice to have at Ka band. This may be situational depending upon where the array is placed in operation. In arid locales, maybe just a nice to have. In areas near bodies of water or where there is grass and trees –implying water- maybe vital and perhaps even urgent. We need the data over time to determine the systems requirement. Our thought is to gather the data involve moving the antennas that were at the Harris Corp. in Florida to a more challenging location and then proving out uplink arraying at Ka band by competitive procurement.

Build a dedicated multipurpose facility heavily weighted toward radar yet with space communication and radio science capabilities for studies of near Earth objects and orbital debris. The antennas can be employed as a single synthesized aperture or sub-arrayed for specific purposes.

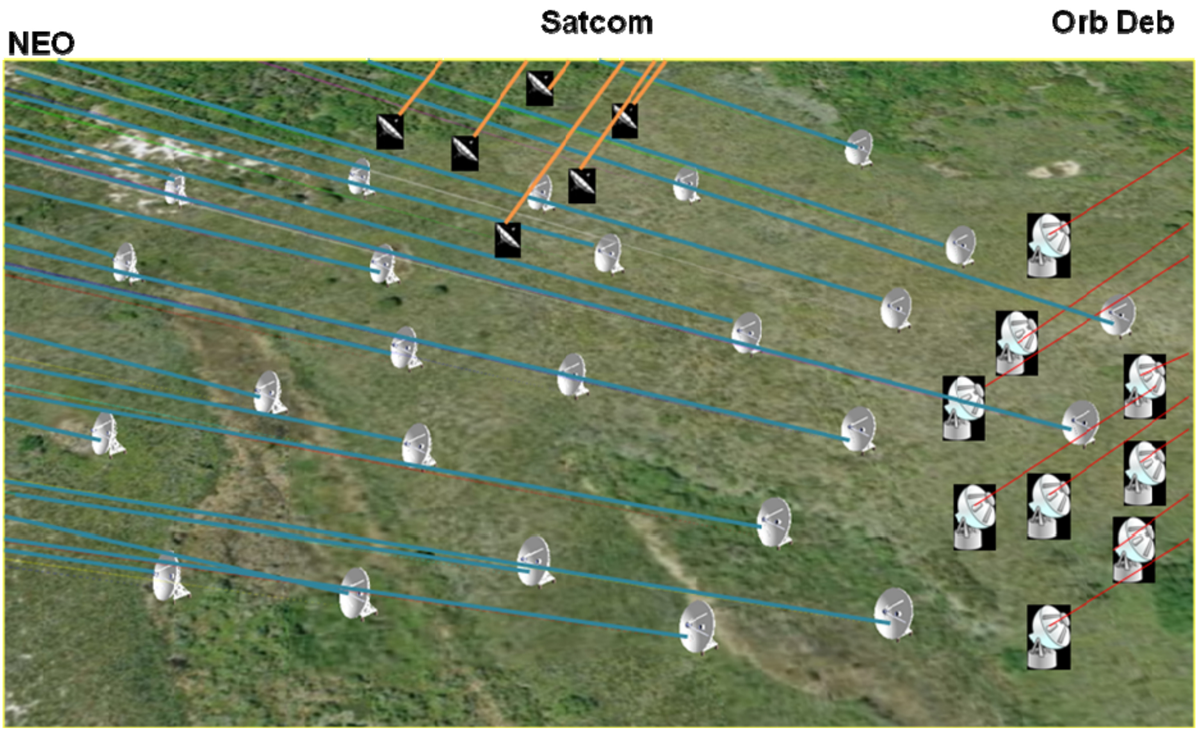


Fig. 18. Conceptual multipurpose array facility.

9. ACKNOWLEDGEMENTS

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