A GEODESIC SPHERE PHASED ARRAY ANTENNA FOR SATELLITE CONTROL AND COMMUNICATION

Boris Tomasic[(1)], **John Turtle**[(2)] **and Shiang Liu**[(3)]

[(1)] *Air Force Research Laboratory, 80 Scott Drive, Hanscom AFB, MA 01731-2909, USA*
E-mail: boris.tomasic@hanscom.af.mil

[(2)] *As (1) above, E-mail: john.turtle@hanscom.af.mil*

[(3)] *The Aerospace Corporation, P.O.Box 92957, Los Angeles, CA 90009-2957, USA*
E-mail: shiang.liu@aero.org

ABSTRACT

This paper presents a highly effective, multi-function, low cost spherical phased array antenna design that provides hemispherical coverage. The antenna consists of a number of near-equilateral triangular planar subarrays arranged in an icosahedral geodesic dome configuration. This novel architecture design, "A geodesic dome phased array antenna" preserves all the advantages of spherical phased array antennas while the fabrication is based on well-developed, easily manufacturable, and affordable planar array technology. The antenna can be used for simultaneous, full-duplex communication and control with multiple satellites, and air/space surveillance over the entire sky.

INTRODUCTION

Within the next decade there will be a dramatic increase in the number of commercial and military satellite constellations providing world-wide telecommunication, environmental, navigation, and surveillance services [1]. The satellites, in LEO, MEO, and GEO orbits, will need a network of ground stations to serve as the gateways for satellite tracking, telemetry, and command (TT&C) operations and/or payload message/data routing. A typical ground station will require one or more large, high performance antennas at L and S-band with hemispherical coverage for communicating with LEO and MEO satellites during the time when they are above the local horizon. Two types of antennas can be used for the ground station: mechanically steered reflectors or electronically steered arrays (ESA). Due to their relatively low initial cost, satellite operations (SATOPS) have almost exclusively used reflector antennas. However, their effectiveness and operability are limited due to their high operation and maintenance cost, susceptibility to single point of failure, low antenna utilization, inflexibility to adapt to new mission and operational requirements, long down times, and inability to be maintained under operational conditions. Thus, there is a great need to improve the operating efficiency and mission capabilities of the present satellite control network with a better antenna.

In [2] we show that ESA can provide superior performance and greatly enhance present SATOPS system capability and capacity. On the other hand, it is well-known that ESA can be expensive and thus have been used only when necessary. With the rapid expansion of personal and wireless communications (PCS), the major components needed in active phased array antennas, such as low noise amplifiers (LNA), power amplifiers (PA), phase shifters, connectors, etc., have became an order of magnitude cheaper. As a result the high acquisition cost of ESA has been decreased to a point where the phased array antenna for SATOPS has emerged as a viable alternative to mechanically steered reflector antennas [2-6].

Furthermore, in [2] and [3] we show that of all ESA architectures, a spherical array is the optimal choice for ground-based satellite control antennas in terms of performance and minimum number of radiating elements, which ultimately translates to antenna cost. However, since the fabrication and assembly of curved surface arrays is difficult and expensive, to this date large spherical phased arrays have not been implemented in practice. A novel antenna design, "A Geodesic Dome Phased Array Antenna" (GDPAA) is proposed in [2] and [3]. In this design, which is also briefly described herein, the desired spherical array surface is approximated by a number of flat panel subarrays. In this manner, the design preserves all the advantages of spherical phased arrays while maintaining the ease of fabrication afforded by well-developed planar array technology.

In this paper we describe a low-cost, multi-function, multi-beam GDPAA for horizon-to-horizon satellite operations. The geodesic antenna, about $10m$ in diameter, consisting of 675 flat panel facets, will support two independent transmit (Tx) beams and two independent receive (Rx) beams. Specifically, we address the development and demonstration of low-cost subarray technology which is the fundamental building block for the realization of this large spherical array. The Electromagnetic Technology Division of the Air Force Research Laboratory (AFRL/SNH)is in the process of designing and fabricating one of the 675 flat panel subarrays.

GEODESIC DOME PHASED ARRAY ANTENNA

The general configuration for a spherical array consists of a large number of radiating elements placed on a spherical surface as schematically shown in Fig. 1. The basic theoretical and experimental aspects of spherical phased arrays are given in [7-9]. For a given beam direction only a sector of the array elements is excited while all other elements are turned off. The active sector is the area encompassed by a cone angle of $2\alpha_0$ degrees, with its axis coinciding with the antenna beam direction, and is the part of the sphere that is turned on to receive (or transmit) electromagnetic energy. Beam scanning is accomplished by activating different sectors of the spherical surface. All array elements in the active sector are phased to produce an equi-phase front normal to the desired beam axis. Each array element must have an RF on/off switch and a phase shifter. The radiating elements in the active sector are assumed to have symmetry in the plane perpendicular to the axis of the antenna beam, and consequently a spherical array can be used to cover the hemisphere with practically identical beams. Thus, in contrast to other array configurations which suffer from beam degradation as the beam is steered over wide angular regions, spherical arrays can provide uniform patterns and gain over the entire sky. In addition, in [10] we have shown that the spherical array has much lower polarization losses and mismatch losses in comparison to multi-sided pyramid array structures. Furthermore, in contrast to conventional multi-face pyramid structures which suffer from gain degradation due to beam squint as the frequency changes, spherical arrays have no beam shift vs. frequency, resulting in much wider signal bandwidth [10].

To illustrate this, Figs. 2 and 3 compare the gain patterns of the $10m$ spherical array and an equivalent planar array with the aperture equal to projected area of 120 degree active sector on the sphere. Specifically, Fig. 2 exhibits the patterns, at a center frequency of 2.000 GHz with the main beam pointing in the z-direction, which is broadside for the planar array. We assumed that the planar array is impedance-matched at broadside with no polarization loss. Consequently, it has about 1.3 dB more gain at the peak of the beam than the spherical array, which has about a 0.33 dB impedance-mismatch loss and a 0.92 dB polarization loss. Changing the frequency to 2.010 GHz, and the beam pointing direction to $\theta_0 = 60^0$, $\phi_0 = 0^0$, we see from Fig. 3 that a spherical array maintains practically the same gain, except for a 0.1 dB reduction due to frequency change, while the planar array has about 6.2 dB less gain (3 dB scan loss, 0.7 dB loss due to beam squint, 0.5 dB impedance-mismatch loss and 2 dB polarization loss, assuming 2:1 axial ratio in the element pattern).

With all advantages that spherical arrays offer, however, they have not been used in practice primarily because implementation of curved beamforming network (BFN)/radiators, fabrication, and assembly are much more difficult than for the architectures based on planar array geometry. A Geodesic Sphere/Dome Phased Array Antenna that preserves all the advantages of spherical arrays while its fabrication is based on well-developed, easily manufactured, planar array technology is proposed and described in [2-6,10]. It is constructed with many near-equilateral triangular planar subarrays arranged in an icosahedral geodesic dome configuration. This "faceted" dome antenna provides communication function for SATOPS and radar function for air/space surveillance with full hemispherical coverage while exhibiting the following advantages over the conventional pyramid-like and conformal array structures:

1. Keeping the architecture locally planar and globally spherical allows the array to be constructed in flat panel subarrays which are assembled to form the hemispherical dome structure. This is technically and economically viable because the design avoids the fabrication complexity associated with conformal (curved) arrays since the subarray fabrication is based on well-developed, easily manufacturable planar array technology. Moreover, the geodesic dome is a practically realizable structure with well-known mechanical design and fabrication techniques [11,12];

2. The Geodesic Dome antenna preserves all the advantages of spherical phased arrays [4,10] such as: uniform beams over a hemisphere; high gain, high instantaneous bandwidth, low mismatch and polarization losses, and low life cycle cost. Above all, it requires about 20% fewer radiating elements and transmit/receive (T/R) modules than other array configurations.

We have designed a geodesic dome phased array antenna that meets basic requirements for Space-ground link system (SGLS) and Unified S-band (USB) satellite operation as shown in Fig. 4. The antenna, about $10m$ in diameter, will support two independent Tx beams and two independent Rx beams. It consists of 675 flat panel facets (subdivision frequency $\nu = 6$). One of the panel subarrays is presently being fabricated and will be tested by AFRL/SNH. Each panel consists of a multi-layer beamforming network (BFN), 78 wide-band circularly polarized (CP) radiating elements and T/R modules, a beamsteering controller/computer (ACC), and software that will seamlessly integrate the geodesic dome antenna with the existing US Air Force Satellite Control Network. The controller, in addition to performing the present dish antenna functions, will be capable of exploiting all "nice" features of a phased array antenna such as multiple, simultaneous, independent beams, fast beam switching/steering, adaptive pattern control, etc., for improved SATOPS.

The BFN distributes the RF power to, and combines the RF signals from, individual transmit/receive (T/R) modules. It accommodates two independent transmit and receive beams (four total beams) with full duplex operation. Low cost, multi-layer BFN including radiating elements was designed by Alpha Omega Electromagnetics, LLC [13]. As shown in Fig. 5, the multi-layer BFN structure consists of four RF feed layers and several layers for DC power and digital control signals to the T/R modules. The corporate feed of the typical RF- layer is shown in Fig. 6.

Broadband microstrip elements are integrated with BFN, Fig. 5. Each patch is fed by two orthogonal probes capacitively coupled to the BFN. The element performance was simulated with finite element code for infinite periodic structures [14]. Good theoretical performance was demonstrated for input VSWR of less than 2:1 and axial ratio of less than 3 dB in conical scan volume of 60 deg in frequency band 1.7-2.3 GHz.

The T/R modules have been designed, fabricated and tested by Princeton Microwave Technology, Inc. As seen, the T/R module connects to a multi-layer BFN on one side, and to the wide-band, dual-linear polarized, stacked patch radiating element on the other side. The T/R modules can be reconfigured by ACC software to perform communication and/or radar functions. Extremely low-cost, commercial-off-the-shelf (COTS) components and manufacturing techniques developed by the wireless and PCS industry have been employed. The design details with specifications and performance data are given in [15].

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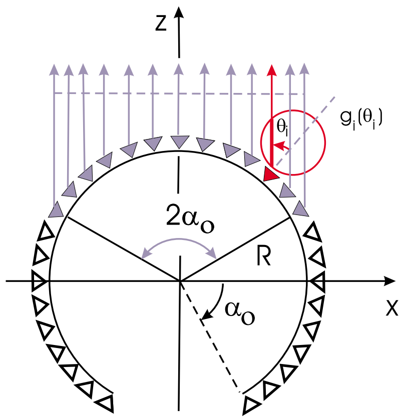

Figure 1: Spherical phased array - basic principle of operation

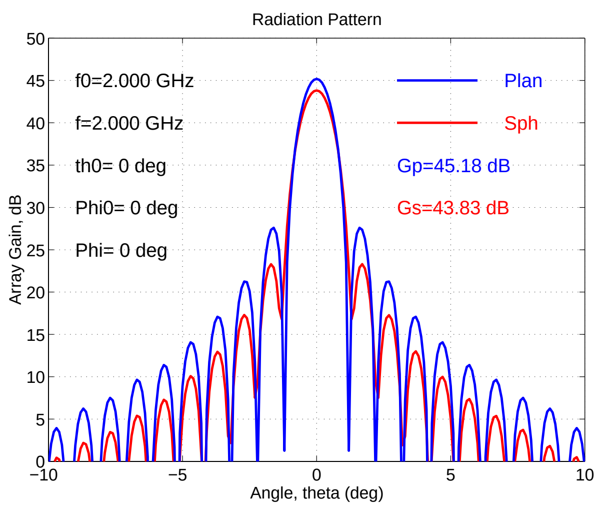

Figure 2: Radiation pattern, $\phi = 0$ cut

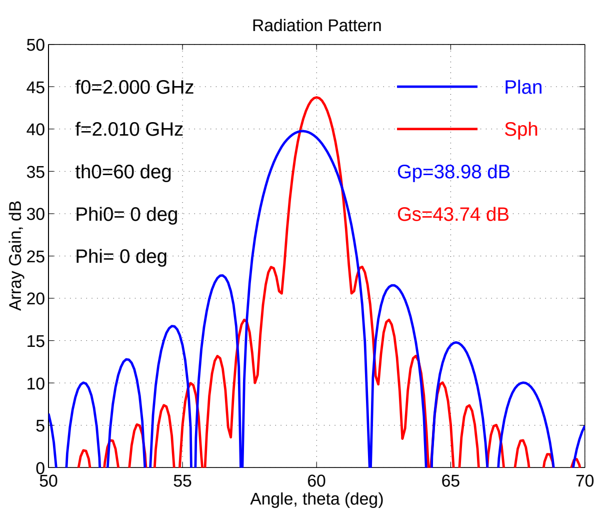

Figure 3: Radiation pattern, $\phi = 0$ cut

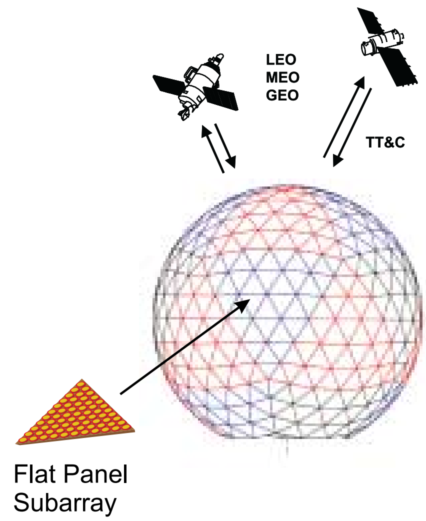

Figure 4: The geodesic sphere phased array antenna (subdivision frequency, $\nu = 6$)

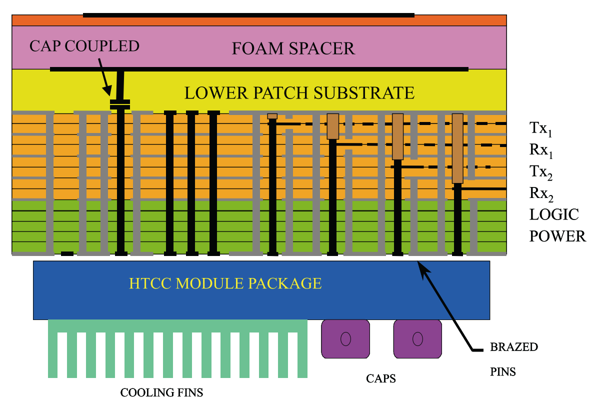

Figure 5: Broadband radiating element integrated with multilayer BFN and T/R module [13,14]

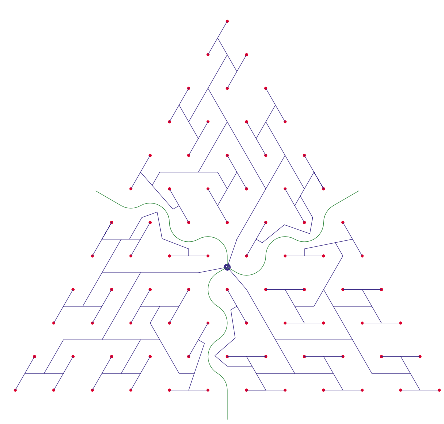

Figure 6: RF-Corporate feed layer of BFN [13]