Applications and Operation Concepts of Large Transmit Phased Array of Parabolic Reflectors

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Abstract—The primary motive[1,2] for large transmit array of parabolic reflectors, also known as Uplink Array, was to explore alternate methods in order to replace the large 70m antennas of Deep Space Network (DSN) such that the core capability for emergency support to a troubled spacecraft in deep space is preserved. Given that the Uplink Array is a new technology, the focus has always been on its feasibility and phase calibration techniques, which by itself is quite a challenge. It would be interesting to examine, however, what else could be accomplished by the Uplink Array capability other than the emergency support to a troubled spacecraft in deep space. Although the Uplink Array calibration and demonstration for proof of concept is still underway at Jet Propulsion Laboratory (JPL), knowledge of various potential meaningful application scenarios as well as operation concepts of Uplink Array is equally important to better understand and fine tune the high level architectural requirements of this big evolving system of systems. Therefore, the objective of this paper is to discuss a few application scenarios and the corresponding operation concepts, such as lunar positioning system, high EIRP uplink and the synergies with solar system radar, and high power RF beams.

TABLE OF CONTENTS

1. INTRODUCTION

Study shows that Uplink Array of small parabolic antennas is increasingly attracting attention. The Uplink Array's most impressing capability is the simultaneous high rate supports. Recent studies at JPL indicated that the general trend for the high rate multi-mission support demands for symmetry between uplink and downlink with the key driver being the human missions. The current high rate definitions stated in most literature are in excess of 100 Mbps per user, and over 1 Gbps in some special cases. Depending on what exactly one defines the user to be, even if the user is defined as one spacecraft out of a cluster that forms a single mission both uplink and downlink array would have similar challenges in multi-spacecraft, multi-mission era, particularly with humans in the loop.

After the preliminary field tests of the high power transmitters conducted by Jet Propulsion Laboratory (JPL), and rigorous simulation efforts jointly with the University of Michigan it was revealed that the Uplink Array of small parabolic reflectors concept is indeed feasible. Although several key technological challenges still exist, as discussed in a previous paper [1]. It was also shown that the cost for the required performance would also be lowered when compared with the larger equivalent antennas [2]. Many techniques for phase calibrations were proposed and examined at various depth and details ranging from antenna aperture size 4m, 12m, and 34m with few hundred watts to 20 kW transmit power per aperture respectively. For instance, some techniques that were examined are: Low Earth Orbit (LEO) radar targets, GPS satellites as radar targets, RF photonic dish probes, holography, ground-based towers, and the Moon–based calibration method, which is the most recent. With the core capabilities that can be offered by the Uplink Array and its incremental effective radiated power (EIRP) more aggressive applications can be envisioned that could not otherwise be conducted by the traditional large DSN antennas. Of course the beauty of the array concept is its scalable nature, which allows the deployment of the future DSN to take place in an evolving fashion. This is an attractive feature particularly in this era of rapid technological cycles. However, it requires novel system design concepts that can leverage on the array evolution. It is hard to envision the design of such a large system centered only on the calibration techniques without consideration of typical application suits, or operation scenarios unique to Uplink Array core capabilities as well as their corresponding operation concepts. This is an area, which has not been fully addressed as of yet in the study of Uplink Array.

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[2] IEEEAC paper # 1570, Final Version, Updated December 21, 2005

Limits of Calibration Methods

In this sub-section, some examples will be provided to show why it is important to start developing Uplink Array application suits, and their operation concepts to help us further sort out which calibration method should be the final choice as we enter the next phase of more detailed and in depth studies. As it might have been expected, inherent in each calibration method that were examined thus far are several hidden assumptions that set the tone for the scope of the array applications, and its operation concepts. For instance, in order to narrow down the trade space of a particular calibration method, one has to make certain assumptions, which potentially rules out certain array applications or design path. As an example, the Moon –based calibration method requires at least a 12m aperture size, 4 kW of element transmit power, 5 minutes of Lunar target observation time, and certain tracking capability for each antenna (i.e., better than a millidegree). On the other hand the tower-based method sets an upper bound on the aperture size to less than 4m, and uses power levels far below that required for the Moon method. The small aperture size, and power per element for tower-based method would definitely put additional operational limits on individual elements for certain applications, such as Radar, and or Lunar Positioning Systems, or direct from Earth power transfer, or some tracking and navigation supports to the Moon and beyond.

The radar calibration methods on the other hand have design implications as well as operational constrains. The design constrains of the Radar-based calibration techniques are manifested by way of requirements on additional receiver capability with subsequent digital processing and data volume reductions, and isolation switches, which could result in ruling out the shared aperture of Uplink and Downlink arrays due to cost and complexity. The Radar-based technique, however, has the advantage of testing the array in a more realistic set of scenarios before using the array signal for real operation. The Radar-based technique also lays out the ground-work for adding the planetary radar applications to the array application suit. The RF/Photonic dish probe method, which is based on fiber-probes placed on antenna aperture sensitive locations would allow shared Uplink and Downlink apertures, and does not have much aperture size and power limits, however, it still requires some far field radar target verification, and needs to be further studied in conjunction with the holography method before any conclusions can be drawn on its limitations for array application suit. Table-1 summarizes some examples for differences in target requirements for LEO, GEO, and Moon distances. As can be seen from Table-1, even within a calibration class, (i.e., radar-based) there are several parameters that not only depend on cost and complexity of the method but they also heavily depend on how the array is going to be used operationally across all types of perceived applications, and modes of operation.

Table-1 Uplink Array Target Requirements

Range to target	500km	24000km	300000km
Position tolerance	1m	50m	630m
1-mdeg position error	8.7m	17.45m	418m
Phase error due to 3mm phase center error (deg)	25.7	25.7	25.7
SNR loss	.22 dB	.22 dB	.22 dB
Required SNR for 1 deg rms error	35 dB	35 dB	35 dB
Moon pixel size req. (phase method)	N/A	N/A	640m
Moon pixel size req. (power method)	N/A	N/A	80m

2. SPACECRAFT & HUMAN EMERGENCY

The initial motive for the Uplink Array has always been its high EIRP required for the spacecraft emergency support, particularly when the 70m and its 400kW S-band transmitter are decommissioned presumably within the next decade [1]. It should be noted that the Deep Space Network (DSN) consists of 70m, 34m, and 26m antennas. The study of large phased array replacement for DSN existing antennas at JPL has traditionally been consisting of large array of small parabolic antennas, or a large flat plate array of dipoles, or waveguides. Early in the studies of the 70m antenna replacements, the large flat plate array was delayed as an option due to primarily its high cost, scan loss, and safety issues for high EIRP scenarios. A table of cost comparison for various sizes and frequencies of flat plate phased arrays with different scan angle coverage is provided in [3]. While this was the case for the 70m and 34m antennas, the 26m antenna replacement study had a different path. For the 26m antenna, the S-band, or X-band flat plate phased array replacement has been proposed particularly for multi-mission supports and GPS network connectivity for the near-Earth Launch and Early Orbit Phase (LEOP) as well as LEO, GEO, and Lunar network synchronization [3]. As discussed in [3] a dedicated flat plate phased array at S-band, or X-band with 12m-15m aperture size could be a cost effective approach to support the near term needs of the first 2M Km activities. However, for the larger DSN antennas, i.e., 34m, and 70m, the more generic and scalable approach to replace the DSN antenna network has been the large array of small parabolic reflectors both in Uplink and Downlink.

The phase calibration methods for the Uplink Array impose many constrains on the Uplink Array, such that many design issues, e.g., combining the Uplink and Downlink apertures, or combining the Radar, or Power Beam with the telecom functions are subject to further elaborations on application scenarios and operation concepts. Therefore, in this paper the focus of application scenarios is on what can be done with the array of parabolic reflectors other than emergency support to a spacecraft at the edge of solar system.

Communications in Spacecraft Emergency Mode

The spacecraft generally has to communicate that it has an emergency. The on-board fault protection (FP) software response to a fault is to enter a safe mode to make the spacecraft safe for a while and to announce the fault to the ground. While in safe mode, the spacecraft relies primarily on the omni-directional antenna, which is a low gain antenna (LGA) with solar panels pointing at the Sun, and Earth viewed within the same hemisphere. The safe mode includes consideration/correction of attitude and communications mode. As an example, FP may orient the spacecraft to Sun point. It may establish a low rate uplink and downlink capability on the low gain antenna (LGA). The ground needs to find out about the emergency by receiving the downlink. The ground could then define, generate and radiate an uplink response to correct the emergency. On the existing projects, the uplink/downlink communication mode for emergencies is usually on the LGA unless FP "knows" that attitude hasn't been disturbed. Except for the changes below, safe mode communications use the same modulation as normal communications (phase modulated carriers with subcarriers). Downlink mode is often 40 bps, though recent missions have supported 10 bps. However, locking up 10 bps at the DSN is so tedious that projects often elect to have 40 bps for the safe mode, risking the loss of coverage at a somewhat wider angle from the LGA. The rationale is that safe mode attitudes will always be such that 40 bps is supportable over 70-m stations. A low frequency (~25 kHz) subcarrier phase modulates the downlink carrier at about 55 deg. The spacecraft emergency is therefore a very high risk, and tedious process and one could imagine the level of difficulty for a high rate stressful human emergency situation. The current DSN capability doesn't allow normal communications in emergency modes, and as mentioned before with the decommissioning of the 70m antenna, and the 400 kW S-band transmitter, the minimum required capability (8 bps) command rate to the troubled spacecraft beyond 4 AU would also be lost as well. On the other hand, Uplink Array of parabolic reflectors allows spacecraft dynamics in various emergency scenarios, including human emergency situations without having to use less effective modulation schemes that are currently used in order to trade for robustness. The current spacecraft limit to receive uplink signals is 2kbps, since the primary need for the uplink has traditionally been considered for command purpose. If this rate is increased to 10 to 100 times then, with an uncoded system at X-band, 10-20 dB increase in EIRP is required. Uplink coding, which can provide higher rates to the spacecraft has historically been considered expensive in terms of its additional decoder complexity on-board the spacecraft. For instance, at a bit error rate (BER) of 1E-5, the uncoded data required threshold is 9.6 dB for E_b/N_o whereas the (7, ½) convolution code required threshold is 4.5 dB for E_b/N_o, assuming the implementation loss doesn't change drastically. Therefore, approximately 5 dB less power is required for a coded uplink for a given data rate as compared to an uncoded X-band uplink. Therefore, coding alone is not adequate if 10 to 100 times more data rate is needed.

According to a study at JPL for the future mission models, the need for higher uplink data rate other than what can be sent to a troubled spacecraft emerges from the paradigm shift in uplink information, i.e., a shift from command only uplink to software upload at rates of 2Mbps and higher. This shift in paradigm is primarily attributed to the human mission era, where uplink and downlink tend to become symmetric in terms of data rate requirements. If this capability, i.e., 10 to 100 times higher data rates is provided by the Uplink Array, then direct-from-Earth (DFE) frequent instrument and payload reconfigurations of space assets can be envisioned. As an example, given the flexibility provided by software radio and the reconfigurable payloads, it is not hard to envision this paradigm shift, i.e., multi-mission frequent software uploads. The software radio architecture allows the ability to include measurements from different frequencies, simply by changing a few key words. New frequencies can be added through simple changes to RF-to-digital front-end filters and selection of local oscillators. Therefore, the need for command shifts towards the need for software upload, and high rate human emergency situations, such as telemedicine. The emergency situations would also be shifted from just saving a troubled spacecraft in deeps space to instant upload of software to a Lander, or a human radio even at distances to the Moon. A simple example is the detection, identification, and communication to a stationary or a moving Lunar surface asset or astronaut direct from Earth. In general, human missions require the integration of command, communication and control to multiple spacecraft, surface based assets, such as rovers, as well as search and rescue of individual explorers. As an example, according to Gary Noreen [4] in order to close the link for a voice channel at 2kbps directly from the Earth to a spacecraft at 2 AU with the 70m antenna, the required transmit power is at least 100 kW. If this requirement is considered in conjunction with simultaneous navigation requirements to a human on the planet surface then much higher power and data rates would be required even to a stationary target location.

Human emergency support may also impose non-overlapping broad-band GPS-like range and phase codes for navigation purposes. The C/A (coarse/acquisition) code and M-Code, or P-Codes (precision) for GPS signals require 2MHz, and 20MHz respectively [5]. Therefore, the integration of navigation and communication architecture for simultaneous mission supports for direct from Earth would require core capabilities offered by Uplink Array with individual antenna sizes large enough, e.g., in excess of 12m for Lunar integrated navigation and communication support. The requirement for minimal of 12m apertures size stems from the fact that any type of lunar pointing and signal processing for the Uplink Array calibration needs a minimum of 12m and 4kW transmit power. This is in addition to other requirements driven by Lunar orbiter support per individual element from navigation and communication perspective. That is, before an Uplink Array beam can successfully be formed, every individual antenna needs to have sufficient power to send the individual PN codes. As will be discussed in the next section, the recent proposed space-based architectures for Lunar Positioning System (LPS) support require multiple antennas from Earth to provide connectivity and network synchronization direct from Earth to Lunar constellations. This type of application, i.e., integrated navigation and communication support from Earth for human exploration era is beyond the core capabilities of the existing DSN and requires the array capabilities. The superiority of phased arrays whether as large array of distributed parabolic reflectors replacement for the large DSN antennas, or in terms of replacement of the 26m DSN antenna with a flat plate conventional S-band phased array for Lunar support is manifested in the following 1) Multi-mission support, 2) integration of Communication and Navigation support, 3) Bandwidth congestion issues, 4) Integration with LEO, GEO constellation, 5) Network synchronization support for the space-based architectures. In the next section, the application of Uplink Array to Lunar Positioning System (LPS) would be discussed with emphasis on direct from Earth search and rescue concepts.

3. LUNAR POSITIONING SYSTEM

As discussed in [3] one of NASA's major long-term objectives is to promote human exploration capabilities beyond low Earth orbits. Mars robotic missions are a logical step towards that goal. However, this requires public engagement and interest in human operations in space at

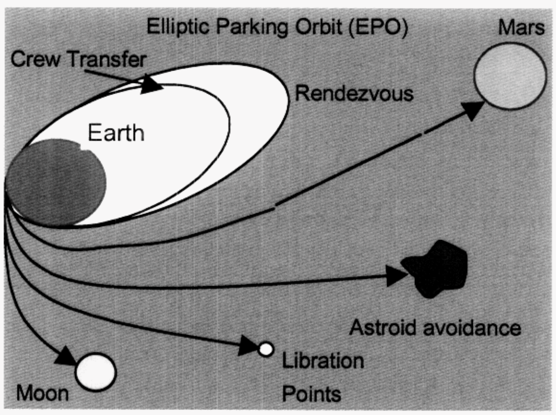

Figure-1 Mission Stages

various intermediate stages, i.e., from LEO, GEO, and HEO, to the lunar missions and beyond. Public participation demands telepresence, and visual aids, such as virtual reality, High Definition TV (HDTV), diverse access to multiple satellite constellations, symmetric and user-specific uplink/downlink, broadband communications to the space transportation facilities, and augmented global positioning systems that operate beyond low Earth orbits up to GEO and HEO. Figure 1 illustrates the mission stages for human exploration to Mars.

GPS Coverage to GEO and HEO

Another major system element on the network connectivity, timing, and orbit information accuracy for future LEO, GEO, and HEO spacecrafts is the future state of GPS network. Conventionally, the GPS receivers pick up signals from the individual satellites and translate them into position information. This is performed through 24 satellites placed at approximately 20,000 km above Earth, which means GPS standard is not directly applicable to GEO and HEO missions because of important differences in altitude, vehicle dynamics, signal levels, and geometrical coverage. Figure 2 illustrates the limited scope of the existing Global Positioning System (GPS).

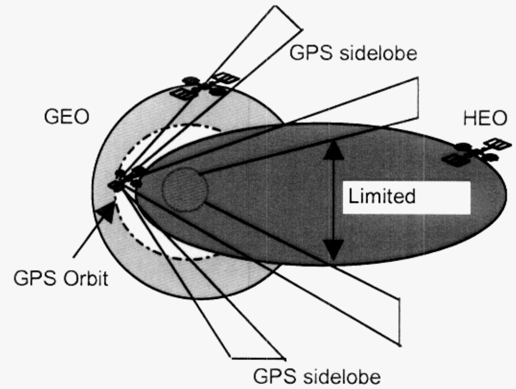

Figure-2 Standard GPS limited visibility to HEO

Therefore, as shown in Figure 2, there are long periods of time when GPS spacecrafts are not available simultaneously to provide a complete position and timing information to GEO, and HEO, and beyond to Lunar orbits. In order to fulfill the new requirements for the systems-of-systems, i.e., synchronization of different satellite networks and constellations located at various orbits of LEO, GEO, and HEO, FAA and other space agencies are bringing new capabilities to GPS to enhance its accuracy as well as its connectivity to higher altitudes. Additionally, the capabilities of Internet satellites have provided GPS with new augmentation such that additional navigation signals are provided for position determination through communication satellites [3]. GPS capability, through phased array systems, provides more accurate relative range among spacecrafts as well as more precise updates of the individual spacecraft attitudes. Therefore, while the standard GPS provides the basic and core capability for orbit information for LEO spacecrafts, the augmentation of GPS with phased-array technology has proven to extend its capability to GEO and HEO [3].

GPS, Lagrange Points, and Lunar Surface Coverage

The recent activities in Lunar explorations and the increasing interest in the Lagrange Libration points (Figure 3), particularly L2 at 1.5 M-kilometer has triggered the exploration of navigation concepts based on GPS to Lunar Libration points. A Lunar relay orbiter placed at this orbit (L2) can provide Earth-to-Lunar far-side and long-range surface-to-surface navigation and communications capabilities. Barton et al [6] studied the use of GPS for navigation enroute between the Earth and the Moon assuming minor modifications to GPS receiver, i.e., 10 dB improvements in GPS receiver sensitivity and a high gain antenna. Barton [6] then showed that this level of GPS when augmented with support from NASA's Tracking and Data Relay Satellite System (TDRSS) could support the L1 Lunar rendezvous scenarios. Later, Carpenter [7] described how the GPS pseudo range in combination with one-way Doppler measurements from Earth-Moon L2 orbit could be used for Cis-lunar transfer. The basic idea in Barton and Carpenter study was to make best use of existing Earth orbiting assets, i.e., GPS and TDRSS combination.

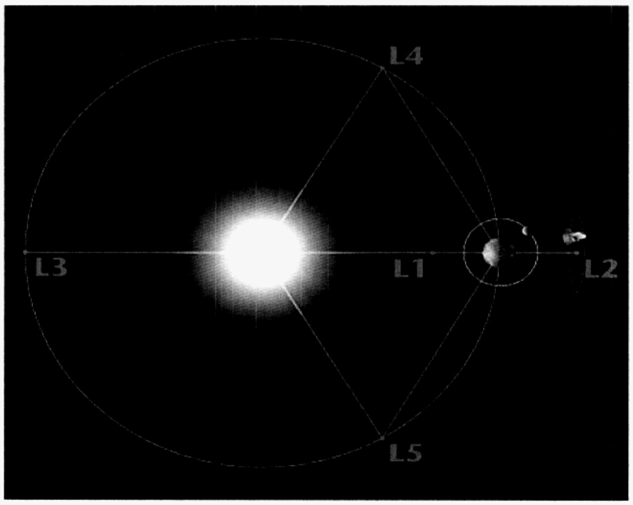

Figure-3 Lagrange Libration Points

The focus of the Lunar surface positioning has been primarily on how to reach the far side, and the high latitude, i.e., near the poles where the science objectives of most missions are concentrated. Several orbit constellations have been considered, however, the low gravity of the moon, and perturbations from Earth makes it difficult to find stable orbits with adequate number of satellites with sufficient view geometry form Lunar surface. Therefore, what is still lacking in Lunar surface positioning study is the direct from Earth support to the near-side, low latitude. The ground support for Lunar positioning system has three major advantages, 1) it provides network synchronization direct from Earth, which would relax the requirements of cross link among orbiters for global Moon coverage, i.e., view geometry, which in turn reduces the delay in processing, 2) it helps minimizing the delay by providing more connectivity taking the load off the user's receiver on the surface of Moon, 3) while the coverage of the near-side (low latitude) doesn't have as much attractive science features in the short term, however, it can be argued that the near side best and most efficient coverage method with minimum delay is through Earth-based techniques. Therefore, the stability of the orbits does not have to be sacrificed for the 100% coverage. More than 49% of the Lunar surface positioning system, including parts of the polar regions, can be done direct from Earth, which will reduce the cost and complexity of station keeping, spacecraft payload, user receiver, and cross link, particularly for moving targets on the Moon.

Lunar Network Architecture

In a previous work [4] Gary Noreen proposed and described the communication architecture for human and robotic exploration that covers Moon and Mars network. The network architecture in [4] is based on the following assumptions in terms of the assets that could be deployed on the Lunar surface: 1) 12 astronauts with omni-antennas with up to 6 simultaneous voice channels monitored from Earth, and each astronaut ventures no more than 100km from the base station. 2) Up to 4 transports carrying humans, such that simultaneous reliable channels of 10 kbps on the forward (uplink) and 1.5Mbps on the return (downlink) can be supported through an Omni, and steered antenna per transport unit. 3) Up to 24 robotic rovers simultaneously using two-way reliable links with up to 100kbps on the forward and 1.5Mbps on the return link. Furthermore, it is assumed in [4] that the Lunar base is placed near a pole, naturally due to the science interest in those poles. The requirement mentioned in [4] for Lunar landing, and/or position determination of the above-mentioned Lunar assets, i.e., rovers, and astronauts, is within 100m accuracy. The data rate needs for several types of applications, e.g., High Definition TV (HDTV) at 20Mbps, Hyper Spectral Imaging (150 Mbps), Radar (100 Mbps), Speech (10 kbps), Video Conference (1.5 Mbps), and Digital Commands (2 kbps) have been fully addressed in [4]. It is then argued that the communication and navigation requirements of a polar base, not in view of Earth could be met by a constellation of three Lunar Telecommunication Orbiters LTO) in conjunction with an augmented ground network.

As discussed in previous section, removing the support from Earth can drastically increase the number of required satellites, and impose stressful orbits that require frequent maneuvers. From system architecture perspective, a near real-time positioning system can not welcome frequent spacecraft maneuvers particularly when the number of viewed spacecraft from Lunar surface is out numbered. To give an example, a typical near real-time Earth target GPS-like position accuracy of 10-100m with over 10-20 km distance from base station would require viewing over 4-7 spacecraft with high SNR all viewed for at least 20-30 minutes [8]. For non-real-time (several hours) processing of up to 20km away from the base station, 20cm accuracy is typical. This is still ignoring multi-path, and other vehicle dynamics, i.e., for a stationary target on the surface. Therefore, what is still missing from the Lunar Integrated Network Architecture (LINA) is 1) the level of contribution of the ground network for simultaneous communication and positioning, 2) scenarios in which the ground network can be more effective than the orbit constellations, 3) techniques, and algorithms that can be used through ground-based network to augment the orbit constellations, and 4) methods to overcome the shortcomings of the existing ground network support through RF arrays core capabilities.

The Ground Network Contributions to LPS

For human explorations, particularly in situations where surface rovers and crew transport are involved, communication signals need to be hand-in-hand coordinated with navigation support without being punctured by nav-oriented PN codes or delays in processing of the surface target state vectors. Here on Earth, with the mature GPS technology, after putting together the Internet-based Global GPS (IGDG), GLONASS, DORIS, SLR, after hours of ground-based processing, one can achieve approximately within 1-10 cm orbital accuracy with GPS network [9]. Note that while GPS system is based on transmit signals from space to the GNSS receivers on the ground, the DORIS and SLR systems are based on beacons transmitted from Earth to satellites. Every global user on Earth is assured of a minimum of eight satellites in view above 7.5 degrees elevation angle,

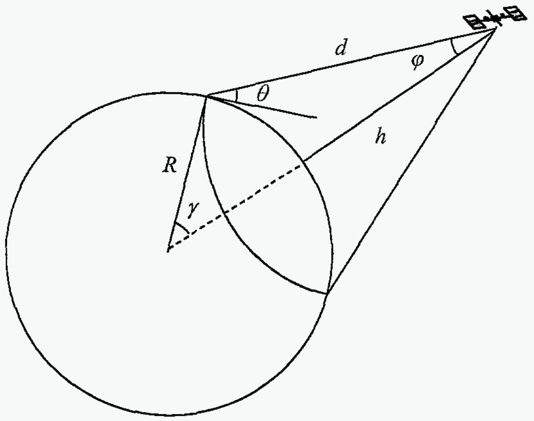

Figure-4 Surface Coverage Geometry

and approximately 99% of the global users are assured of 10 satellites, while half the users would see 14 or more satellites. The near real-time version of the position accuracy would reach as high as 20m under best ideal conditions [9]. In order to examine the level of difficulty of similar 100% Lunar surface coverage even for C/A code (i.e., coarse resolution of 10m surface accuracy to a stationary target) one can begin with the number of satellites for 100% coverage and then add to it the number of required viewing satellites to provide the 10-100m accuracy. Figure 4 illustrates the coverage geometry of a satellite looking down at the planet surface. Based on this geometry, for a street of coverage with width Ψ one can compute the number of required satellites S in each orbital plane according to the following relations [10].

$$Cos(\gamma) = Cos(\Psi) \times Cos(\pi / S)$$

$$Sin(\gamma) \times \tan(\theta) = Cos(\gamma) - \frac{R}{R+h}$$

And the number of required orbital planes p can be computed according to the following relations [10]

$$(p-1) \times (\gamma + \Psi) - 2\Psi = \pi$$

The total number of satellites would then be $N = p \times S$. Now, according to [10], the optimum total number N of satellites for a street coverage mentioned above is the one that minimizes the angle γ (central angle) to each satellite from the center of the spherical formed by 3 satellites subject to the conditions that a) they cover the sphere, and b) the central angle γ is minimized. This results in N=5 for the Lunar surface coverage. On the other hand, the range code PR of a GPS-like signal from a lunar orbiter is given by

$$PR = D + C(\Delta T_{rcvr} - \Delta T_{s/c})$$

where, C is the speed of light, the correction delta times in the parentheses are for user receiver and the spacecraft clock respectively, ignoring all other higher order terms, and D is the geometric range given by,

$$D = \sqrt{(X-x)^2 + (Y-y)^2 + (Z-z)^2}$$

In the above relation, the X, Y, Z correspond to the spacecraft coordinates while the x, y, z are the user coordinates. The spacecraft coordinates by themselves have to be known precisely relative to another reference point and get updates of ephemeris transmitted to the user constantly, including any recent maneuvers. Together with the time, there are 4 unknowns to solve per unit time. Therefore, combining the coverage requirements and the GPS requirements together, the minimum required number of independent satellites would rapidly increase to beyond 12. Statistically speaking, from experience with Earth-based GPS system, there needs to be another redundancy factor added to this number (i.e., 12 satellites) in order to make sure there are at least 4 non-maneuvering and well-behaved satellites available for user processing, not counting the spares. Therefore, the total minimum number of satellites could be overly excessive. It should be mentioned that on Earth, on the other hand, the orbiter constellation for 100% Lunar surface coverage requires multiple antennas per spacecraft to provide connectivity in hand-over situations. For instance, considering the hand-over in transit conditions, for every two satellites with direct link to Earth one would need three Earth station antennas per complex. Therefore, One can imagine why Carpenter [7] did not consider Earth station support as much as GEO, and TDRSS.

As mentioned previously, given the low gravity of the Moon, and the Earth perturbations, except for the polar orbits, it is very inefficient and costly to try to resolve all 100% coverage and availability for Lunar Positioning System (LPS) by Lunar orbiters alone. The GEO-based, and TDRSS-based supports have already been discussed by Carpenter [7]. There are only two other fundamental solutions to this problem. One way to reduce the number of required satellites is to use cross-links, and the other way is to split the coverage between direct from Earth, and the orbiters. The cross-link for the purpose of Lunar Positioning System (LPS) is definitely not the cost effective approach due to much additional satellite payload complexities and coupling of the errors and biases, which could further accumulate the bias. One could imagine the exponential growth in network complexity if two-way range and Doppler is used for moving targets on the planet surface. That is, all these complexities are still for the non-stationary targets (users) on planet surface. There are many hidden constrains for the cross-link approach. The computational load on-board the satellite and the spacecraft antenna dynamics, slew rates, and pointing requirement alone would very well result in formidable cost and complexity and further elaboration on the cross-link complexity is beyond the scope of this paper. The alternate solution, i.e., more active support from Earth requires new core capabilities not provided by the existing DSN, and it also requires new concepts not previously addressed by the previous authors. The new core capabilities for Earth-to-Lunar coverage need to be applicable to Comm/Nav network architecture in an integral fashion. In order to better explain how the Uplink Array could come into the picture of Lunar Positioning System with new concepts for Earth-based support to future Lunar missions, a brief description of the Moon-based phase calibration method for the Uplink Array is described next.

Uplink Array and Moon-based Phase Calibration

There are two main classes of radar targets for calibrating the Uplink Array, i.e., the near field, and the far field targets. The need for the far field target for the calibration of phased array has already been discussed [1]. The far field target for the Uplink Array at X-band, and Ka-band frequencies with a baseline of 1km falls well beyond 60, 000 km, and 230, 000 km. The target ephemeris need to be known with accuracies shown earlier in Table-1. Obviously, Moon is the only far field target that satisfies the requirements for being used as the Uplink Array calibration target.

Of all the calibration methods proposed for the Uplink Array, the Moon-based technique bears in it some interesting features, which indicates that the Uplink Array is an excellent candidate for applications to Direct-From-Earth support for Lunar Positioning System. The concept of Moon-based calibration of Uplink Array has previously been discussed in detail [11]. Basically, selected patches (targets) of Lunar map are used to generate the phase center reference for the Uplink Array. In doing so, each 3-D image generated by pairs of antennas in the array is compared to a common reference image. Each pixel in the image corresponds to a Delay-Doppler point. Figure 5a & 5b illustrate the basic concept. There are many functions inherent in the process of Moon-based calibration of the Uplink Array that seems to be shared with the steps necessary for Direct-From-Earth Lunar Positioning System. Some of the shared functions are: Connectivity to GPS network and the GPS-like synchronization of the antenna elements, the need for atomic clock accuracy for the time-base from Earth-to-Moon, the pixel-by-pixel registration to within 10-100m accuracy, the coordinate transformations of the individual point targets on the Lunar surface, the topocentric corrections of the individual pixels on the Lunar surface, the automatic target recognition of calibration target features (e.g., Tycho crater center peak, and the known features on the rim), and the automatic focusing of the array signal on the target of interest through iterative phase conjugation. In the next few paragraphs some examples of Lunar map through DSN Goldstone Solar System Radar (GSSR) is addressed to further elaborate on the relation of Uplink Array to individual pixel locations on the Lunar surface.

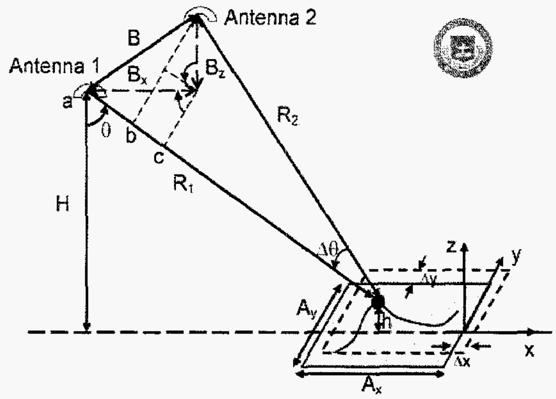

Figure 5a Individual Pixel's Geometry - InSAR Concept Courteously - University of Michigan, [11]

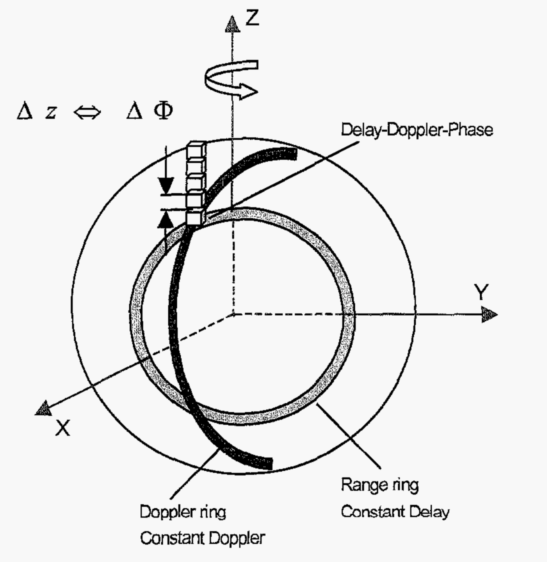

Figure-5b InSAR 3-D Individual Pixels on Lunar Surface

DSN and InSAR Image of the Moon

Throughout a sequence of X-band Experiments with Goldstone Solar System Radar (GSSR) in 1990's radar maps of the Moon were generated with 100m resolutions, which were also verified with data obtained from Clementine, as well as Arecibo and Haystack observation radar [12]. The maps of the Moon were generated using Interferometric Synthetic Aperture Radar (InSAR) techniques. The Goldstone Solar System Radar (GSSR) is equipped with X-band (8510 MHz) 500kW (average power) transmitter with 35% efficiency, and it receives echoes from Mercury, Venus, Mars, the satellites of Jupiter and Saturn, the Moon, and asteroids and comets.

The Moon-based calibration for the Uplink Array, however, was envisioned for the communication and navigation applications. Therefore, the non-radar antennas of DSN, e.g., the 34m antennas, need to be upgraded accordingly to fulfill the functionality of the Delay-Doppler mapping with telecom/nav application in mind. This effort is currently ongoing at JPL using the experience of GSSR observation of the Moon. Moreover, the extension of the concept to smaller antennas as low as 12m aperture size was also investigated for the larger array of small antennas. The study of systematic targeting on Lunar surface for Uplink Array is of dual purpose, 1) Explore and prepare for near-real time experiment opportunities with natural as well as man-made targets on Lunar surface for calibration purpose, 2) Prepare for new human explorations on Lunar surface, e.g., communication to the rovers, robots, Lunar network, etc., while utilizing new array communication and radar concepts. It should be noted again that, although such kind of pointing to the Moon, and other targets have been conducted for DSN radar applications with single antennas, it has not been done as of yet for DSS 24, DSS25, X-band non-Radar transmitters, neither has it been introduced for the large array of smaller antennas (e.g., 12m). The core capabilities of the Uplink Array for Lunar Surface Positioning System for stationary as well as moving targets, such as rovers, and transport vehicles with simultaneous broadband two-way communications to multiple targets is an attractive feature that can hardly be ignored in the human exploration era. When the techniques of Synthetic Aperture Radar (SAR), and GPS, and the properties of phased array (e.g., multi-mission support) are combined in the Uplink Array many of the bottlenecks of the Lunar Positioning System can be resolved as discussed further in the following paragraphs.

Uplink Array, GPS, and Synthetic Aperture Radar

The integration of communication and navigation architecture to Moon/Mars and beyond will require time-base in the order of 10 nanoseconds for several hours, which is typical of the GPS system. The GPS network is based on transmitted range and phase codes utilizing atomic clocks, which are received and regenerated by the user's receiver. The receiver computes the phase shift necessary to match the transmitted code. If these atomic clocks are to be used by the Lunar orbiters and get transmitted to the Lunar surface, and if they need to also be synchronized to time reference on Earth, relativistic time corrections have to be constantly applied to the time reference at every sample. In other words, keeping the Lunar assets synchronized with the Lunar orbiters, and knowing their relative positions to the Lunar orbiter reference frame is one thing, and synchronizing the Lunar network assets with oscillators on the Earth is yet another challenge.

By nature, the GPS system is a one-way system, i.e., the user doesn't send his regenerated code back to the transmitting orbiter. Therefore, in order to solve for the four required unknowns of user (x, y, z, t) minimum of 4 viewing satellites are necessary. This indicates if the user knows his/her 3-D position already, then the user (target) only needs to know the time stamp for the 3-D map relative to a frame of reference. In this case, a near-real time map of the user (target) on the Lunar surface and its neighborhood pixels can dramatically reduce the requirements on the user receiver in terms of internal clock, processing, and the required number of viewing satellites in Lunar orbit. Recall that the number of Lunar orbiting satellites is constrained by several factors mentioned in previous paragraphs. To say the least, the accuracy of maneuvering satellites for orbit corrections is within hundreds of meters making them unavailable for Lunar target position location.

Hybrid Lunar Positioning System Architecture Concept

In order to reduce the reliance of surface targets on the Lunar orbiters, the user would need to have Digital Elevation Models (DEM) and high resolution Lunar maps installed on his receiver with powerful processors that can compute all coordinate transformation, topocentric corrections, and relativistic translation of time. Such requirements are already overwhelming for a single stationary user (target) on Lunar surface. Therefore, it would be very useful to have a mechanism that synchronizes several reference points on the Lunar surface, e.g., base stations to an Earth-based antenna and oscillators all in parallel through simultaneous independent pixel observations of a large sector of the Lunar surface. This is where InSAR mapping of the Moon with the phased array of small antennas come into play with Lunar Positioning System and GPS-like signaling scheme.

The height difference (i.e., height statistic) is estimated by the difference, or correlation of coincident SAR images. The handful of pixels, then serve as the set of targets that form the basis for the phase coherence of the transmitted individual signals. InSAR data gets affected by the distortion of radar signal by the projected scene topography onto the slanted delay-Doppler plane. Each pixel in the SAR image must be corrected in terms of radiometry and phase by taking into account the Digital Elevation Models (DEM) data obtained from databases. The Digital Elevation Models require some ground truth data for verification of model parameters. InSAR signal processing is required to filter the interferogram phase estimate with highest SNR (e.g., pixel registration, resolving migration through focusing algorithms, etc.). InSAR main output is the accurate estimate of DEM, however, through an iterative process, one can start with a coarse estimate of DEM at low quality in the chain of SAR signal processing, and end up with high quality height statistics. The coarse resolution means ~ 1km, which is readily available for Lunar surface topography [12]. The accurate height statistics is highly dependent on high accuracy of projected components of the baseline estimate. This is where the Uplink Array geometry has an advantage over the usual InSAR geometry. That is, the space-based InSAR typically requires centimeter level accuracy to provide the acceptable height statistics on the ground. The InSAR orbital uncertainty is offset by the ground calibration targets placed at precisely known locations. This is the inverse of the requirements of the Uplink Array, where the antenna locations are precisely known while the challenge is in the targets orbital accuracy. The interferometer geometry is estimated through minimizing the sum of squared error between the InSAR and the DEM height estimates:

$$\min \sum_{k} \left(h_{InSAR} - h_{DEM\_Moon}\right)^2$$

Note that there is a circular relationship between the interferometer geometry and the DEM accuracy. Therefore, this could be an iterative process, where one has to start with a coarse DEM. In this cycle, if a separate GPS-like system exists around the Moon (i.e., the Lunar Orbiters), the position information obtained from GPS can be used to improve the DEM accuracy, which will further improve the InSAR pixel registration, and vise versa, the InSAR precise knowledge of control points can help correct the clock error, or multipath issues for the times the orbiters in view are at low elevation angles. In a sense, the SAR signal transmission direct from Earth acts like an additional degree of freedom in the Lunar Orbiters. The clock accuracy requirements for generating the interferogram of the InSAR through the Uplink Array is exactly the same as GPS network, i.e., they both require atomic clock accuracy for several hours.

The current state-of-the art resolution of the InSAR image of the Lunar surface at X-band is within 100m with scan mode SAR, which in some occasions, depending on target locations, the accuracy can reach to better than 10m with spot mode SAR. From the orbiting satellite, a typical clock error of 1 nano-second, which is a typical clock error after about 3-4 hours [5], a position error up to approximately 30cm could occur. Obviously, more than one satellite needs to be viewed to cover all three dimensions. Therefore, the network of orbiters has to be synchronized according to a common reference. Sharing of the orbiter and Earth-based InSAR control points, therefore, not only help fine tuning the 3-D DEM, but also helps overall network synchronization of orbiters, Lunar assets, and the Earth stations. Therefore, by exploiting the GPS mature system concepts, and InSAR's excellent range and range rate capabilities at X-band some of the intricate system constrains of Lunar Positioning System can be resolved. It should be mentioned that combining SAR and GPS system concepts have been used in Ground Moving Target Indicator (GMTI) systems, and in topocentric corrections of GPS observations [13]. Therefore, it is possible to utilize InSAR-GPS combined processing method to improve the resolution and accuracy of the resulting SAR image, or use GPS-derived topocentric delay corrections to SAR image for better quality. The topocentric variations cause mis-interpretation of the InSAR image results. Through double-differencing algorithm, the topocentric variations of two InSAR images can be removed by referencing them to an epoch of GPS observation. Alternatively, the GPS-InSAR can be interleaved for surface position accuracy, or used as alternate approach when one is available, and the other is not by sacrificing the system resolution [13].

InSAR with Uplink Array versus Space-based Radar

Although the high resolution InSAR imaging of the Moon has a relatively decent history [14], however, the implementation of InSAR with the Large Array of Parabolic Reflectors (i.e., Uplink Array) is a new concept, which has been started at JPL as a method for phase calibration of the Uplink Array by using the Moon visible regions. In doing so, JPL, and the University of Michigan jointly study the implementation of InSAR with Uplink Array. There are a few subtle differences of the InSAR with Uplink Array and the traditional InSAR with Space-based radar.

In the Uplink Array case, the precise known antenna positions on the ground, and the precise Lunar ephemeris is the good indication of having at least a nice jump start, with the only remaining challenge being the SNR per pixel size of 100m dimensions. According to the joint study by JPL, and the University of Michigan [11], the InSAR at X-band with Uplink Array is feasible with as small as 12m aperture size per element. Table 2 illustrates some SNR values per pixel size.

Table-2 Pixel SNR with RMS Phase Error [11]

Pixel Size (m)	SNR (dB)	STD(deg)
80	16.6	8.60
640	34.6	1.05
5120	52.7	0.14

The phase error statistic, which is related to the slope error, and in turn, to height statistic, depends on the type of terrain variations. When viewed from Earth, a highly desirable feature of the Moon is the highly accurate and precise repeat pass information from Lunar surface [11]. The Lunar observation is highly repeatable due to precisely known ephemeris data for the Moon, and the slow variation of geometry fits the needed time for calibration. If there are scatterers that cause too much errors, they can be either be removed via post processing before selecting pixels of interest for calibration, or we may focus iteratively- to only observe the dominant few scatterers with prominent features through phase conjugate algorithm [15]. Such precise ephemeris calculations, and, therefore, network synchronization is not feasible with space-based radar InSAR without an order of magnitude more cost and complexity.

Uplink Array and Power Levels to the Moon

The existing 34m antennas (67dB Gain, 20kW power) provide sufficient SNR if Moon was a perfect sphere. The Fresnel zone of the Moon has a diameter of ~ 380m, which corresponds to –68.36 dBm reflected power. The reflected power per individual 4m (70% eff., 400W transmit power, 47.6dB gain) antenna would have been –124.15 dBm, whereas for 12m, 4kW is –94.19 dBm. If on the receive side we use DSS 13, the corresponding numbers will be –104.75 dBm, for (4m TX, 400W, 34m RCV), and –84.77 dBm for (12m, 4kW, 34m). The reflected power of DSS24, and DSS25 arrayed would have been –68.36dB plus the additional 6dB enhancement for voltage addition of the arrayed signal, and for the corresponding 4m the arrayed gain would be –124.15dBm+6dB. Therefore, the power levels of the echo from the Moon is not an issue, however, the challenge is in picking the right pixel size when using the InSAR technique and collecting the aggregated power from individual pixels while preserving the 3-D position resolution. The position uncertainty is not an issue at Moon's distance, and the ephemeredes are accurate within 1-10 milli-arc seconds.

The roundtrip light time can also be estimated to accuracies within nanosecond level. The challenge of the aperture size and the corresponding transmitter power with the lower limits of 12m, and 4kW has to do with the maximum coherent observation time of the target on the Moon, and its projected Doppler spread. Since, most coherent observation times of the Moon for a given target is within 5-10 minutes for a steady SNR variations, the resulting lower limit for aperture falls around 12m unless more sophisticated InSAR, and is currently under investigation by JPL, and the University of Michigan.

Uplink Array InSAR Pixel Size Constrains

The area of the radar resolution cell is ~ $(c\tau)^2$ and the baud length τ determines the number of pulses to be used to reach adequate SNR threshold. Needing too many pulses may cause premature decorrelation, which in turn limits the pixel size. Note that the surface height statistic is directly related to the scatter function, which in turn is a function of view angle. The SNR and reflected signal phase estimation accuracy are also related by

$$\sigma_\varphi = \frac{57.3^\circ}{\sqrt{SNR}}$$

where the signal to noise ratio is given by [16],

$$SNR = \frac{P_{tx} \times G_t \times \sigma(\theta)}{4\pi R^2} \times A_{scatter} \times \frac{A_{rx}}{4\pi R^2} \times \frac{1}{KT_{sys}B} \times N_{Code} \times PRF \times T_{obs}$$

and the term $\sigma(\theta)$ refers to the scatter function affected by surface height slope statistics, dictated by view geometry, the $A_{scatter}$ corresponds to the contributing area of the target, N_{code} is the number of codes, e.g., 4095 used to build the PN sequence, B is the receiver bandwidth, T_{sys} is the total system noise temperature, including the Moon and sky background, and T_{obs} is the target observation time. The target observation time is bounded by the transmitter coherent length as well as the Lunar libration factors, typical values are 5-10 minutes for Lunar orbital variations to be within bounds of interest [17]. PRF has to be adjusted such that adequate SNR is collected while the pulses are still correlated. So, coherence length of transmitters and correlation length of pulses have to match. Receiver clock has to be adjusted to account for Doppler variations. The phase error induced by the lunar surface variation due to height statistics and the actual phase error due to transmitter coherent time shall be distinguished from each other as two ingredients of the target-induced phase shift. And, the way to do that is to pick the target observation time such that it fits the following relation [16]

$$\Delta\varphi_{error}(T_{Coh}) = 2 \times \pi \times f_o \times T_{obs} \times \sigma_{Allan}(T_{Coh})$$

For example, if the DSN transmitter maximum coherence time (T_{Coh}) is 400 seconds for, say 12 degrees rms, then the maximum observation time is about 400 seconds, or ~ 6 minutes. The target cross range resolution is limited by the spectral resolution, which is given by [16]

$$\delta\nu = \frac{1}{\tau_{\text{int}}}$$

$$\delta\nu \equiv \text{Spectral Resolution}$$

$$\delta_{\text{Dop}} = \frac{\lambda}{2\omega} \times \delta\nu \times \frac{1}{Sin\varphi}$$

where φ is the angle to the surface normal. A typical value for the spectral resolution corresponding to 20m cross range resolution is ~ 0.001 Hz at X-band [16]. The range resolution is provided by narrow pulses, which lower the SNR per individual point target (delay-Doppler cell) observation. Since the radar transmitters cannot provide arbitrary amount of power in a short time, therefore, a technique called pulse compression is used, i.e., use the energy of a long pulse, and resolution of a short pulse. For a hybrid GPS-SAR system, the PN codes could be selected in such a way that the two systems could assist one another in a bistatic mode, i.e., illuminate the target via a Lunar base tower, or an orbiting satellite with a PN code and observe by the Earth station, or vise versa.

The phase of the transmitted signal alternates between 0-180 degrees according to a PN sequence with code lengths of typical values of 4095, which corresponds to 4095. This many pulses have to fit in the total coherent time of the individual transmitters of the antenna elements, e.g., $T_{Coh} \sim$ 400 second. Note that the short individual pulse corresponds to the baud length, i.e., the time it takes for the modulated signal to change phase to a random phase between 0-180 degrees. When this is done according to a PN sequence, then highly narrow autocorrelation peaks can be generated for the 100m-scale resolution suitable for Uplink Array calibration, which is also adequate for Lunar Positioning System. Each target cell acts as a calibrating target and is treated independently, i.e., each pixel contributes independently to the SNR except when some further averaging, or neighborhood pixel processing is done before adding to the next sampled image.

SAR-based Lunar Surface Navigation Analogy to VLBI

The Very Long Base Interferometry (VLBI) has been long known as an established method for deep space navigations. Feinian Wang, et al. [11] compared the VLBI concept to InSAR. One can see that the usage of known radio stars for deep space spacecraft navigation is very similar to using the InSAR of the Lunar known features for Lunar Positioning System. While the radio stars known position helps defining the spacecraft relative position, the known target features on the Lunar surface helps identifying the position and velocity of Lunar surface targets. In VLBI, we get a broadband (noise) signal from a distant point target, and use cross correlation to improve the signal-to-noise ratio (SNR). Targets of VLBI have to be collected (selected) from various areas of the sky. For InSAR, we use point target aggregated all in one basket on the Lunar surface to estimate the phase difference of signals at different antenna array elements. InSAR is an active technique which includes the transmit chain. Moon is a closer target than the radio stars, i.e., within 2.5 seconds round trip time. Therefore, referencing targets relative to known InSAR image control points direct from Earth with closed loop beacon tracking of surface targets on the Moon is feasible. Figure 5a illustrates the pixel geometry, and the following equations [11] show the analogy of InSAR to VLBI. Notice how the target geometry (i.e., coordinates) can be extracted from antenna element geometry, which can be extracted from the reflected signal phase term ϕ_{oc}.

$$P_1 = K_1 \times \exp\left(j\left(\frac{2\pi R_1}{\lambda}+\theta_o\right)\right)\cdot S_1 \cdot \exp\left(j\left(\frac{2\pi R_1}{\lambda}+\theta_1\right)\right)$$

$$P_2 = K_2 \times \exp\left(j\left(\frac{2\pi R_1}{\lambda}+\theta_o\right)\right)\cdot S_2 \cdot \exp\left(j\left(\frac{2\pi R_2}{\lambda}+\theta_2\right)\right)$$

$$S_1 \approx S_2 = S$$

$$P_1 \cdot P_2^* = K_1 \cdot K_2 \cdot |S|^2 \cdot \exp\left[j\left(\frac{2\pi(R_1-R_2)}{\lambda}+\theta_1-\theta_2\right)\right]$$

$$\phi_{oc} = \frac{2\pi(R_1-R_2)}{\lambda}+\theta_1-\theta_2$$

With InSAR, the pixel is illuminated by one of the antennas, and then both antennas measure the scattered signal. The echo will contain the scatter function of pixel plus the phase term due to the path length (Geometry). Through the InSAR process, the scatter function cancel in the receiving process of identical antennas, and the geometry is recovered. By adding the PN codes, more target information can be embedded in the signal return, including target type, and velocity.

Earth-based LPS for Lunar Moving Targets

Engagement of the educational and entertainment-based Missions implies telepresence on Lunar surface simultaneously to multitude of institutions. In a rover mission study at Carnegie Mellon University [18], Bapna et al., investigated the Earth-Moon communication from a Lunar rover. Bapna et al, argued that for a typical 1000 km traverse of Lunar rovers while communicating with 7.5 Mbps, the traditional telemetry between Earth and a mobile platform on the Moon with continuous communication and positioning is prohibitive with direct support from Earth. Bapna states that the need to relay the position and communication data via a stationary Lander, or an orbiter severely limits the excursion of the rover to distances less than 3-4 km. Furthermore, this limited distance for traverse is tied with substantial demands on power, thermal, and communications sub-systems for the Lander as well as the orbiter.

While the orbiters provide visibility of the far side of the Moon, however, during occlusion times the communication channel would be severely limited to narrow band scenarios particularly while the rover is roving. Bapna et al. concluded that the traditional Omni-directional antenna for mobile communication is an inefficient approach for the Lunar-based rovers to communicate with Earth while moving. Bapna proposed directional antennas, such as phased arrays for the rover together with 3 Earth station antennas with diameters 22m or more placed around the globe with preferred X-band frequency, .5m effective phased array antenna aperture, 28.9 dB transmit gain, 3.6 degrees beam width, and 12 W per rover transmit power to provide 7.5 Mbps in a 10Mhz bandwidth. If we plug these rover link parameters in a SAR signal-to-noise ratio formula stated earlier, the combined SNR (i.e., rover antenna plus the Earth-based) corresponds to surface resolution of 1m-10m. Figure 6 illustrates the X-band radar return from the Lunar disk corresponding to various delays, i.e., view angles [19].

Notice the high reflectivity at near normal incidence corresponds to the quasi-specular region of the Lunar center when directly illuminated from Earth. Therefore, by replacing the low reflectivity (i.e., .07) of Lunar surface with an antenna of 28dB gain is more than adequate for simultaneous positioning of the rovers while closing a broadband communication link. The phased array antenna that can steer and lock to Earth station antenna creates a specular target that stays within view geometry long enough for the SAR signal from an equivalent area of nearly 5km.

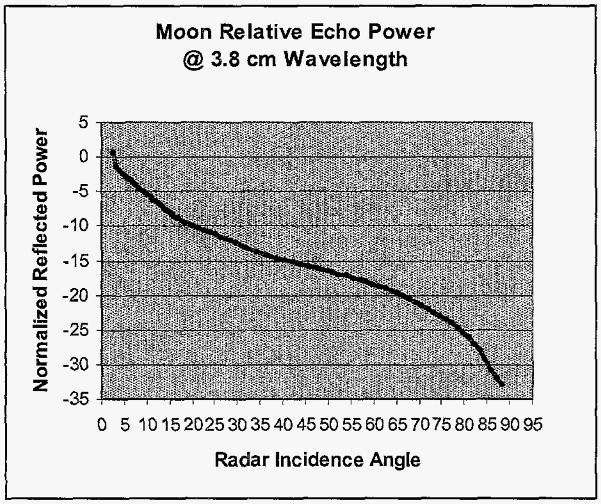

Figure-6 Radar Reflectivity of the Moon [19]

Doppler Constrains of Lunar Surface Moving Targets

The basic principle of detecting moving targets in the SAR interferometric image is described by Sanyal et. al. [20]. According to Sanyal, in the phase image, i.e., the interferogram, all non-moving surface targets appear as a continuum of phase difference while the moving targets appear as sharp discontinuities. By comparison of the intensity image and the phase image the moving targets can be detected. Generally, direct radar tracking of the surface targets without SAR processing would not last more than a short duration. The radar pulse return from the moving target is given by [20]

$$S_r(f) = P(f)\exp[-i\frac{4\pi}{c}(f+f_o)R(t)]$$

where $R(t)$ is the range to the target, f is the baseband frequency, f_o is the carrier frequency and $P(f)$ is the spectrum of the transmitted pulse. For the moving target, the $R(t)$ can be expanded as

$$R(t) = R(t_o) + \dot{R}(t_o)t + \frac{1}{2}\ddot{R}(t_o)t^2$$

which when substituted in the previous equation of the returned signal would result in

$$S_r(f) = P(f)\exp[-i\frac{4\pi}{c}(f+f_o)R(t_o) - i\frac{4\pi}{c}(f+f_o)\dot{R}(t_o)t$$
$$-i\frac{2\pi}{c}(f+f_o)\ddot{R}(t_o)t^2]$$

As can be seen from the above equation, the phase term $f\dot{R}\,t$ causes a range migration. That is, without the motion compensation techniques applied to the SAR image, the moving targets would appear shifted in a different location far from the original target location. This shift in cross-range (i.e., Doppler dimension) is proportional to $R\times v_t / V_{LOS}$ where v_t represents the target velocity vector normal to the line-of-sight velocity vector V_{LOS}. Sanyal [20] shows that through the following simple temporal transformation and comparison of intensity image and phase image this apparent shift in target location can be removed, i.e.,

$$t = \frac{f_o}{f+f_o}\times t'$$

By substituting the t' the phase term that varies with both time and frequency can be removed, and the target will remain in the range pixel regardless of its velocity. Note however, that the delay-Doppler image is based on multiple compressed pulses with a constrained Pulse Repetition Frequency *PRF* according to the following relation [16]

$$\frac{4\times\omega\times R_m}{\lambda} \le PRF \le \frac{1}{\tau_{depth}}$$

Where τ_{depth} corresponds to the delay depth of the Moon, which is 11.6 milliseconds, ω is the angular velocity of the Moon, and R_m is the average Moon radius. On the other hand, the admissible Doppler shift for the moving target on the surface with velocity v_t is constrained by [16]

$$-\frac{PRF}{2} \le \frac{2v_t}{\lambda} \le \frac{PRF}{2}$$
$$PRF = 3\times f_D(3dB) = \frac{6\times\omega\times R_m}{D}$$

where D corresponds to the ground based antenna effective diameter, and $f_D(3dB)$ is the normalized Doppler spread within the antenna footprint. There are also other constrains on *PRF* for element-to-element synchronization, i.e., maximization of the pulse overlap probability, which need to be considered [21]. By working with the pixel characteristics, antenna element diameter, and computation of the corresponding interferogram, one can estimate the type and velocity of the Lunar surface target through the target signal critical parameters, (e.g., SNR, Doppler shift, pulse length, *PRF*, *PN* code, etc.). Target recognition in SAR imagery has been well established in the literature [22], particularly for cooperative targets. Since the target Doppler profile is known for every pixel within a 10-100m resolution, any moving target on the Lunar surface can easily be detected after the ephemeris corrections are applied, although the range of detectable velocity is a function of antenna diameter. Note that the two dimensional 10-100m of range and cross-range resolutions are obtained based on the pulse compression ratio, and total observation time of the target.

Two main components contribute to the relative velocity of Earth-to-Moon, namely, the elliptical orbital motion of the Moon ~ +/- 56.3 m/s, and the spin of Earth, both of which are well known and can be corrected for the observed echo, or retransmitted signal from the Lunar surface target. Depending on how much time we have available for target processing, the position and velocity of the target can be estimated in the Lunar SAR imagery within a few minutes through partitioning of the InSAR pixel and process in parallel. Lunar maps with 1-2km accuracy at X-band were provided by Zisk et. al. [14]. As discussed in the previous sub-section, depending on how big of an antenna the surface target can carry on-board, different position accuracies up to within 1m can be achieved.

4. Solar System Radar Array

One of the major national assets within the DSN is the Goldstone Solar System Radar (GSSR), which is the largest of its kind in the world. GSSR primarily consists of a 70-m antenna with a 500-kW transmitter. GSSR provides images of Mercury, Venus, Mars, the satellites of Jupiter and Saturn, the Moon, and asteroids and comets. It also provides statistics of the orbital debris that result from spacecraft activities and the residual parts of the rockets. GSSR's most interesting pictures are the ones jointly generated in bistatic mode with the National Radio Astronomy Observatory's (NRAO's) Very Large Array (VLA) in the New Mexico desert. The eventual decommissioning of the 70-m antenna would result in loss of a major national asset unless it gets replaced with an alternate large-aperture antenna with transmit capability. Unfortunately, as of this date, there is no technical approach for performing the GSSR functions with the Uplink Array.

Similarities of Radar and Telecomm Array

Developing an array capable of communications as well as active radar sensing and passive astronomical observation aids the development of extremely large apertures for solar system exploration. Since the initiative of the Uplink Array was primarily based on closing the command link to a troubled spacecraft in deep space, the other functions of DSN, particularly the radar, and radio science have not been addressed as of yet. However, the study of various methods for Uplink Array phase calibration revealed some of the key advantages of the radar techniques.

Based on what is known up until now, Uplink Array phase calibration does need an in-orbit target to point to it in the radar mode even if it is just for verification of the ground-based near field methods, e.g., tower-based targets, or RF/Photonic dish probes. In doing so, if the radar techniques for the phase calibration are adopted, several functional requirements of the Telecom-design of Uplink Array would already be meeting the objectives of a Radar-design Uplink Array. Some examples of the similarity in requirements are the delay-Doppler capabilities and the flexibility in generating radar-like signaling, such as binary phase coded signals with digital pseudo-random sequence much similar to that used for Code Division Multiple Access (CDMA). The pulse compression nature of such signals provides significant protection against normal interference. The inclusion of additional radar frequency, other than the uplink echo signal, would require some RF switching capability added to all or portions of the array. There is a cost, and performance trade required to identify whether it would be more cost effective to add the switching electronics to each individual aperture elements, or to use slightly larger apertures (e.g., 12m transmit and 15m receive) for the radar receive sub-array.

Array and the Effective Isotropic Radiated Power (EIRP)

The gain of the 70m antenna at S-band is 62.7 dB, while at X-band the gain is about 72.9 dB. The S-band transmitter for Uplink emergency is 400 kW and the high power X-band transmitter for the GSSR with 70m antenna is 500 kW. The corresponding required Effective Radiated Power (EIRP) for the Uplink emergency telecom support and for the GSSR radar would be 0.7 TW and 9.7 TW respectively. The EIRP for an individual 12m (4 kW) antenna at X-band is about 92.86 dBW. Ignoring the combining loss for the array, the corresponding number of elements for radar would be about 71, while 20 for the telecom emergency command. Alternatively, for a 4m aperture size and 1kW of power per element, the corresponding number of elements would be about 426 for radar and 118 for the telecom. If we were to use 15m (4 kW) elements, the corresponding number of elements for 70m equivalent EIRP at X-band for radar and telecom array would be 57, and 16, whereas for 15m (6 kW) it would be 47, and 13 respectively. Therefore, the only reason to separate the radar and telecom array apertures would be the difference in cost of 13-20 RF switches and frequency converters. As mentioned before, the Master clock, transmitter modulator, Exciter requirements, and signal distribution network would be the same. The microwave component technology at X-band is mature enough to sustain the cost of a dozen of RF switches. Although a comprehensive trade study for the radar versus telecom array has not been conducted yet, however, depending on the cost and complexity of the additional RF electronics for radar array, the optimal aperture size might shift upwards towards 15m (6 kW). Alternatively it may dictate a heterogeneous array of 12m and 15m apertures. If the radar and telecom array are separated, much of the similarities in calibration, and operation concepts, interference handling, and back end signal processing would have to be duplicated. In other words, if we were to build a radar array, we would need less than 10% of the array to be modified for telecom purpose.

Effects of Radar Array Element Aperture on Calibration

So far, in all Uplink Array trade studies, the focus of attention in terms of power and aperture has been treated somewhat loosely. That is, only the total required EIRP has been discussed, and the aperture size and the transmitted power per aperture element have not been rigorously analyzed. One approach to identify the trade between power and aperture is to start with the target size when the radar technique is used for calibration. The minimum target size, whether it is for point targets, or extended targets (e.g., Moon) will determine the minimum aperture size as well.

Calibration target size is perhaps the most important factor that summarizes the story of Uplink Array phase calibration with radar technique, since it sets the tone for the signal amplitude, integration time, and the periods of calibration. Several system parameters (e.g., transmitter power, antenna gain, maximum duty cycle, false alarm rate, system noise temperature, sampling intervals, integration time and coherence length of the transmitted signal, and minimum detectable power) have to be taken into consideration along with possible measurement errors before the optimal size of the calibration target can be estimated, which then determines the target cost, orbital accuracy, mass, and RF electronics that can be incorporated.

To give an example of the effect of target size, consider the Rayleigh approximation that is valid when the target diameter is d <λ/5 while the optical region begins when d >10λ. Therefore, the target size for X-band falls within the range d >10λ (e.g., 30-40 cm), and if we use a sphere with no aspect angle changes, a non-fluctuating target can be assumed at LEO orbit altitudes (500km). If GPS sensors can provide within 1m target position uncertainty within this range, then even a 1 m-deg pointing error would correspond to ~ 8m offset at 500 km, which could miss the calibration target if the target is as small as 40 cm. Given the measurement error covariance that can be tolerated along the size of the target helps completing the search in available target catalogs. Most cataloged targets of opportunities are identified by their size, followed by the accuracies of their range, velocity, and acceleration. Note that the range, velocity, and acceleration errors map onto the phase error. We already discussed in the previous papers [3, 29] that the key cost driver of the Uplink Array is the transmitter.

The most important factors that identify the cost of a transmitter are mainly the following, 1) average power and efficiency, 2) peak power and duty cycle it can tolerate, 3) phase stability. Obviously, in the trade of power for aperture one is more limited by the transmitter power, since the phase stability of transmitters become harder as the power increases naturally due to thermal issues. Therefore, if we further reduce the key cost factors to one number, it probably all boils down to the average power of the transmitter. So, a good start for the entire end-to-end error analysis and determination of the target characteristics is to pick an average power level for the individual transmitters. This is not hard to find given the baseline that has been already defined for the minimum array effective aperture dimension, which is to be of 34m, or 70m equivalent. The size of the individual array element antenna size will then be a matter of calculation of power density limits that are safe to operate without causing any microwave power hazard or interference to the neighborhood channels, or to the flying nearby targets. Therefore, before identifying the next most important factor on the ground side for the Uplink Array design, i.e., element spacing, and other secondary characteristics of the Uplink Array, one has to know the intervals of time needed for the calibration, i.e., time windows, which all depends on target size. Since we already assume that we know the transmitter average power, then the maximum phase stability, and coherence length of transmitter signal can be identified, and we would know how often we need to calibrate. That is, the intervals of time as well as the integration time can be identified. Therefore, the end game scenario of the phase calibration is basically the target (pixel) size that can lead us to a stable and repeatable calibration. Therefore, the most critical task begins with target radar cross-section, which leads to the target size of interest.

The best place to start the target size estimate is with the smallest detectable size when the array is in radar detection mode. This limit is basically equal to the limit of the background noise power level after integration at the receiver IF filter. The receiver integration time, and sampling time (number of samples N_s within the integration window) will be known based on the IF filter bandwidth (sampling), and transmitter maximum coherent length t_{int}. After integration of N_s samples the received signal power echoed back from the target will be obtained from the following relation,

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

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

Radar Array and Telecomm Array Element Spacing

The pointing requirements, and element spacing of a radar array is also somewhat different from the telecom array. This is due to the fact that, normally, for the telecomm array, the radar function is primarily required for detection mode, rather than search and tracking mode unless study shows that search and track is required for the calibration target of the telecomm array. The final signal-to-noise ratio in terms of total pulse energy (E) that intercepts the target is simply a multiplication of the signal power to noise ratio by the total dwell time, or the integration time t_{int}.

The integration, or dwell time, on the other hand, depends on the search volume, which in turn depends on whether all the elements are operated in a coherent array mode or the elements are operated independently, or in groups (sub-array). If the search solid angle is represented by Ω then for a linear array with a baseline of length L the integration time is given as the following relation [23],

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

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

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

Now, assuming all T/R array elements have identical characteristics, a figure of merit for selection of the array mode versus independent element operation mode is the ratio of the array SNR in coherent mode to the array SNR in independent mode, which can be expressed as follows [23],

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

where L stands for the maximum length of the array and d is the spacing between the array elements of aperture size A. According to this relation, the element spacing for which the array in coherent mode should be used is simply set by the following bound,

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

Furthermore, assuming the number of elements are much more than 10, the above criteria simplifies to the following,

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

Therefore, it is better to operate the array elements independently for the search mode and use coherently for tracking or calibration mode. Based on this relation, for a radar array that operates in coherent (i.e., array mode), the element spacing is somewhat larger than for a telecom array that only operates in detection mode. The pay off for the radar array is very high, particularly in light of the discussions above and the many common needed functions. Much of the techniques, as well as hardware electronics of the telecomm array and radar array are the same. The hybrid architecture concept of SAR and GPS for integrated lunar surface positioning and navigation was also discussed in previous section and indicated other potential benefits when radar and telecom array are jointly optimized. The scaleable high EIRP scenarios of radar array with multitudes of baselines will mitigate the requirements for deep space probes in many applications. The other operational scenario of combined radar and telecom array is the multi-mission support and network synchronization of widely separated spacecraft, particularly those needing synchronization for single image or single science events.

5. High Power Beam Array

In the last section the primary differences as well as the common system aspects of the large array of parabolic reflectors with regards to telecom and radar applications were discussed. The other promising application for the large transmit array of parabolic reflectors is the direct high power transfer from Earth to deep space. High power or direct energy transfers to/from space whether through microwave or high energy laser pulses have been an area of interest for many years. There are several advantages to the high power transfer to deep space. For instance, sailing through impulsive or continuous photon pressure, transfer of power to a spacecraft in deep space, which doesn't receive direct sunlight, or providing direct assistance in spacecraft maneuvering from Earth. From communications perspective also, the power capability, and energy storage capacity of the spacecraft, particularly in deep space, determines the maximum spacecraft transmit power to ground. That is, the space communications is always either limited by bandwidth, or spacecraft power, or both. The energy storage subsystem of a spacecraft comprises a significant portion of its mass (e.g., 20%), which doesn't have any other useful function other than power system. If the photovoltaic arrays can be remotely illuminated through directed power from Earth not only the spacecraft would be able to carry more powerful transmitters onboard, but also the additional saving in mass could be used for other useful purposes. The available power from Earth could be used by the spacecraft to generate power, convert it to lasers, or microwave, whichever one fits the operation scenario. The direct power transfer would also pave the road for hybrid architecture concepts of RF and optical communications by the spacecraft payload.

In 1987, Canada successfully flew its stationary high altitude relay platform aircraft using direct power transfer though microwave beams. On the other hand, Japan successfully flew a microwave power plane as part of a project called MILAX, and in 2003, David Criswell [24] proposed Lunar Power System (LPS) concept, which would involve 20, 000 to 30, 000 reception stations on Earth to accept power beams and convert to electricity. Criswell concept was motivated by the predicted requirement of steady 20 terawatts of power to accommodate the 10 billion Earth's population by 2050. Criswell's concept is further considered as one option to attack the future energy crisis, which would provide the technology to make direct use of the Sun's energy through Lunar-based stations and use the Sun as a replacement for fossil, or nuclear energy source. The LSP concept is based on utilization of a small fraction of the solar power incident on the Moon, which is converted to microwave beams, and then through a large phased array, the high power beams are directed to receivers on the Earth, called rectennas, which convert the microwave energy to electricity. The generated power is adequate to supply 2 kWe/person on Earth for centuries. The microwave power beam was first considered by NASA and the Department of Energy (DoE) in 1970s under a project named Solar Power Satellite Reference System [24].

The outcome of the power beam technology in 1970's was the development of rectennas, where the solar arrays, and antenna technology are combined to provide the microwave-to-electricity conversion capability with RF power intensity of 230 W/m^2. One-square kilometer of rectennas can have an average output power of 180MWe, which produces every year the electric energy equivalent to burning 3.3 million barrels of oil, or 650, 000 tons of coal [25]. To give another quantitative example, in 1980's technology level, an area on the Moon half the size of a football field could supply 4 kWe at Earth by converting Sun's power to microwave beam and redirecting to Earth [25]. The rectennas would occupy as little as 5% of the land area per unit of received energy that is devoted to production and distribution of electricity [25]. Therefore, when discussing high power microwave beams through the use of large phased array of parabolic reflectors, the array could be used in receiving, and/or transmit mode depending on which direction the power is being transferred, i.e., from Earth-to-Space, or from Sun-to-Moon-to--Earth. Through the large phased array of small parabolic reflectors the safety concerns of the high power beams will be addressed more effectively since the power distribution near each individual aperture will be reduced or scaled to a safe threshold.

High Power Laser versus Microwave Power Beam

The beauty of the large phased array of parabolic reflectors is that it makes the microwave power beams comparable, or even, beyond what could be achieved with high energy laser pulses while still possible to transmit power in all weather conditions as opposed to laser beams. There are several types of lasers that can be used for power source with the Free Electron Laser (FEL) and chemical lasers in the Mega Watt, and the solid-state laser arrays in Kilowatt ranges. The FEL, which is in the MW ranges, however, inherently operates in the pulsed mode. For a FEL the pulses may be as short as 20 ps with a repetition rate as high as 20 MHz, which could result in large average powers. However, the photovoltaic array to receive such peak powers must be capable to receive such high peak powers. In other words, the transfer of the high power to the target of interest is one thing, and its utilization at the receiver side is yet another issue, whether for powering up the on-board units that require electric power, or to provide beam riding (i.e., sailing), or photon pressure. Reception of the high power at microwave frequencies seems to be more within reach as compared with the high energy laser pulses. For instance, ultra light materials, such as Carbon microtruss have been built and tested in laboratory at X-band frequencies with up to 1kW/cm^2 power densities and in excess of 2000 K absorption [26]. In addition to safety issues, the high energy laser as a source of direct power transfer is limited by the wavelength in terms of its atmospheric transmission.

Phased Arrays and Power Beams

Traditionally, much like the high energy lasers, the high power microwave beam has also been primarily considered in pulsed mode, and requires similar levels of sophistication as does the high energy laser. Figure 7 illustrates the ranges of peak power versus average power that can be achieved with microwave [27].

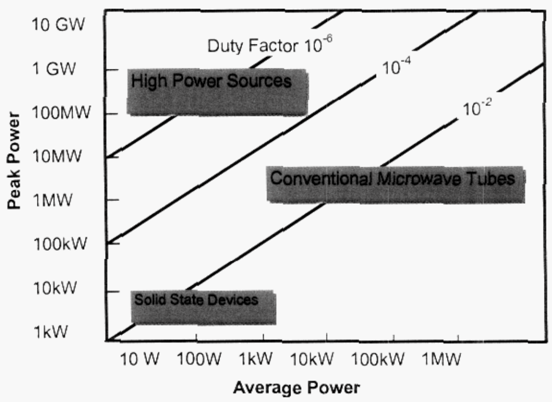

Figure-7 Microwave Peak and Average Power Domains

As shown in Figure 7, the high power microwave sources with peak powers of several GWs with pulse durations ranging from 10's to several hundred nano-seconds for frequency ranges of 1-10 GHz have been reported [27]. Also, peak powers in excess of 10 GWs for a single pulse of 100ns at 1 GHz have been reported for microwave frequencies. The relative frequency stability and the pulse-to-pulse phase coherence, which is required for the high average power as a result of pulse repetition rate is in the order of several 10s of minutes for the high power microwave beams. With the large phased array of parabolic reflectors, however, the antennas could operate in CW mode, or in pulsed mode (through modulation) while generating high average power without having to pulse the microwave source. The pulse mode, however, could be in form of modulator-driven PN sequencing as described in the previous section where the high power signal could be spread in such a way to avoid both RF interference and also observe safety issues. The PN sequencing advantage of the array would therefore be three-fold, 1) spread of energy to avoid turning the atmosphere into a microwave oven, 2) create high energy pulses when needed in pulse mode, such as when generating delta-V to a spacecraft through a fraction of a second, and 3) generate high signal-to-noise ratio radar pulses when the array is used to map a distanced target with high resolution. Therefore, with this type of operation, i.e., PN sequencing, and large phased array of parabolic reflectors, hours of high power transfer of microwave beams will be provided with the level of accuracies provided by atomic clock technology. This is in contrast to the 10s of minutes of high average power produced through pulse-to-pulse coherence of high peak power pulses. Although phased array laser power beams could also be done with power control through pulse width modulation (PWM), however, the ranges of power are limited to several kilowatts, and the beam quality is far below the desired level such that the laser array cannot be used for dual usage of telecom and power beam. The microwave high power beam quality, on the other hand, has the advantage that simply adding more elements to the telecom array, or by using a slightly larger element size (e.g., 15m) the telecom, radar, and power beam functions could all be utilized. As mentioned in the previous paragraph, the safety and interference issues for the radar, telecom, and power beam are handled in the same way with no additional complexity.

Recent DSN High Power Beam Experiments

Experiments with Carbon fiber materials have been conducted at JPL and at the University of California, Irvine [26]. Accelerations of several times the Earth's gravity were observed through illumination of a 10g/m^2 Carbon microtruss material with 1 kW/cm^2 power density in a 6 by 4 feet vacuum chamber at JPL microwave facility. Then, in June 21, 2005, the planetary society launched a spacecraft named Cosmos-1, which was supposed to be used as a demonstration and proof of concept for the microwave power driven spacecraft sailing. The spacecraft was built in Russia with funds and technical supports from the planetary society. Although the spacecraft didn't make it to the experiment phase due to technical problems at launch, however, chances are that another spacecraft would be launched to test the microwave power beam as well as the solar sail concept.

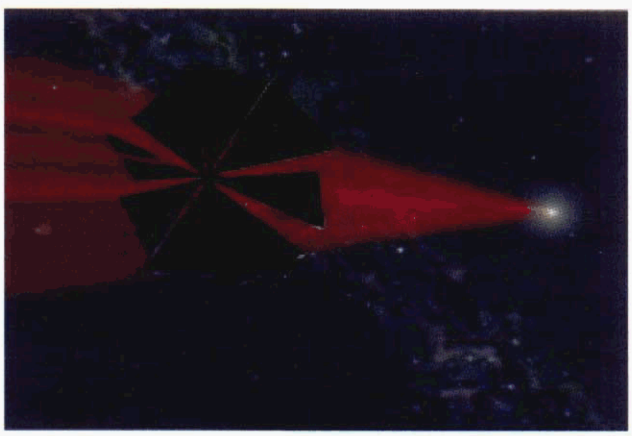

Figure-8 Cosmos-1 Giant Wings to Ride on Power Beam [http://www.planetary.org/programs/projects/solar_sailing]

The Cosmos-1 spacecraft with giant wings of carbon ultra light weight material is illustrated in Figure 8. The giant wings are used to absorb the high power for sailing purpose. What is interesting is that the DSN 70m antenna and the 500 kW radar transmitter were also reserved to transmit high power beams to the Cosmos-1, and track the received telemetry in order to compare the Sun-driven sail and high power microwave beam by measuring Doppler shifts. Cosmos- altitude was going to be 800 km with orbit velocity of 7.4 km/s. The DSN frequency resolution for carrier determination is about 0.1 Hz, which could be used to detect the delta-V in the order of 10^{-3} Hz with ~ 100 seconds observation time [28]. The DSN 70m antenna and the corresponding 500 kW transmitter were going to be used in two modes of operation, namely, the impulsive mode, and the tracking mode. In the impulsive mode, the impulse from the beam was going to last .07 seconds in order to provide 10^{-7} m/s^2 to the 100 kg Cosmos-1 spacecraft. The acceleration provided in the tracking mode was calculated to provide 10^{-8} m/s^2, which is an order in magnitude lower than the impulsive mode. However, the duration of the tracking mode was calculated to occur for 200 seconds, which results in several times higher net acceleration compared to the impulsive mode.

6. SUMMARY AND CONCLUSIONS

For several decades, flat plate phased array technology has played a critical role in radar tracking as well as imaging of multiple targets with ranges extended to somewhat beyond Earth's atmosphere for some of the large aperture flat plate phased arrays, such as Pave Paw, and Cobra Dane [29]. In recent years, the broadband communications, and directing of microwave power beams have also been added to the menu of phased array applications. The applications of phased arrays to distances of Moon and beyond, however, preclude the flat plate phased arrays due to cost, thermal balancing, scan loss, and high power hazards. Although some of the more simplified functions, such as generic telecomm and tracking to Moon distances could be envisioned with a dedicated flat-plate phased array as a replacement of the 26m antenna, the more natural extension of the flat plate phased arrays for power and aperture distribution is the large phased array of parabolic reflectors. The Progress in atomic clocks, precise signal distribution network, GPS, VLBI, SAR, and high power beam technologies provide the means to further stretch the phased array technology into a new era of antenna networking over relatively large baselines. Although the large phased array of parabolic reflectors in receiving mode, such as VLA have been built, tested, and operated for over two decades, the large transmitting phased array is still in its early days of research and development. The nature of the large, global, multi-purpose systems, such as Deep Space Network (DSN) requires certain new paradigm of system architecture and engineering in order to take into account the evolution of the phased array network in an optimal fashion over decades ahead. On the other hand, the large phased array of small parabolic reflectors bears in it several critical technologies that have long been of interest to several organizations, and technology sectors. Much of the progress in the last four years of study of the large phased array of small parabolic reflectors at JPL, and the University of Michigan has been centered on techniques of phase calibration. It was revealed throughout the studies that majority of the proposed calibration techniques heavily depend on the ultimate application domain and operation concepts of the large array before a comprehensive long-term master plan can be developed. In this paper four main streams of applications for such array were discussed with emphasis on how the Uplink Array could play some critical roles in the new era of human exploration of the solar system. It was also shown to some level of details how the telecomm, radar, and high power beam share design concepts as well as beam quality, element size, calibration methods, calibration target size, element spacing, and microwave components. Although not clearly pointed out, however, it was also revealed that concepts of heterogeneous array, i.e., various aperture sizes under the umbrella of one large system with overlap of certain common resources, such as calibration targets, radar receivers, larger (15m), and smaller (12m) should be allowed rather than using a fixed aperture size with uniform spacing and fixed power level for all elements. In other words, it pays off to combine the three major functions in a large heterogeneous array, rather than three independent systems, simply because every one of the applications mentioned in this paper requires the functionalities of the other. What is still missing is comparison of the large RF array with an optical Telescope Array, and whether a hybrid RF/Optical phased array is feasible and whether it is the cost effective approach.

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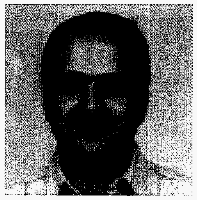
BIOGRAPHY



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