PROSPECTS FOR TRACKING SPACECRAFTS WITHIN 2 MILLION KM OF EARTH WITH PHASED ARRAY ANTENNAS

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ABSTRACT

Recent advances in space technology for Earth observations, global communications, and positioning systems have created heavy traffic at a variety of orbits. These include smart sensors in low Earth orbits (LEO), Internet satellites in LEO and GEO orbits, Earth observing satellites in high Earth orbits (HEO), observatory class satellites at Lagrangian libration points, and those heading for deep space. In such an integrated operations environment, future ground tracking antenna networks, such as JPL/NASA's Deep Space Network (DSN) may be required to provide highly agile beams, flexible scheduling, and the capability for simultaneous tracking of multiple spacecrafts at various orbits. In this paper the possibility of cost-effectively replacing the DSN's 26-m antennas with a network of phased array antennas capable of tracking various types of spacecrafts that are within 2 million km of Earth is examined.

1.0 INTRODUCTION

Over five decades have passed since the beginning of the phased array technology development. The high-speed beam steering capability of phased array antennas made it a good candidate for simultaneous tracking of ballistic trajectories at altitudes beyond the Earth's atmosphere. Then, almost a decade later, space surveillance was also added to the list of capabilities of the large phased array antennas. Today, many phased array antenna systems exist that are capable of space surveillance and satellite tracking. Examples of phased array antennas with space surveillance capabilities are AN/FPS-17, BMEWS, PAVEPAWS, COBRA DANE, Millstone, and Haystack which have contributed to space science as well as satellite detection and tracking [1].

In the following sections, we shall discuss the motivations for introducing phased array antennas as a viable technology to enter Deep Space Network (DSN), which is primarily composed of large reflector antennas, e.g., 26-m, 34-m, and 70-m. Of these three large antenna sizes, the prime focus of this paper is the 26-m antennas. For reasons discussed later, the 26-m antenna seems an appropriate candidate for the initial feasibility studies for phased array applications to DSN.

The paper is organized as follows; in section two, highlights of NASA's strategic plans for phased array antenna applications will be discussed. The specifics of DSN capabilities of the 26-m antennas will be addressed in section three. The candidate alternatives to the 26-m antennas are discussed and evaluated in section four with primary emphasis on phased array as compared to other options. The paper will conclude with a summary and conclusions in section five.

2.0 PHASED ARRAYS & NASA'S STRATEGIC PLANS

There are three primary motives for considering the application of phased array antenna systems in the context of Deep Space Network (DSN). First, the NASA strategic plan with regard to more effective utilization of space communication technology calls for phased array antenna systems [2, 3, 4, 7]. Second, the multifunction capabilities of phased array antenna systems can enhance the versatility of certain DSN applications, e.g., In-Situ, formation flying, and robotics [5]. Third, the growing wireless and space-based Internet networks that use phased array antennas will be creating a strong infrastructure that is anticipated to make phased array systems even more appealing from networking perspective. In order to further understand the contribution of the phased array systems in DSN activities within 2M-kilometer distance from Earth, a brief discussion of the current, and/or near future activities within this range seems necessary.

2.1 Human and Robotic Missions

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 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, diverse access to multiple satellite constellations, broadband communications to the space transportation facilities, and augmented global positioning systems that operate beyond low Earth orbits up to GEO and HEO, and collision avoidance to space debris [6]. Public access in turn requires dynamics of channel assignments for uplink as well as downlink with beam switching capabilities while the ground station antenna is tracking the related spacecraft. Figure 1 illustrates the mission stages for human exploration to Mars.

2.2 Space-based Internet

Recent advances in phased array technology and the migration to Ka-band frequencies has triggered the beginning of a new era in space-based Internet. User-friendly control of the on-board scientific instruments, global data distribution, and high-speed wireless mobile communications are made possible through phased array systems on-board several communication satellites. Examples are GLOBALSTAR, SPACEWAY, and IRIDIUM. On the ground, several low cost phased array designs are currently proposed for terrestrial mobile as well as for multi-satellite communications. Infusion of Space-based Internet technology is included in several NASA's Enterprise missions (e.g., Technology for Space Internet Services (TSIS) NASA Strategic Enterprise: Space Flight) [7]. The goal is to develop the network technology required to make every future NASA's space asset Internet Protocol (IP) compliant and act as a node on the Internet [7]. This applies in particular to the low Earth orbits (LEO), the high Earth orbits (HEO), and the Lagrange libration points L1, and L2 for near term, and for Interplanetary Networks (IPN) in the longer term.

Transmission of larger data volumes with increased data rates with on-board local area network (LAN) and cluster of spacecrafts with formation flying and inter-satellite wide area network (WAN) architecture is yet another aspect of NASA's vision of Space-based Internet. This includes user-tailored direct downlink at reduced cost of data transmission with capability of point-to-multipoint communications for science missions.

The phased array system is the natural choice to provide the flexibility required for IP-based mission operations of the future with the capability to interface with other global networks particularly within the 2 Million km of Earth [8].

2.3 GPS and High Earth Orbits

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 (Fig. 2). Therefore, there are long periods of time when GPS spacecrafts are not available simultaneously to provide a complete position and timing information. In order to fulfill the new requirements for 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 [9]. 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 [10]. GPS capability, through phased array systems, provides more accurate relative range among formation flying spacecrafts as well as more precise updates of the individual spacecraft attitude. 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 [9].

Figure 2 illustrates the view angles for GPS for LEO, GEO, and HEO. Low signal levels to GEO, and special orbit geometry of HEO put the current limits on GPS service to these orbits. However, the narrow and multiple beams of phased array from each individual satellites can enhance the connectivity and signal combining such that multiple GPS satellites could become visible to GPS receivers, thereby extending its service to GEO, and HEO in near future [10]. DSN uses GPS receivers on the ground for clock synchronization and media calibration, not for navigational purposes. However, the new GPS capabilities for GEO, and HEO coverage make GPS more appealing for future DSN usage within this range, particularly for networking DSN to other space-based systems and orbital management of clustered spacecrafts within LEO to HEO.

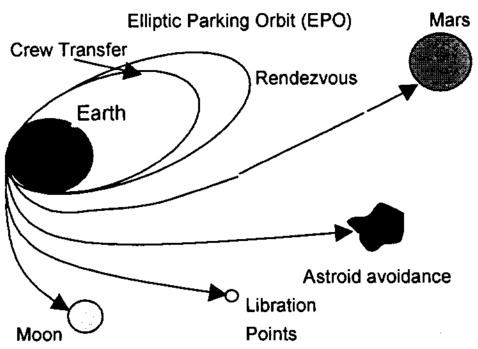

Figure 1. Mission Stages

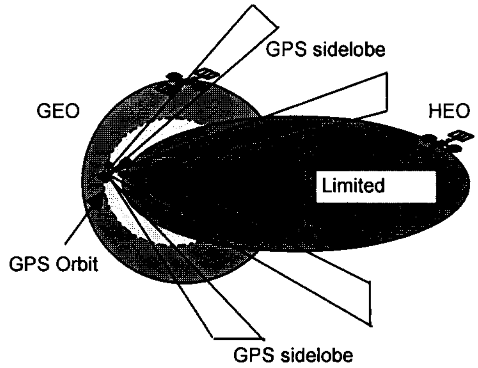

Figure 2. Standard GPS limited visibility to HEO

2.4 Lagrange Libration Points

The Lagrange Libration points (Fig. 3), particularly L2 have interesting properties that make them appealing for NASA astronomy missions that want to look away from the Sun and the Earth as heat sources, and for military to observe the Earth without much interference from the Sun. More specifically, the Sun-Earth (S-E) Lagrange libration points, L2 in particular, at 1.5 M-kilometer have the following advantages: 1) Lagrange points, Fig. 3, are the best place for day/night infrared observation of the Earth without much difference in day/night system performance. The aperture size (subtended angle) of the Earth which is one of the dominant heat sources for satellites near the Earth becomes small, and all the heat sources, i.e., Sun, Earth, Moon are almost in the same direction. 2) Large areas of the sky can be observed. Also, with the help of a stable gravitational condition at S-E L2, very long integration is possible. 3) While Lagrange points do not provide flight time advantages, they usually offer tremendous savings in mass, and cost for the missions. Both robotic and human mission planners are taking note of this potential. 4) Optical relay terminal in these locations might make sense as well given the location's low sky obscuration and availability of human servicing. 5) The Space-Based Infrared System (SBIRS), which is an integrated system of systems with multiple space constellations with elements in LEO, GEO, HEO and the Lagrange points, is bringing new infrastructure and activities within the 2M-kilometer range.

To conclude this section, the recent related activities within the 2M-kilometer can be summarized as a) Space-based Internet era began with phased array systems, b) GPS extended service to GEO, and HEO and formation flying was made possible with phased array systems, and c) capabilities of phased array antenna systems is a core capability required for future ground-based stations for the 2M-kilometer range. In the followings sections, the characteristics and shortcomings of the DSN 26-m antenna for the 2M-kilometer range will be discussed followed by some comparisons with other alternatives, including the phased array system.

3.0 CURRENT DSN CAPABILITIES WITHIN 2M-KILOMETERS

The DSN is comprises of three complexes (roughly 120 degrees apart over the globe) in Canberra (Australia), Madrid (Spain) and Goldstone, (California). As mentioned above, DSN facilities are used to track and communicate with interplanetary spacecrafts as well as with spacecrafts in high Earth orbits that are beyond the Tracking & Data Relay Satellite Systems (TDRSS). Currently, the 26-m antennas, one per DSN complex, are used primarily for tracking Earth-orbiter spacecrafts, most of which are in orbits between 160-1000 km above Earth. Therefore, their primary current usage is for launch and early orbit phase (LEOP), initial acquisition, and spacecraft emergencies. The X-Y mount of the DSN 26-m antennas allows the antenna to point low on the horizon to pick the fast-moving Earth orbiters as soon as they rise to view. The maximum tracking speed is 3 deg/sec and supports S-band uplink as well as downlink. Some examples of the missions that have been recently supported by the 26-m antenna subnet in the year 2002 are: NOAA-M (LEOP), TDRS (LEOP & Launch), GOES (Emergency), SOHO (Continuously), and Hubble Space Telescope (Emergency). Once the trajectory predicts are generated for the 34m antennas the 26-m antenna hands over the tracking to the 34m antennas. The 26-m antenna only provides S-band telemetry at near Earth orbits.

The 26-m antenna is generally a busy antenna, and has demands from several outside agencies. Most of the missions listed above are actually booked for the 26-m antenna's support for many more years. Figure 4 shows the antenna with its two small acquisition-aid reflectors (1.8-m at S Band and 1.2-m at X band) attached to the opposite sides of the large reflector.

The 26-m antenna subnet is very different from the other DSN large antenna systems, i.e., the 34-m, and 70-m network. The antenna is getting too old and inefficient to support the longer-term missions. There have been several attempts in the past to study the impacts of phasing out the 26-m antenna and replace it with either a new one with the same size, or with other alternatives, such as, arrays of smaller 12-m antennas, a 34-m antenna, and/or a phased array system. Some of the key issues with the 26-m antenna are listed below: The antenna is old (1967), has no X-band telemetry capability; LNA temperature is high; Not very immune to RFI; Different receiver system from other stations, i.e., incompatible; No support for multiple spacecraft launches; When some missions demand longer hours of support, several others get hit; Multiple launches during a short time window can cause schedule problems; Inefficient for formation flying missions of the future (lack beam hopping capability); Inefficient for communication and tracking at early orbit phase (lack beam agility and multiplexing capability); No broadband communication capability (lacks X-band telemetry); Limited slew rate for multiple launches in a short period; Not compatible with Space-based Internet concept; Lacks the schedule flexibility, e.g., time multiplexing.

In some near Earth missions of future, the spacecraft is expected to communicate during the maneuvers and other critical events. Therefore, communications, navigation, and tracking need to be working together more synergistically. For instance, before a maneuver takes place, having the Earth antenna within the boresight of the spacecraft antenna while maneuver is taking place is important. Ordinarily, downlink communication during maneuvering is only limited to carrier-only, so that the Doppler data can be extracted. However, future missions desire telemetry capability during spacecraft maneuver as well. In the following sections the options that are under study for the replacement of the 26-m antenna will be briefly discussed.

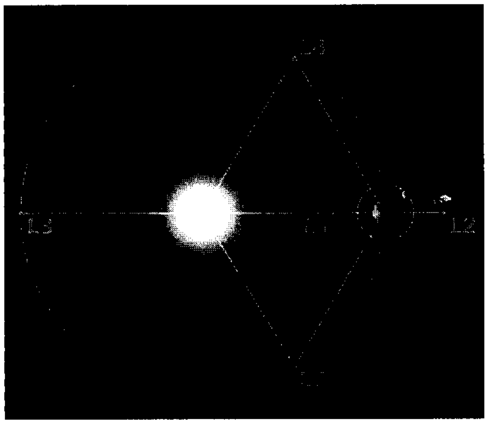

Figure 3. Lagrange libration points

Figure 4. The 26-m reflector antenna

4.0 OPTIONS FOR REPLACEMENT OF 26-M ANTENNAS

A number of options are being explored in connection with the upgrade and/or replacement of the 26-m antenna. These options are briefly discussed below.

Option 1: refurbishing the 26-m antenna. This is perhaps the lowest cost of all the options. However, it does not allow for additional requirements and capabilities that will be needed for the future missions as outlined previously in any substantial way. This option includes but is not limited to: putting new receivers, putting new LNAs, replacing the small reflectors acquisition aids by phased arrays, etc.

Option 2: Use of some elements of the future array of 12-m antennas. JPL/NASA is in the process of developing a large array of small reflector antenna as a substitute for the large main reflector antennas of the DSN used for deep space communications [2-4]. It is possible to dedicate one or more of these antennas as a functional replacement for the 26-m antenna. This is tentative at the present but may become a viable option once the array of small antennas becomes a reality. The problem, however, is that the array of 12-m antennas lacks the uplink capability, at least in the current design although efforts are being made to add uplink capability to the array of small (12-m) antennas.

Option 3: an additional 34-m instead of 26-m antenna. DSN has a number of 34-m beam waveguide reflectors in all its three main ground complexes. It might be cost effective to use one of these as a replacement for the 26-m antenna. However, these antennas have an Az-El mount and are slower than the X-Y mount in 26-m antenna, which allows for the speedier pointing of the antenna, specially to points low on the horizon to pick up the fast-moving Earth orbiters.

Option 4: phased array antenna. The phased array antenna may be a very promising option in two functional capacities, either as a substitute for the acquisition-aid small side reflectors of the 26-m antenna or as a replacement for the 26-m antenna itself. It is this second option, which will be addressed here, although the first option could be more viable in the near future. In previous sections a number of issues were discussed which make the use of an array with fast beam pointing as well as multiple beam capabilities a very enticing option. The exact type and structural architecture of the array, whether planar or multi-faceted or tilted with a mechanical azimuth rotation, were discussed in a previous paper [2]. Table one provides a comparison of the characteristics and functional capabilities of the 26-m reflector versus a comparable planar phased array.

Although the array has a superior performance in almost all categories, there are a couple of challenges that have to be addressed. The main technical issue is the low noise temperature requirement and whether non-cooled array modules and LNA's can provide adequate performance or whether they must be cooled. The second and related issue is the cost of such an array. Tables 2 and 3 provide cost comparisons for phased arrays for several different antenna sizes including the 12- and 70-meter reflector antennas for deep space communications, estimated for development in the next 5 to 10 years.

Table 1. The 26 M antenna S-band capability versus S-band Flat Panel Array (FPA*)

	Aperture Diam.	Gain Zenith	Gain 30° El.	HPBW deg	Aperture Efficiency	Polarization
Reflector	26 m	52.8	52.8	0.4+/-.03	60%	RCP/LCP
FPA*	37 m	57.3	54.3	0.26/0.36	90%	RCP/LCP
	Coverage	# of passes	Multiple Beam	Beam Switching		
Reflector	Restricted	6 per day	No	No		
FPA*	Unrestricted	Unlimited	Yes	Yes		
[redacted]						
	Tx Power (dBm)	Stability	Cooling			
Reflector	47-63	'+/-0.25 dB/8hr	Fair			
FPA*	47-63	TBD	Difficult			

Table 2. Phased array cost for various sizes & frequencies, case 1: gain equal to reflector at zenith

Reflector Diam.	12m ($2M)			26m ($10 M)		
Array Diam.	12m			26m		
Frequency	S	X	Ka	S	X	Ka
# of elements	20 x 10^3	300 x 10^3	5 x 10^3	100 x 10^3	1.5 x 10^6	24 x 10^6
Unit cost	$40	$60	$100	$40	$60	$100
All units	$0.8M	$18M	$500M	$4M	$90M	$2.4B
Assembly (%40)	$0.3M	$7M	$200M	$1.6M	$36M	$1B
Total cost	$1.1M	$25M	$700M	$5.6M	$126M	$3.4B

Table 3. Phased array cost for various sizes and frequencies, case 2: gain equal to reflector at 30° El.

Reflector Diam	12m (($2M)			26m ($10M)		
Array Diam	14m			37m		
Frequency	S	X	Ka	S	X	Ka
# Of elements	28 x 10^3	420 x 10^3	7 x 10^6	140 x 10^3	2.1 x 10^6	34 x 10^6
Unit cost	$40	$60	$100	$40	$60	$100
All units	$1.1M	$25M	$700M	$5.6M	$126M	$3.4B
Assembly (%40)	$0.4M	$10M	$280M	$2.2M	$50M	$1.4B
Total cost	$1.5M	$35M	$980M	$7.8M	$176M	$4.8B

5.0 SUMMARY AND CONCLUSIONS

The continuing demand for the aging antennas of JPL/NASA's Deep Space Network has mandated a new and fresh look at different approaches to providing vital services to NASA's future missions. A particular case of interest is the relatively old 26 meter reflector antennas which are primarily used for tracking Earth-orbiter spacecrafts, most of which are in orbits between 160 and 1,000 kilometers above the Earth, but also are used for tracking spacecrafts within 2 M-kilometers of Earth up to the Lagrange L2 point. Options for replacing and/or improving and augmenting the performance of these antennas were discussed. The use of phased array system as a viable replacement was also discussed in light of NASA's strategic plans for IP-based missions and increasing DSN interest within the 2M-kilometer range. Although a much more detailed study remains to be performed, at present it can be concluded that the phased array system indeed can be a cost-effective and technically advanced alternative to the 26-m antennas. Despite the relatively high cost figures for larger aperture phased arrays the technology trends for the next decade of phased array systems show signs of significant improvement in cost and performance, particularly when synthesizing large phased arrays with aggregation of smaller apertures [5,11].

6.0 ACKNOWLEDGMENT

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