Trends in Development of Broad-Band Phased Arrays for Space Applications[1,2]

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Abstract— Occasionally, it is argued that the cost and size of the phased array antennas are prohibitive for space applications. It should be noted however, that combining the communication, imaging, and multi-target tracking capabilities of a broad-band phased array antenna has made it an attractive solution for high speed mobile ATM networks, air traffic control, collision avoidance systems, wireless local area networks (WLAN), and radar imaging. Miniature phased arrays for smart sensor probes, and robotic networks seem yet other domains of new phased array applications, which could as well be utilized for inter-planetary applications. The increasing usage of the phased array antennas is playing a key role in lowering the cost and size of the T/R modules, packaging, cooling, and integration at an amazingly fast pace. One of the beauties of phased array antennas, which is occasionally overlooked, is its modular nature, i.e., if the first module prototype is successful, one can add more modules, with minimum down time. Reflector antennas don't have this scalable feature without much more complexity, or down time. While there are several programs, that are employing phased array antennas for earth orbits, there has not been sufficient effort in the development of phased array antennas for applications from high earth orbits to deep space vehicles and robotic networks.

In this paper we will discuss and analyze various ways that phased array technology can be utilized to provide multifunction capabilities for planetary space applications. It will also be shown how phased array antennas add much flexibility to deep space applications, e.g., ground support systems, Mars networks, and monitoring high-speed robotic missions. Various beam-forming network architectures including power dividing/combining and phase-shifting techniques will be outlined and ways to reduce cost, weight and complexity of T/R modules and beam-formers will be discussed.

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1. INTRODUCTION

The Deep Space Network (DSN) is facing new challenges as it enters a new paradigm in its architecture, antenna size, networking, and services. Several key parameters are being stretched at the same time. Since 1987 the number of NASA missions have increased by a factor of four and it is expected to remain steady at that level. The data volume is going to be expanded 10 to 100 times or perhaps even higher. The desire for higher data rates has already encouraged rapid development of the Ka-band systems and services for deep space applications. The resulting Ka-band capability for DSN will be at least four times the X-band capacity.

This migration to new frequency range poses new challenges in terms of mission requirements, mitigation of weather effects, public engagement in high-bandwidth services, to name a few. The new era of Internet satellite networks on the other hand, has started to use Ka-band phased arrays for earth orbits. New wealth of experience is now available for phased array applications in space, which could be absorbed and infused for NASA's deep space applications in various forms, ground tracking systems, *In-Situ* networks, and robotic missions.

The other key change that the DSN is facing in the foreseeable future is the need for the long-haul trunk lines resulting from the planetary local area network. This requires searching new ways for connecting to the global Internet network, and new web-based applications for data transfer, or for public engagements. This may include connection to Internet satellites, or other high-speed ATM networks in the wireless, and the fiber networks. Therefore, much like the time for a stand alone PC has expired, the DSN antennas need to find their new identities in the new network-ready antenna era.

In a recent paper by Jamnejad et al. [1], a DSN antenna

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history and the effect of aging was thoroughly discussed. As mentioned in that paper, the prime focus for antenna capability study was originally the 70-m antennas. As will be discussed later in this paper, none of these large aperture antennas were designed for networking. Furthermore, the maintenance and upgrade cost for the Ka-band requirements pose additional challenges in making the right choice. Therefore, many options were outlined and discussed in detail by Jamnejad and others, which for convenience will briefly be outlined here. In particular, total of seven options were proposed for future study, namely the following:

1. Continue with the existing 70-m stations with minor modifications
2. Modify the existing 70-m stations for extended life and reliability
3. New 70-m single aperture antenna
4. Array of four 34-m antenna
5. Array of many small 12-m dish antennas
6. Array of flat-plate antennas
7. Spherical reflector antennas

The interested reader may refer to that paper for a detailed analysis of each of the above-mentioned options. Various proposals, experiments, and demos have been conducted since then. In particular, a large array of 12-m reflectors has attracted some attention as it inherits lots of technologies from its predecessors VLA, and VLBI and upcoming Allen Telescope Array (ATA). In this large array of 12-m reflectors, the uplink capability has not been incorporated in the design. One reason that the uplink capability is presently ruled out from the array of large reflectors is that it complicates the handling of noise and interference on the downlink signals. The other reason for not having the uplink capability on this array of 12-m antennas is the extra load that the transmit electronics will put on each antenna and the operational complexity due to factors such as calibration, beamforming, and shadowing. In short, option 5 has attracted the foremost attention from this list, while option 4, (i.e., the array of 34-m antennas) is also entering a new phase of demonstration for uplink capability, some time in the near future.

The flat-plate phased array, which is the prime focus of this paper was considered as option 6. In the paper by Jamnejad, the cost and complexity of the single large aperture phased array for capabilities equivalent to a 70-m antenna was discussed in detail. In a later section of this paper, we will revisit the cost of the large flat-plate array preceded by discussions on trends in phased array technology, and deep space applications.

As discussed by Jamnejad, the flat-plate array cost and complexity for 70-m equivalent capability resulted in delaying that option to a time when either new alternate applications are proposed, or that the key cost drivers are studied in detail for more realistic figures. In doing so, the focus of this paper will be on a) technology trends that help us foresee the readiness of DSN for absorbing the flat-plate, or conformal phased array, and b) ways to derive the technology heritage for deep space applications of phased array antenna systems.

A limiting factor for the flat-plate array is its scan loss factor, which is inversely proportional to the sine of the scan angle. For example, in order to provide the same gain as a 70-m reflector at 10° elevation angle, the aperture area of the flat-plate array antenna needs to be proportional to $1/\sin(10°)$, i.e., roughly 5.8 times that of the 70-m reflector. This translates into an equivalent diameter of 168m. The Ka-band performance analysis for the 70-m antennas on the other hand shows that a more realistic angle to begin a tracking pass is 30°, which translates into a 99m equivalent aperture diameter for flat-plate array.

Finally option 7 is an innovative idea called the SPHERE (Spherical Pair of High Efficiency Reflecting Elements) concept. Here the idea is to construct an antenna pair, where each element rotates only in azimuth, never in elevation. Because elevation is fixed, gravity-induced surface deformations will not be a concern. One of the pair would cover low elevation angles whereas the other would provide the complementary high elevation coverage. Elevation pointing would be effected by motion of the prime focus feed assembly, as in the Arecibo Radio Telescope.

2. REVIEW OF KEY TRENDS & TECHNOLOGIES

The world's first demonstration of array antenna was for transatlantic wireless communication experiment by Marconi in December of 1901, which was a historical event. However, the trends in development of phased array antennas were shifted towards tracking multiple targets for aerospace applications, where the take off in array theory and experimentation took place within the last three decades. Recent advances in MMIC technology as well as many other key technologies have provided a wider spectrum of applications for phased array antennas. While active MMIC-based phase steering techniques are already on a fast paced trend, many other techniques, such as Steerable Plasma Mirror, Rotman lens, Ferroelectric lens, VVD materials, and laser-assisted array, etc., for phase shifting have entered the scene as well.

Array processing & digital beamforming

The other catalyst for the rapid growth of phased array antennas is the amazingly growing processing speed of the digital processors, and DSP architectures, followed by analog-to-digital (A/D) converter speed. Digital beam-forming techniques allow multiple layers of processing in a distributed manner, i.e., multiple beams in different sub-arrays can be generated as illustrated in Fig. 1.

As illustrated in Figure 1, the processing can be distributed among various array elements for load balancing, computational efficiency, architectural flexibilities, and cost effectiveness. Moreover, as indicated by the dotted lines,

calibration level, RFI cancellation layer, and beamforming layers can be different for more efficient array resource allocations. This feature is particularly useful for large arrays for fault tolerance, modularity, and shared resources to optimize array utilization of its resources.

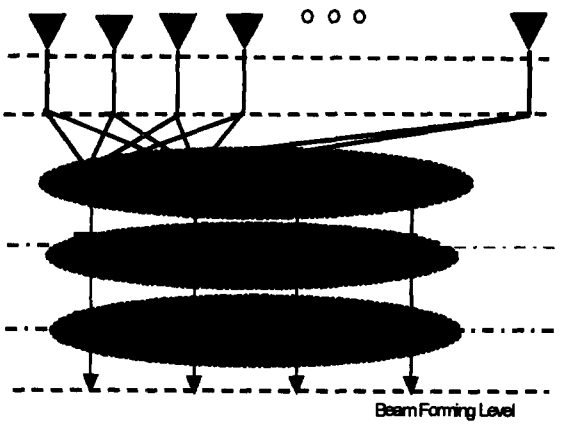

Figure 1. Typical schematic for multi-layer processing

Although this concept can be extended for array of reflector antennas as well, however the overhead for array of reflectors will be more complex as will be discussed later in this paper. This primarily because of larger element spacing and separation of signal processing sub-system and its placement in a separate building. The important thing is that a single large reflector does not have any of these features. As shown in Figures 2a, & b, each sub-array can be managed through a set of processors with tasks well distributed among DSP chips for uniform thermal and electrical distribution as well as reducing risk of array failure.

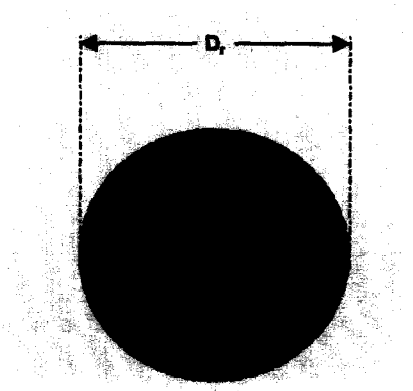

Figure 2a. Element spacing control through digital control

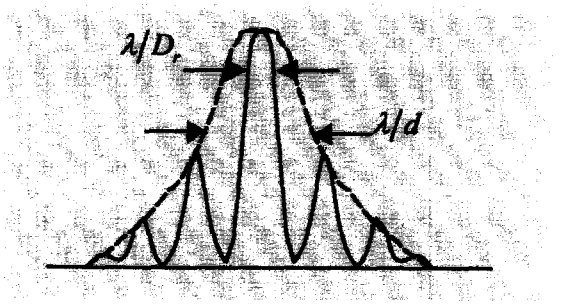

Figure 2b. Null control with element spacing

Sub-arraying helps modular architecture flexibility as well as more efficient side-lobe control. As illustrated in figure 3, in the direct digital beamforming, each element of the array can be used in more than one beam. This adds reliability, redundancy, and flexibility. The *f/d* ratio for the reflector antenna is therefore traded with the number of beams N_B versus the number of elements N_E to form a particular beam. The DSP chips required per MHz of IF bandwidth increases linearly with BW. However, through creative architecture techniques and task sharing of distributed processing as depicted in figure 1, the number of DSP chips required can be further reduced. Note that every DSP chip can receive data from all or a subset of elements. Antenna efficiency can therefore be traded with computational efficiency of the DSP architecture.

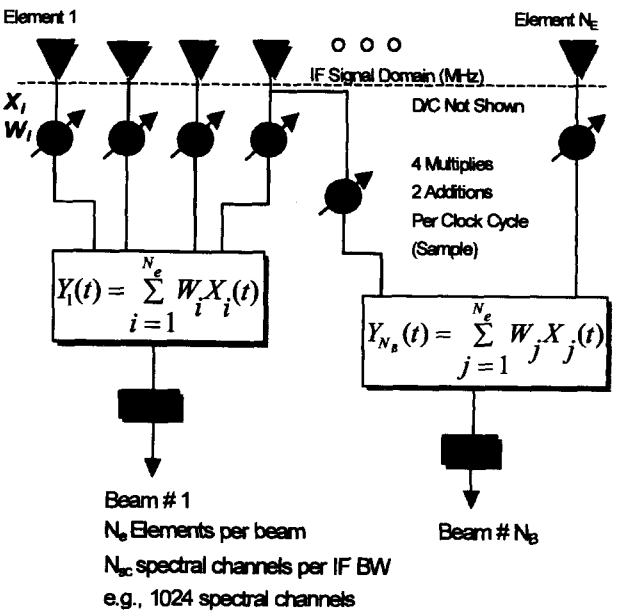

Figure 3. Direct digital beamforming

Several DSP tasks may be defined and conducted at independent levels such as beamforming, direction estimate of signal arrival, demodulation, RFI cancellation, self-

calibration, and diagnostics. Note that this architecture allows a scalable feature, where a small 1-m module can be built, tested, and put in operation, and later, as more funding becomes available, more modules are added in.

Using FPGA, together with DSP combines the flexibility in array configuration with processing speed of FPGA, which is typically 10 times faster than DSP. The DSP bandwidth can be dynamically traded with duty cycle through decimation. The DSP for array processing can be characterized by line input/output bandwidth, number of microprocessors and bus speed for each, i.e., total bandwidth, number of direct memory access (DMA), which determines the trade between background processing and core processing, SRAM on the chip, which brings data blocks on the chip for signal processing. The DSP main performance parameter is dominated by coding efficiency, and the I/O bandwidth.

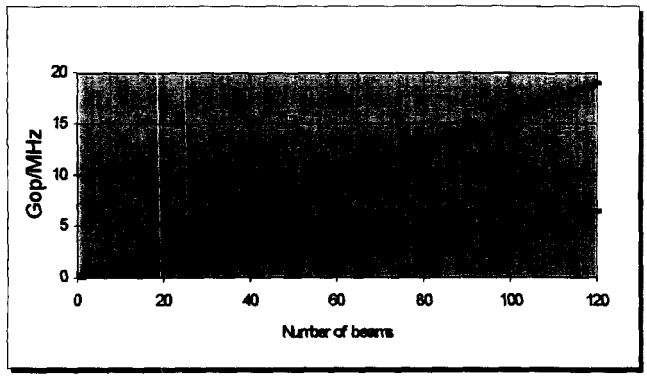

Figure 4. Direct beamforming processing operations required with 7 (red), versus 20 (blue) elements per beam.

As an example, using a 1-GFLOP DSP, e.g., TMS320C6701, 4800 DSP chips with typical 30% efficiency are required for 100 MHz bandwidth, 64 beams, and 1024 spectral channels, and 20 elements per beam. Comparatively, only 500 FPGA is required to do the same job. Note that the cross correlation beams, i.e., power beams are computationally more demanding. Since different bandwidth per beam is possible through digital processing, more flexibility is provided in scheduling, traffic management, and load balancing. Furthermore, issues, such as weather diversity is easier to program, and plan with the added flexibility provided by digital beamforming. A user can actually subscribe to a timeshare of specific beams and switch his share to a different beam when his time expires on a particular beam, or set of beams. The digital steps are obviously easier to work with than the more stringent and time consuming mechanical steps. Moreover, modes of array operation are more controllable than the classical large reflector. For instance, certain waveform, modulation, or coding can be applied to each individual beam based on mission requirements, or weather conditions.

Array components and key structural elements

The heart of a phased array is the T/R module, followed by a power distribution network, cooling system, and command and control software. The T/R module by itself consists of Power amplifiers, low noise amplifiers, phase shifters, attenuator, filters, and switches. Note that the packaging and redundancy, and ease of part replacement are critical functions in the array design. A typical time frame for replacement of a T/R module is within half hour. The top level control of the array consists of the exciter, receiver, IF filters, A/D converter, and beam controller. Packaging of the array modules should have good thermal interface, mechanical interface, ease of access to RF/DC through built-in connectors, small size for multi-layer substrate, and multi-chip MMIC so that multi-function feature is feasible. The RF/DC connectors should be slide in rather than soldered to minimize thermal and electrical imbalance in points of electrical contacts. Thermal balance is one of the most critical functions of the array. That is, the radiation pattern and beam pointing accuracy is directly affected by temperature variation. Typical pointing offset is about 0.5 deg/C. A typical T/R module requires 6 MMIC chips, each consisting of a number of FETs, i.e., solid-state power amplifiers. The number of FETs dictates the MMIC complexity. The number of functions added to the MMIC chip is also a trade parameter.

Phased array principle is based on power combining of several smaller transmit modules. Figure 5 illustrates two concepts of tile, and tray. While the tile approach is bandwidth limited with challenge in thermal management, the tray approach is broadband with good heat sink capability, which generates parallel independent outgoing waves. High efficiency power amplifiers indicate two major parameters at macro level, i.e., operating near saturation for dc/ac power conversion efficiency, and small cross section.

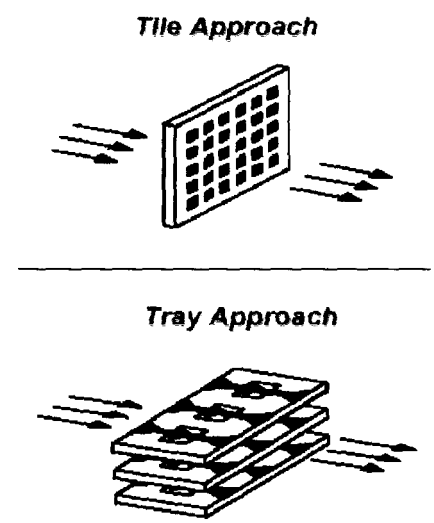

Figure 5. Power combining scheme for element modules

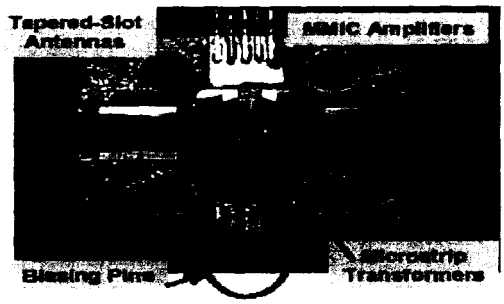

Figure 6a. 32 MMIC, 8-tray, i.e., 4 MMIC per tray

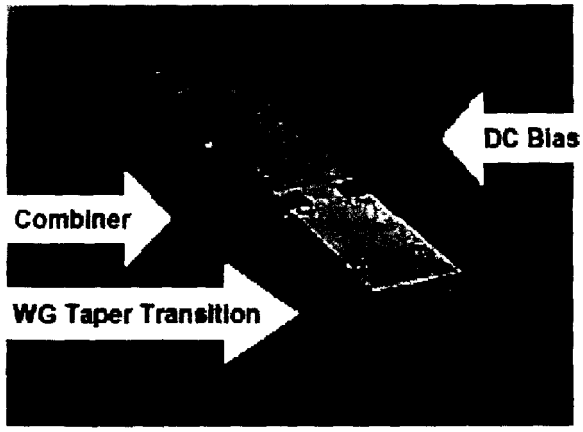

Figure 6b. Combiner MMIC with external circuits

While high efficiency favors the use of small area devices, the broadband feature of the array favors the high output impedance. Other key parameters depend on the intrinsic properties of the solid-state material, which differentiates the Si-Ge based, GaAs, and the GaN. While Silicon-based modules are good for designing cost effective prototype arrays, a jump in efficiency is acquired by the more expensive and relatively new Galium Nitride technology.

The low phase noise favors using a large number (N) of amplifier modules, since the excess noise goes down as 1/N. Broadband phased arrays require thermal balancing, either through a tile, or tray approach. Thermal characteristics of the array make beam alignment a challenge. There is always a trade between thermal balance, power combining, and phase noise. Good power combining efficiency runs above 70% depending on the bias circuit being on, or off the chips.

Another key technology that is growing rapidly for phase shifting of the array elements is the photonic controller. Spatial light modulators are used as distributed optical gain control devices to implement vector modulation to generate the desired RF signals with correct amplitude and phase. This scheme is called photonic beamforming. The advantages include smaller size devices in power distribution network, wider system bandwidth, remote control capability through laser beam.

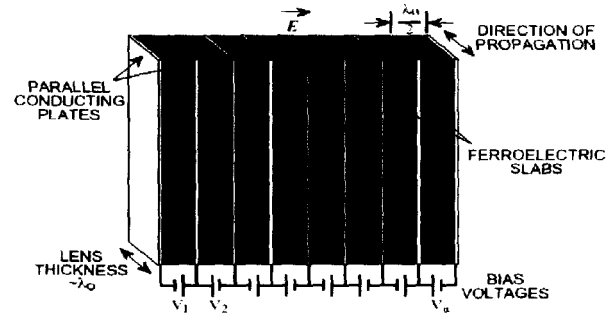

Figure 7a. Ferroelectric phase shift concept

The key driving technologies for optical beamforming are spatial light modulators (SLM), deformable mirror devices (DMD), multiple quantum well (MQW), and ferroelectric liquid crystals. Optical beamforming is also a suitable platform for conformal array architectures. This is done through the elegant feature of the fiber optics prism antenna feed, which uses numerous fiber links with varying lengths. The microwave signal is modulated on an optical carrier. The carrier going through each fiber link can be either delayed, or given a relative phased shift by changing the frequency of a tunable laser. Up to 30% bandwidth is achievable through optical bemforming techniques. Figure 7 below illustrates the structure of Ferroelectric Lens, which is another layer technology for phase shifting.

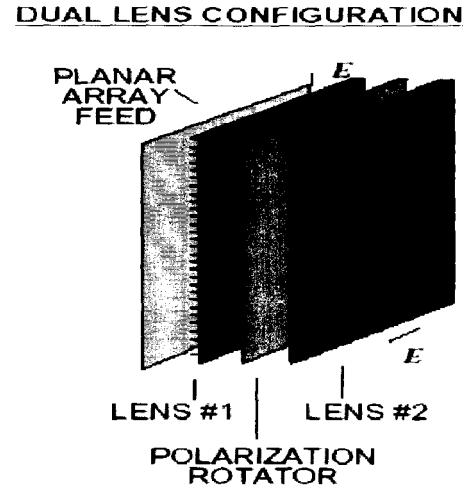

Figure 7b. Ferroelectric Lens for phase shift with two-layers

Plasma mirrors allow wide instantaneous bandwidth and were primarily brought into phased array system design to provide a higher level of integration for phase shifting. Plasma mirrors help avoiding multiple connections, which is normally required for each array element to the phase shifters. Plasma mirrors have another nice feature, i.e., the transmit and receive beams can be independently controlled. Phase shifters are one of the limiting factors of instantaneous bandwidth that can be allocated to each beam. Typical bandwidth range for broadband phased array is currently considered as 1 GHz. For broadband phased arrays,

the beam-steering function and beamforming function need to be decoupled. This is a constraint, which is imposed by the phase shifter mechanism, since it involves both functions. A rule of a thumb for instantaneous bandwidth of phased array is that 1% bandwidth almost equates 1-deg beamwidth. For example, an L-band (1.5 GHz) phased array of 1-deg beamwidth corresponds to 15 MHz of instantaneous bandwidth. However, partitioning the array into smaller sub-arrays, and delaying the signal to each sub-array can achieve substantially larger instantaneous bandwidth. This means, force the signals of the sub-arrays to arrive simultaneously at the target. Through this technique, the recent phased arrays can achieve at least ten times more bandwidth than the conventional arrays, i.e., 200 MHz bandwidth for L-band.

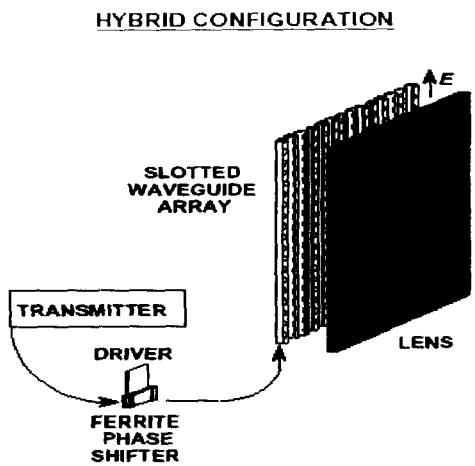

Figure 7c. Ferroelectric phase shift and array elements

The plasma mirror-based antenna provides true-time delay steering since all ray path lengths are equal for each mirror orientation.

Together with the phase shifter technology, thin film, and high speed digital processing, phased arrays for multi-function purposes are becoming an engineering reality. Multi-function phased array antennas may cover radar and communication, and imaging applications all in one package. From frequency point of view, the technology for phased array has come a long way too, i.e., from the first UHF PAVE PAW to the recent Theater Missile Defense System L-band, and Multi-Faced high bandwidth X-band APAR, and the recent Ka-band phased arrays.

The new technologies mentioned so far contribute to development of new creative modular architectures, such as row-column steering techniques, instead of element phase steering, which results in a major cut back in cost as well as complexity. The modular architecture for large phased array helps lowering the design cost, as well as the operational cost, particularly at times of array element failures. Thin film and composite materials with highly stable thermal and electrical characteristics, on the other hand, make the heat dissipation of large high power arrays more feasible. It worth mentioning that one major challenge of large phased arrays is the element-to-element variation and uneven heat distribution across the array surface and in the electronics.

3. MAJOR ARRAY ANTENNA SYSTEMS

In this section some of the state of the art phased arrays that brought new technology trends through shifts in theories and applications will be discussed. In order to better project the trends in phased array technology and derive the heritage and lessons learned we may look at the following areas:

A. Large arrays
B. Mobile applications
C. Commercial satellites
D. Miniature arrays

Each of these categories provides insight for various deep space and robotic mission applications. Although there are many large arrays built over the last three decades, few are the best representatives of large array development. These are the COBRA DANE, PAVE PAW, PATRIOT, THAAD, APAR, AMSAR, AESA, FSX, and PHALCON.

Development of these key arrays resulted in cost and complexity reduction techniques, such as row-column steering instead of element phase steering, and the novel steerable plasma mirror developed by NRL.

PAVE PAW is the Air Force space command radar with long-range capability designed by Rome Air Development Center (RADC). This large array has a primary mission of detecting ballistic missiles launched from the sea, and a secondary mission of detection and tracking of earth orbiting satellites. PAVE PAW initial operation started in 1980. The scan angle is +/- 60°, which means for the 360° coverage three faces are required. The array is housed in a 32-m building with three sides. Each radiating element is connected to a solid-state power module with 325 Watts of power, and a low noise receiver for the return signal. The beam width is 2.2 deg. The total peak power of the array is about 582 kW, and the average power is 145.6 kW.

COBRA DANE is another wide bandwidth large-scale array with 95 ft diameter, 200 MHz bandwidth, and 2.5 ft range resolution. It can resolve the image of a target and track it as well. COBRA DANE is a C-band array, and has 2700 MMIC T/R modules. Total of 579 Million dollars is the estimated cost for 29 systems. That is the functions of target tracking and identification are combined. COBRA DANE has 16% bandwidth capability, which is considered a broadband array. The other large array is THAAD, which is an X-band array that consists of 25, 344 MMIC T/R modules and radiating elements. THAAD is one of the largest arrays in terms of the number of T/R modules. Like COBRA DANE, THAAD uses sub-array time-delay steering to prevent pulse distortion for its wideband waveforms. With

65000 T/R modules built for a number of THAAD systems, the cost of each T/R module dropped to within $1000 range.

The other types of interesting arrays that contribute to the volume production of phased array are the types of arrays developed for mobile cellular communication for terrestrial applications. Future telecommunication systems for wireless cellular applications require fast steering beams to track the mobile users in order to provide them with high data rate. The scope of this problem is similar to multi-target tracking of cellular users with unknown directions of motion within the cellular architecture. Karttumen [2] discusses adaptive techniques using phased arrays for tracking mobile users in a cellular network. The multipath and diffraction of the signals from buildings and trees have been studied under various conditions. Since the array signal beams add up in the far field, the effect of phase distortion of individual signals before they add up is critical. The more the individual signals get distorted in phase through multipath and diffraction around the buildings, the less the coherent combination of beams in the far field of interest would be.

Figure 8a. COBRA DANE & PAVE PAW phased arrays

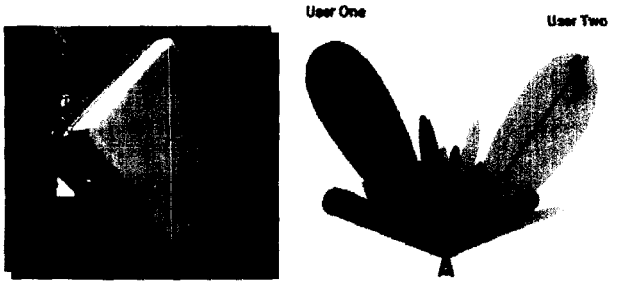

Figure 8b. Mobile application of phased arrays

The third category of phased array antennas is the ones used for on-board spacecraft for narrowband, such as ICO, and Global Star, and broadband, such as Spaceway. For instance, Global Star with 48 satellites uses 91 transmit elements per antennas on-borad. This adds up to 7300 T/R modules for the constellations. Each Spaceway downlink phased array antenna consists of 3500 elements. The Spaceway phased array generates 1000 watts of average RF power, with total of 12 hopping beams per polarization. The 24 beams cover the entire CONUS for up to 16 Mbps per user, while a minimum service to each user is 2 Mbps.

Figure 9 illustrates NASA's Ka-band phased array for space applications. It uses tray approach as discussed in previous section with 8 element modules per tray. Radiating elements are arranged in two rows with 16 elements per row, total of 288 elements make up the entire array. The phase noise contribution of the array elements to the communication signal sent, or received by the array is insignificant. The phase shifters change by 0.3 degrees, which add up to total of 4 degrees in the far field. This is insignificant relative to the 45 degrees phase shift of the QPSK signal. Moreover, the beam alignment of 0.5 degrees corresponds to 0.1 dB loss. The element gain variation stayed within 0.3 dB rms. The element module accuracy for a 3-bit phase shifter was about 11° rms. The NASA Ka-band array has a scan capability of +/- 60 degrees.

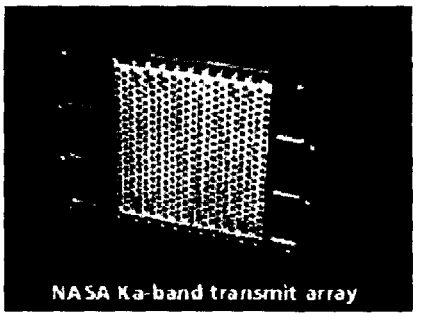

Figure 9. NASA Ka-band array

Widespread use of Internet satellites will eventually lead the end user to switch to small phased arrays for his/her backyard. That is, the conventional reflector antennas will face pointing problems as the market migrates to Internet satellites. Examples are hand-over from one satellite to another, or user selection of one satellite versus the other. Also, at times, the user may need to search for the signal through steering the beam. Small-scale phased arrays are also more suitable for mobile smart science Ka-band terminals.

The other category of phased array that have attracted attention for sensor networking, auto industry, and medical field is that of the miniature arrays. Masaaki Kanno et al. [3], discuss an X-band GaAs MMIC T/R module for conformal array antenna. The overall package measures 19 mm in diameter and weights 18 g with a transmit power over 2 W and duty cycle of 10%. The gain for transmit and receive is 20 dB, and the noise figure is below 6 dB. With a 5-bit phase shifter they achieved about 5 degrees rms phase error. The array is packaged in a cylindrical format. Figure 10 illustrates some typical miniature phased arrays.

4. Trends in Space Applications of Phased Arrays

As mentioned in pervious sections, the tracking capability of the phased array combined with the new broadband communication application also made it suitable for wireless applications and high-speed ATM networks. Wide spread mobile platform phased array and the ground-based wireless

sector all encourage the end-user to seek for a phased array antenna in the near future market. That is, the current dish antenna, which is widely used for satellite broadcasting may soon be replaced by small affordable phased arrays that are capable of pointing to multiple satellites.

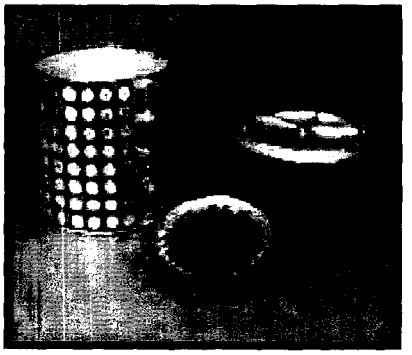

Figure 10. Examples of miniature phased arrays

The experience earned in commercial communication applications of space-based phased arrays is now being merged with defense based tracking applications, which is giving birth to large-scale phased array applications for ground and space. Example of large-scale global coverage space-based phased array with heritage from Iridium is STARLITE, which consists of 24 low-orbiting, low cost satellite constellation for detecting ground moving targets.

Although there are many drivers for the recent choices of phased arrays on-board commercial satellites, the key motive for Ka-band phased arrays for Internet satellite era is two fold. First, the narrower beam and its smaller footprint on earth allow adapting to the cellular architecture, in order to take advantage of the frequency reuse concept. Secondly, moving to Ka-band indirectly indicates sacrificing the power efficiency by 10 to 15%, unless an array of amplifiers are used. The high-speed agile beam hopping of the phased array is another key driver for its recent presence in earth orbit Internet satellite applications. Hundreds of cells can be covered in a matter of nanoseconds, which indicates, with only a small number of independent steered beams an entire continent can be covered with broadband services. Today, the effort in migration to Ka-band has become a concurrent event with migration to arrays in one form, or the other.

Moving to space from ground and aerospace applications of phased array brought many new challenges, particularly for array alignment in a thermally isolated payload. As mentioned earlier, array element electrical, and thermal characteristics have serious affect on the pointing accuracy. Particularly for large number of elements, in large arrays, in space, or on the ground, any uneven temperature gradient will result in unacceptable amplitude and phase errors. Therefore, particularly for space applications, i.e., a thermally isolated payload, certain desirable features need to be considered, such as: high radiation efficiency, low mutual coupling, low intermodulation, repeatable retransmission characteristics, and low sensitivity to manufacturing tolerances.

Light composite materials have been developed, such as Nomex honeycomb and quartz fiber, which have ultra stable temperature characteristics. These materials are suitable to form a laminated, integrated antenna with layers of beamforming circuits, and patch antenna. Most recent techniques for array alignment, on-board the spacecrafts, use a few of the central elements for beacon so that the beacon elements and the communication elements have similar thermal profile. Calibration of on-board phased arrays for space applications is among the most challenging tasks in phased array system design.

In other aplications, Netherlands Foundation has developed an approach for designing large ground phased array antennas for Research in Astronomy [4]. The design objective was to use the array for its imaging capability more than communication to and tracking of the spacecrafts in deep space. An 8-element Adaptive Antenna Demonstrator (AAD) was built and tested as a first stage of a larger project for Square Kilometer Array Interferometer (SKAI). This module was then put in a larger 1-m module of 64 elements, named OSMA with the objective that the final system would consist of 10^8 receiving elements and with sensitivity two orders of magnitude beyond their current telescopes. The key function of the array that makes it suitable for imaging, or tracking applications is the digital beamformer algorithm, while the key components affecting the array's instantaneous bandwidth for communications application are the phase shifters. Through modular approach, it is possible to design large array systems with each sub-array tailored to a specific application, i.e., acquisition, tracking, telemetry, and imaging.

Compact Phased Array & Large Reflector Array

Quite interestingly, parallel to the compact phased array antennas for aerospace applications, reflector antennas have also come a long way within the last three decades. Although for a rather different type of application, i.e., imaging and passive sensing of the universe, the array interferometer technology brought together many large antennas with a yet cumulatively larger collecting area. While the basic principles are very similar, however, there are wide differences in architecture, infrastructure requirements, and methods of beam combining, and operation concepts. While the telecommunications aspect of the phased array demands simultaneous uplink and downlink capability, the radio astronomy and imaging aspect of the array rules out the powerful signal transmission as far away from the extremely sensitive receiver for imaging.

Adaptive beamforming is a unique feature of phased arrays that is very well appreciated by radio astronomers and telecommunication and tracking engineers. In both domains, with the use of deep nulls through beamforming methods, it

is much easier to avoid interference from a large number of earth orbiting satellites. Also, some deep nulls may be useful for calibration strategies as well. The other nice feature of the array that attracts the attention for deep space applications is its capability for beam multiplexing, and more relaxed geometrical constraints. It is also easier to schedule the array for issues related to weather in Ka-band applications. Therefore both telecommunications engineers and radio astronomers with interest in deep space have reason to believe that phased array antenna system is the way to go. However, there are rather stringent requirements that make it difficult to design multifunction array for deep space applications to meet the imaging and the tracking requirements simultaneously as THAAD, or PAVE PAW.

The narrow arc resolution required for radio astronomy applications is about 100 μarcsec, which is infeasible to acquire with a single aperture. The imaging dynamic range is another factor that cannot be achieved with a single aperture. Another key difference is that the telecommunication and tracking applications do not require a semi-hemispheric coverage of the sky at one snap shot. The small dish provides the wide field of view while the synthesized beam provides the narrow spatial resolution. Another important feature that is mutually exclusive for telecommunication and radio astronomy of deep space applications, are the low frequency coverage, and the resolution of the spectral lines as needed for radio astronomy. That is, for compact arrays, the beamsteering and phase technology is dictated by the frequency of operation. Receiver performance below 10 GHz for current state-of-the-art receivers with cooling systems is backgroud-limited, not electronics-limited. Therefore, the only way to acquire more sensitivity, i.e., more increase in G/T, is to have a larger collecting area. The large collecting area independent of electronic design was a major leap by large array of reflectors.

The Uplink Transmission Challenge & Reflectors

Achieving coherence for uplink transmission while the reflector antennas are several meters apart is an extremely difficult task for deep space applications. Although there is only one to two kilometers of the atmosphere that causes the tropospheric phase distortion, however, the signal round-trip delay of at least several minutes make it difficult to calibrate the fast changing atmosphere. For the downlink applications, the signal coherent summation takes place on the receiver side with known exact position. However, adding independent uplink beams to a spacecraft in deep space with uncertainty of its exact location is much more challenging. There are no laws of physics however, to rule out the feasibility of this concept as of yet.

For telecommunications application of arrays, as discussed earlier, phase drifts of +/- 5 degrees are well within the specification. This is based on the assumption that the elements of the array don't always add in one direction to shift the net EIRP by more than the acceptable range. For instance, a phase offset of 30° contributes 0.1 dB loss to the EIRP. If there is no phase offsets between any of the array element reflectors, the total transmitted power will be $N^2 \times P$. Where, P is the individual transmit power of each element, and N is the number of array reflectors. If we refer to this figure as a 100 % coherence, then the partial coherence would mean, having some acceptable phase errors. Simulation study shows that up to 80% coherence can be tolerated, i.e., as shown in figure 12, comparing 100% coherence with 80% coherence for a 200 W SSPA, a total power of $N^{1.8} \times P$ may still result in an economical number of elements. Figure 11, and 12 further illustrate that sacrificing complexity of 100% coherence with simplicity, yet acceptable results of partial coherence is more encouraging, particularly for plink applications.

Calibration techniques for keeping the array coherent for Uplink and Downlink are very different. Current DSN capability for phase stability is within a few parts in 10^{-15}. This means, for an rms error within 12 degrees, at X-band, the time frame for a practical instrument calibration is 400 seconds for a power hit less than 0.1 dB. Uplink from a large number of reflectors to multiple spacecrafts requires further attention. While spatial characteristics of large reflector arrays are more difficult to deal with, the temporal characteristics of compact phased arrays, i.e., the impulse response, is more challenging due to other transient effects, not discussed here. In short, reflectors have simple, and short impulse response, and have a few parts. Since the compact phased arrays adjust the beam through phase shifting rather than physical path delay, the impulse response is more complicated, i.e., longer impulse response.

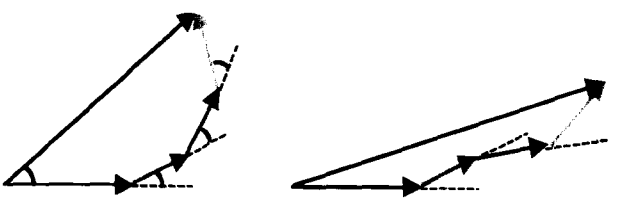

Figure 11. For a 100-element array, at least 3 would have to go 180° out of phase from the rest before losing 0.25 dB

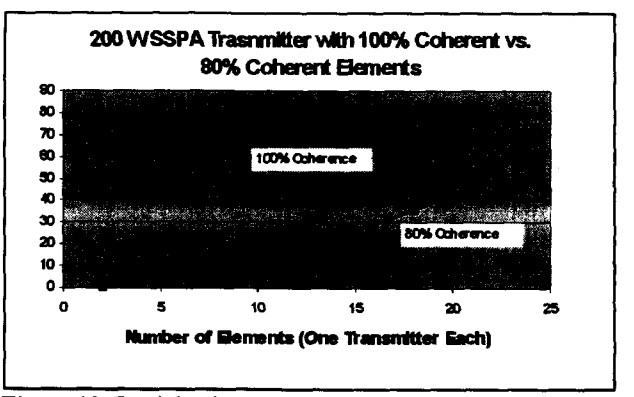

Figure 12. Partial coherence versus 100% coherence

Phased Arrays For Robotic & In-Situ Applications

Many robotic systems use optical sensors for vision-assisted guidance of the robots, such as infrared cameras. However, in order to connect the robot to a larger communication network, the flexibility RF antenna is required. For slow dynamics, and small low data rate communication of the robot, e.g., a rover, there is not much of earned value to switch to a more complex, but capable phased array. However, as the speed and the dynamics of the robot increases for faster and more involved missions, re-pointing in a more dynamic environment would require slew rates beyond the capability of a reflector dish. Typical slew rates required are in the order of 30° to 60° with beam pointing accuracy within 2° for planetary applications. The maximum slew rate for the reflectors at reasonable size for rover applications is slightly over 10^0 or 12°. Figure 13 [5] shows some typical angular positions of the robot with respect to relay station.

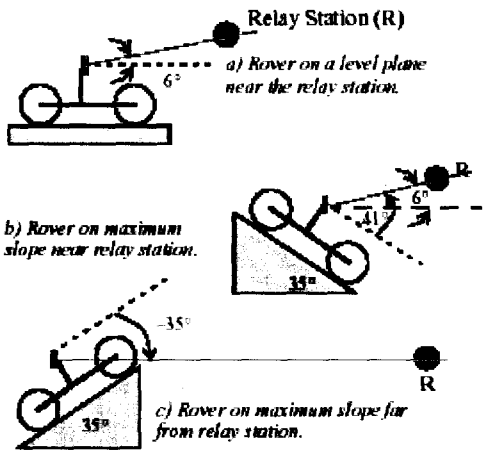

Figure 13. Typical communication scenario to the robot [5]

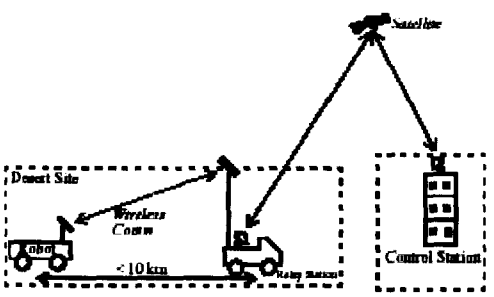

Figure 14. Typical angular positions for the robot [5]

As shown in figure 14 [5], a dynamic robot needing to keep pointed at the spacecraft in orbit requires re-pointing its beam at all times. Another area of interest is the geometrical constraints often imposed by the Sun-Mars-Earth (SME) angle. That is, future missions, particularly the ones that would be using Ka-band for link to Earth, would often face much geometric restrictions depending on the location of the antenna on the spacecraft and its flexibility and speed to rotate. To keep the SME angle below 42°, i.e., a typical requirement, indicates a tolerance of *COS* (42°) loss, which results in losing 25% of solar array power. This is the penalty for not pointing the antenna direct to earth. Therefore, the trade off is a matter of cost analysis. The solar energy cost for 25% loss versus the phased array is the trade.

5. NOISE AND G/T IN PHASED ARRAYS

In many applications of the phased array antennas the question of minimizing antenna noise temperature and thus optimizing the signal-to-noise-ratio (SNR) for reception of week signals becomes paramount. This is particularly true for extremely weak signal reception from spacecraft in deep space. This signal-to-noise ratio (SNR) is directly related to a figure of merit, the ratio of the gain to the noise temperature (G/T).

The total noise temperature is a combination of sky noise temperature and internal noise temperature due to the losses at various antenna elements and the receiving network. For a given antenna gain, the various noise components have to be minimized in order to provide the optimum G/T ratio. The use of very low loss waveguide components and cryogenically cooled low noise amplifiers, such as masers and low noise HEMTs, are part and parcel of this process.

The received noise temperature by the antenna is a gain weighted average of the incoming sky noise temperature. For high gain antennas with beamwidths of only a fraction of degree and very low sidelobes, pointing at high elevation angles, the noise contributions from low elevation angles and near the horizon sources, as well as the ground, are highly suppressed. In arraying a number of high gain antennas, the received power is proportional to the sum of the aperture areas, and the temperature is approximately the sum of received noise temperature at individual antennas, which are either uncorrelated or partially correlated. The G/T is

$$G/T = (\Sigma\, G_n)/(\Sigma\, T_n/N) \qquad (1)$$

In the case of a phased array of closely space elements (typically half a wavelength) the question arises as to whether due to the very low-gain or broad beam pattern of individual elements, the received noise is much larger particularly due to the noise from low elevation angles. It has been shown that in this case the total noise temperature received by the array is approximately the sky noise temperature averaged by the gain of the array antenna and not individual elements. Hence

$$G/T = G_{arr}/T_{arr} \qquad (2)$$

And the received noise is similar to that of a large equivalent reflector antenna. Indeed by tapering the power distribution over the array much lower sidelobes can be achieved in order to even further reduce the received noise.

By placing low noise amplifiers immediately following the

antenna elements, the effect of the network noise can be substantially reduced; but the noise figure of the LNA becomes the dominant factor. Reduction of this figure may require cryogenic cooling, which for a distributed network of elements over the total array aperture (as opposed to localized cooling of a single LNA for a reflector antenna) could be a daunting task.

6. COST DRIVERS

Throughout the paper it was discussed that today's applications of phased array antennas include ground, airspace, air traffic control, Internet satellite communications, wireless communications, traffic collision avoidance systems, landing systems, sensor networks, as well as new medical applications through miniature arrays. Although phase shifter technology is a key cost driver in T/R modules, several other factors, especially with the recent new technologies, play critical role in cost, and performance of the phased array antenna for a particular application. Examples are advances in thin film technology, and cost effective materials with stable thermal and electrical characteristics for high frequencies, high power, and high data rate applications. The volume of production as well as the competitive market place for commercialization of phased array components and systems are the primary cost cutters.

Cohen [6] discussed the cost trends of phased array in a paper in 1996. In that paper, the factors that affect compact phased array cost are listed as the following:

1. MMIC development
2. Packaging
3. System design
4. Environment considerations

Cohen further breaks down the cost trend for each category. The cost of the T/R module is radically decreasing. For instance, according to Cohen [6], the cost & development factors for GaAs MMICs have reduced an order of magnitude from 1986-1996. The lowest cost MMIC is obviously the Si-Ge, followed by GaAs, and GaN respectively. The system analysis task should start with non-linear active device modeling as the highest priority. Once the power level requirements are specified with active device modeling, the next step would be to develop and accurate Power Add Efficiency for modules power combining cost. Other costs include the simulation design tools, which are normally MATLAB, and CAD systems for the mechanical design.

The Multi-chip assembly cost heavily depends on the access to a good database for thermal expansion, elasticity, conductivity, and water absorption properties of materials to be used in the phased array system. Cohen [6] further states that it is critical to have an accurate housing structure model and the interconnection layers. Roughly, 50% of the cost goes to T/R modules, 40% to sub-array manufacturing, and the remainder 10% for array integration and test.

The greatest saving in array development starts with a good computer aided design tool, and access to good database for material properties. The requirement for an equivalent 70-m capability for the phased array is beyond a feasible consideration at present time for Ka-band. A cost trade analysis for large compact array versus large array of reflector is currently under study. One thing is for sure, the compact phased array does not require as much land and infrastructure as the large array of reflectors does. That is, the land, building, and maintenance cost of a large array of reflectors should be taken into account when compared with a compact phased array.

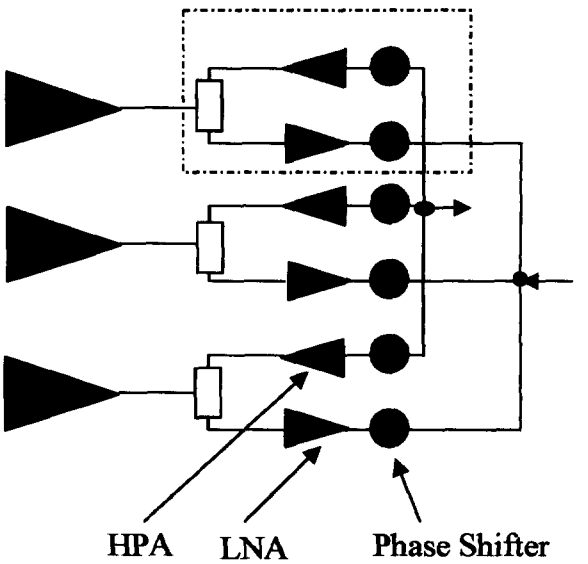

Figure 15. Active array, and T/R modules

7. SUMMARY & CONCLUSIONS

In this paper the key technologies governing the design of the phased array were discussed, and the potential use of phased array for deep space applications was elaborated. In light of the current trends in the marketplace for phased array systems, future use for deep space applications is promising. However, further cost and trade analysis are required before a cost effective design for deep space application is realizable. In doing so, a beginning step is the trade study for the replacement of the 26-m antenna of DSN. Selection of the right size of the aperture, and a mission model for a substitute phased array in place of the 26-m antenna will set a corner stone in phased array technology for deep space applications, and will be addressed in a future paper .

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REFERENCES

[1] Vahraz Jamnejad, John Huang, Barry Levitt, Tim Pham, and Robert Cesarone "Array Antennas for JPL/NASA Deep Space Network", IEEE Aerospace Conference, Big Sky, Montana, March 9-16, 2002.

[2] P.T. Karttumen, et al, "Tracking of Mobile Users in a Mobile Communications System Using Adaptive Convergence Parameter," Helsinki University of Technology, Laboratory of Telecommunications Technology, Otakaari 5A, FIN-02015 Espoo, Finland.

[3] Masaaki Kanno, et al, "Miniatutized X-band MMIC T/R Module for conformal Array Antenna," pp. 17-20, Proceedings of IEEE International Symposium on Phased Array Systems and Technology, October 15-18, 1996.

[4] Grant Hampson, et al, "The Adaptive Antenna Demonstrator," IEEE Digital Signal Processing Workshop, Bryce Canyo, Utah, 1998.

[5] Deepak Bapna, et al, "Antenna Pointing for High Bandwidth Communications from Mobile Robots," Field Robotics Center, The Robotics Institute, Carnegie Mellon University.

[6] Eliot D. Cohen, "Trends in the Development of MMICs and Packages for Active Electronically Scanned Arrays (AESAs)," pp. 1-4, Proceedings of IEEE International Symposium on Phased Array Systems and Technology, October 15-18, 1996.

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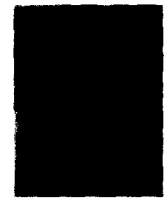

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