MULTIPATH LIMITING ANTENNA DESIGN CONSIDERATIONS FOR GROUND BASED PSEUDOLITE RANGING SOURCES

A Thesis Presented to

The Faculty of the Fritz J. and Dolores H. Russ College of Engineering and Technology

Ohio University

In Partial Fulfillment of the Requirement for the Degree

Master of Science

by

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November, 2001
ACKNOWLEDGEMENTS

First, I would like to thank my parents and my sister for their endless support during my Masters’ program. It was the encouragement of my parents that kept my ambition strong and the kindness of my sister that kept me going through the difficult times. In addition, I would like to express gratitude to my colleagues and friends in the Avionics Engineering Center. They made things entertaining while providing the encouragement to finish this document. I sincerely thank my advisor, Dr. Chris Bartone, for providing the ideas and advice that kept this project moving forward as well as for his numerous reviews of this document. I would also like to thank the members of my committee: Dr. Roger Radcliff, Dr. Frank van Graas, and Dr. Bob Williams for their review of this document. I would especially like to thank Lukas Marti for his encouragement and words of wisdom during the 700 miles of bike riding that we accumulated over the past two years. My gratitude also goes to the School of Electrical Engineering and Computer Science for their financial support through the Stocker Research Associateship. Additional Funding for this research was also provided, in part, by the Federal Aviation Administration under Aviation Research Cooperative Agreement 98-G-002. I also thank Bryce Thornberg for letting me spend some time working with him and his world-class team at DB Systems. Finally, I thank God for helping me find the physical, mental, and emotional strength required to discover the highest summits in life.
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LIST ACRONYMS

LAAS – Local Area Augmentation System
GPS – Global Positioning System
DGPS – Differential Global Positioning System
WAAS – Wide Area Augmentation System
VDB – Very High Frequency Data Broadcast
APL – Airport PseudoLite
WBAPL – Wideband APL
LGF – LAAS Ground Facility
IMLA – Integrated Multipath Limiting Antenna
D/U – Desired-to-Undesired Ratio
HZA – High Zenith Antenna
MLA – Multipath Limiting Antenna
BPF – Band Pass Filter
A/D – Analog to Digital Converter
AGC – Automatic Gain Control
UNI – Ohio University Airport
A/C – Aircraft
nmi – Nautical Mile
TDP – Touch Down Point
ATLAS – Antenna Test Laboratory Automated System
AF – Array Factor
EF – Element Factor

SLL – Side Lobe Level

OLS – Ordinary Least Squares
1. BACKGROUND

1.1 Local Area Augmentation System

The Local Area Augmentation System (LAAS) is a ground-based augmentation system that extends the capabilities of the Global Positioning System (GPS). The LAAS is essentially a Differential Global Positioning System (DGPS) system in that it removes common errors from the navigation system to produce a highly accurate position solution. While LAAS can be used for a variety of applications, this document will assume its use in a high accuracy approach and landing system. There are three major components of LAAS as can be seen in Figure 1-1.

![Figure 1-1: LAAS Overview](image_url)
The first major component of LAAS is the satellite subsystem, which provides space based ranging sources [1] [2]. These ranging sources can be provided by GPS or the Wide Area Augmentation System (WAAS). For the purposes of this document, these ranging sources will be provided by GPS.

The second major component of LAAS is the ground subsystem, which provides the differential corrections via a Very High Frequency (VHF) data broadcast (VDB) [1] [2]. The VDB also transmits some integrity-related information as well as some other pertinent information. Another part of the ground subsystem consists of ground-based ranging sources to increase the availability of LAAS for high availability applications such as Category III approaches. These ranging sources consist of airport pseudolites (APLs), which transmit a GPS like waveform. A specific type of APL that transmits a wideband code is known as a Wideband APL (WBAPL) [3]. All of the components in the ground subsystem are commonly referred to as the LAAS Ground Facility (LGF).

The final major component of LAAS is the airborne subsystem, which includes the user equipment needed to receive GPS and WBAPL transmissions and process this information to produce a highly accurate differential position with high availability, continuity, and integrity [1] [4].
1.2 Prototype LAAS Ground Facility

A prototype LGF is located at the Ohio University Airport (UNI) in front of runway 25, which was chosen primarily for logistic reasons such as electricity and available land. This prototype LGF has three antenna sites labeled as FLD1, FLD2, and FLD3 as shown in Figure 1-2, which are located approximately 300 meters prior to runway 25.

![Figure 1-2: Prototype LGF at Ohio University – Not to Scale](image)

Each precisely surveyed site consists of one integrated multipath limiting antenna (IMLA) and accompanying receivers. Both GPS and WBAPL signals are received at FLD1 and FLD2. The FLD3 site has historically been used for APL transmission. The VDB antenna, for broadcasting differential corrections and associated data, is located on top of the fiberglass shelter. The antenna separation distances were selected in order to minimize ground multipath. For the GPS case, the antennas must first be placed far enough apart to minimize the multipath correlation [5]. Then in the pseudolite case, the
antennas should be placed in order to take advantage of multipath mitigation in the antenna pattern as discussed in Section 3.1.

1.3 Multipath

The dominant error source in DGPS applications is multipath. Multipath occurs when a signal arrives at its destination via multiple paths resulting from reflections and/or diffractions. Multipath can be troublesome to navigation ranging systems when the signal amplitude of the multipath is strong relative to the direct signal. In addition, since reflections and diffractions involve larger path lengths than the direct signal, they incur a time delay, which can effect GPS code or carrier measurements. This time delay can be a significant problem for GPS since it performs time-based ranging measurements. Multipath can come in four basic types.

1. Ground reflection
2. Obstacle reflection
3. Obstacle diffraction
4. Higher order terms (involving combinations of types 1 through 3)

These types of multipath are illustrated in Figure 1-3. A ground reflection is denoted as multipath 1, an obstacle reflection is labeled as multipath 2, and an obstacle diffraction is labeled as multipath 3.
An example of the fourth type of multipath would be if the GPS signal had been reflected off the building and then off the ground before entering the reception antenna. These reflections and diffractions can cause errors to GPS when the ground, buildings, vehicles, aircraft or any other objects are electrically large with respect to the GPS signal. Ground multipath from WBAPL transmissions is one of the largest concerns for the LAAS because of its close proximity to the ground and its static geometry.

The research performed for this thesis deals mainly with antenna techniques to reduce ground multipath. By shaping the antenna gain pattern appropriately, the amount of multipath that enters the receiver front end can be significantly reduced. A common way to characterize multipath is in terms of a power ratio referred to as the desired-to-undesired (D/U) ratio. The D/U ratio is also known as direct-to-indirect ratio, down-to-up ratio, and a variety of other names. The D/U ratio is calculated for a given elevation.
angle in order to assess the ground multipath rejection capability of an antenna and thus tells how many dB of multipath can be rejected after the radio frequency (RF) stages of a transmitter and before the RF stages of a receiver. The ability to quantify the multipath rejection at 20 dB, for example, allows the amount of multipath error to be bounded to less than 0.15 meters. D/U is shown graphically in Figure 1-4 and will be used throughout this research.

Figure 1-4: Graphical Illustration of the D/U ratio

1.4 Integrated Multipath Limiting Antenna

Pioneering work at Ohio University led to the development of a dual antenna system to reduce multipath errors before they ever enter the receiver front end [6] [7] [8]. The IMLA was designed to provide full hemispherical coverage while maintaining excellent multipath performance. It consists of two integrated antennas as shown in Figure 1-5: a High Zenith Antenna (HZA) to receive GPS information from high elevation satellites (30 deg through 90 deg) and a Multipath Limiting Antenna (MLA) to receive GPS
information from low elevation satellites (3 deg through 35 deg). The original 14-element MLA (Model #200) was designed to minimize ground multipath as follows [7]:

1. Minimize multipath in the reception of GPS (5 deg to 35 deg)
2. Minimize multipath in the reception of the APL (0 deg)
3. Minimize multipath in the transmission of the APL signal (−3 deg) to the LGF reception antennas and also to aircraft on final approach.

The MLA is a 2.2-meter linear dipole array as shown in Figure 1-5 where it is mounted on top of a three-meter metal pole. The mounting pole is used to keep the antennas at all three sites at the same height at UNI. On top of the MLA is a junction box where the HZA is fed and the power is connected to the obstruction lights. The HZA is under the cone shaped radome in Figure 1-5. Additional detail on the original MLA and HZA can be found in [5].
1.5 Concept of Receiver Dynamic Range

Dynamic range can refer to many different things, but for the purposes of discussion in this paper, it will refer to the range of power levels that can be applied to a receiver while still providing a linear output. This is highly dependent on receiver architecture since it is determined by the component in the receiver with the smallest linear region. Consider, as an example, the basic GPS receiver shown in Figure 1-6. Assume, for example, that the linear regions of the pre-amp, bandpass filter (BPF), down conversion mixers, automatic gain control (AGC), and the analog to digital (A/D) converter, are 95 dB, 110 dB, 40 dB, 45 dB, and 32 dB respectively. The receiver RF dynamic range is determined by the down conversion mixer at 40 dB. This demonstrates how the dynamic range is receiver dependent since it can vary with differing internal components. Typically, a receiver can process a range of power levels spanning 35-40 dB before it begins to saturate. In some cases, a receiver can continue to produce near-linear outputs as far as 15 dB into saturation because the A/D will simply “clip” the peaks of the signal without corrupting the carrier phase information.

![Figure 1-6: Basic GPS Receiver](image)
If the dynamic range is exceeded and highly nonlinear outputs resulted, this can lead to meter level biases. In experimental tests, the bias ranged from 3 - 3.5 meters for power level variations over 40 dB when using a wideband code [9]. Tests are still ongoing to better characterize these biases. Along with ground multipath, a bias of this type could be one of the largest errors in DGPS when a WBAPL is integrated. In safety of life applications, such as precision approaches and landings, this is an important consideration because the user depends on the accuracy of the DGPS/WBAPL information being provided.
2. PHASE I – SITING INVESTIGATION

This section describes a study that was conducted to determine the “optimum” ground location for an APL transmission antenna with respect to minimizing an airborne receiver’s dynamic range requirement. The main purpose of this study was to determine the effect of APL siting on the received power at the aircraft on a final approach path. “Optimal” antenna locations will be presented as part of the results of the study [10].

2.1 Siting Study - Background Information

The results found in this study were determined based upon the gain pattern of the original MLA (i.e., Model #200) used at UNI and a top-mounted aircraft (A/C) GPS patch antenna (i.e., Sensor Systems Model # S67-1575-14). Each antenna can be thought of as either a transmitting or a receiving antenna because of reciprocity, but discussion will be clearer if a consistent label is used. For the APL ground-to-air link, the transmitting antenna was the MLA and the receiving antenna was the GPS patch antenna atop the aircraft.

The simulation developed for this test was performed in Matlab™ v5.2. It implemented a 3-degree approach path from 1 nautical mile (nmi) until the touchdown point (TDP) on the runway.
2.2 Siting Simulation Parameters

The first step in setting up the simulation was to acquire high fidelity antenna pattern data for both antennas involved and put them in a comparable form. Free space antenna radiation pattern data were obtained from outdoor antenna ranges, as previously documented, for the gains of the MLA [5] and the GPS patch [11] antennas. Next, some constants such as frequency and transmit power were defined. With this information, the received power at the A/C could be calculated and plotted vs. slant range.

The available free space MLA antenna pattern data covered only elevations from $-35$ deg up to $+35$ deg. A much wider range of elevation angles was required to simulate an approach so the remaining gains from 35 deg up to 90 deg in elevation were approximated with first order polynomials; the resulting approximation can be seen in the composite elevation radiation pattern plot in Figure 2-1. The first slope of the approximation, from 35 deg to 80 deg in elevation, approximates the gradual decay of the antenna gain as the elevation angle increases. The sharp roll off from 80 deg to 90 deg was hypothesized because the MLA is a broadside vertical dipole array with very little gain in the vertical direction. This was not found to be a severe approximation because later simulations with more complete data produced very few noticeable changes in the results.
The gain data for the A/C antenna, Figure 2-2, was obtained from the Naval Air Warfare Center Antenna Test Laboratory Automated System (ATLAS) database that was collected on the outdoor antenna range at Patuxent River, Maryland [11].

Vertical polarization data was selected for all simulations because it provides better power coupling performance for the APL link [12].
The central equation used to simulate the approach scenario was the Friis transmission equation, which can be described as [13]:

\[
P_r = \left( \frac{\lambda}{4\pi R} \right)^2 \frac{G_t \cdot G_r \cdot P_t}{L_{TX} \cdot L_{RX} \cdot L_p}
\]

where:

- \( P_r \) = Received power [w]
- \( P_t \) = Transmitted power [w]
- \( \lambda \) = Wavelength [m]
- \( R \) = Range between antennas [m]
- \( G_t \) = Transmitting antenna gain [unitless]
- \( G_r \) = Receiving antenna gain [unitless]
- \( L_{TX} \) = Transmitter cable losses [unitless]

**Figure 2-2: Aircraft GPS Antenna Gain vs. Zenith Angle for Vertical Polarization.**
$L_{RX} = $ Receiver cable losses [unitless]  
$L_p = $ Power loss associated with transmitter pulsing [unitless].

The plots in Figure 2-1 and Figure 2-2 represent the values used for the two gain terms ($G_t$ and $G_r$) in Equation 1. Figure 2-1 is plotted with respect to elevation angle (the angle above the horizon) while Figure 2-2 is plotted with respect to zenith angle (the complement of elevation angle). The transmitted power ($P_t$) was assumed to be one Watt throughout. The frequency of operation for this analysis was the GPS L1 frequency (1575.42 MHz). It is important to note that for the comparisons that will be made in this research, the absolute power is not as important as the relative power received in a free space-only environment for candidate APL locations. By using these values in Equation 1, a value for the received power ($P_r$) was calculated and plotted. Starting at 1 nmi the operational range was decreased as the simulated A/C approached the TDP. This operational range is not the separation between antennas since the APL transmission antenna location is independent of the TDP. The magnitude of the slant range from the A/C reception antenna to the APL transmission antenna is used as the antenna separation range ($R$) (i.e., slant range) for the calculation. Determining this parameter was a matter of solving a continuously changing geometry problem for each candidate APL site location as the aircraft approached. The transmitter cable loss ($L_{TX}$) is a term that accounts for the losses occurring on the transmitter side of the link (assumed to be 3 dB). Equivalently, the term ($L_{RX}$) accounts for the losses on the reception side of the link (assumed to be 6 dB). The final loss term that was considered ($L_p$) represents the nominal transmitted power loss that results from transmitting a pulsed signal as opposed
to continuous. This loss associated with pulsing was assumed to be 10 dB for a 10% duty cycle.

2.3 APL Candidate Location Grid

Figure 2-3 illustrates a grid of candidate APL locations and the local reference coordinate system. As a convention in this paper, the distance that the APL antenna is located before the TDP will be referred to as the **advance** and the distance that it is located to the side of the TDP will be referred to as the **offset**.

**Figure 2-3: Candidate APL Locations and Local Reference Coordinate System**
2.4 Resulting Power Profiles

All of the power profiles shown in this section (Figure 2-4 through Figure 2-19) illustrate the corresponding received power for particular candidate locations of the APL transmitting antenna. For each location, vertical lines were plotted to mark the decision heights corresponding to Category I, II, and III (200, 100, and 50 ft, respectively). In addition to the received power profile, the received power due only to free space path loss (i.e., no antenna pattern variation) was plotted for comparison.

When analyzing the two dimensional power profiles in Section 2.4.1 (Figure 2-5 through Figure 2-13) it is important to examine three main characteristics that are illustrated in Figure 2-4. The first characteristic is any difference between the solid thick curve (top) and the dashed curve (bottom); this difference illustrates unique characteristics introduced by the antenna patterns of the MLA and the A/C antenna. This can be in the form of rapidly varying or slowly varying curve differences. A second characteristic to analyze is the location of the peak power with respect to the decision heights. If a large peak occurs near a critical point decision height, a bias could potentially be introduced during a critical point in the landing process. This should be avoided when siting the APL antenna.
The final characteristic to be discussed is the overall flatness of the curves as this dominates the dynamic range requirement. In order to limit the dynamic range required, the received power curves should be as flat as possible.

The first plot in the series, Figure 2-4, is the received power profile for the approximate APL location currently in use at UNI (i.e., the FLD3 location). This location has been used in APL research to date and was selected primarily due to logistic considerations. This location is close to the existing LAAS shelter, which has power, heating, cooling, and road access. The dynamic range requirement can be determined by looking at the range of power levels that a receiver has to process over the last one nmi of the approach. In this case, the requirement is about 20 dB for the APL signal from one nmi to the 100 ft decision height. However, the rapid power level variations that occur near the 100 foot decision height are undesirable because they could cause undesirable secondary tracking effects.

The major visible difficulty in Figure 2-4, at a slant range of about 0.35 nmi, is a rapid power variation (a.k.a. distortion). This variation is due to the lobes of the A/C antenna pattern above ±125 deg from zenith (below the aircraft fuselage). Since the A/C antenna is top-mounted on the aircraft fuselage, and the APL signal comes from below the aircraft horizon; the lobes of the pattern are used to receive the transmission. From 0.3 to 0.4 nmi on the approach, the received power rapidly changes over a span of 20 dB.
Figure 2-4: Received Power vs. Slant Range for Offset=40 ft and Advance=2000 ft

The rapid changes in APL signal power level at the airborne receiver are very undesirable for the APL link and improvements with better siting of the APL transmitting antenna are investigated here. The rapid variations in signal power level can affect the AGC in the GPS receiver channel being tracked and can cause the tracking loop bandwidth to expand.

As stated in Section 1.5, a typical receiver has a dynamic range of around 30 – 35 dB where the mixer usually begins to saturate. Pseudorange measurements may still be linear while in saturation up to 40 to 45 dB. Figure 2-4 is undesirable because it has the most distortion of any of the locations examined, but it does not have the most
demanding airborne user dynamic range requirements because the distortion reduces this requirement.

### 2.4.1 Two Dimensional Power Profiles for Various Candidate APL Locations

In the two dimensional power profiles (Figure 2-5 through Figure 2-13), the received power variations for the APL ground-to-air link are plotted for various candidate APL antenna positions. The APL position is labeled with a coordinate pair of the form \([\text{Offset}, \text{Advance}]\), as indicated in Figure 2-3.

![Graph](image_url)

**Figure 2-5: Received Power vs. Slant Range for Offset=100 ft and Advance=100 ft**
In Figure 2-5 through Figure 2-7, the advance is held constant at 100 ft while the offset is varied from 100 to 1000 ft. For a small offset of 100 ft, such as Figure 2-5, the peak power profile is very sharp. The peak gets more rounded in Figure 2-6 as the offset increases, while in Figure 2-7 it is much less pronounced for a large offset of 1000 ft. This makes sense because a larger offset means that the transmitter and receiver will be further apart throughout the approach and the A/C will thus receive less power due to free space path loss alone. Thus, we can conclude that the offset dominates how pronounced the power peak will be.

Figure 2-6: Received Power vs. Slant Range for Offset=500 ft and Advance =100 ft
For the next group of three plots (Figure 2-8 through Figure 2-10), the advance is increased to 500 ft and the offset is again varied from 100 ft to 1000 ft. As evident earlier in Figure 2-4, the small distortion observed at the peak in Figure 2-8 is due to the side lobes of the A/C antenna pattern for large angles from zenith (negative elevation angles). Figure 2-9 and Figure 2-10 do not have this distortion because the APL transmitter is offset far enough away from the A/C to keep the elevation angles outside the region of the A/C antenna side lobes. Another important observation is that the peak of the power curve has moved further away from the TDP (i.e., towards the A/C) when compared to Figure 2-5 through Figure 2-7; this effect is undesirable. Logically, the peak will occur at a slant range where the separation between antennas is at a minimum.
Having the peak power occur before the TDP is generally not a good attribute since the peak should be kept as close as possible to (or behind) the TDP. This should be avoided unless the peak power value can be kept well within the dynamic range of the receiver.

Figure 2-8: Received Power vs. Slant Range for Offset=100 ft and Advance=500 ft
Figure 2-9: Received Power vs. Slant Range for Offset=500 ft and Advance=500 ft

Figure 2-10: Received Power vs. Slant Range for Offset=1000 ft and Advance=500 ft
The next three power profiles (Figure 2-11 through Figure 2-12) illustrate the last advance examined in the location grid of 1000 ft for the same three offsets of 100, 500, and 1000 ft. The side lobes of the A/C patch antenna are again responsible for the distortion that is very clearly observable in Figure 2-11. The peak and the distortion have now shifted to the right on the plots and now occur directly over the 50 ft Category III decision height. This is clearly a "worse" location since it would require a large receiver dynamic range of almost 35 dB for the APL signal over the last 1 nmi of the approach. This is determined by looking at the largest difference in power level changes. As the offset is increased in Figure 2-12 and Figure 2-13, the distortion is reduced, but the peak power level still occurs very near to the Category II / Category III decision heights. For this advance, the best-case scenario is Figure 2-13 with a dynamic range requirement of only 15 dB for the APL signal. Figure 2-13 also portrays the best APL antenna location for all of the offsets and advances that were directly considered in this study.
Figure 2-11: Received Power vs. Slant Range for Offset=100 ft and Advance=1000 ft

Figure 2-12: Received Power vs. Slant Range for Offset=500 ft and Advance=1000 ft
Figure 2-13: Received Power vs. Slant Range for Offset=1000 ft and Advance=1000 ft

2.4.2 Composite Power Profiles

The first three composite power profiles illustrated in this section (Figure 2-14 through Figure 2-16) aggregate all of the power profiles presented in Figure 2-5 through Figure 2-13 to linearly interpolate what would happen in between the selected APL antenna locations for a fixed advance 100, 500, and 1000 ft respectively. A solid thin line is plotted across the surfaces at the slant range corresponding to the decision heights of Category I/II/III.
The peak movement trend (along the slant range axis) as well as the peak power level variation trend are both apparent by examining all of the composite power profiles in this section (Figure 2-14 through Figure 2-19). Figure 2-14 shows that the peak is flattened as the offset is increased for a fixed advance of 100 ft. In Figure 2-15, the same flattening tendency can be seen with the entire surface at a slightly higher overall power level because of the larger advance of 500 ft.
Figure 2-15: Power Profile Variation with Advance = 500 ft and Increasing Offset

Figure 2-16 illustrates where the distortion begins to appear and generally shows the highest overall power level for every offset because it has the largest fixed advance of 1000 ft. Note that the 50 ft decision height line is masked by the advancing peak of the distortion.

Similarly, the next set of three composite power profiles (Figure 2-17 through Figure 2-19) identify the effect of changing the advance for a fixed offset. These can be considered a slice of the composite power profiles shown in Figure 2-14 through Figure 2-16.
Figure 2-16: Power Profile Variation with Advance = 1000 ft and Increasing Offset

For each plot, the value of the advance is labeled for each peak shown. In Figure 2-17 the peaks at each advance are closest to the TDP. There distortion is again evident for the advance of 1000 ft. Then, in Figure 2-18, the peaks move even further away from the TDP. They are now clustered around the 50 ft decision height. The peaks shift closer to the 100 ft decision height in Figure 2-19. Figure 2-19 has the lowest overall power level because the antenna is offset by 1000 ft; the furthest offset investigated here. Thus, the peak movement away from the TDP (peak occurs earlier in the approach) is directly proportional to increases in the advance of the WBAPL antenna site location. A power peak earlier in the approach is undesirable because pseudorange biases could arise
over critical decision heights in the aircraft approach. Peak movement in this manner is conceivable since the aircraft flies over the APL sooner when the antenna is located with a larger advance.

Figure 2-17: Power Profile Variation with Offset = 100 ft and Increasing Advance
Figure 2-18: Power Profile Variation with Offset = 500 ft and Increasing Advance

Figure 2-19: Power Profile Variation with Offset = 1000 ft and Increasing Advance
Based on the observed peak movement from the composite power profile plots of Figure 2-14 through Figure 2-19, one would expect the power level peak to move behind the TDP if the antenna was also located behind the TDP. Without considering power levels that are too small, the best APL antenna site, of those considered, is at (Offset, Advance) = (1000, 100), shown in Figure 2-7 with only 12 dB of APL signal power variation over the last 1 nmi of the approach. Furthermore, if this peak projected power level of -98 dBm is compared to a nominal GPS signal power level of -130 dBm, the peak pulsed WBAPL signal will only be 32 dB above the nominal GPS level for the last one nmi of the aircraft approach. The best locations from a dynamic range point of view will provide an acquirable power to the A/C receiver on approach while minimizing the A/C dynamic range requirement. The location of [Offset, Advance] = [1000,100] offers the smallest dynamic range requirement and a slowly changing power level at the peak out of all the candidate APL antenna locations explicitly investigated.

Figure 2-20 illustrates the power level variation that would be observed for all WBAPL MLA locations in a 3000-meter square for a 3 deg aircraft approach. The runway TDP is located at the [Offset, Advance] coordinate of [0,0] and the aircraft approaches from the direction of positive advances along the zero offset centerline. Notice that the "V-shaped" region in front of the TDP in Figure 2-20, which has a larger power level variation than those further from the runway. The large spike directly in front of the TDP shows the largest power level variation because the aircraft is flying over the transmitting antenna at the lowest height of its approach path.
Figure 2-21 illustrates a generalized sketch demonstrating the relative quality of each location investigated based on the results discussed. This is not intended to be an exact sketch, nor all-inclusive, but merely a guideline to demonstrate the trend. As alluded to earlier, it is possible that better APL locations exist behind the TDP. These locations will continue to decrease the available power at the receiver while shifting the power peak behind the TDP, thus keeping the peak of the power curve away from critical decision heights. This would also allow approaches and landings from both sides of the runway with the same quality of service.
Figure 2-21: APL Siting Location Trends Under Power Level Considerations Alone

One factor should be kept in mind when the WBAPL MLA is placed at a location other than the runway TDP. The first null in the original 14-element (Model #200) is located at −3 deg to minimize ground-to-air multipath for an A/C on a 3 deg approach path, assuming a single ground bounce. When the APL transmitting antenna is located away from the TDP, the -3 deg ground-to-aircraft multipath reduction has been slightly depreciated because multipath reflected toward the aircraft will no longer be radiated at −3 deg. While small movements in advance away from the TDP (100 – 500 ft) will have
little effect, large movements (2000 - 3000 ft) will degrade this WBAPL ground-to-air multipath rejection.

These results do not conclusively point to the best location for an APL antenna with regard to all possible considerations, but conclusions can be drawn from these demonstrable trends regarding power levels and receiver dynamic range.

2.5 Siting Conclusions

From the data presented in Figure 2-4 through Figure 2-19, it can be seen that the advance dominates where on the x-axis (slant range) the peak of the received power curve falls with respect to the decision heights. With a large advance and no offset, the aircraft must fly over the APL transmitting antenna during its approach. This can cause unwanted irregularities in the received power at the aircraft during a critical period in the landing process. Since the A/C reception antenna is mounted on top of the aircraft in order to receive the GPS information from satellites overhead, sub-optimal reception of ground transmissions may occur if the WBAPL is received in irregular parts of the A/C antenna pattern (negative elevation angles). Figure 2-4 illustrates a case of poor APL siting where the transmission antenna is almost directly below the aircraft at critical decision heights and power fluctuations are induced by the A/C antenna pattern side lobes.
In turn, the offset dominates how pronounced the peak of the APL received power curve will be. Increasing the offset puts the transmitting antenna further from the runway and thus further from the receiving aircraft antenna. This leads to a more constant received power at the aircraft and a flatter power profile curve thus providing for a reduction in the aircraft receiver dynamic range requirements. Airport siting restrictions, however, will limit the size of the offset in many cases.

From these observations, it is apparent that the advance should be small in order to make the peak occur after the decision height has been reached during an approach. Ideally, this value would be as small as is convenient for the installation. While it was not explicitly considered, the advance could even be negative with respect to the TDP.

The offset does not seem to have such a critical point, but it should be set to maintain a relatively flat received power profile. It should be as far from the runway centerline as possible and still be receivable by the aircraft on approach; a 1000 ft offset was the maximum considered here and was, therefore, the best.

The previous results demonstrate that proper siting of the APL can reduce the airborne user dynamic range requirements by approximately 20 dB. This is a significant improvement and should be considered in APL siting as a minimum.
3. PHASE II – PATTERN INVESTIGATION

In addition to properly locating the ground APL transmission antenna, the gain pattern of the transmitting antenna can be shaped in such a way to maximize APL performance [10]. This section will discuss these considerations, as well as other operational requirements. A new WBAPL MLA gain pattern was designed with three main goals. First, the design should maintain or improve the multipath rejection ability of the WBAPL MLA at the LGF with respect to the original 14-element MLA. Second, the pattern should provide adequate gain to ground and airborne WBAPL receivers. Finally, the coverage volume should include reasonable gain for as much of the upper hemisphere as possible (0 to 360 deg in azimuth and 0 to 90 deg in elevation) in order to provide “overflight” and en route coverage. The following paragraphs will discuss an idealized gain pattern and some of the design tradeoffs.

3.1 Regions of the WBAPL MLA Pattern Defined

An ideal antenna pattern for WBAPL transmission consists of several regions of criticality and each region has a function for airport operations with different objectives and tradeoffs. In general, the primary objective for the negative elevation angles of the pattern (below the horizon) is multipath rejection toward the ground. Close to the horizon, however, the objective is to obtain maximum gain above the horizon while
minimizing the multipath below the horizon. Table 1 presents the particular objectives for each region in this antenna design in the general order of importance.

Table 1: Critical Regions of APL MLA Gain Pattern

<table>
<thead>
<tr>
<th>Elevation Angle</th>
<th>Primary Objective</th>
<th>Secondary Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3° to 0°</td>
<td>LGF – MR</td>
<td>APL Range – Gain (above the horizon)</td>
</tr>
<tr>
<td>-1° to 1°</td>
<td>LGF – Gain</td>
<td>Other Multipath Rejection</td>
</tr>
<tr>
<td>1° to 5°</td>
<td>A/C on Final - Gain</td>
<td>A/C on Final - MR</td>
</tr>
<tr>
<td>-5° to -1°</td>
<td>A/C on Final - MR</td>
<td>Sufficient Gain Above the Horizon</td>
</tr>
<tr>
<td>5° to 35°</td>
<td>APL Airport Coverage - Gain</td>
<td>No Performance Reduction Elsewhere</td>
</tr>
<tr>
<td>35° to 60°</td>
<td>GPS/APL Airport &amp; en route Coverage – Gain</td>
<td>No Performance Reduction Elsewhere</td>
</tr>
</tbody>
</table>

In Table 1, each region has a primary objective as well as some secondary considerations. Under each objective, the target of transmission (e.g. LGF or A/C) is labeled as well as an indication of the goal. The objective of a region might be labeled with “Gain” if the goal is to maximize the range. If the objective were labeled “MR” then the objective would be multipath rejection. “LGF – Gain” would indicate, for example, that the goal is to provide enough gain to maintain the APL link to the LGF.

Some of the angular regions of importance in the transmission pattern overlap, but they each have distinctive objectives. In the first region, -3 deg to 0 deg, the objectives are rejection of ground multipath from the WBAPL toward the LGF while not degrading the antenna’s operating range above the horizon. In the next region, -1 deg to 1 deg, the objectives are to provide sufficient gain to maintain the link between the transmitting
WBAPL MLA and the LGF WBAPL reception antennas while rejecting all types of multipath. Next, from 1 deg to 5 deg, the goal is to provide sufficient gain for the WBAPL transmissions to reach the approaching aircraft while minimizing ground multipath at the aircraft WBAPL receiver. From −5 deg to −1 deg, the goal is to reject potential ground multipath transmissions without degrading the gain above the horizon. From 5 deg to 35 deg, the objective is to provide WBAPL coverage to the entire airport region without giving up performance elsewhere. From 35 deg to 60 deg, the antenna should deliver airport coverage as well as the option of en route navigational coverage without sacrificing performance elsewhere. Finally, from 60 deg to 90 deg, the requirements are still being refined.

3.2 Pattern Characteristics

This section will describe the development of a practically attainable antenna pattern for WBAPL transmission that will accomplish the overall goals listed in Table 1.

Figure 3-1 illustrates a potential siting configuration for a WBAPL transmission antenna and a single LGF receiving antenna.

Consider the region −3 deg to 0 deg shown in Figure 3-1, where the multipath is assumed to be directed from a single surface bounce off of the ground between the WBAPL MLA and the LGF reference antenna. Multipath reduction is critical for these angles because
any radiation from the WBAPL MLA from –3 deg to 0 deg can induce ground multipath at the LGF reception antennas.

Figure 3-1: Ground Station Geometry for Single Multipath Reflection (not to scale)

Multipath reduction is accomplished through a sharp antenna pattern rolloff between –3 deg and 0 deg of the MLA amplitude pattern, where all signals radiating in this region are transmitted with reduced gain.

Figure 3-2 shows the positive elevation angles of the desired gain envelope that could meet the requirements outlined in Table 1.

At approximately 0 deg in elevation, the WBAPL signal will be transmitted to the other LGF reference antennas. This region of the antenna has a minimum gain of -17 dBil. This power level is sufficient to support the APL to LGF link with approximately 100 meters of spacing using the transmission equation shown in Equation 1.
A maximum gain of 3 dBil is also specified in order to prevent saturating the receivers in the LGF. Around 3 deg in elevation, aircraft will be coming into the airport on final approach. More power is required than at 0 deg in order to communicate with the aircraft, so a minimum gain of -5 dBil is required based on the link margin calculated by Equation 1. Otherwise, the maximum gain is only specified to constrain pattern ripple to less than 6 dB if the full envelope is used. Above 40 deg in Figure 3-2, the pattern is allowed to degrade slightly because of practical limitations of linear dipole arrays. The only way to slightly extend the coverage is by adding more elements or selecting a different type of radiating element. The gain is not specified above 60 deg because it will rapidly decline and may not be reliable for pseudolite transmission. The inflection points in Figure 3-2 are summarized in Table 2.
Table 2: Inflection Points for the Desired Elevation Gain Envelope Figure 3-2

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-17</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>-5</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
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<td>0</td>
<td>40</td>
<td>6</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>60</td>
<td>-2.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The minimum multipath performance specified for the WBAPL MLA is shown below in Figure 3-3 in terms of a D/U envelope and summarized in Table 3 where the inflection points are tabulated. The D/U ratio is found by subtracting the gain at a negative elevation angle from the gain of the corresponding positive elevation angle. Thus, the quantities in Figure 3-3 can be used to determine the maximum gain for the negative elevation angles, which were not shown in Figure 3-2.

Two D/U quantities are important to consider for WBAPL transmission. The first involves a direct WBAPL signal toward an aircraft on approach at approximately 3 deg and an indirect signal directed toward the ground at −3 deg which would be reflected toward the A/C. In this case, the D/U would be calculated by subtracting the undesired signal, at −3 deg, from the desired signal, at 3 deg. The second type of D/U quantity involves multipath directed toward the LGF reception antennas. In this situation, the D/U would be calculated by subtracting the undesired signal, at −3 deg, from the desired
signal, at 0 deg. The D/U calculation for this situation is best explained by the following example.

For the geometry shown in Figure 3-1, consider the indirect signal; the WBAPL signal would be attenuated once by the transmitting MLA antenna pattern (at least –35 dB) and then a second time (at least –35 dB), both at –3 deg. This would lead to at least 70 dB of multipath rejection for the indirect signal path not including ground attenuation. Now consider the direct signal path at 0 deg. The transmitting MLA antenna pattern attenuates this signal by 17 dB and the reception MLA antenna pattern also attenuates the signal by 17 dB for a total attenuation of 34 dB on the direct signal path. For the link between the WBAPL transmission MLA and the LGF reception MLA, there would be a D/U ratio of 36 dB (70 dB – 34 dB).

![Figure 3-3: APL MLA Minimum Desired-to-Undesired Ratio](image-url)
Table 3: Inflection Points for the Desired-to-Undesired Ratio Plot of Figure 3-3

<table>
<thead>
<tr>
<th>Elevation Angle [Deg]</th>
<th>D/U Ratio [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2.5</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>36</td>
<td>20</td>
</tr>
<tr>
<td>60</td>
<td>20</td>
</tr>
<tr>
<td>61</td>
<td>0</td>
</tr>
</tbody>
</table>

The specifications in Figure 3-3 and Table 3 provide at least 20 dB of D/U up to 60 deg. This is quite acceptable for non-precision approaches, where only simple tracking is desired, but from 3 deg to 35 deg the specification provides an excellent D/U of 30 dB for precision approach applications. At an elevation angle of 2.5 deg, there is a “knee” in the minimum D/U ratio. When moving up from the horizon to 2.5 deg, the D/U is pushed up to 25 dB in order to provide a sharper rolloff about the horizon. To conform to the gain envelope and minimum D/U specification from +3 deg to -3 deg in elevation the gain would have to be monotonically decreasing at a minimum rate of 5 dB per deg.

Based upon the design requirements of Figure 3-2, Figure 3-3, Table 2, and Table 3 a contract was let for the implementation and fabrication of a prototype WBAPL MLA [14]. A theoretical gain pattern resulting from this effort is shown in Figure 3-4 [14] as the dashed trace. The gain follows the specification envelope closely; however, the actual gain pattern will likely have higher side lobe levels below the horizon. At the time
of this publication, the WBAPL transmission antenna is still in development with the contractor. To help build confidence in this WBAPL antenna design, the pattern was also independently synthesized. The results of this validation will be presented in Chapter 4.

![Theoretical WBAPL MLA Gain Pattern and Limit Lines](image)

**Figure 3-4: Theoretical WBAPL MLA Gain Pattern and Limit Lines**

### 3.3 Theoretical WBAPL Coverage Assessment

A study was conducted to determine the antenna coverage region based upon a theoretical WBAPL transmission antenna pattern [10] presented in Figure 3-4. The simulation used the link equation described in Equation 1 to determine the received
power. For this simulation, the location of the WBAPL MLA was fixed at an arbitrary location and aircraft flyovers at heights of 1000 ft and 30,000 ft were simulated in a 20 nmi square around the WBAPL MLA transmission antenna site. Particular emphasis in this analysis phase was placed on the amount of coverage that could be provided at higher elevation angles if the WBAPL was used for en route applications. The A/C reception gain pattern is the same as used previously, however, a linear approximation has been applied as illustrated in Figure 3-5. The theoretical pattern shown in Figure 3-4 was used as the WBAPL transmitting gain.

Figure 3-5: Aircraft Antenna for GPS Reception with Superimposed Pattern Approximation
The theoretical transmission antenna pattern, shown in Figure 3-4 (labeled 20 Element Standard Spacing), provides uniform coverage for the region surrounding the airport at low to moderate elevation angles, but the gain is greatly reduced at high elevation angles, a.k.a. a zone of silence. Since this “cone” shaped region could not be eliminated, attempts were made to minimize it in the design. Figure 3-6 illustrates the resulting power that an aircraft would receive around the airport region at a height of 1000 ft. It clearly illustrates a 0.2 nmi zone of silence around the APL transmission antenna. This zone of silence occurs over the WBAPL transmission antenna when the received signal falls below a peak power level of $-130 \text{ dBm}$ in all of the cases presented here. Since both the transmission and reception antennas have an essentially symmetric pattern as a function of azimuth angle, Figure 3-6 can be mirrored on the other side of the cut away. This cone of silence indicates that if an aircraft were to fly over the antenna at 1000 ft, there would be approximately a 0.2 nmi diameter circle where the aircraft could not receive the WBAPL signal. This diameter equates to only a 3.5 second outage at 200 nmi/hr. Also, notice that a relatively constant power level is shown over the 1 nmi square region depicted in Figure 3-6.

Figure 3-7 shows the cone of silence that would result for an aircraft height of 10,000 ft over a 40 nmi square region. This scenario was selected because it demonstrates WBAPL MLA coverage on a similar scale to the LAAS VDB antenna coverage. The LAAS VDB specification provides a cone of silence of 5 deg from center in the coverage
region, which would result in a 0.144 nmi zone of silence at an aircraft height of 10,000 ft [1] [4].

Figure 3-6: Received Power for an Aircraft Height of 1,000 Ft over a 1 nmi Region

Figure 3-7 shows that for the WBAPL MLA, the cone of silence is roughly 38 deg from center resulting in a total zone of silence of 1.3 nmi or 24 seconds at 200 nmi/hr. Due to the expanded region of consideration, 40 nmi in Figure 3-7 vs. 1 nmi in Figure 3-6, a larger power level variation of 20 dB is observed.
Figure 3-7: Received Power for an Aircraft Height of 10,000 Ft over a 40 nmi Region

Figure 3-8 illustrates the aircraft received power levels resulting from an aircraft flyover at a height of 30,000 ft to illustrate the WBAPL coverage for potential application to en route navigation. As the aircraft height increases, the theoretical aircraft passes much more slowly through the elevation angles with a gain null resulting in a larger zone of silence. For a height of 30,000 ft, the zone of silence has a diameter of roughly 2.5 nmi, which would equate to 45 seconds at 200 nmi/hr.

The results shown in Figure 3-6 through Figure 3-8 indicate that the theoretical WBAPL transmission antenna offers sufficient coverage for low height overflight in and around
the airport facility in the case of a missed approach, neglecting antenna shadowing from aircraft altitude effects.

![Graph of received power](image)

**Figure 3-8: Received Power for an Aircraft Height of 30,000 Ft over a 20 nmi Region**

Depending on the transmitted power levels, it may also have sufficient coverage volume to offer the option of en route navigation for large areas surrounding an airport facility with the exception of a cone shaped region directly above the antenna.
4. PHASE III – ANTENNA DESIGN ANALYSIS & SYNTHESIS

4.1 Design Overview

The design of the original MLA was concerned primarily with not allowing multipath into the receiver front end as well as minimizing APL radiation into the ground. These objectives were successfully achieved since the MLA works very well for receiving GPS signals from satellites at elevation angles of 5 deg to 35 deg, receiving the WBAPL signal at 0 deg, and minimized APL radiated energy below 0 deg in elevation.

With the refinement of the MLA for DGPS (16 element extended aperture array, i.e. Model 200A) complete, a new WBAPL MLA for pseudolite transmission was pursued. During this new development effort, the antenna design was optimized for WBAPL transmission. The original design (14 element array, i.e., Model #200) was used as a baseline since it performs reasonably well in the field. Vertical polarization was still desired since it provides better power coupling performance for the APL link [12]. The multipath performance of the original MLA was also still desirable and this was to be maintained or improved for the WBAPL. Two main improvements were desired. First, the original MLA had a region of excessive gain (5 dB higher than nominal from 5 deg to 15 deg). This region caused undesirable effects in the case of pseudolite transmission and radiated energy in undesired directions. Second, and less important, the coverage of the MLA gain pattern above 35 deg was not sufficient to provide coverage to support
potential LAAS applications such as aircraft overflight given that the HZA is not used for pseudolite transmission. Consequently, the goals of the new design were to expand the coverage volume while reducing the gain hump and still maintaining (or improving) its multipath performance about the horizon. To summarize, the overall priorities for the APL transmission antenna pattern were in order of importance:

1. Vertical polarization.
2. Maintain or improve D/U about the horizon.
3. Reduce gain variation over the elevation angles 5° to 40°.
4. Increase coverage volume above 35° with some nominal value of gain.

With these priorities in mind, a specification was created for the desired gain pattern. This specification was submitted to a contractor for synthesis and fabrication. Additionally, independent synthesis was performed within the scope of this thesis in order to attain some level of validation of the design. This synthesis will be discussed in Section 4.2.

4.2 Antenna Pattern Synthesis

Numerous methods exist for creating a desired antenna pattern for various applications. In general, these can be broken down into three categories as discussed in Balanis [13]. First, null placement allows the designer to place beam nulls in any direction. This
method can be used in any applications where energy should not radiate (or be received) in a given direction. Next, a pattern can be designed where the only requirement is a narrow main beam and uniformly low side lobes. An antenna such as this might have applications in radar to minimize erroneous reflections. Finally, beam shaping techniques allow the antenna pattern to be shaped in order to direct energy in prescribed directions. This method has applications in footprint pattern antennas directed toward the earth. Because of the demanding performance requirements for pseudolite transmission, beam shaping pattern synthesis techniques were used.

From a multipath perspective, beam shaping allows the antenna to direct the largest amount of its energy above the horizon while minimizing the energy directed toward the ground. Beam shaping is accomplished by summing several patterns with desired power levels. This technique will be referred to as summation synthesis and will be discussed in Section 4.2.1. It can be carried out using a combination of the aforementioned techniques as well as null filling based upon a Taylor pattern [15]. Summation synthesis provides several benefits including side lobe level control, beam placement, and uniform coverage. There are, however, several inherent tradeoffs in this technique that will be further discussed in Section 4.4. With these concepts in mind, a systematic procedure will now be outlined for the synthesis of a summed Taylor pattern with null filling for WBAPL transmission applications.
4.2.1 Summation Synthesis

The first step required for synthesis is to identify the desired pattern. A convenient means for doing this is to set gain variation limits of the pattern in the form of an envelope. These limits will then serve as inputs into the computer synthesis program that will be discussed in Section 4.2.5. For the WBAPL, this envelope was previously defined in Figure 3-2 and Figure 3-3 using the overall requirements of Table 1. After synthesizing the desired antenna pattern, the next step is to determine the amplitude and phase distribution required to create such a pattern. Summation synthesis is a procedure that can be used to achieve this goal.

Summation synthesis has been so labeled because it is performed by summing a series of easily formed patterns to yield a more complex pattern. Two types of patterns will be added in this type of synthesis. The first pattern in the summation will be referred to as the central pattern since it is positioned in the center of the overall pattern. The central pattern is very important since future patterns will be overlaid and aligned with it. If the side lobes of this central pattern are too high, the side lobes of the overall pattern will be commensurate. Therefore, it is important to start with a central pattern that does not limit the performance of the total pattern. The second type of pattern in the summation will be referred to as constituent patterns. These space-filling patterns are used to fill the nulls in the central pattern so there can be as many constituent patterns as there are nulls to be filled. The parameters of this type of pattern can be modified independently
of the central pattern in order to provide better performance. Summation synthesis is a relatively simple way to develop complex antenna patterns using numerical techniques. Next, some techniques for creating central and constituent patterns will be discussed. The starting point used for creating both central and constituent patterns is a uniformly weighted power pattern. Several techniques are then used to manipulate the uniform pattern in order to provide the desired performance, which will be discussed in 4.2.3. Some basic antenna array concepts will be presented in Section 4.2.2 in order to provide the necessary background to understand some of the more complex ideas contained in this document.

4.2.2 Phased Array Background

A basic linear array consists of multiple elements arranged in order to provide additional directivity and pattern control. From this, a phased array adds the ability to direct the main radiating beam by controlling the phase distribution between elements. Some of the required terminology will be discussed in this section. The sketch in Figure 4-1 illustrates a simple twelve element linear array.

Notice in this figure the overall length is labeled as L. This quantity can be found analytically by multiplying the number of elements, N, by the inter-element spacing, d. The center of the array is indicated by the L/2 label. Finally, notice that the elevation
angle, $\theta_{EL}$, is shown to be equal to zero for a beam pointed in the broadside direction (Normal to the array). In this case, $\theta_0$ corresponds with the main beam pointing direction used in Equation 3.

Figure 4-1: Typical Phased Array

The radiation pattern of an array is characterized by the product of its array factor (AF) and its element factor (EF). This is true according to the pattern multiplication rule, which holds if the elements are identical [13]. For the synthesis done in this document, the element factor was assumed to be unity, as would be the case for an isotropic element. An AF for uniform amplitude and phase excitation, can be written as:
\[
AF_n = \frac{\sin\left(\frac{N}{2} \cdot k \cdot d \cdot \cos \theta_{EL} + \beta\right)}{\frac{N}{2} \cdot k \cdot d \cdot \cos \theta_{EL} + \beta}
\]  

(2)

where:

- \(AF_n\) = Array factor normalized by \(N\) [unitless]
- \(N\) = Number of elements [unitless]
- \(k\) = Wave number = \(\frac{2\pi}{\lambda}\) [rad/m]
- \(d\) = Inter-element spacing [m]
- \(\theta_{EL}\) = Elevation angle [rad]
- \(\beta\) = Progressive phase shift [rad].

The major design variables in this equation are the number of elements, the element spacing, and the progressive phase shift. The element spacing should be less than 1 wavelength in order to prevent the formation of grating lobes (secondary main beams). The number of elements allows more energy directivity and the phase shift allows the main beam to be pointed in a desired direction, \(\theta_0\) (a special case of the angle from the vertical axis). For a fixed frequency and element spacing, the main beam can be pointed in the direction by solving for the progressive phase shift, \(\beta\), by:

\[
k d \cos \theta_0 + \beta = 0
\]

(3)

where:

- \(k\) = Wave number = \(\frac{2\pi}{\lambda}\) [rad/m]
- \(d\) = Inter element spacing [m]
- \(\theta_0\) = Main beam pointing direction [rad]
- \(\beta\) = Progressive phase shift [rad].
One must be cognizant of the element factor and the array factor since the multiplication of these two factors creates the overall antenna pattern. In practicality, the designer has less control over the element factor than the array factor and can merely select an element to meet the design requirements. The array factor, however, can be shaped in various ways. If the designer knows what effect the element factor will have, the array can be shaped in such a way to compensate for these effects. Consequentially, the element factor will be ignored from this point forward and all synthesized pattern data will only reflect the array factor. Phenomena such as mutual coupling and other physical design constraints will not be considered. The procedure outlined in Section 4.2.3 is simply a proof of concept to attain some level of validation of the predicted WBAPL radiation characteristics.

4.2.3 Pattern Formation Tools

Several synthetic tools exist that can be used to create patterns with desired characteristics for use in summation synthesis. This section will discuss seven generic pattern synthesis tools: Uniform Power Patterns, Symmetric Taylor Side Lobe Suppression Patterns, Critical Point Determination, Aperture Distribution Determination, Asymmetric Taylor Side Lobe Suppression Patterns, Arbitrary Side Lobe Control, and Null Filling. These tools will then be used as part of a more specific discussion, tailored to the WBAPL MLA design, which follows in Section 4.2.5. The foundation upon
which the synthesis techniques of Chapter 4 are built is a technique developed by
Taylor [15], which can be used for side lobe level control.

4.2.3.1 Uniform Power Patterns

As a baseline, it is constructive to examine a standard sum power radiation pattern with
uniform excitation and no progressive phase shift as calculated by the following equation
[16]:

\[
S(u) = 20 \log_{10} \left( \frac{\sin(\pi \cdot u)}{\pi \cdot u} \right) \quad [\text{dB}]
\]

(4)

where:

\[ u = \text{Normalized elevation angle} \quad \text{[unitless]} \quad \text{- Defined in Equation 5.} \]

Such a pattern is portrayed in Figure 4-2. The power plotted on the y-axis has been
normalized by its maximum value so it is labeled as relative power. As introduced by
Woodward [16], the x-axis is a normalized elevation angle, \( u \). Equation 5 provides a
mathematical explanation of this quantity. The variable \( u \) is used to refer to the
normalized angles in order to provide integer spacing between pattern nulls. This
normalized elevation angle can be described as:
where:

\[ u = \frac{2 \cdot a}{\lambda} \cdot (\cos \theta - \cos \theta_0) \]  

[unitless]  

\[ \frac{4}{\lambda} \]  

[rad]  

\[ \theta = \text{Elevation angles} \]  

[unitless]  

\[ \theta_0 = \text{Main beam pointing direction} \]  

[rad].

Figure 4-2: Standard Power Pattern with Uniform Excitation vs. Normalized Elevation Angle

The aperture variable, \( a \), is half the length of the continuous line source and can be calculated for the discrete case by multiplying the number of elements, \( N \), by half the
element spacing, $d$, as shown here: $a = \frac{N \cdot d}{2}$. For the case of the WBAPL MLA, the variable $d$ is assumed to be $\lambda/2$. The GPS L1 frequency is 1575.42 MHz so the wavelength is used for this calculation is 19.04 cm. The elevation angle $\theta$, in units of radians, are the angles that are to be normalized. The variable $\theta_0$ determines the main beam pointing direction in radians. Figure 4-2 shows that Equation 5 produces uniform integer spacing between the nulls of the pattern everywhere except between the two nulls surrounding the main beam. Contrarily, Figure 4-3 shows the same pattern plotted against the elevation angle, $\theta$, in units of degrees. It is evident in Figure 4-3 that the nulls are no longer spaced by a uniform amount with respect to elevation angle, $\theta$.

The first orientation, shown in Figure 4-2, uses a normalized elevation angle, $u$, and is more convenient to visualize and simulate so it will be favored throughout this document. Using the pattern shown in Figure 4-2 as a starting point, several tools will now be discussed which modify this pattern to meet various needs in the overall pattern synthesis.
Figure 4-3: Standard Power Pattern with Uniform Excitation vs. Elevation Angle

4.2.3.2 Symmetric Taylor Side Lobe Suppression Patterns

In many cases having lower side lobes is a desirable quality. This can be achieved by adjusting the placement of the nulls along the real axis of the uniformly weighted pattern. Software was written with the ability to reduce the side lobe levels to some known value as discussed in Taylor’s paper [15] and will be outlined here. A "Taylor" pattern with reduced side lobe levels can be used as the central pattern in the synthesis procedure in order to reduce the overall side lobe levels in the final summed pattern.
A region, known as the pattern region, is created where the designer can have influence over the side lobe levels. The pattern region is a range of normalized angles defined by an interval \([-\bar{n},+\bar{n}]\), where \(\bar{n}\) corresponds to a specific value of \(u\), \([-6 \leq u \leq 6]\) for example. Within this region, the side lobe levels can be reduced to any assigned power level. Beyond the pattern region, \([-6 > u > 6]\), the side lobe power levels decay at an unperturbed rate of \(u^{-1}\). It should also be noted that while the main lobe occurs within this region, it remains unperturbed. Depending on how much suppression has been requested, the procedure may require several iterations to reach the assigned level. A suppressed side lobe Taylor pattern was achieved with the following:

\[
S(u) = 20 \cdot \log_{10} \left( \frac{\sin(\pi u)}{\pi u} \prod_{n=1}^{\bar{n}-1} \left( 1 - \frac{u^2}{u_n^2} \right) \right) \quad \text{[dB]} \tag{6}
\]

where:

- \(u\) = Normalized elevation angle [unitless]
- \(\bar{n}\) = Pattern region limit [unitless]
- \(n\) = Incremental variable [unitless]

In order to generate a pattern using Equation 6, the cumulative products in the numerator and denominator are generated as the synthesis software sweeps through the angles from 360 deg to 180 deg when looking at the total pattern (corresponding to 180 deg to 0 deg in elevation mirrored in azimuth). The products are then multiplied by the \(\sin(\pi u)/\pi u\)
term, put into units of dB and then plotted. Another quantity needed in the cumulative product of Equation 6 is the new null placement locations, which are defined by:

\[ u_n = \sqrt{\frac{A^2 + (n-1)^2}{A^2 + (\bar{n} - 1)^2}} \]  

[unitless]  

(7)

where:

\( \bar{n} = \) Pattern region limit  
\( A = \) Indirect measure of side lobe level  

Equation 7 shows where the nulls must be placed in the new pattern in order to suppress the side lobes of the current pattern. This procedure simply shifts the null locations in order to increase or decrease the side lobe levels (SLL). Equation 7 is dependent on the desired SLL, which is indirectly captured in the quantity A (describes the side lobe peaks that occur on each side of the main beam). In order to determine A, the actual side lobe level must be input into the following:

\[ A = \frac{\cosh^{-1}\left(\frac{SLL}{10}\right)}{\pi} \]  

[v]  

(8)

where:

\( SLL = \) Side lobe level  
[dB].
The major disadvantage to using this technique is that some side lobes are suppressed that may not necessarily need to be since all side lobes are suppressed by the same amount. Also, the spacing of nulls around the main beam becomes wider than a uniformly weighted pattern. This makes it more difficult to fill nulls in subsequent steps as will be discussed in Section 4.4. The principles of the Symmetric Taylor pattern are illustrated in Figure 4-4 where the side lobes in a control window of [-6, +6] (i.e., \([-\pi, +\pi]\)) are suppressed to -25 dB (i.e., SLL = -25). This means that six peaks on each side of (and excluding) the main beam have been suppressed and the first one has a maximum relative power level of -25 dB. The remaining side lobes outside of the control window have not been directly suppressed, but their power level will be pulled down by the first six and are thus indirectly affected.

![Figure 4-4: 25 dB Suppressed Side Lobe Taylor Pattern, Control Window = 6](image-url)
4.2.3.3 Critical Point Determination

As part of the generation of Symmetric Taylor patterns, it is necessary to determine the peak and null locations. This will be required in future stages of synthesis so it will be discussed as part of the creation of symmetric patterns. The same technique is applied to determine the peak and null locations for every pattern that is created for this synthesis. Critical points (both peaks and nulls) were found by differentiating the pattern of Figure 4-4 and locating the zero crossings. This procedure is illustrated in the top curve of Figure 4-5. Figure 4-4 has been repeated in the bottom trace of Figure 4-5 for added clarity. This differentiation returns an array of critical points. Since the peaks and nulls alternate, every other critical point was stored in an array of peaks and the remaining points were stored in an array of nulls. The locations of these peaks and nulls are plotted as circles on the bottom trace of Figure 4-5. Locating the peaks and nulls is a procedure that is used for every type of pattern throughout the synthesis process. In order to fabricate patterns such as the uniform power pattern and Symmetric Taylor pattern using a linear array, the aperture magnitude and phase distribution must be known so they can be applied to each element of the array. Consequently, the topic of aperture distribution will be considered before discussing other types of patterns.
4.2.3.4 Aperture Distribution Determination

Taylor distributions are continuous functions which may or may not be practical to manufacture so several iterations may be required to find a realizable distribution. These complex distributions were calculated using the following equation [15] [16] [19]:

\[
h(a) = \frac{1}{2a} \sum_{m=-(n_z-1)}^{n_z-1} S_0 \cdot e^{-jm\pi / a} \quad (9)
\]

where:

- \( m \) = Summation variable, peak locations [unitless]
- \( S_0 \) = Pattern amplitude [\( \text{v} \)]
\[ \zeta = \text{Current array position} \quad [\text{m}] \]
\[ a = \text{Half of the continuous line source length} \quad [\text{m}] \]

The distribution calculated by \( h \) is a complex quantity so the magnitude is used to find the amplitude distribution (in volts) and the angle is used to find the phase distribution (in degrees). After the continuous aperture distribution has been determined, it must be converted into a discrete version for the number of elements to be used in the design. One rough way to achieve this is through Woodward sampling [16]. This method discretizes a continuous aperture distribution so that the proper amplitude and phase can be individually applied to each element of the array. It has been shown that simply sampling the continuous function can lead to significant pattern deviations [13]. Determination of a more accurate aperture distribution is possible by considering root matching, but is beyond the scope of this document [13] [20]. The aperture distribution for the Symmetric Taylor pattern of Figure 4-4 is shown in Figure 4-6. One important thing to note in Figure 4-6 is that symmetrical patterns have a flat phase distribution. Additionally, it is best to have the fewest number of extreme variations in phase from one extreme to another. The difficulties with extreme variations will be more apparent after the discussion of null filling in Section 4.2.3.7.
4.2.3.5 Asymmetric Taylor Side Lobe Suppression Patterns

Another useful tool that allows the designer to independently control the SLL on each side of the main beam is referred to as a modified Taylor pattern [17] or Asymmetric Taylor pattern. It is also important in pattern synthesis because both sides of the main beam may not have the same side lobe requirements. In addition, by allowing higher side lobes the problem of beam broadening discussed in Section 4.4 can be minimized. This is true, to a lesser extent, if higher side lobes are allowed on only one side of the pattern. Equations similar to those in the Symmetric Taylor expressions (Equation 6 and
Equation 7) were used except that null placement is treated independently on each side of the main beam by redefining the normalized elevation angle variable $u$. The control window can be defined with independent values of $\bar{n}$ on each side of the pattern such that $-\bar{n}_L < u < \bar{n}_R$. This radiation pattern can be described as an asymmetric power pattern [17] as:

$$S(u) = 20 \cdot \log_{10} \left( C_0 \frac{\sin(nu)}{mu} \prod_{n=-(\bar{n}_L-1)}^{\bar{n}_R-1} (1 - \frac{u^2}{\hat{u}_n^2}) \right) \text{ [dB]}$$ \hspace{1cm} (10)

where:

- $\bar{n}_L =$ Left side of the control window \hspace{1cm} [unitless]
- $\bar{n}_R =$ Right side of the control window \hspace{1cm} [unitless]
- $u =$ Normalized elevation angle \hspace{1cm} [unitless]
- $\hat{u}_n =$ Root positions \hspace{1cm} [unitless] – Defined in Equation 11
- $C_0 =$ Scaling constant \hspace{1cm} [unitless]

The quantity $C_0$ is a multiplicative scaling constant, which can be used to shape the overall pattern according to some envelope. For the purpose of illustration, this constant is set to one. Normally, this value would be taken from a predefined pattern envelope and it might vary as the synthesis moves along the aperture. The asymmetric root positions used in Equation 10 are defined separately for each asymmetric side of the pattern by:
\[ u_n = \frac{n}{A_R^2 + (n-1)^2} \Rightarrow n = 1, 2, \ldots, (\bar{n}_R - 1) \]

\[ u_n = -\bar{n} \left[ \frac{A_L^2 + (n+1)^2}{A_L^2 + (\bar{n}_L - 1)^2} \right]^{1/2} \Rightarrow n = -1, -2, \ldots, -\bar{n}_L - 1 \]

where:

\( \bar{n}_L \) = Left side of the control window [unitless]
\( \bar{n}_R \) = Right side of the control window [unitless]
\( A_R \) = Measure of the side lobe level on the right side of the pattern [\( \nu \)]
\( A_L \) = Measure of the side lobe level on the left side of the pattern [\( \nu \)].

Using this technique, the exact side lobe levels are no longer achieved, but slight modifications to the initial side lobe design height can compensate for the difference [17]. This is somewhat inconsequential to this research because exact side lobe values are not as important as other parameters in the design. The pattern resulting from this calculation is shown in Figure 4-7 where a 45 dB suppressed SLL is used on one side of the main beam and a 15 dB suppressed SLL is used on the other side of the main beam. For this calculation, a control window of eight was used, so control is only imposed on eight side lobes on each side of the pattern as denoted by \( \bar{n} = 8 \). A byproduct of the Asymmetric Taylor technique is that the radiation pattern produced by Equation 11 does not achieve these exact side lobe levels (i.e., 38 dB vs. 45 and 20 dB vs. 15 dB). Notice that the main beam has also shifted slightly to the left and up resulting from the asymmetric side lobe suppression.
Figure 4-7: Asymmetric Taylor with 45 dB / 15 dB Suppression with Window = 8

The aperture distribution in amplitude and phase for the pattern of Figure 4-7 is presented below in Figure 4-8. Symmetric radiation patterns tend to have flat phase distributions such as shown in Figure 4-6. However, asymmetric radiation patterns have variations in their phase distribution as can be seen in Figure 4-8. In the case of the purely asymmetric pattern distribution shown in Figure 4-7, the phase distribution in Figure 4-8 is slowly varying from −50 deg to 50 deg. Slow variations are easier to create and make the fabrication process simpler than the case of rapid phase variations.
4.2.3.6 Arbitrary Side Lobe Control

The next tool will prove to be invaluable in the final synthesis procedure. It allows the side lobe level of any single or group of side lobes to be set to an arbitrary level. With this ability, the designer can tweak the final design by dropping the power level of targeted side lobes that appear to be too high. This is achieved through the iteration of Equation 12, which defines a ratio of the “desired” pattern peaks to the “starting” pattern peaks [18] as:
\[
\frac{S(u_m^p)}{S_0(u_m^p)} - 1 = \frac{\delta C}{C_0} + \sum_{n=-(\bar{n}_l-1)}^{\bar{n}_l-1} \frac{\frac{u_m^p}{u_n^2}}{1 - \frac{u_m^p}{u_n^2}} \delta u_n \quad \text{[unitless]}
\] (12)

where:

\(S(u_m^p)\) = Height of the \(m^{th}\) side lobe in the desired pattern \([\text{v}]\)

\(S_0(u_m^p)\) = Height of the \(m^{th}\) side lobe in the starting pattern \([\text{v}]\)

\(u_m^p\) = Location of the \(m^{th}\) side lobe \([\text{unitless}]\)

\(C_0\) = Multiplicative constant \([\text{unitless}]\)

\(\delta C\) = Multiplicative constant Perturbation \([\text{unitless}]\)

\(\bar{z}_{ii}\) = Starting pattern root locations \([\text{unitless}]\)

\(\bar{u}_n\) = Root perturbations \([\text{unitless}]\)

\([-\bar{n}_l, \bar{n}_n]\) = Interval containing the pattern region (control window) \([\text{unitless}]\).

This equation is a ratio of two voltage patterns. In the summation, it should be noted that the quantity \(n=0\) is excluded in order to avoid perturbing the main beam. It should be noted that the entire patterns of \(S(u)\) and \(S_0(u)\) are not required for this synthesis. Instead, the height of the peak side lobe levels of \(S(u_m^p)\) and \(S_0(u_m^p)\) are used at their side lobe locations, \(u_m^p\). The desired pattern is a known quantity since it was established by the design criteria. The desired pattern peaks, \(S(u_m^p)\), were generated simply by sampling the side lobe levels of the final pattern. An entire starting pattern can be generated by any of the pattern generation techniques discussed and then sampled at the specific peak locations defined by \(u_m^p\) to then form, \(S_0(u_m^p)\). These starting pattern peaks should resemble the desired pattern peaks as closely as possible to minimize the calculation iterations. For the purposes of the WBAPL MLA, the starting pattern is an Asymmetric Taylor pattern, which is then sampled at \(u_m^p\) and iterated using Equation 12.
until specific arbitrary side lobe levels are attained. The quantity, $C_0$ is a constant that allows the pattern to be scaled and will be perturbed by $\delta C$, a single perturbation that attempts to match the desired pattern amplitude. The vector, $u^p_m$, contains the locations of the side lobe peaks of the respective voltage patterns (i.e., starting or desired). The starting pattern nulls are contained in the vector, $\hat{u}_n$, which can be perturbed by the quantity $\delta u_n$ at each null location (i.e., $n$) within the control window. Finally, the control window is defined by the interval $[-\bar{n}_L, \bar{n}_R]$ where $\bar{n}$ is an integer along the $u$ axis. The subscripts $L$ and $R$ indicate the left and right cutoff values of the pattern region. The pattern region is simply the part of the pattern within the control window; only side lobes within the control window are directly affected by side lobe suppression.

With all of the quantities of Equation 12 defined, this equation will then be perturbed in order to determine the values of $\delta C$ and $\delta u_n$ that create the best matching radiation pattern with arbitrarily suppressed side lobes. This perturbation involves an ordinary least squares (OLS) solution for the $(\bar{n}_R + \bar{n}_L - 2)$ values of $\delta u_n$ and the single value of $\delta C$. There are $(\bar{n}_R - \bar{n}_L - 2)$ different perturbations of $\delta u_n$ because the summation goes from $(\bar{n}_L - 1)$ to $(\bar{n}_R - 1)$. Equation 12 is arranged as a ratio so that it is in a form easily solved by ordinary least squares. A variable substitution will be made in order to clarify the solution of $\delta C$ and $\delta u_n$. The subscript $m$ indicates the $(\bar{n}_R + \bar{n}_L - 1)$ peaks of the radiation pattern, while the subscript $n$ indicates the $(\bar{n}_R + \bar{n}_L - 2)$ null locations in the radiation pattern. The variable $Y$ will be a matrix of dimension $[(\bar{n}_R + \bar{n}_L - 1) \times 1]$ containing the values of the pattern peak ratio, $[(S(u^p_m) / S_0(u^p_m)) - 1]$ on the left side of
Equation 12. The right side of Equation 12 can be thought of as a coefficient matrix, $H$, multiplied by an unknown matrix, $X$. The relational coefficient matrix $H$, of dimension $[(\bar{R} + \bar{L} - 1) \times 2]$, contains the coefficients of the unknowns. Then, the variable $X$ will represent the vector of $(\bar{R} + \bar{L} - 1)$ unknowns, one $\delta C$ term and $n$ $\delta u_n$ terms. Notice that the relational coefficient matrix, $H$, will always be square after the column of ones is included. After variable substitutions, Equation 12 can be rewritten in the form:

$$ Y = H \cdot X $$

where:

$Y =$ Response matrix. The voltage pattern ratio, $y = S(\delta u)/S_0(\delta u) - 1$.
$H =$ Relational coefficient matrix. Coefficients denoted by $H_{mn}$.
$X =$ Explanatory matrix. Unknowns, $\delta C$, $\delta u_m$.

This equation must be solved for $X$ in order to determine the perturbed values of $\delta C$ and $\delta u_n$. This is done by inverting the $H$ matrix and multiplying by $Y$. This OLS was solved iteratively by using the solution to the first OLS as the starting pattern for the next until the perturbation terms, $\delta C$ and $\delta u_n$, were less than a target threshold of $10^{-4}$. The final pattern is then found by inserting these perturbations into the equation for the final desired pattern as [18]:

$$ Y = H \cdot X $$

(13)
where:

\[ S(u) = (C_0 + \delta C) \frac{\sin \pi u}{\pi u} \prod_{n=\tilde{n}_1-1}^{\tilde{n}_2-1} \left(1 - \frac{u}{\tilde{u}_n - \delta u_n}\right) \prod_{n=\tilde{n}_1-1}^{\tilde{n}_2-1} \left(1 - \frac{u}{n}\right) \]  

1. \( C_0 \) = Multiplicative constant [unitless]
2. \( \delta C \) = Multiplicative constant perturbation [unitless]
3. \( \tilde{u}_n \) = Starting pattern root locations [unitless]
4. \( \delta u_n \) = Root perturbations [unitless]
5. \([-\tilde{n}_1, \tilde{n}_2]\) = Interval containing the pattern region (control window) [unitless]
6. \( u \) = Normalized elevation angle [unitless]

A theoretical application of an antenna pattern with arbitrary side lobe suppression is demonstrated in Figure 4-9 when the peaks with the circles on top are within the control window and thus will be suppressed to the specified SLL (-40 dB). The side lobe heights within the control window of \([-6, 6]\) can be controlled using Equation 13. In Equation 13, the side lobe levels are not defined using the “A” quantities used previously. Instead, the heights of the peaks are defined for the desired pattern in terms of the voltage value of \( S(u^0) \). The two side lobes on each side of the main beam in Figure 4-9 demonstrate the grouping ability whereby two lobes are suppressed to the same amount, 40 dB in this case. The next lobe, moving away from the main beam, is allowed to pass the function unchanged, while the following lobe is individually suppressed by 40 dB. The final lobe is left unmodified. In this case, both sides of the pattern are symmetrical. In most situations where this capability is useful, the side lobes will not be symmetrical.
Theoretically, this tool is able to accomplish everything that the previous techniques could, but with more precision. It should be noted, however, that the achievability of the final antenna pattern becomes degraded because the detail in rapid phase variations resulting from an asymmetric pattern are difficult to capture with a limited number of elements. While this tool is very powerful in principle, it should be used sparingly in order to end up with a design that can be more easily constructed. It is advantageous to use because it limits the SLL reduction to only those side lobes that require suppression to a specified level. This technique minimizes many of the detrimental effects discussed in Section 4.4 including main beam broadening.
The aperture distribution for the pattern in Figure 4-9 is shown in Figure 4-10. The radiation pattern is symmetrical so the phase distribution is essentially flat.

![Figure 4-10: Aperture Distribution for Pattern Shown in Figure 4-9](image)

4.2.3.7 Null Filling

The final tool to be discussed allows the designer to fill the nulls over a specified region. This ability is incredibly powerful because it enables an antenna to deliver relatively uniform energy over a wide region. This scheme has been used in many applications from communications to radar. The concept is simple; a main beam of a constituent
pattern is placed at every null location over the region of interest in the central pattern. When the constituent and central patterns are added together, these main beams fill the final pattern with energy in the nulls, thus flattening out the overall pattern. The key to achieving this without seriously degrading the final pattern is discussed in a paper by Woodward [16]. He demonstrates that if the main beam of each constituent pattern is placed at the nulls of the central pattern in such a way that all of the nulls coincide; the patterns can be summed without interfering with each other. By specifically weighting each constituent pattern, the final summed pattern can be shaped to conform to a composite envelope.

4.2.4 WBAPL MLA Central and Constituent Pattern Generation Summary

The first step in the WBAPL MLA pattern synthesis is the generation of the central and constituent patterns. The pattern generation procedures used to create both the central and constituent patterns are summarized in Figure 4-11. The darkly shaded blocks indicate loop decisions. The lightly shaded blocks indicate steps where no calculations are required; they simply involve initializations and defining basic variables. The static constants defined in Block #1 are those that do not change from simulation to simulation and are summarized in Table 4.
The next block, Block #2, defines the dynamic constants, which can be changed as design parameters in the simulation. The dynamic constants are summarized in Table 5.
Table 5: Dynamic Constants Used in the Antenna Pattern Synthesis

<table>
<thead>
<tr>
<th>Constant Name and Label</th>
<th>Constant Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Beam Pointing Direction, $\theta_0$</td>
<td>274 [deg]</td>
</tr>
<tr>
<td>Number of Elements, $N$</td>
<td>20 [unitless]</td>
</tr>
<tr>
<td>Inter-Element Spacing, $d$</td>
<td>$\lambda / 2 = \sim 0.095$ [m]</td>
</tr>
<tr>
<td>Angles to Sweep Including Step Size, $\theta$</td>
<td>360 : -0.125 : 180 [deg]</td>
</tr>
<tr>
<td>Continuous Line Source Half Length, $a$</td>
<td>$N \cdot d / 2 = \sim 0.952$ [m]</td>
</tr>
<tr>
<td>Central Pattern, Left Cutoff</td>
<td>$N / 2 = 10$ [unitless]</td>
</tr>
<tr>
<td>Central Pattern, Right Cutoff</td>
<td>$N / 2 = 10$ [unitless]</td>
</tr>
<tr>
<td>Central Pattern, Left Side Lobe Suppression</td>
<td>18 [dB]</td>
</tr>
<tr>
<td>Central Pattern, Right Side Lobe Suppression</td>
<td>20 [dB]</td>
</tr>
<tr>
<td>Constituent Pattern, Left Cutoff</td>
<td>$N / 2 = 10$ [unitless]</td>
</tr>
<tr>
<td>Constituent Pattern, Right Cutoff</td>
<td>$N / 2 = 10$ [unitless]</td>
</tr>
<tr>
<td>Constituent Pattern, Left Side Lobe</td>
<td>25 [dB]</td>
</tr>
<tr>
<td>Constituent Pattern, Right Side Lobe</td>
<td>1 [dB]</td>
</tr>
</tbody>
</table>

Block #3 is not implemented unless there are some outlying side lobes that need to be brought into the envelope. This is implemented by using a multiplicative mask to manually change the height of a side lobe as needed, but remains all ones as a default. In Block #4, an initial guess pattern is created with some previously defined suppressed side lobe levels. This is typically a standard uniform power pattern as shown in Figure 4-2. The first block within the iteration loop (labeled as Loop #1) locates the zero crossings of the starting pattern by differentiating the pattern and finding the zero crossings. Then, in Loop #2, the software records the peak and null locations for use in Equation 11. Next, in Loop #3, an ordinary least squares procedure is initiated, using Equation 13, to perturb the roots. In Loop #4, a new pattern is generated using the
perturbed roots as shown in Equation 14. Then, in the final block of the iteration, Loop #5, the resulting pattern is compared with the requirements and if it is not within its prescribed tolerance ($10^{-4}$), it is iterated again until the side lobes meet the requirements. This iteration usually takes fewer than three times to settle on a nearly exact pattern match. Once the requirements are met, the central or constituent pattern generated in Loop #4 can be used in the null free synthesis procedure.

4.2.5 WBAPL MLA Composite Pattern Synthesis with Null Filling

From a multipath perspective, the rising edge of the central pattern should be positioned in order to mitigate radiation in the negative elevation angles while providing sufficient gain at zero elevation to complete the ground-to-ground APL link. With this goal in mind, the pattern was shaped to provide uniform gain for positive elevation angles ($u > 0$, a.k.a. $\theta > 270$). Next, the nulls were located so that constituent patterns could be placed in these locations for null filling. Using the procedure outlined in Section 4.2.4, the constituent patterns were generated so that their main beams were shifted to these null locations. After all of the nulls of the central pattern in the positive elevation angles were filled, all of the constituent patterns as well as the central pattern were summed to form the total summed pattern as illustrated by the solid line of Figure 4-12. Finally, the aperture distribution for the final summed pattern was generated using Equation 9.
In Figure 4-12 there are several additional items to note. First, the y-axis is displayed as a linear voltage scale as opposed to the relative power in dB that has been previously used. This is done because of the additive nature in obtaining the final pattern and to better illustrate how the patterns are overlaid. Next, notice that the central pattern is completely displayed from \(-10 < u < 10\) with a dotted line. The entire central pattern is shown so that the constituent pattern alignment is more obvious since the central pattern determines the null locations for all constituent patterns to follow. Only the main beams of the constituent patterns (dashed lines) are plotted on top of the central pattern in order to make the plot less cluttered in Figure 4-12. In reality, all of the side lobes of each constituent pattern will be present and will affect the total pattern.
When creating central and constituent patterns, there is a delicate balance regarding how much side lobe suppression will create the desired pattern. For the synthesis illustrated in Figure 4-12, the right side of the total pattern (positive elevation angles) does not require as much suppression because the constituent patterns will be added on top. However, the left side (negative elevation angles) requires as much suppression as possible to obtain good D/U ratios. This suppression should not go unnecessarily far because it might create a more pronounced hump near the horizon as will be discussed later in Section 4.4. If there is not enough suppression, the pattern will have large ripples throughout the final summed pattern. In this same region, left side, the outlying side lobes of the constituent patterns will also be present. If they are higher than the central pattern side lobes, then the central pattern has probably been suppressed too far and the constituent pattern side lobe levels will dominate the final pattern.

Too much suppression on each side of the constituent pattern has differing effects on the final summed pattern. If too much suppression is applied to the left side of the constituent pattern, less coverage at higher elevation angles results. After the coverage has been reduced to a certain point, an additional null will form around 75 deg or 80 deg. Too little side lobe suppression on the left side of the constituent pattern, however, leads to a hump near the central pattern’s main beam. The opposite trend is true for the right side of the constituent patterns. Too much suppression leads to a hump near the central
pattern’s main beam and too little suppression leads to reduced coverage at higher elevation angles.

For the WBAPL transmission antenna synthesis, the central pattern was centered at roughly 274 deg in order to have the rising edge zero elevation angle crossing at about –18 dB. This rising edge of the final summed radiation pattern is better illustrated in terms of dB and elevation angle, \( \theta \), as shown in Figure 4-13. The central pattern shown in Figure 4-12 is an asymmetric power pattern because the side lobes on the right are suppressed to 18 dB and 20 dB on the left. The nulls of the central pattern were then located as illustrated by the vertical stem lines in Figure 4-12. With the nulls of the central pattern located, the constituent patterns were then generated for overlay in the null locations illustrated in Figure 4-12. These constituent patterns are created in the same way as the central pattern. For the WBAPL MLA synthesis, the constituent patterns are asymmetric except that the left to right side lobe suppression ratio is different (e.g. 18 dB / 20 dB for the central vs. 25 dB / 1 dB for the constituent pattern).

The corresponding aperture distribution for the final pattern of Figure 4-13 is plotted in Figure 4-14, which shows the relative amplitude distribution in the top trace and the relative phase distribution in the bottom trace. The amplitude is smoothly varying over the aperture. Also, note that the required range of amplitudes is not excessive. The phase, however, has periodic discontinuities. If elements of the beam are located near these discontinuities, slight variations in the array can change the antenna pattern dramatically.
Figure 4-13: Controlled Null Free Pattern

Figure 4-14: Aperture Distribution for Pattern Shown in Figure 4-13
Since the aperture distribution is a continuous function, it needs to be discretized so that it can be applied to the individual radiating antenna elements of the array. As mentioned in Section 4.2.3.4, there are errors associated with simply sampling a continuous aperture distribution. As one might expect from sampling theory, however, the magnitude of these errors decreases as the number of elements increases because each element can capture more detail of the amplitude and phase variations in the aperture distribution. For the 20-element antenna considered in this synthesis, the sampled aperture distribution is illustrated in Figure 4-15.

![Sampled Aperture Distribution](image)

**Figure 4-15: Sampled Aperture Distribution for the 20-element MLA for the Validation Synthesis Pattern**
4.3 Overall Functional Synthesis Summary

The synthesis procedure was developed in Matlab v5.3. This development environment allowed for maximum flexibility since real-time operational efficiency was not required. The scripts used to perform the synthesis were developed modularly in order to ease the debugging process. In this section, the scripts will be functionally discussed without treating the details of the source code. A block diagram is presented in Figure 4-16 to clarify the required steps.

Figure 4-16: Block Diagram of Null Free Pattern Synthesis
Each block represents a module in the source code. The first three blocks are shaded to illustrate that they are simply for initializations and basic definitions relating to the pattern generation. The variables defined in Block #1 and Block #2 are the same as listed previously in Table 4 and Table 5. Block #3 defines the pattern shaping (a cosecant squared shape for example) if any is required. In this case, it is desired that the top of the main region of the WBAPL MLA pattern (5 deg – 60 deg) be flat so the shaping envelope is a constant value of unity. Block #4 defines the central pattern. The central pattern can be defined using any of the previously discussed tools; it can be a uniform power pattern, a Symmetric Taylor pattern, an Asymmetric Taylor pattern, or a pattern with arbitrary side lobe levels. This process was explained previously in Section 4.2.4 and detailed in Figure 4-11. Upon construction of the central pattern, control returns to Block #5 of Figure 4-16 where the nulls are located by differentiating the pattern function and recording the zero crossings. In Block #6, the regions of the central pattern are identified where null filling is desired. The pattern generation procedure of Figure 4-11 is implemented again to create constituent patterns whose main beams are shifted into the identified nulls of the central pattern. After all required nulls are filled, Block #7 indicates that the central and each of the constituent patterns should be summed to produce the final summed pattern. Finally, in Block #8 the amplitude and phase distributions are determined as described in Section 4.2.3.4 for the final summed pattern before plotting the output in Block #9.
4.4 Tradeoff Analysis

Most attempts to improve a pattern result in some secondary detrimental effects as well. The key to a good design is to achieve the most benefit with the least detriment by deciding which unfavorable effects are acceptable. This section is dedicated to presenting the design characteristics and what must be sacrificed to achieve them.

One example is the pursuit of minimum side lobes. Side lobe levels can be reduced at the cost of main beam broadening, which occurs when the locations of the nulls in the pattern are perturbed. This effect is clearly illustrated in Figure 4-17. The new pattern (shown with a solid line) has arbitrarily reduced side lobe levels and consequently, its main beam is considerably wider than the original main beam (shown with the dashed line). One would expect that beam broadening is acceptable for an antenna that is trying to fill a large region (~5 deg to 60 deg) with uniform energy. In this case, a broader beam might appear to be helpful but it is not acceptable when the patterns are summed with the purpose of null filling because the first null location gets moved further from the peak of the main beam thus pushing away the location of the first constituent main beam. Because the first constituent pattern is further away from the central pattern, a single large ripple (or a hump) in the overall pattern close to the center (at the horizon) will be formed. A rapid rise time (or steep roll off) about the horizon results from a narrow main beam and is desired in this design to sharply minimize radiation transmitted toward the ground. A broader main beam can decrease the rise time of the central pattern’s main
beam (and thus the final pattern as well) to unacceptable levels as shown in Figure 4-17. The main beam of the central pattern has its null locations spread so far that the next two constituent beams would be clumped too closely together.

![Figure 4-17: Beam Broadening Resulting from Side Lobe Suppressions](image)

In a similar scenario, decreasing the rise time (narrowing the main beam) too much in the constituent patterns can cause ripples throughout the pattern because the power levels drop too much between constituent main beams. A rapid rise time is not necessarily a good quality for the constituent patterns because the main beams must be broad enough to fill the space between nulls with enough energy to reduce ripples. Ripples occur because there is too much (or too little) space between constituent main beams in the
final summed pattern thus allowing the power level to drop further from peak to peak.

If left unchecked, these ripples can cause unacceptable gain variations in the final antenna pattern. This type of ripple control is examined in detail in a paper by Hyneman [19]. Since pattern ripple is related directly to the width of the main beam of the constituent patterns, the synthesis can be performed to balance sufficient beam width with minimum ripple. Since the main beams of the central and constituent patterns have different requirements, it is often necessary to use different beam widths for the main beam of the central pattern and the main beam of the constituent patterns. This will reduce the ripple problem by using beams tailored for the two unique requirements.

4.5 Design and Synthesis Validation

The final summed pattern, which was synthesized for validation, presented above in Figure 4-13, is similar to the patterns produced by the contractor. It should be kept in mind that a direct comparison cannot be made between the final summed validation pattern and others because the validation pattern does not include the effects of the elements factor. Since the point of the validation was to show that a similar pattern was possible and that it was comparable to that developed by the contractor, this section still demonstrates some level of validation through shape, elevation angle alignment, and a variety of other quantifiable qualities regardless of the element factor. A pattern comparison is shown below in Figure 4-18. The pattern with “x” markers is a plot of preliminary data from outdoor antenna range measurements performed by the contractor.
It should be noted that at the time of publication of this document, the antenna is still in development and the final range data has not been collected. The "+" marker trace in Figure 4-18 shows the theoretical pattern synthesized by the contractor. Finally, the remaining curve, shown with a star, indicates the validation synthesized pattern performed here. The zero crossing amplitude level is nearly the same for all three sets of data. In addition, the positive elevation coverage is also very similar.

![Figure 4-18: MLA Pattern Comparison](image)

While there is substantial variation in the negative elevation angles, it should be noted that the emphasis is on side lobe suppression to a predefined level and not on replication of an exact side lobe structure. No valid comparison could be made for these negative
angles so the negative elevation angles have been omitted from this comparison. For the positive angles, however, such an error plot would clearly show the differences between the synthesized validation pattern and the antenna range-measured data, as illustrated in Figure 4-19. This figure shows that the final summed pattern has a substantially higher pattern ripple. The cause for this ripple, as discussed in Section 4.4, was the narrow main beams of the constituent patterns as well as a main beam that was broadened by side lobe suppression. One final observation to be made is that there is a positive bias (3 dB average) in the difference pattern shown in Figure 4-19. This can be attributed to the fact that the side lobes of the final summed pattern are suppressed further than the range measured data and thus the energy in the positive elevation angles is higher. When the side lobes of the constituent patterns are suppressed, their main beams broaden and the total energy in the pattern region increases because there is more overlap of each constituent pattern. The direct comparison of Figure 4-19 may not be totally appropriate since the validation pattern did not include an element factor. Since the validation effort simply sought to be a proof of concept, however, the comparison of Figure 4-19 illustrates that such a pattern is possible and can be manipulated in such a way to closely approximate any shape.
Figure 4-19: Positive Angle MLA Pattern Difference
5. CONCLUSIONS

This research was conducted in order to optimize the WBAPL MLA for pseudolite transmission. To that end, three phases of study were conducted. The first stage modeled the ground-to-air link between the WBAPL transmitting MLA and the reception antenna during approaches with an attempt to define optimal WBAPL antenna locations. The second stage was performed to characterize the basic pattern requirements of the WBAPL transmitting MLA. This second stage also sought to project a hypothetical coverage volume given a preliminary pseudolite antenna pattern. The third stage was performed to attain some level of validation for the new WBAPL MLA transmitting antenna pattern measured by an external contractor through the independent synthesis of a similar antenna radiation pattern.

The most notable result from the first phase was the presentation of more ideal pseudolite antenna locations. It was noted that proper siting of the WBAPL antenna can reduce the dynamic range requirements of an airborne receiver by as much as 20 dB which is significant and should be included in WBAPL siting criteria.

The second phase presented some of the design considerations and established gain envelope specifications for the new WBAPL MLA. This second phase also hypothesized potential coverage volumes based upon a theoretical WBAPL MLA transmission pattern. After running several simulated approaches over an arbitrary
antenna location, a cone of silence in the coverage volume was identified which would affect users who fly directly over the antenna. This was shown to be of little consequence for typical flight scenarios.

The antenna synthesis discussed in the third stage was presented as a proof of concept in order to attain some level of validation of the antenna design. It served to independently validate the antenna design that is currently in the process of development by an outside contractor. This validation has not been exhaustively tested and is not designed to include every possible consideration. The process of antenna synthesis implemented here requires a substantial amount of user intervention and thought, but still yielded results within the scope of this investigation. The final summed pattern obtained in the validation study seems to match very well with the measured data and provides additional confidence in the design.
6. RECOMMENDATIONS FOR FUTURE WORK

Some considerations for future work would be to conduct laboratory tests to verify the results of the siting and coverage volume simulations. This would also prove (in the affirmative or negative) the existence of a dynamic range induced bias within a receiver. This could be extended further by examining different receivers and comparing the effects of exceeding their dynamic ranges.

There are also some considerations for future work in the antenna pattern synthesis section. The first consideration would be to include the element factor of a dipole antenna and attain more complete validation of the WBAPL MLA. Another consideration might be to make the software more automated, requiring less forethought by the user. In addition, more provisions could be made for practical antenna effects such as mutual coupling, extended element spacing (greater than $\lambda/2$), and others. In the ideal case, a user could input the desired envelope and some design parameters such as pattern ripple, rise time, and main beam position and the software would return a pattern with minimal side lobes and the best D/U ratio. The existing software could return a series of potential aperture distributions and select the best based on given criteria. Aperture distributions would be more practical to build and the synthesis software would require less user feedback in selecting which phase and amplitude distributions are more practical.
REFERENCES


ABSTRACT

DICKMAN, JEFFREY. MASTER OF SCIENCE, November 2001
Electrical Engineering

Multipath Limiting Antenna Design Considerations for Ground Based Pseudolite
Ranging Sources (101 pp.)

Advisor: Chris G. Bartone

The next generation of advanced aircraft landing system will utilize the Global
Positioning System (GPS). The availability of GPS is augmented by the use of
pseudolites "pseudo satellites." Pseudolites transmit a GPS-like signal that can be used
as a ranging source in place of or in addition to ranging sources from a satellite. The
Local Area Augmentation System (LAAS) is being used to further augment GPS for
precision approaches and landings by using a concept known as Differential GPS
(DGPS). One major error source in DGPS is due to transmitted signal reflections
(multipath) off nearby obstacles. Efficient antenna design can be used to mitigate
multipath by severely attenuating signals from negative elevation angles.

The research contained in this document was conducted in order to optimize the current
wideband airport pseudolite (WBAPL) multipath limiting antenna (MLA) for pseudolite
transmission in the LAAS. To that end, three phases of study were conducted. The first
stage modeled the ground-to-air link between the WBAPL transmitting MLA and the
reception antenna during approaches with an attempt to define optimal WBAPL antenna
locations. The second stage was conducted to characterize the basic pattern requirements
of the WBAPL transmitting MLA and sought to project a hypothetical coverage volume
given a preliminary pseudolite antenna pattern. The third stage was performed to attain