GPS Ground Station Antenna for Local Area Augmentation System, LAAS

Alfred R. Lopez
Marconi Aerospace Systems Inc.
Formerly GEC-Marconi Hazeltine Corporation

BIOGRAPHY

Alfred R. Lopez is a Life Fellow of the IEEE. He received a BEE from Manhattan College in 1958 and an MSEE from the Polytechnic Institute of Brooklyn in 1963. He is a Senior Mender Technical Staff at MARCONI. He started his career at Wheeler Laboratories in 1958 as an antenna design specialist. He has made significant contributions to the theory and practice of electronic scanned antennas. From 1969 to 1990 he was involved with the development of the Microwave Landing System. He has published several articles in IEEE publications, has been issued 29 U. S. Patents, and has received several IEEE Awards, one being the 1988 IEEE Antennas and Propagation Society's Harold A. Wheeler Award.

ABSTRACT

The requirements for a LAAS ground station are such that unusual antenna specifications need to be defined and implemented. For code tracking, the group delay variation over the coverage should be specified; this is not a typical antenna specification. For carrier-phase tracking, the phase center variation over the coverage should be specified; also not a typical antenna specification. The impulse response over the coverage should be such that any waveform degradation is within acceptable limits.

Listed below are the key requirements for a near ideal GPS Ground Station Antenna.

- Hemispherical Coverage (down to 3° elevation)
- Right Hand Circular Polarization Over Entire Coverage
- 3 dB/Degree Cutoff at Horizon
- Sidelobes > 23 dB Down from Peak in Lower Hemisphere
- Point Phase Center
- Point Group-Delay Center

A concept that incorporates some of these features was developed in 1996, U. S. Patent, 5,534,882 [1]. More recent developments have resulted in an antenna configuration that incorporates all of the desired features. This paper presents the basic concept disclosed in the issued patent and the additional attributes of the improved design. Such an antenna has been developed. It operates at the L1 and L2 frequencies. Measurements of breadboard and production prototype antennas have verified the performance.

INTRODUCTION

Multipath represents the dominant error source in satellite-based precision guidance systems [2]. For LAAS the mulitpath delay at the reference antenna is less than 15 meters. The design of the ground station reference antenna is key in the mitigation of multipath errors associated with these short delays. A good deal of effort has been expended in developing antenna solutions to this problem [3,4,5]. One solution [3,4] utilizes two antennas to provide the required hemispherical coverage.

21 Elements, 11 Elements Excited
11-Way Power Divider at Base
Equal-Line-Length Cables to Elements

Figure 1. Ground Station Antenna -- Model ARL-2100

This approach requires two receivers for each reference antenna and a somewhat complex process for handoff between antennas. The antenna described in this paper (see Figure 1) requires one receiver and offers other advantages with respect to processing satellites at low elevation angles.

ACCURACY AND ANTENNA PARAMETERS

The LAAS ground facility, LGF, consists of a small collection of high quality GPS reference receivers and antennas at known, surveyed locations on the airport property. The receiver measurements at the surveyed locations are used to determine an average correction that is broadcast to approaching aircraft using a VHF data link. A set of tentative requirements for precision approach using LAAS is presented in [6]. This set of requirements indicates that a 2-sigma (95 percent probability) error of 1 meter is required for control of the aircraft under fault free conditions and for system integrity and continuity. The table shown in Figure 2 presents an allocation of this 1-meter error tolerance amongst the LAAS components. Most of the allowable error is allocated to the airborne subsystem component.

	Allowable Error 95 Percent Probability (Meters)
1. System/ Integrity / Continuity (Root Sum Square Allocation amongst 2 & 3)	1.00
2. Airborne Subsystem	0.94
3. LAAS Ground Facility Correction	
Receiver Processing	0.22
Antenna	
Multipath	0.25
Phase	0.05
Group Delay	0.05
Root Sum Square	0.34

Figure 2. System Accuracy Allocation

The LGF correction allocation is distributed amongst its error components. The antenna error consists of multipath, phase, and group delay components. The phase and group delay components are related to the antenna physical configuration, where the phase and group delay centers are not necessarily a point. The multipath error component can be used to quantify the ground reference antenna's height above ground, down-up gain ratio, and the pattern cutoff on the horizon.. Figure 3 shows the geometry for the reference antenna and the local ground. The local ground should exist over a circular area with a radius equal to at least twice the height of the antenna phase center above the ground.

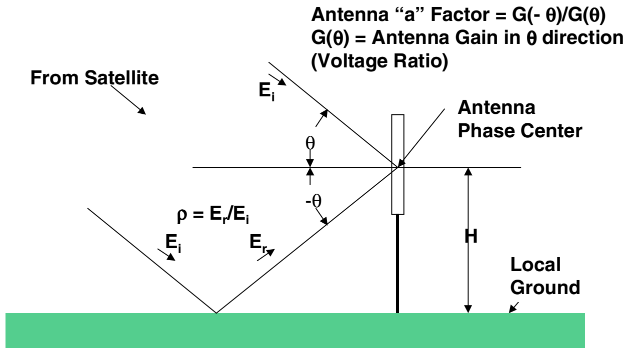

Figure 3. Ground Station Antenna Environment

The equation that relates the peak multipath correction error to the LGF antenna parameters is presented in Figure 4. It is noted that the error can be reduced by lowering the antenna height, reducing the "a" and ρ factors, and by increasing the number of reference antennas.

If we equate the peak multipath correction to the 2-sigma multipath error in Figure 2 we can quantify the antenna parameters. For practical reasons the antenna phase center height can not be equal to zero. A height of 3 meters assures insensitivity to possible local traffic. The local ground can be treated such that ρ is very small. A conservative assumption, without any ground treatment, is ρ = 0.707 (-3 dB). For LAAS, the minimum value for M is 3. If ΔC ≤ 0.25 meters then a, the down-up gain ratio, is ≤ -20 dB.

$$\Delta C = \frac{2Ha\rho}{\sqrt{M}}$$

C = Average correction for M reference antennas
ΔC = Peak error in average correction attributed to local ground multipath
H = Height of reference antenna above local ground
a = Ratio of antenna gain at negative elevation angle to gain at the positive elevation angle, antenna down-up gain ratio (voltage ratio)
ρ = local ground reflectivity and polarization loss factor (voltage ratio)
a ρ = Indirect-to-direct multipath ratio

For ΔC ≤ 0.25 m, H = 3 m, ρ = 0.707 (- 3 dB), M = 3
a ≤ 0.102 (≤ -20 dB)

Figure 4. LAAS Reference Antenna Requirements

The desired system coverage is down to 5° in elevation angle. To assure coverage at this angle the initiation of satellite processing should be possible at angles above 3°. An elevation antenna pattern cutoff of 3 dB/° will provide an "a" factor of –18 dB at 3°. The "a" factor can be specified to be ≤ -20 dB for elevation angles above 5°.

ARRAY ANTENNA DESIGN

The basic equation for an array antenna radiation pattern is presented in Figure 5. The Model ARL-2100 array is a collinear array consisting of 21 radiating elements, an 11-way power divider located at the base, and 11 coaxial cables. The combination of the power divider and the coaxial cables is specified to have equal line length from the antenna input port to all the radiating elements. This array feed network operates at the L1 and L2 frequencies and has a very wide signal bandwidth. The excitation of the array elements is given in Table 1.

$$E(\theta) = g(\theta)AF(\theta)$$

Where

$E(\theta)$ = Radiation Pattern

$g(\theta)$ = Element Factor Pattern

θ = Pattern Angle

$$AF(\theta) = \text{Array Factor Pattern} = \sum_{n=-\frac{N-1}{2}}^{\frac{N-1}{2}} a_n e^{j2\pi n \frac{d}{\lambda}\sin(\theta)}$$

Where

a_n = Element Amplitude and Phase Excitation

d = Element Spacing

λ = Free Space Wavelength

N = Total Number of Array Elements (N is odd)

Note: E(θ) is valid if all elements are identical and there is a sufficient number of dummy elements such that pattern factor multiplication is valid.

Figure 5. Array Antenna Radiation Pattern

Table 1. Array Amplitude and Phase Excitation

Element No.	*Excitation*	
	Amplitude (Voltage Ratio)	Phase (Degrees)
1 (Bottom)	0	
2	0.0553	180
3	0	
4	0.0623	180
5	0	
6	0.1055	180
7	0	
8	0.1985	180
9	0	
10	0.6320	180
11	1.0000	90
12	0.6320	0
13	0	
14	0.1985	0
15	0	
16	0.1055	0
17	0	
18	0.0623	0
19	0	
20	0.0553	0
21 (Top)	0	

This excitation and the wideband feed network provide phase and group-delay centers that are coincident points within the tolerances given in Figure 2. The antenna group delay from the surveyed point (phase center) to the antenna input port is 10.2 nanoseconds.

Perhaps the most critical part of the array design is the element in the array environment. As noted in Figure 5, in order that multiplication of the element and array-factor patterns is valid, all elements must operate in identical environments. To assure this condition 10 dummy elements (zero excitation) had to be provided.

The element and the complete array were designed using WIPL software [7]. The element was designed to be double-tuned for operation at the L1 and L2 frequencies. The loss in array gain caused by reflection and mutual coupling is less than 0.4 dB. The active element pattern modulates the array-factor pattern and establishes the polarization characteristic of the array antenna. The element is design to provide right-hand circular polarization from -10° elevation to zenith. This feature enhances performance at low elevation angles (<10°). Reflections from vertical surfaces are converted to left-hand circular polarization and suppressed by the polarization mismatch factor. This element is similar in configuration to those described in [8, 9].

The vertical height of the collinear array is specified such that the slope on the horizon and the sidelobe (down-up gain ratio) requirements are satisfied. This basic tradeoff is presented in [10]. A vertical active height of 5.93 Feet (1.81 m) satisfies the array pattern requirements with a array-factor sidelobe level of –30 dB. The actual height of the antenna is 7.25 Feet (2.21 m); the extra height is required to house the power divider and cabling at the base of the antenna.

The sidelobe performance of a collinear array is limited by the amplitude and phase excitation errors. The achievable peak sidelobe level for a production antenna is limited by practical error tolerances for the amplitude and phase excitation. The sidelobe components are defined in Figure 6.

The relationship of error tolerances to achievable sidelobe levels is presented in Figure 7 [11] for the case where the array-factor sidelobe level is set at 3 dB below the tolerance sidelobe level. Setting the array-factor sidelobe level below this value does not substantially improve the overall sidelobe performance, but, it will degrade the sharp-cutoff performance on the horizon. The figure presents the relationship of the design sidelobe level (95% probability sidelobe level for the combined array-factor and tolerance sidelobes) and the peak amplitude and peak phase errors. A Monte Carlo method was used to verify a few points on the chart. In a set of 100 antennas, 5 will have one sidelobe above the design sidelobe value. For convenience, the amplitude error, expressed as a voltage ratio, is set equal to the phase error in radians.

Tolerance Sidelobe Level	SL_T	RMS sidelobe component attributed to array excitation amplitude and phase errors
Array-Factor Sidelobe Level	SL_{AF}	Peak sidelobe component for error-free array excitation
Design Sidelobe Level	SL_D	Desired peak sidelobe level (95 percent probability that combined components (SL_T and SL_{AF}) will not exceed SL_D)

$$SL_T = \sqrt{\frac{2\frac{\delta^2}{3}}{G(1-2\frac{\delta^2}{3})}}$$

δ = Peak amplitude error (voltage ratio)
δ = Peak phase error (radians)
G = Directive Gain (G = 2 for hemispherical coverage)

Figure 6. Array Performance Limited by Tolerances

Figure 7 indicates that the required tolerances for –40 dB sidelobes (±0.1dB amplitude and ±0.5° phase) are impossible to achieve, the required tolerances for –30 dB sidelobes (±0.2dB amplitude and ±0.1.6° phase) are really not practical, while the tolerances for –23 dB sidelobes (±0.6dB amplitude and ±0.3.6° phase) are achievable.

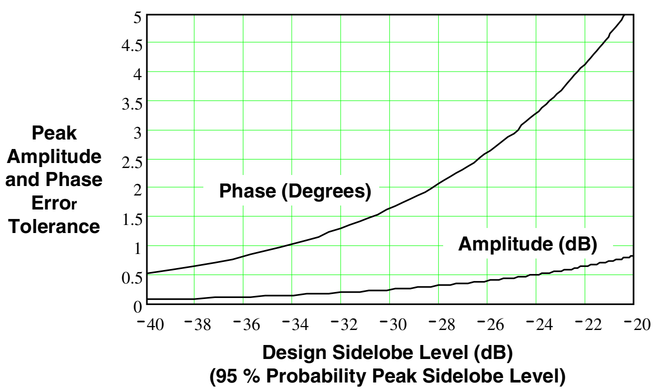

Figure 7. Array Performance Limited by Tolerances, Cont'd

Figure 8 shows the computed array factor patterns for zero errors and one case for an peak amplitude error of 0.5 dB, uniformly distributed between –0.5 dB and 0.5 dB, and an peak phase error of 5°, uniformly distributed between -5° and 5°.

Figure 9 shows the result of the WIPL computer software simulation [7] of the complete 21-element array. The simulation includes mutual coupling effects. It does not include amplitude and phase errors. Note that the element factor modulates the array-factor envelope and that a dip in the pattern exists at 70° elevation.

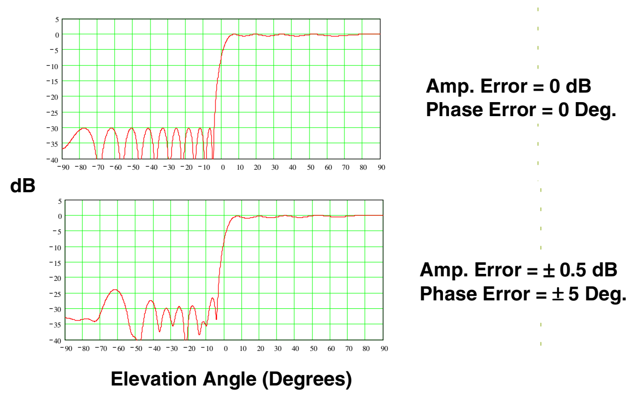

Figure 8. Array Factor Pattern

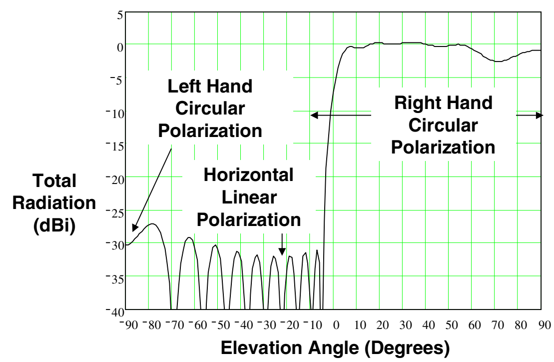

Figure 9. Computer Simulation of 21-Element Array Antenna

Figure 10 shows computed and measured installed pattern for the Model ARL-2100 brassboard. The computed pattern is generated using the equation:

$$F(\theta) = E(\theta) - E(-\theta)e^{-j2\pi\frac{2H}{\lambda}\sin(\theta)}$$

Amplitude and phase excitation errors are included in the array pattern. H = 1.3 meters. The measured pattern [12] is obtained by recording and plotting the carrier-to-noise-density ratio versus elevation angle for several satellites over a 24-hour period. The brassboard antenna was installed at a site with the antenna phase center at a 1.3-meter height. The green curve in Figure 9 is the plot for one representative satellite, PRN 6. One part of the curve is the data for the time interval between satellite rise and zenith times; the other is for the time interval between zenith and set times. The displacement between the two curves is indicative of the lack of complete omni-directionality of the brassboard antenna. The multipath elevation lobing factor has a maximum of ±0.75 dB. This corresponds to a multipath indirect-to-direct ratio of –21 dB. For comparison the installed patterns for a choke-ring antenna (blue curves) were measured. The improved performance of the Model ARL-2100, at low elevation angles, is clearly evident.

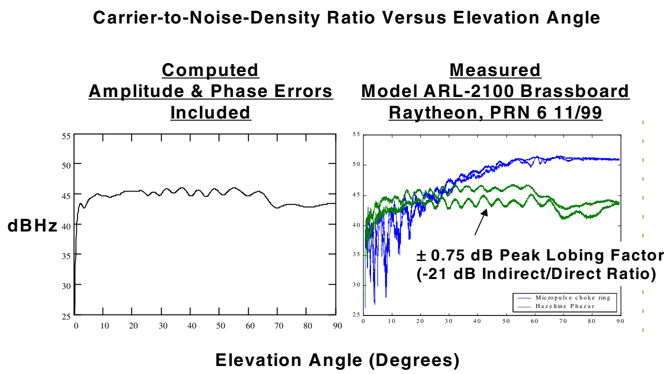

Figure 10. Installed Performance

SUMMARY

- A concept for a near ideal ground station antenna for LAAS augmentation systems has been described.
- A practical and affordable antenna has been developed
- A brassboard and 5 production prototype antennas have been built and tested
- Field testing has verified the design
- L1 and L2 operation has been demonstrated

ACKNOWLEDEMENTS

The author is much appreciative of the motivation and support of Jack Flynn, Marconi. The concept for the practical array implementation is credited, in part, to Edward Newman and Richard Kumpfbeck of Marconi. Marshall Wax, of Marconi, was the lead engineer for the design, implementation and testing of the Model ARL-2100 antenna. The motivation and help provided by Paul Kline and Rod Stangeland of Honeywell, and the help provided by Tom Zaugg, of Raytheon, is appreciated.

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