

Forward Scatter Radar for Future Systems



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ANTENNAS AND RADAR SYSTEMS FOR INTEGRATING NAVIGATION AND COMMUNICATION CAPABILITIES WITH WEAPON PLATFORMS

We are in the age of electronic warfare, in which radar and communications technologies are integral components of weapon systems. The development of technologies that advance our ability to execute electronic attack, provide electronic support, and uphold electronic protection on weapon systems is currently a priority within the Department of Defense. During previous global conflicts the technological development of electronic countermeasure, radar and communication systems, and electronic counter-countermeasures was at a feverish pace. The best technologies in each area



Director's Corner

provided a tactical advantage over the adversary on the battlefield. More than half a century after WWII, radar is still a critical element to every defense program.

The history of radar can be traced back to the origin of the field of electromagnetics. After James Clerk Maxwell first suggested the existence of electromagnetic waves, Heinrich Hertz demonstrated that electromagnetic waves would be transmitted through certain materials and reflected off of others. In 1906, German inventor Christian Hülsmeyer received a patent (No. 810,150) for a wireless transmitting and receiving mechanism for electric waves. This device could observe the presence of a ship at a distance of up to three kilometers. However, it was several more decades until a complete radar system was developed (i.e., system capable of object detection and distance identification). The US Navy referred to the concept as Radio Detection And Ranging, thus forming the acronym RADAR. In 1939, the first US radar to enter operation was deployed on the *USS New York* battleship. This milestone was

achieved after more than 15 years of research and development by the Naval Research Laboratory (NRL), which began when NRL scientists unintentionally made their first radar detection as they conducted communication experiments. This was in effect the first demonstration of a bistatic, continuous wave radar system. A brief list of milestone achievements, such as this, is presented in the article on forward scatter radar systems included in this issue of the *WSTIAC Quarterly*. The article also provides a background on multistatic and forward scatter systems.

For the past nearly 90 years, NRL has been working on researching and developing radar technologies. That work continues today, because radar is still a critical component of all weapon and defense systems. In the area of communication, NRL has also led the development of antenna technologies for communicating with navigation satellites. This issue of the *WSTIAC Quarterly* presents an article on reducing the cost and complexity of phased array antennas that can be used to communicate with geostationary satellites.



The XAF radar system on the USS New York. This was the first operational US radar, and it was invented, developed, and installed by the NRL. (Photo courtesy of NRL)

The development of electromagnetic devices and systems is no less important today than it was during WWII. Any technological and tactical advantage that we can give our weapon systems and warfighters is important. Thus as

long as our military is required to be capable of handling operations across the globe, the importance of communication and navigation satellites and our development of radar and antenna technologies will continue to grow

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Forward Scatter Radar for Future Systems

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ABSTRACT

This paper reviews the concept of a forward-scatter radar (FSR) which exploits the enhanced bistatic radar cross-section of a target in the forward direction (as opposed to the conventional back-scatter direction). FSR has the potential to reliably detect and track small air-vehicles with high sensitivity. Fundamentals of radar (including monostatic, bistatic, and multistatic) and a brief history are presented. Limitations of FSR radars are presented along with methods for overcoming them based on new technologies – accurate electromagnetic simulators, mesh networks, global positioning system (GPS) location of illuminators and receivers, and smaller and lighter transmitters and receivers. A program plan to accomplish these goals is given in the Appendices, along with an example of solving the target location for three transmitters and one receiver.

INTRODUCTION

In conventional radar configurations, the transmitter and receiver are collocated, and thus can be considered monostatic radar. Conversely, bistatic radar is composed of a transmitter and a receiver that are physically separated. Multistatic radar has transmitting and receiving apertures located in various positions. A recent paper makes it clear why a new look at multi-static systems is necessary at this time.

“Compared to conventional radars, multistatic radars have the potential to provide **significantly improved interference-rejection**, tracking and discrimination performance in **severe EMI and clutter environments**. They can potentially provide significantly improved target tracking accuracy because of the large baseline between the various apertures. The resulting angular resolution can be orders of magnitude better than the resolution of a monolithic system (single large radar). The same angular resolution can provide improved interference rejection.”[1]

In addition, orthogonal frequency division multiplexing (OFDM) can improve the performance of a radar network, in which each radar system would be either monostatic or bistatic. This configuration enables the classification of objects by ensuring each object is observed from different angles.[2]

What is Forward Scatter Radar?

The concept of forward scatter radar can be briefly described as a bistatic or multistatic configuration where the bistatic angle is close to 180 degrees. The bistatic angle is the angle at which the transmitted electromagnetic energy is scattered off of the target and received, as shown in Figure 1.

As shown, a typical transmitting site contains an oscillator, direct digital synthesizer (DDS), amplifier, driver, and antenna. A typical receiver site contains an oscillator, mixer, DDS, and acquisition system, and antenna. The three-dimensional location of each FSR is obtained

through individual links with the GPS satellites. These links require a separate GPS antenna and receiver.

PHENOMENOLOGY

The forward scattered lobe was first predicted by Gustav Mie in the early 1900s.[3] It is produced when an electromagnetic wave illuminates an object and casts a shadow. The shadow occurs because electrical currents are induced in the object whose secondary radiation cancels the incident wave. By Babinet’s Principle, these currents are equivalent to the radiation from currents that flow on a planar aperture whose shape is the same as that of the shadow, as shown in Figure 2.[4]

Another explanation is that the interference between the inci-

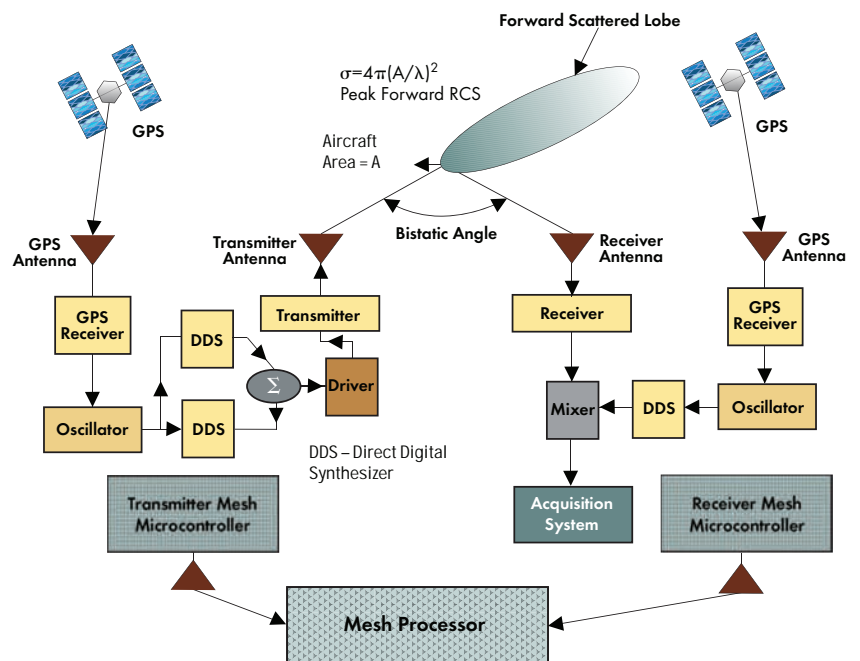


Figure 1. Forward scatter radar layout.

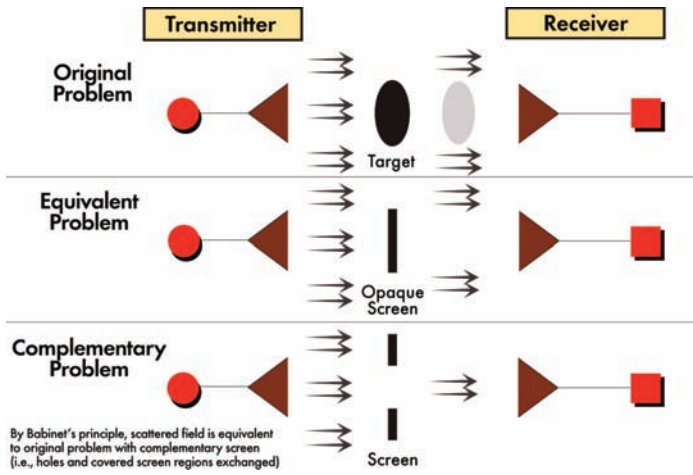


Figure 2. Illustration of Babinet's Principle.[5]

dent and scattered wave front produces a wave front that is nearly the same as the incident wave front except for having a shadow region that corresponds to a "hole" in the wave front. This radiation is independent of the materials from which the body is made. Several studies have confirmed these results experimentally.[6]

Using these principles, the radiation pattern in the forward scattered region is proportional to the magnitude of the two-dimensional complex Fourier transform of a uniform aperture shape that is the same shape as the shadow, as given by Equation 1.[5]

$$\sigma = \frac{4\pi}{\lambda^2} \left| \iint \exp(j\vec{k}\vec{r}) dS \right|^2 \quad \text{Equation 1}$$

Where

- \vec{k} – Wavevector to field point, $k = \frac{2\pi}{\lambda} (\cos(\theta_x), \cos(\theta_y), \cos(\theta_z))$
- λ – Wavelength
- k – Wavenumber, $k = \frac{2\pi}{\lambda}$
- \vec{r} – Aperture vector to x,y point
- dS – Area elements, $dS = dx dy$
- $\cos(\theta_x), \cos(\theta_y), \cos(\theta_z)$ – Direction cosines

This pattern may be computed in various ways including approximating the shadow shape by a polygon.[7] These relationships can be simplified to yield the peak radar cross section (RCS), σ_{pk} , of the forward scattered lobe, as given by Equation 2.[7]

$$\sigma_{pk} = 4\pi \left(\frac{A}{\lambda} \right)^2 \quad \text{Equation 2}$$

Where

- σ_{pk} – Peak RCS of forward scattered lobe
- A – Shadow Area

Similarly, the approximate angular width of the forward scattered lobe is determined by Equation 3.[7]

$$\theta(\text{degrees}) = \left(\frac{180}{\pi} \right) \left(\frac{A}{L} \right) \quad \text{Equation 3}$$

Where

- L – maximum width or height of shadow

To get an idea of the magnitudes, the peak RCS and azimuth and elevation beam widths at L-Band and S-Band for a sample

unmanned vehicle can be estimated as follows. The overall length and width are assumed to be 5 ft (1.5m) and 2 ft (0.6m), respectively. The side projected area is 0.9m². For L-Band (1GHz) the wavelength is 0.3m, and for S-Band (3GHz) the wavelength is 0.1m. The peak radar cross sections are:

$$\sigma = 4\pi \left(\frac{A}{\lambda} \right)^2$$

$$\text{For L-Band } \sigma_s = 4\pi \left(\frac{0.9}{0.3} \right)^2 = 113\text{m}^2 = 20.5 \text{ dBsm}$$

$$\text{For S-Band } \sigma_s = 4\pi \left(\frac{0.9}{0.1} \right)^2 = 1018\text{m}^2 = 30.0 \text{ dBsm}$$

The angular widths in azimuth and elevation of the forward scattered beam, θ_{AZ}, θ_{EL} are then:

$$\theta_{AZ} = \frac{180}{\pi} \frac{\lambda}{\text{Length}}, \quad \theta_{EL} = \frac{180}{\pi} \frac{\lambda}{\text{Width}}$$

$$\text{For L-Band } \theta_{AZ} = \frac{180}{\pi} \left(\frac{0.3}{1.5} \right) = 11.4 \text{ deg}, \quad \theta_{EL} = \frac{180}{\pi} \left(\frac{0.3}{0.6} \right) = 28.6 \text{ deg}$$

$$\text{For S-Band } \theta_{AZ} = \frac{180}{\pi} \left(\frac{0.1}{1.5} \right) = 3.8 \text{ deg}, \quad \theta_{EL} = \frac{180}{\pi} \left(\frac{0.1}{0.6} \right) = 9.4 \text{ deg}$$

As a result, it is more difficult to detect the target returns and avoid false-targets or interference at L-Band compared to that at S-Band. In addition, it is easier to locate the transmitters at L-Band than at S-Band. (More accurate simulation of the electromagnetic scattering from these aircraft can be obtained using 4NEC2, a method-of-moments code based on Numerical Electromagnetic Code (NEC) which is openly available.)

Because of the narrowness of the forward scattered lobe, positioning the 3D location of transmitters with respect to the mesh receiver for an acceptable link margin is an important task. Figure 3 plots the angular beamwidth of the forward scattered lobe versus the length of the object for 300 MHz, 1 GHz, and 3 GHz. Clearly, going to the lower frequency increases the width of the forward scattered lobe.

Figure 4 presents a simple two-dimensional example will be presented in which the target's range from the transmitter is determined via measurement of target's azimuth (az) angle with respect

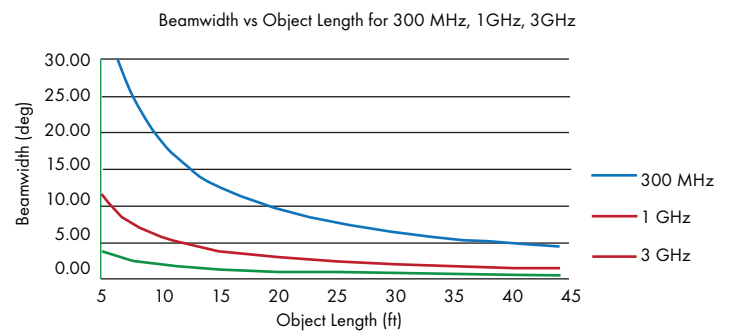


Figure 3. Beamwidth of forward scattered lobe versus length of object.

Table 1. Peak RCS of a sample unmanned vehicle at L- and S-Band.[8, 9]

UAV	Overall Length (ft)	Width (ft)	L-Band Peak RCS (dBsm)	L-Band Angular Widths Azimuth, Elevations (deg)	S-Band Peak Side RCS (dBsm)	S-Band Angular Widths Azimuth, Elevation (deg)
Sample Vehicle	5.0	2.0	20.5	11.4, 28.6	30.5	3.8, 9.4

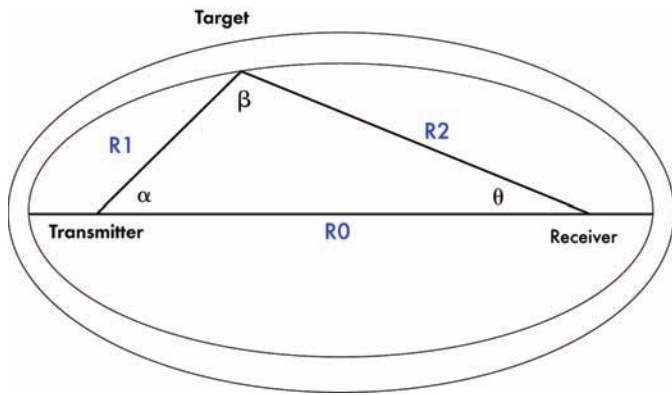


Figure 4. Bistatic triangle in which constant range contours of the monostatic system, become ellipsoids with the receiver and transmitter at the foci.[10]

to the receiver, bistatic differential range (BR), and range between receiver and transmitter (R1).

$$\Delta R = c\Delta T = (R1 + R2) - R0 \quad \text{Equation 4}$$

$$R2 = \frac{\Delta R}{2} \left[\frac{\Delta R + 2R0}{\Delta R + R0(1 - \cos \theta)} \right] \quad \text{Equation 5}$$

Where

- R0 – Baseline distance between transmitter and receiver
- R1, R2 – Distances from transmitter to target, target to receiver, respectively
- θ – Angle between baseline and line from receiver-to-target
- ΔR – Distance difference between direct path signal
- ΔT – Time difference between direct path signal and radar signal
- c – Speed of light = 3×10^8 m/s

For typical values of $\Delta T = 10^{-6}$ sec, $\Delta R = c\Delta T = 300$ m, $R0 = 1000$ m, $az = 0$ to 360° , in 5° increments.

Using three transmitters and one receiver, the bistatic triangle can be solved by the method described in Reference [11]. This is described in Appendix I.

HISTORICAL PERSPECTIVE AND CURRENT CHALLENGES

Brief History of Forward Scatter Radar

Forward scatter radar has had a long history of developments. Some milestone events are listed below.

- 1922: First radar detection – demonstration of a bistatic, continuous wave (CW), interference radar to detect a wooden ship (Taylor and Young, Naval Research Laboratory (NRL))
- 1930: First aircraft detection – accidental detection of an aircraft

- several kilometers from the radar transmitter (Hyland, NRL)
- 1932: Long range (50 nautical miles) aircraft detection (Taylor, Young, and Hyland)
- 1950s: Development of semiactive missile seekers
- 1960s: Development of radar to detect low-altitude, bomber aircraft – Brigand and Flutter (AN/FPS-25)
- Developments from 1970s through 2000s:
 - Survivability against antiradiation missiles (ARMs)
 - Project MAY BELL 1970 (Declassified in 1996). See Appendix I.
 - Enhanced performance in specific scenarios
 - Smaller, lighter, more efficient transmitters and receivers
 - GPS links
 - Silent Sentry System[12] – Uses existing FM or TV radiation to locate targets

Why Forward Scatter Radar Now?

Forward scatter radar is not a new concept, but there have been some significant challenges. Some primary issues with forward scatter radars have been outlined in literature, and these are listed below.[1, 2, 11]

1. Need for cooperation between sites. In particular, wide-band data links are needed to allow correlation or interferometric detection methods to be used.
2. Difficulty of coordinate conversion, arising from hyperbolic contours or constant time difference between each transmission and receiving station.
3. Need for high rejection of electromagnetic interference (EMI) jamming and clutter that is not offered by monostatic radar.
4. Use of orthogonal frequency division multiplexing for radar and communications

Limited coverage is another shortcoming of the forward scatter geometry due to a narrow angular width of the forward scattered lobe. The coverage can be estimated using the radar range equation (see Equation 6), for which typical parameter values can be used to determine the signal-to-noise ratio (SNR).

$$SNR = \frac{P_{avg} G_t G_r \lambda^2 \sigma}{(4\pi)^3 U^2 R^2 L k T \left(\frac{1}{\tau}\right) F} \quad \text{Equation 6}$$

Where

- P_{avg} – Average transmitter power
- G_t – Transmit antenna gain
- G_r – Receive antenna gain

Table 2. Radar parameters for SNR.[14]

Parameter	Symbol	Value	+/- dB
Average Power (W)	P_{avg}	3360	35.3
Transmit Gain (dB)	G_t	3.0	3.0
Receive Gain (dB)	G_r	3.0	38.6
Wavelength (m)	λ	0.1	-20
Bistatic RCS (m)	σ	1.0	0
Range between transmitter and target (nautical miles)	U^2	25	-93.3
Range between receiver and target (nautical miles)	R^2	25	-93.3
Loss (dB)	L	15.1	15.1
kT (dB)		-204	204
Integration time (s)	$1/\tau$	0.1	-10
Noise figure (dB)	F	2.8	-2.8
$4\pi^3$		1984	-33
SNR (dB)		13.4	13.4

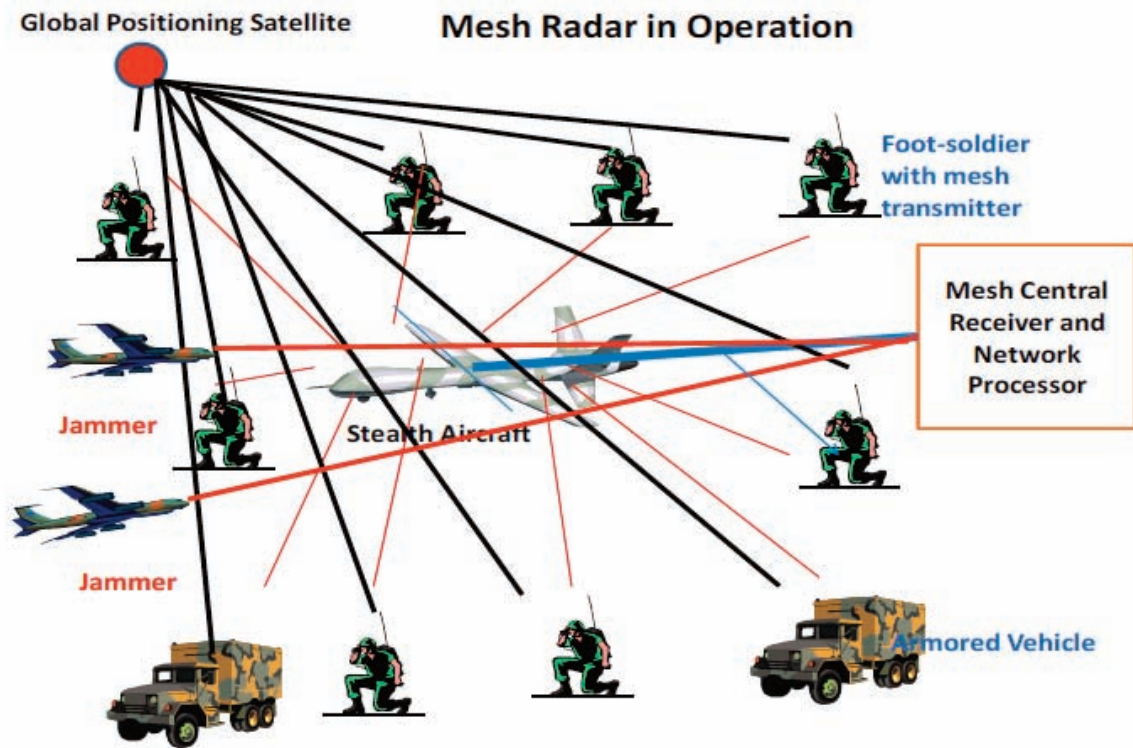


Figure 5. Illustration of mesh radar in operation.

- U – Transmitter to object distance
- R – Receiver to object distance
- L – Loss
- k – Boltzmann’s constant
- T – Noise temperature
- τ – Integration time
- F – Noise figure

Values of these variables for solid state phased array radar are provided in Table 2.[13, 14]

These are still challenging issues but now they have realistic solutions that should be reinvestigated. These include:

1. Management of complex transmitter/receiver geometries. This has been accomplished through the use of many transmitter or receiver sites. Each transmitter and receiver has its own GPS link. These links supply the site’s three dimensional coordinates. Small and light GPS units have already been demonstrated in automobiles. Mesh networks have provided reliable military communication between sites. Multiple sites plus the potentially long baselines result in improved accuracies, better interference rejection, and improved tracking and navigation.[1]
2. A mesh processor unit requires a special antenna, receiver, signal processor, and data processor that can detect the target and measure its elevation and azimuth. This antenna must have sufficient angular and azimuth resolution to be able to detect the target return. Detection of targets in strong Doppler modulated clutter. Techniques involving clutter excision have demonstrated successful performance (e.g., bistatic alerting and cueing system). These involve:
 - a. Deterministic elimination of main lobe clutter
 - b. Range or range-doppler averaging constant false alarm rate (CFAR) for homogeneous sidelobe clutter
 - c. Sidelobe blanking of sidelobe discretets

3. High time-bandwidth product waveform
4. Rejection of ambiguous targets
 - a. Algorithms have been found to eliminate ghost targets from the target displays.
5. Direct-path cancellation has been demonstrated.
6. Synchronization between transmitters and receivers can be achieved by utilizing coded waveforms.
7. Smaller and lighter transmitters and receivers have been developed that can be easily carried by foot-soldiers.

An illustration showing the features of a potential system incorporating these achievements is shown in Figure 6. A program plan is needed to implement such a system. An outlined plan is given in Appendix III.

CONCLUSION

In conclusion, the following milestones must be achieved before an FSR can be considered feasible:

1. Increase range of RF signals using efficient GaN transistors
2. Design waveform for optimum clutter and EMI rejection
3. Develop mesh processor that meets radar detection and false-alarm requirements with jamming
4. Develop simulator to estimate performance of mesh network in typical scenarios with jamming
5. Innovate transmitting and GPS antennas for foot-soldier and armored vehicles
6. Develop receiving antenna with sufficient azimuth and elevation resolution in jamming environment

APPENDIX I: Calculation of Aircraft Position with Coupled Non-linear Equations for 3 Transmitters and 1 Receiver

The unknowns are: R_0 , x_A , y_A , z_A , where

- R_0 – Range from aircraft to receiver
- x_A , y_A , z_A – Cartesian coordinates of aircraft

x_0, y_0, z_0 – Cartesian coordinates of receiver
 x_1, y_1, z_1 – Cartesian coordinates of transmitter #1
 x_2, y_2, z_2 – Cartesian coordinates of transmitter #2
 x_3, y_3, z_3 – Cartesian coordinates of transmitter #3

The solutions are obtained by solving the following equations:

$$\begin{aligned}
 R_0^2 &= (x_1 - x_A)^2 + (y_1 - y_A)^2 + (z_1 - z_A)^2 \\
 (Q_1 - R_0)^2 &= (x_1 - x_A)^2 + (y_1 - y_A)^2 + (z_1 - z_A)^2 \\
 (Q_2 - R_0)^2 &= (x_1 - x_A)^2 + (y_1 - y_A)^2 + (z_1 - z_A)^2 \\
 (Q_3 - R_0)^2 &= (x_1 - x_A)^2 + (y_1 - y_A)^2 + (z_1 - z_A)^2
 \end{aligned}$$

Where

Q_1, Q_2, Q_3 – bistatic range measurements

Powell's method or any root-finding algorithm is used to find the zeros of these equations while the incorrect or invalid solutions are discarded.[15]

APPENDIX II: BUOY TACTICAL EARLY WARNING

The Project "May Bell" Technical Workshop, sponsored by Raytheon Company, and held in Burlington, MA, on May 18-22, 1970, is evidence of an early interest in this the application of passive radar. The list of attendees of that conference reads like a "Who's Who" of the defense and intelligence communities. One of the subordinate projects within Project "May Bell" that was discussed at that conference was "Project Aquarius," sponsored by the Advanced Research Projects Agency (ARPA Order No. 1459), and conducted by the Sylvania Electronic Defense Laboratories, Mountain View, CA. "Project Aquarius" was a research project, designed to test the feasibility of detecting submarine-launched ballistic missiles (SLBMs) and low-flying aircraft, using a bi-static, passive radar system Buoy Tactical Early Warning (BTEW).

BTEW-I

The BTEW-I concept involves detection of low flying aircraft at over-the-horizon (OTH) distances by illuminating the target with a transmitter located on an off-shore buoy and reception of the target echo signal at a shore based receiver site via a ground wave propagation mode. Feasibility tests were conducted off the Florida coast using a transmitter located on Carter Cay (just north of Grand Bahama Island) and a receiving station at Cape Kennedy. The path length was 300 km and the target was a Navy P3V Aircraft.

The feasibility tests were successful and demonstrated that standard radar calculation techniques, with application of Barrick's loss model, could be used with reasonable confidence to describe the coverage afforded by the BTEW-1 concept.[16] The tests then established and validated a model for calculating coverage.

Several variations of the original concept were examined, using the model, in a first attempt to assess potential capabilities in application to the defense of the CONUS, of special strategic areas, and of the fleet. The results of these analyses indicate that surveillance can be maintained out to ranges of 300 to 400 km from a shore station with systems of practical dimensions. For example, the east coast of the US from Nova Scotia to the Straits of Florida could be covered by about 10 shore stations and a fence of 30 buoys.

Although the primary objective of the Florida tests was to detect low flying aircraft, there was also the opportunity to observe the launch of a Poseidon missile from sea. Excellent detection results were obtained. No analysis has been attempted to describe the early

warning potential of this kind of system against SLBMs; however, it seems apparent that significant coverage of this threat can be achieved with a very small number of terminals.

BTEW-2

The BTEW-2 concept involves target detection at long OTH ranges by illuminating the target with a buoy mounted transmitter and reception of the target signal at a remote receiver site via sky-wave. Tests of this concept were successful but indicated that coverage would be very limited for any presently practical level of buoy transmitter power. After this project was demonstrated, it was moth-balled by the Navy and never used again.[17]

APPENDIX III: PROGRAM PLAN

To realize the design illustrated in Figure 5, a program plan is needed:

- Proof-of-Concept Demonstration
- System Engineering
- Hardware & Software Design
- Fabrication
- System Test
- Field Demonstration
- Laboratory Demonstration
- Data Analysis
- Producibility and Cost Analysis

To demonstrate performance, an engineering study is first needed.

- I. Design, fabricate and test components – transmitter and transmitting antennas, receiver and receiving antenna, mesh processor, mesh network, signal and data processor, software for detection and tracking.
 - A. Consulting help from mesh network experts: Meshdynamics and Rajant
 - B. Develop simulation to verify and optimize designs that exploit new software packages
 1. Accurate estimates of bistatic RCS of targets using
 - i. Calibrated Measurements
 - ii. Fast Electromagnetic Codes – HFSS, AWR, NEC2, NEC4, 4NEC2, COMSOL, FEKO, CST
 2. Accurate clutter, noise, jamming models
 3. Terrain characteristics
 - C. Fabricate test bed
 1. Measure performance
 - i. Reliability
 - ii. Maintainability
 - iii. Availability
 2. Review results by independent authorities
 3. Determine modification to test bed
 4. Go or no go?
 - i. If go, then proceed with full scale development

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Low Cost Multibeam Phased Array Antenna for Communication with Geostationary Satellites

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INTRODUCTION

The United States Navy uses both military and commercial satellites for communications purposes. In the existing shipboard communication system, a separate antenna, most likely a reflector antenna is used to communicate with each satellite. It is becoming more likely that reflector antennas will make way for the more functional phased array antennas (PAA). PAAs have the advantage of providing multi-function operation and possessing a smaller RCS.[1]

A planar array antenna is made up of $N \times M$ elements that can in principle be used to communicate with several satellites simultaneously by generating multiple independent beams and scanning them in the two orthogonal planes. However, it is very expensive to implement these phased array antennas because they require a total of phase shifters for each beam that needs to be scanned in the two orthogonal planes of the antenna.

The objective of this paper is to describe a technique that can be used for the special case of satellites in the GEO orbit. For these set of satellites, the scanning requirement in the vertical plane is relatively small and is a function of the earth station location (given in terms of the longitude and latitude). A study done by Amitay and Gans[2] discussed a method that allowed PAAs to scan only in one plane while allowing communication with several GEO satellites. However, this technique would work only for a stationary earth station. As the location of the earth station changed, it was necessary for the authors to redesign their antenna system.[3] The objective of this paper is to discuss a method that builds upon the technique discussed in references [2, 3] so as to design a unique concept in which a single planar array (located on a mobile earth station such as a naval ship) will not need to be re-designed each time it was moved to a new location – not a feasible approach for an antenna on a mobile earth station (like Navy ship). To communicate with several GEO satellites, in the proposed method, the beam of an array need to be scanned in one plane only. In the orthogonal plane, the beam position can be fixed to discrete angles using one or two hard-wired squints, which can be implemented using simple, discrete, transmission line lengths at each element. Using this approach, it is possible to reduce the number of phase shifters from NM to only M , thereby reducing the complexity and cost of mobile earth station PAAs significantly.

The paper is divided into three sections. In the next section, a short discussion of GEO satellites has been given followed by a detailed description of the linear array scanning method and a discussion on how this technique will help reduce the complexity of a PAA.

GEOSTATIONARY SATELLITES

A GEO orbit is a special case of the geosynchronous orbit. A geosynchronous orbit is a path around the earth with an orbital period that matched the Earth's sidereal rotation (i.e., the satellite hovering in

this orbit will take 24 hours to go one round of its path). This synchronization means that an observer at a certain location of the Earth will be able to observe the satellite at exactly the same point every day. Every geosynchronous orbit has a non-zero inclination or eccentricity, the satellite foot print on the Earth looks like a figure "eight" with a satellite is visible at the same place once every solar day. The special case of the geosynchronous orbit is a circular orbit located directly above the Earth's equator[4]. This special orbit is referred to as the GEO orbit. For this paper, we are interested in satellites hovering only in the GEO orbit. GEO orbits are important because satellites in this orbit appear stationary with respect to a fixed point on the Earth (i.e., they do not trace a figure eight unlike the satellites in the geosynchronous orbit). This means that an antenna on the surface of the Earth can point to a fixed location to maintain a constant communication link with the satellite (e.g., Dish Network dishes).

METHOD OF LINEAR SCANNING

To track a GEO satellite accurately with a PAA, the phases of each element of the array must be controlled to direct the beam in the two orthogonal planes. For this two-dimensional beam scanning, a complicated phase control system is needed. Since many of the satellites that a naval ship needs to communicate with are GEO satellites, it is possible to scan the beam in only one direction as long as the GEO satellites are located in the cardinal plane of the array's sine space.

Figure 1 shows the geometry of the problem. The coordinate system of the Earth is represented by (X_0, Y_0, Z_0) , while the coordinates of the antennas located on the Earth surface is represented by (X_e, Y_e, Z_e) . The local coordinates of the antennas itself are given by (X, Y, Z) . All these coordinates are shown in Figure 2. Figure 2 defines a segment of the GEO orbit as the GEO arc (GA). The GA can be defined as either the part of the GEO orbit that the ship antennas need to scan or the only part of the arc that is visible from the ship. In the study discussed in this report, we are only interest-

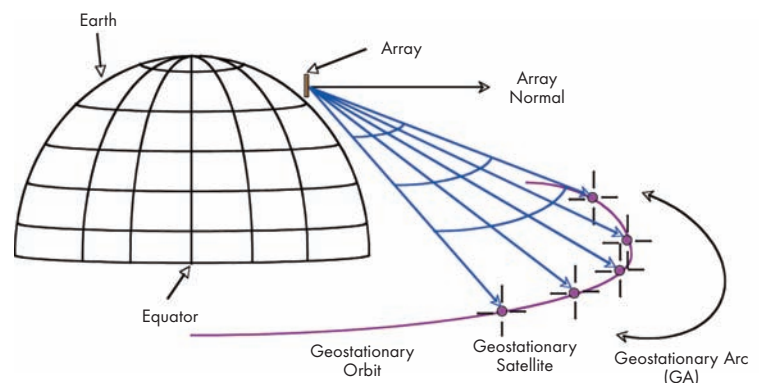


Figure 1. Earth and earth station antenna array and geo satellite geometry.

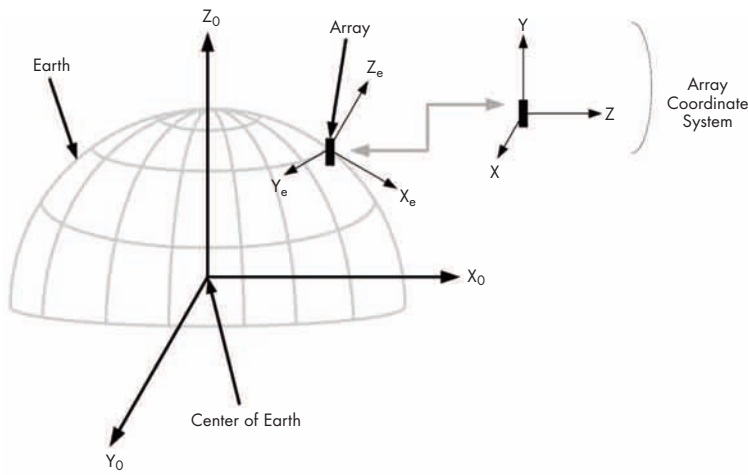


Figure 2. Representation of the three coordinate systems, centered at earth, earth station and antenna array.

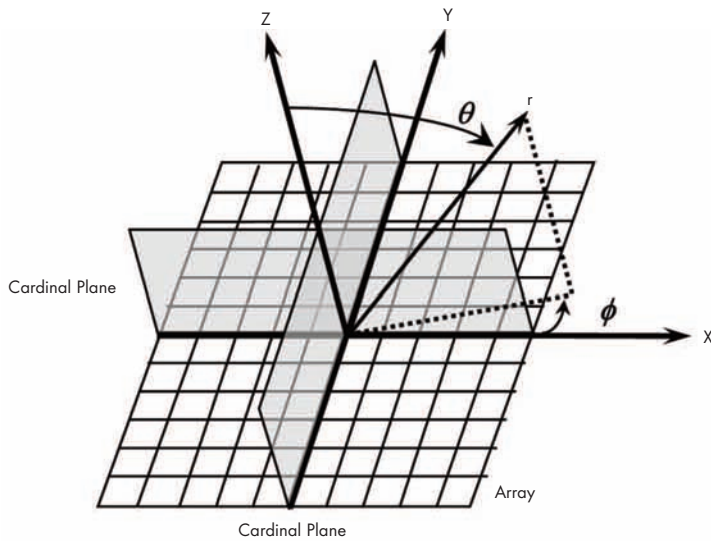


Figure 3. Rectangular array cardinal planes.

ed in the satellites that are located on the GA.

Figure 3 shows the cardinal plane for a planar array. The elements of this array are located on a rectangular grid and the cardinal planes are the x and y axes. In other words, if the y -axis is the vertical axis of the array (as shown in Figure 2) then by using the proposed method, the array will need to scan the beam in only the x - z (horizontal) plane of the array.

The proposed method can also be used in the case when there is a need to communicate with two satellites located in a geosynchronous orbit by mechanically positioning the antenna such that the two satellites now lie in one of the cardinal planes of the array. Linear scanning will then be sufficient to communicate with two satellites.

Details of the Linear Scanning Technique

First, consider the case when the y -axis (Y) of the array is parallel to the Z_0 axis as shown in Figure 2. If the earth station is on the equator, then the GA can be mapped exactly onto the array's cardinal plane (x - z). However, as the earth station moves away from the equator (increasing latitude), it is possible to only approximately map the GA onto a plane parallel to the cardinal plane (see Figure 4). Figure 4 shows an example of a GA mapped onto the cardinal plane of an array for increasing latitudes. At the equator, the GA maps exactly onto the x - z cardinal plane but as the latitude increases, the mapping is no longer exact. This means that the array will

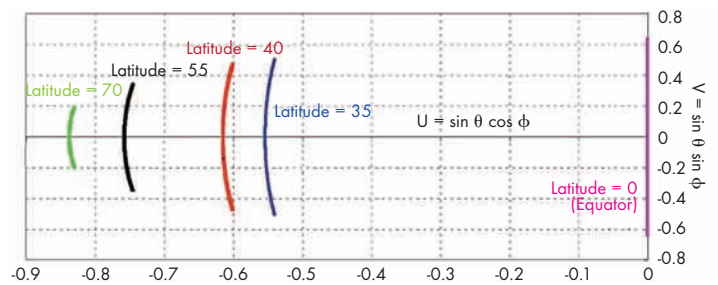


Figure 4. Mapping a 60° GA onto the cardinal planes of an array located at increasing latitudes.

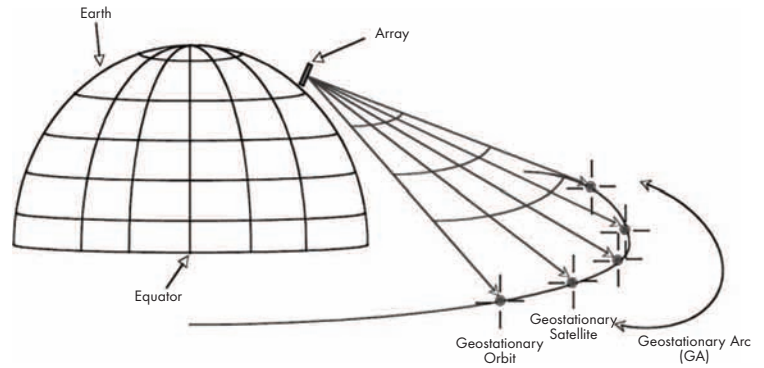


Figure 5. Tilting of planar array to point the beam to cover GA.

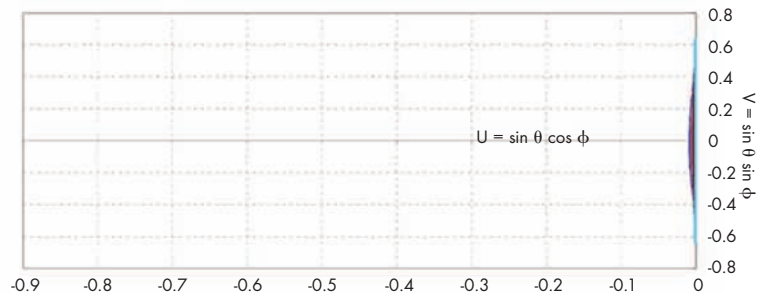


Figure 6. Effect of tilting on the mapped GA curves.

need to scan the beam in both planes to set up a communication link with the satellites from a mobile earth station.

Now, if the array were to be tilted such that the array normal pointed at the GA as shown in Figure 5, then the mapped GA curves will move very close to the cardinal plane of the array as shown in Figure 6. As the curves get mapped close to the cardinal plane, it is possible to use only a linear scan to track the GEO satellite. However, the errors while tracking the satellite can still be large, as shown in Figure 7, which is the same as Figure 6 on an expanded scale.

Optimization of Hard-Wired Squints

In Figure 7, the mapped curves of the 60° GA deviate at most by 0.6° (will be shown in Figure 8) from the cardinal plane of the antenna. It should be noted, that the mapped curves for a wider angular range for the GA are expected to deviate a bit more from the cardinal plane.

Figure 8 shows the peak deviation, or what is more commonly referred to as the main beam pointing error for the 60° GA as the latitude varies from 0-70°. For the results discussed in this section, the longitude was varied from 70°W-130°W (CONUS) but the results will be valid for any 60° longitudinal range. From Figure 8, it can be observed that the maximum beam pointing error for the assumed range of latitudes and longitudes is about 0.6°. If the vertical beamwidth is wide enough (greater than 1.2°) to cover a beam pointing error of 0.6° without a significant decrease in the antenna

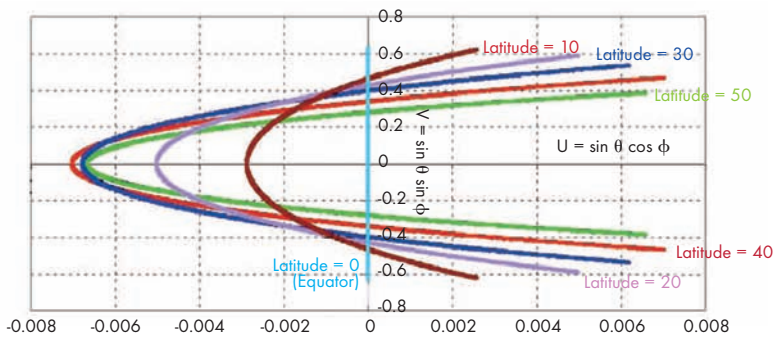


Figure 7. Detail view of Figure 6 – optimum mapping of 60° GA (using only mechanical tilt) onto the cardinal planes of an array located at different latitudes and the center longitude of the 60° GA.

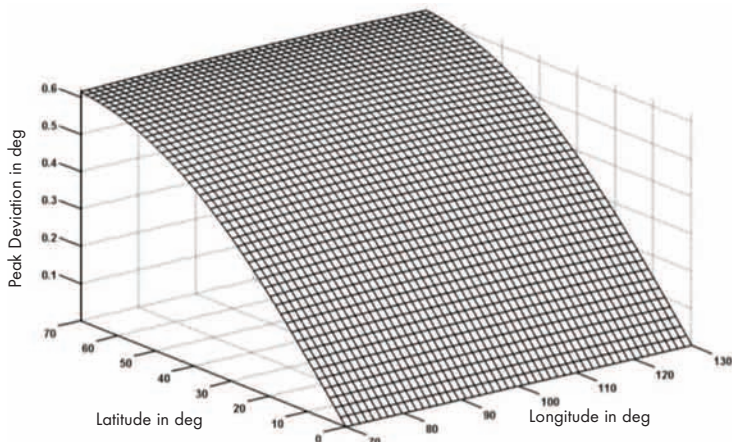


Figure 8. Array beam pointing error as a function of earth station's longitude and latitude using only mechanical tilt.

gain, then it is possible to scan the beam in only the azimuthal direction and still be able to maintain a link with the satellite as the earth station moves from a latitude of 0° to a latitude of 70° merely by mechanically tilting the array.

Practically, PAAs used for satellite communications need beamwidths that are much narrower than 1.2°, hence a beam pointing error of 0.6° is too large. Amitay and Gans[2] in their paper have discussed a method whereby it is possible to significantly reduce the beam pointing error by adding an electronic squint on top of the mechanical tilt at each longitude and latitude position that the earth station moves to. To confirm this, we have calculated the maximum electronic squint that would be needed for each earth station position to minimize the beam pointing error. Figure 9 shows these values. If these calculated electronic squint values were to be applied to the antenna position at the appropriate longitude and latitude position, then from Figure 10, we can determine that it is possible to reduce the beam pointing error to as small as 0.0013°.

This approach, however, involves changing the squint value (using variable squint) for each earth station position, which is difficult to achieve on a moving earth station because using a variable squint is akin to having a limited scan capability in the vertical plane. This is complex and difficult to achieve because new phase adjustments at each element will be needed each time the location of the earth station change. We would instead like to use only one or a maximum of two fixed squints that will allow us to reduce the main beam pointing error such that an antenna with a vertical beamwidth less than 1.0° can be used.

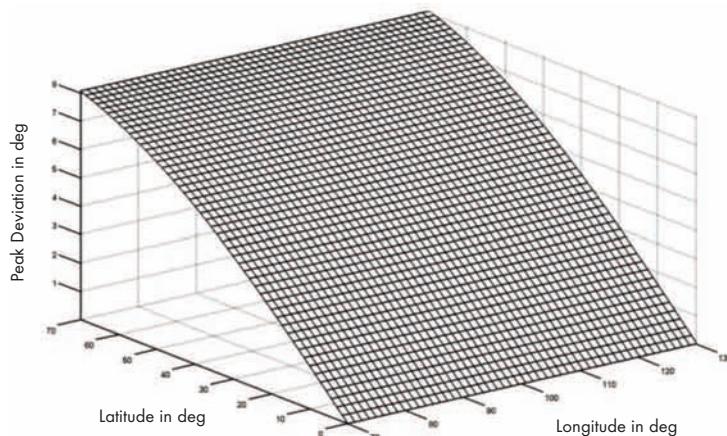


Figure 9. Required electronic squint for different station location.

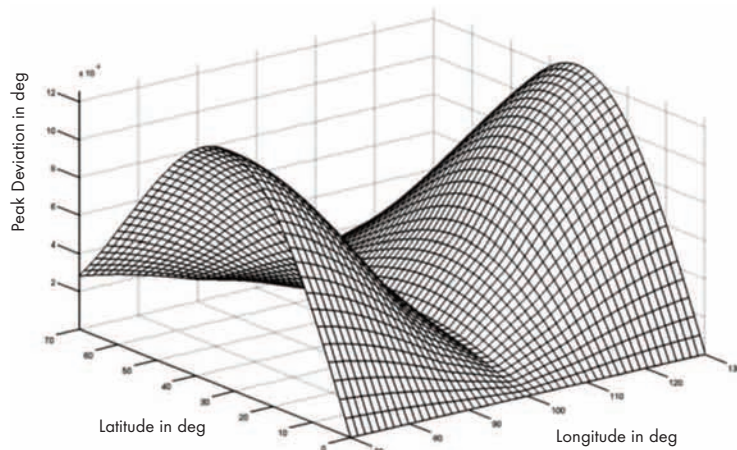


Figure 10. Array beam pointing error for different earth station locations when the electronic squint calculated in Figure 8 are implemented.

One Hard-Wired Squint

In this section, a short description is provided of the steps needed to calculate an optimized value for one hard-wired squint. From Figure 9, we have learned that the maximum electronic squint needed is about 8.04°. So let us start with the assumption that one optimized fixed squint is close to a value of 4.02° (= 0.5 of 8.04°) to cover all the latitudes and longitudes of interest. With this fixed squint value applied at every element in the PAA, calculate the maximum beam pointing error for all latitudes (0-70°) and longitudes (70-130°). Change the electronic squint value by a fixed amount (0.001°) and repeat the above step until the maximum beam pointing for all the latitudes and longitudes is the smallest possible. For this example, it was determined that the maximum main beam pointing error of 0.352° is achieved when a single hard-wired squint of 3.675° is applied at all the elements. Although this main beam pointing error is not as small as 0.0013° which can be obtained if the electronic squint were to be calculated for every location, it is smaller than the error of 0.6° that was obtained when only mechanical tilt was used. The main beam pointing error for all locations in the latitudes and longitudes of interest are shown in Figure 11, when a hard-wired squint of 3.675° is implemented. It may be noted from Figure 11 that the maximum beam pointing error is 0.352° when one optimized squint is used.

Implementing a single fixed squint behind each element is a trivial process that can be realized by placing hard-wired transmission line lengths corresponding to the desired electronic squint value. The corresponding line lengths need to be added behind each element.

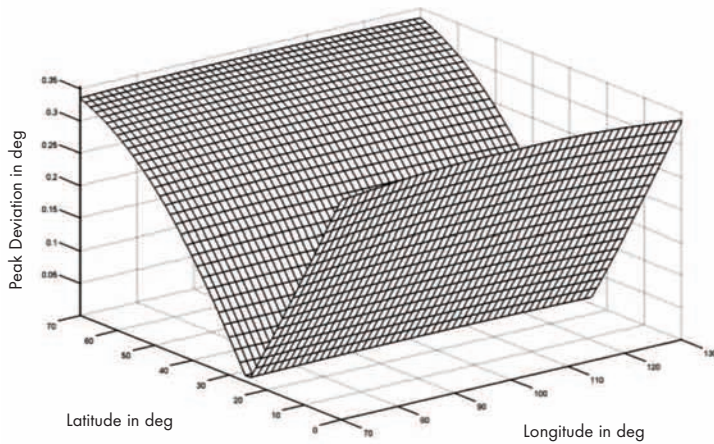


Figure 11. Array beam pointing error for a range of earth station locations when only one hard-wired squint of 3.675° is implemented and array orientation is optimized.

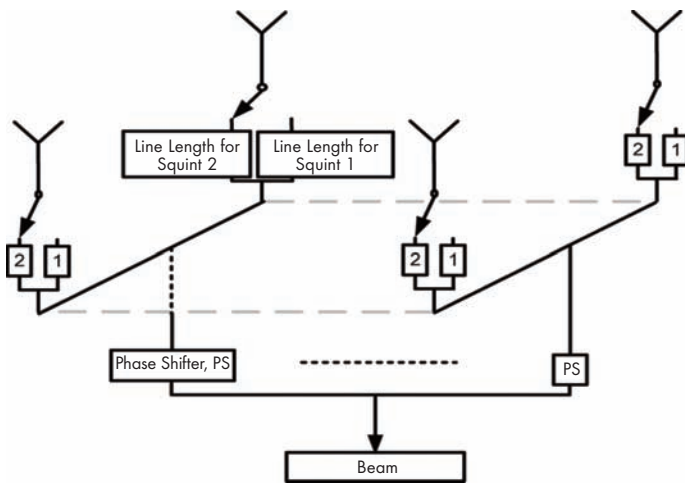


Figure 12. Beamformer for PAA with full scanning capability in azimuth and two fixed scan angles in elevation.

If a beam pointing error of 0.352° is still too large, then additional hard-wired squints can be used to further reduce this error. In the next sub-section, a case of two hard-wired squints is considered.

Two Hard-Wired Squints

Once again, let us consider the same example as above, but this time there will be two different hardwired squints to choose from. To determine the values of these two optimized squints, we will start the optimizing process from initial squint values of 6.03° (= 0.75 of 8.04°) and 2.01° (= 0.25 of 8.04°). These values were chosen because they are symmetrically positioned over a squint range of 0.0° and 8.04°. Using a similar optimization process as described above for a single fixed squint case, it was determined that the optimum squint values are 5.78° and 1.88°. Using these squint values gives a maximum beam pointing error 0.18°, which is about one half of the error obtained using a single fixed squint.

To implement two hard-wired squints, it is necessary to have two separate fixed length transmission lines behind each element along with a switch as shown in Figure 12. The elevation direction of the main beam is fixed to one of two positions depending on the latitude position of the mobile earth station. In contrast, there is full scanning capability in the azimuthal direction (to scan over the GA) with the use of phase shifters.

The hard-wired squint will be chosen depending on the latitude position of the mobile earth station. For example, if the earth sta-

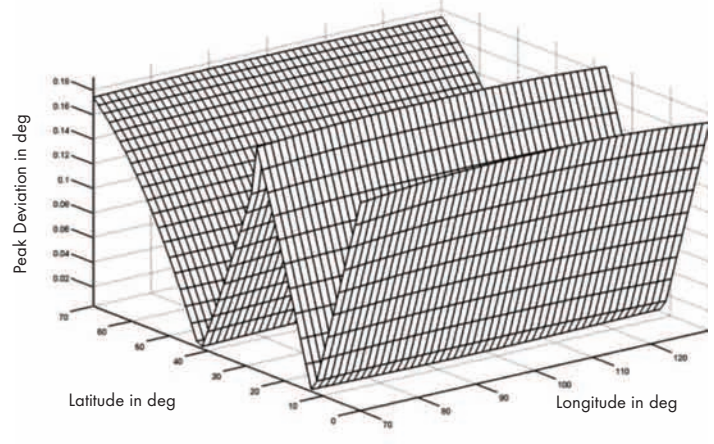


Figure 13. Array beam pointing error for a range of earth station locations with two hard-wired squints (5.78° and 1.88°) implemented.

tion is located at latitudes north of 26.38°N, then the fixed squint of 5.78° will need to be used. For latitudes south of 26.38°N, the fixed squint values of 1.88° will be used. Figure 13 shows the main beam pointing error for all latitudes and longitudes of interest. From the symmetry, it is obvious that the squint value of 5.78° should also be used when the earth station is located at latitudes south of 26.38°S and the squint value of 1.88° should be used for latitudes north of 26.38°S.

It is possible to reduce the beam pointing error further by increasing the number of fixed squints. However, increasing the number of fixed squints will lead to an increase in the complexity of the antenna system. Furthermore, for the case of the GEO satellites (the main interest for this report), one or at most two fixed squints are sufficient.

CONCLUSION

We have adapted a design concept by Amitay and Gans for a fixed earth station and modified it for a mobile earth station by using one or at most two fixed squints for a range of latitudes and longitudes. This approach results in a simplified design that enables a reduction in both the cost and complexity of a phased array antenna. In this design, a single planar array consisting of $N \times M$ elements can be used to communicate with several GEO satellites simultaneously by generating multiple beams that need to be scanned only in one plane thereby requiring only M instead of NM phase shifters for each beam. At the same time, only one or two hard-wired squints are needed in the orthogonal plane.

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NEW RADAR SYSTEMS UNVEILED AT LAKENHEATH –

Senior Airman David Dobrydney

The 48th Fighter Wing became the first US Air Forces in Europe unit to receive new radar systems for air traffic control. The Digital Airport Surveillance Radar and Standard Terminal Automation Replacement System became operational Nov. 18 as part of a project conducted by officials with the Air Force Electronic Systems Center and Federal Aviation Administration to replace aging technology at Department of Defense airfields. “This is a real team effort, and we appreciate it,” said Col. John Quintas, the 48th Fighter Wing commander. “This improvement is about safety and will make our ability to go to war safer and more reliable.”

The new DASR system is a replacement for the Generalized Proportional Navigation system previously used to track aircraft and weather conditions in the vicinity of civilian and military airfields. “The old GPN-20 radar is being replaced by DASR to improve reliability, provide additional weather data, reduce maintenance cost and improve performance,” said Xavier Rayford, a 48th Communications Squadron telecommunications specialist and the DASR installation project manager.

In order to get the most use from the DASR system, the STARS consoles were concurrently installed in place of the older Automated Radar Terminal Systems at the radar approach control facility. Master Sgt. Klane Pierce, the 48th Operations Squadron assistant chief controller, said STARS

will allow him and his co-workers to do their job more effectively. “The new digital system provides a clearer picture of all aircraft that we’re controlling, both at (Royal Air Force) Lakenheath and (RAF) Mildenhall,” he said. “There are a lot of smaller aircraft and gliders that in the past may have not been detected, or we couldn’t see because of ground clutter. The new system eliminates these problems.”

Besides the ability to see aircraft more clearly, Mr. Rayford added that the new systems are designed to allow for growth in activity on the flightline. “The STARS system is designed to accommodate air traffic growth and the introduction of new automation functions which will improve the safety and efficiency of the US National Airspace System as the legacy systems are replaced,” he said.

Senior Airman Jacob Tucker and Master Sgt. Jae Ewing monitor aircraft Nov. 22, 2010, in the Radar Approach Control facility at Royal Air Force Lakenheath, England. They are using new Standard Terminal Automation Replacement System equipment recently installed as part of a replacement program under the Air Force Electronic Systems Center and the Federal Aviation Administration. Airman Tucker is an air traffic control journeyman with the 48th Operation Support Squadron, and Sergeant Ewing is the 48th OSS senior watch supervisor. (US Air Force photo/Senior Airman David Dobrydney)

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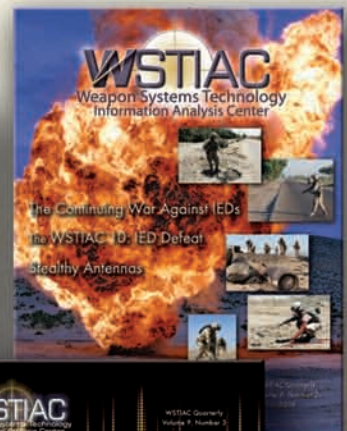
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