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Low Cost Multibeam Phased Array Antenna for Communication with Geostationary Satellites

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14. ABSTRACT The U.S. Navy uses both military and commercial satellites for communication purposes. In the existing shipboard communications system, a separate antenna, most likely a reflector antenna, is used to communicate with each satellite. In the future, it is expected that these reflector antennas will be replaced by multi-function, low RCS (radar cross section) phased array antennas. In this report, we have designed (based on an existing method suggested by Amitay and Gans) a unique concept in which a single planar array (on a mobile earth station) can be used to communicate simultaneously with several geostationary satellites by generating multiple independent beams. These beams will need to be scanned in only one plane, thus reducing the number of phase shifters required for each beam. In the orthogonal plane, one or two hard-wired squints will be used to fix the beam position. This method will help to reduce the cost and complexity of phased array antennas on mobile earth stations.					
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1 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 NM 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 Refs [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.

2 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).

3 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 interested in the satellites that are located on the GA

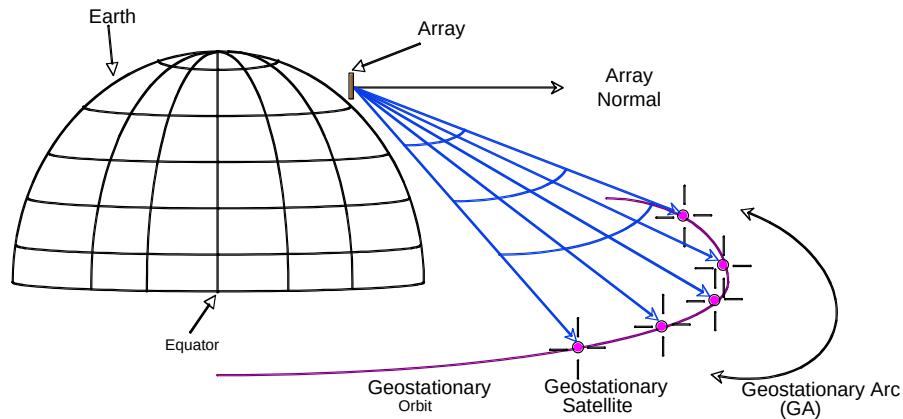


Figure 1: Earth and Earth Station Antenna Array and GEO Satellite Geometry

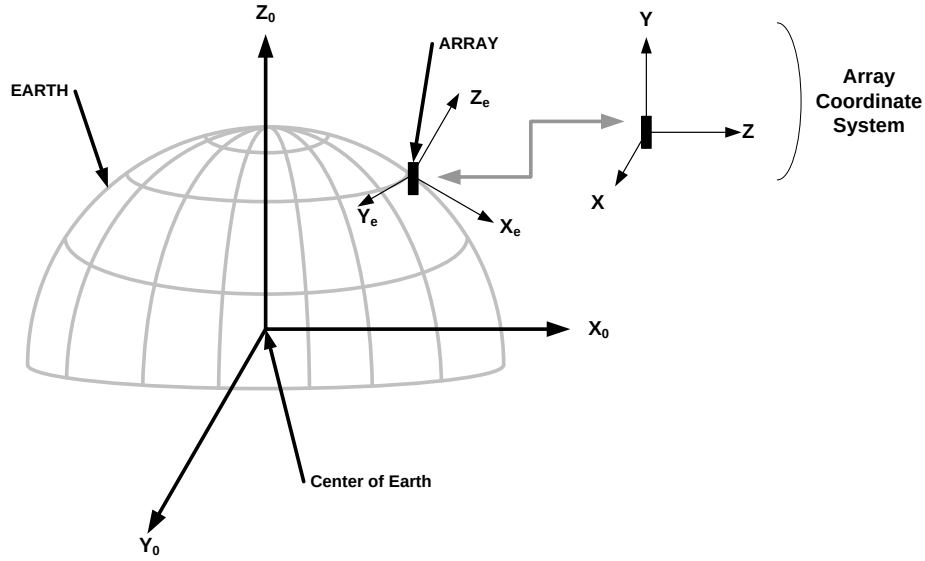


Figure 2: Representation of the three coordinate systems, Centered at Earth, Earth Station and Antenna Array

Figure 3 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.

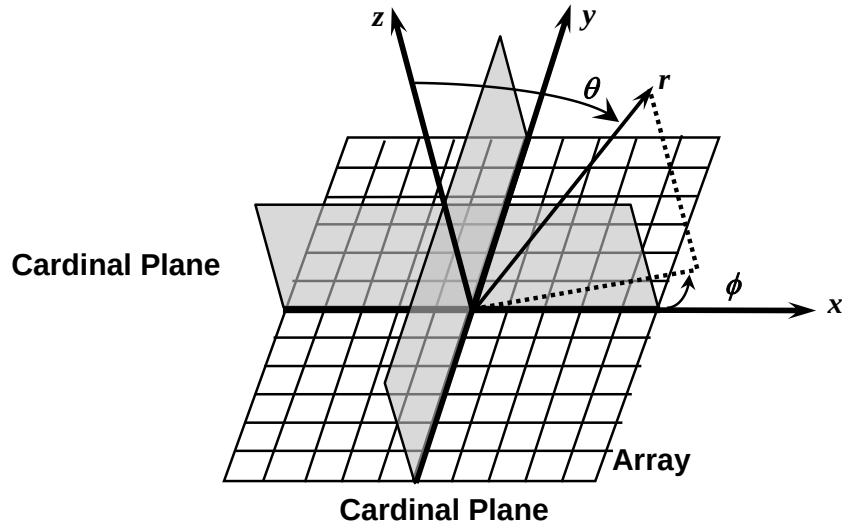


Figure 3: Rectangular Array Cardinal Planes

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.

Let us now look at the linear scanning technique in more detail.

3.1 Details of the Linear Scanning Technique

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

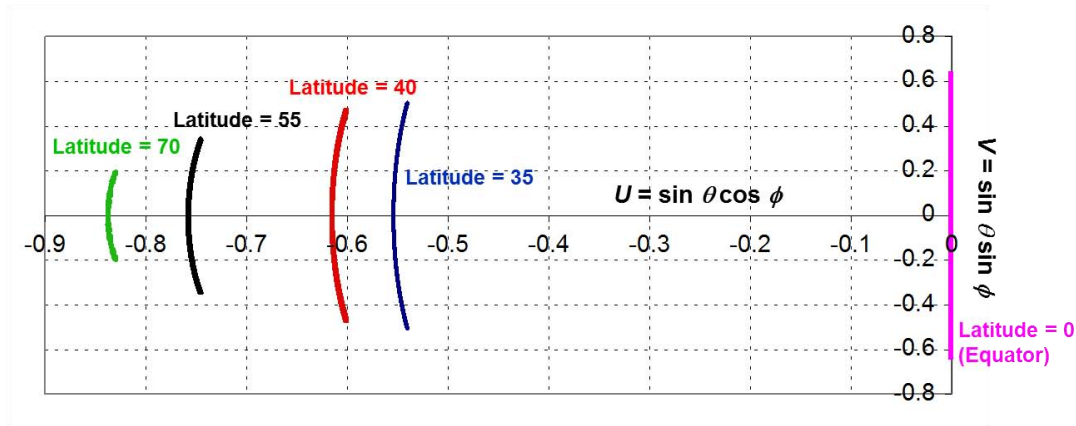


Figure 4: Mapping a 60° GA onto the Cardinal Planes of an Array Located at Increasing Latitudes

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.

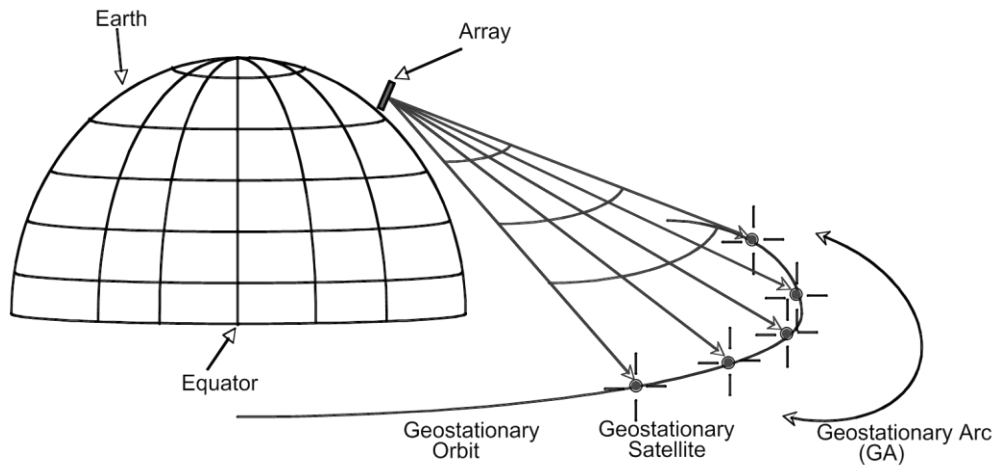


Figure 5: Tilting of Planar Array to Point the Beam to Cover GA

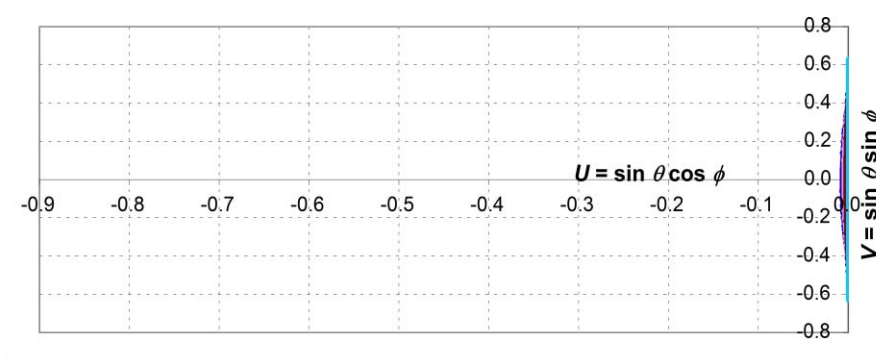


Figure 6: Effect of Tilting on the Mapped GA Curves

3.2 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.

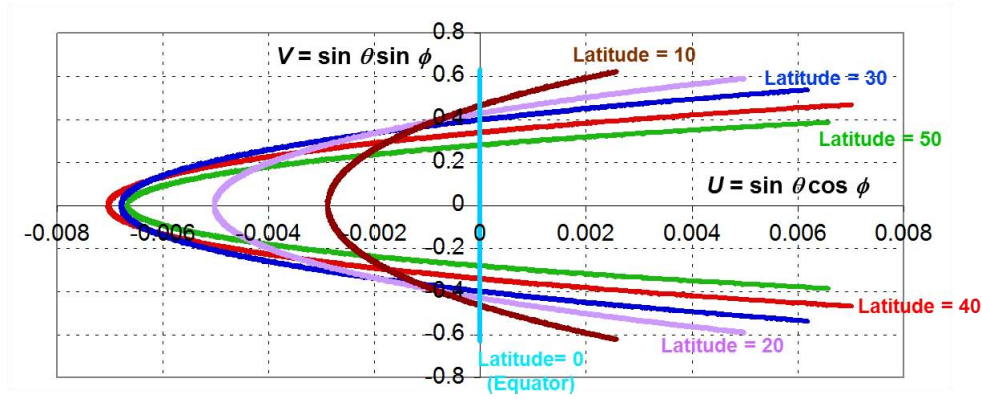


Figure 7: Detail View of Figure 6 – Optimum Mapping of 60° GA (Using only Mechanical Tilt) onto the Cardinal Planes of an Array Located at Different Latitudes and the Center Longitude of the 60° GA

Figure 8 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 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.

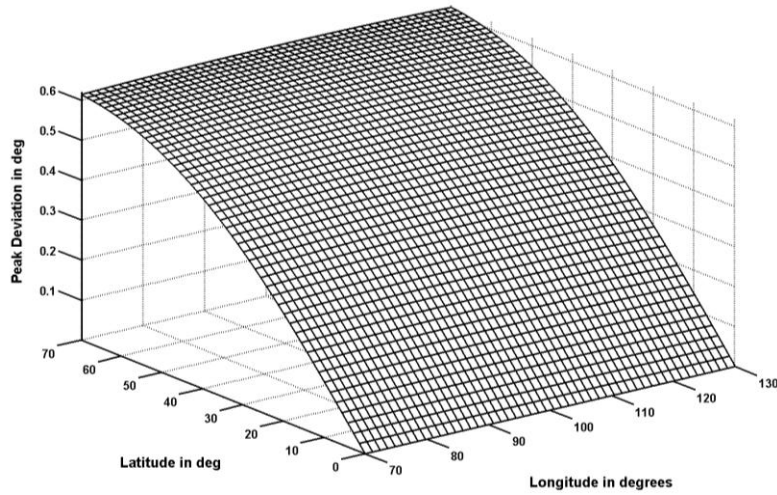


Figure 8: Array Beam Pointing Error as a Function of Earth Station's Longitude and Latitude using only Mechanical Tilt

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° .

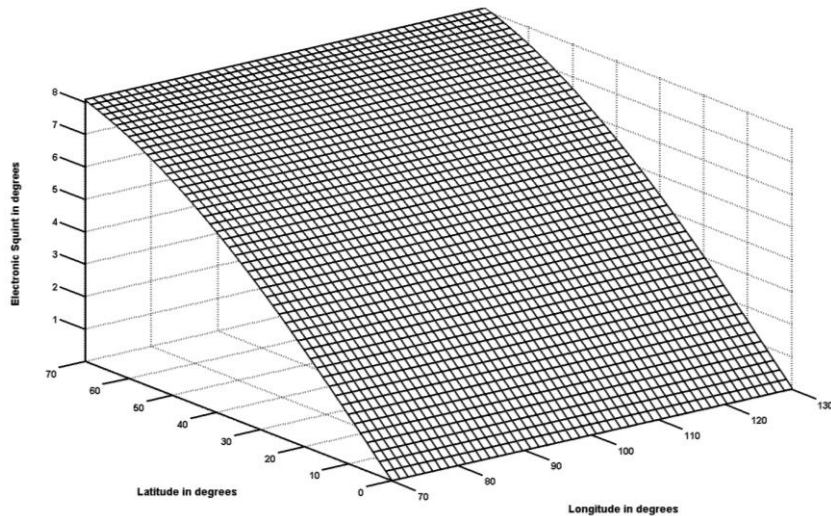


Figure 9: Required Electronic Squint for Different Station Location

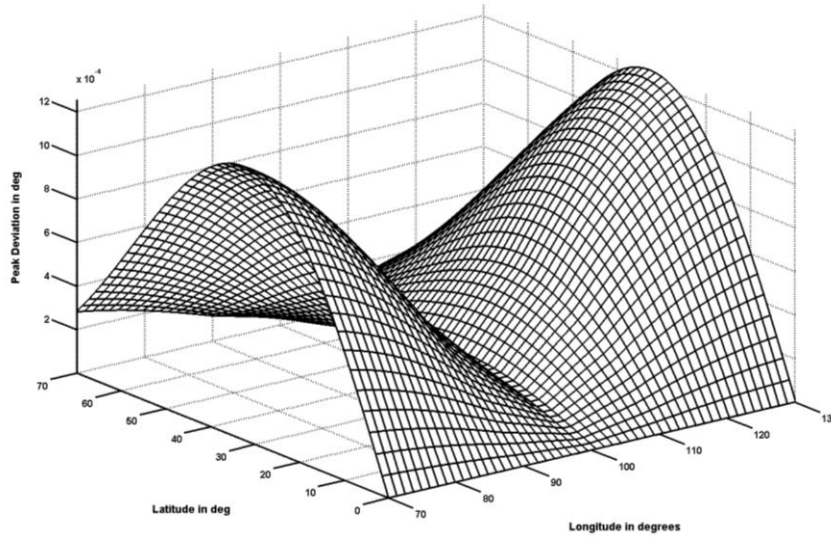


Figure 10: Array Beam Pointing Error for Different Earth Station Locations when the Electronic Squint Calculated in Figure 8 are implemented

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.

3.2.1 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.

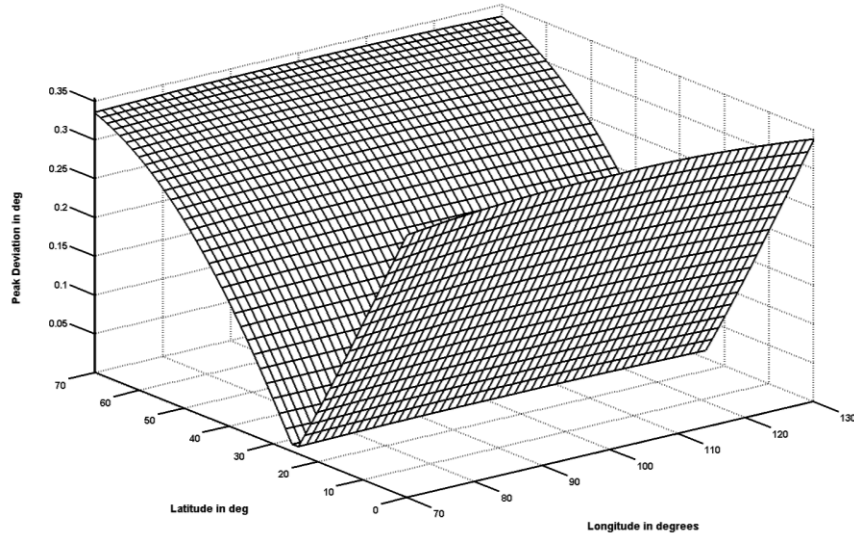


Figure 11: Array Beam Pointing Error for a Range of Earth Station Locations when only One Hard-Wired Squint of 3.675° is implemented and Array Orientation is optimized

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.

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.

3.2.2 Two Hard-Wired Squints

Once again, let us consider the same example as above, but this time there will be two different hard-wired 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 station 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 .

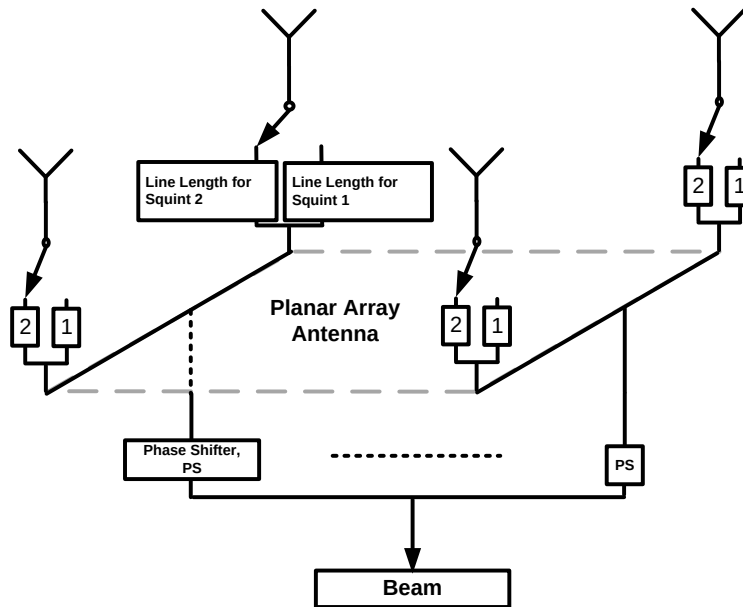


Figure 12: Beamformer for PAA with Full Scanning Capability in Azimuth and Two Fixed Scan Angles in Elevation

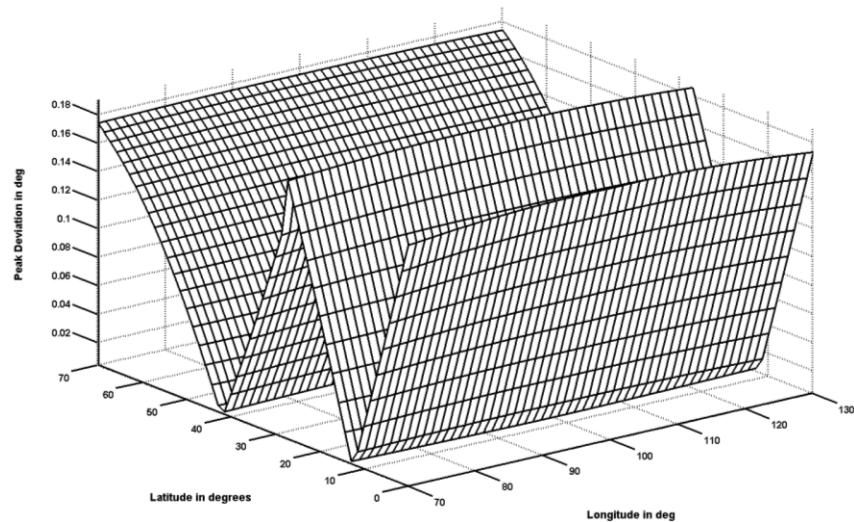


Figure 13: Array Beam Pointing Error for a Range of Earth Station Locations with Two Hard-Wired Squints (5.78° and 1.88°) implemented

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.

4 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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