LAAS/GBAS Ground Reference Antenna With Enhanced Mitigation of Ground Multipath

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BIOGRAPHY

Alfred R. Lopez is a Life Fellow of the IEEE. He is a Hazeltine Fellow and Engineering Fellow with BAE Systems, Greenlawn, NY. He started his career at Wheeler Laboratories in 1958 as an antenna design specialist. He has made 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 extensively in IEEE publications, has been issued 46 US Patents, and has received several IEEE and BAE Systems awards. He is the inventor of the ARL-1900 Ground Reference Antenna.

ABSTRACT

The concept for the ARL-1900 LAAS/GBAS ground reference antenna was first described at the ION 2000 National Technical Meeting. This antenna has the following features:

- One-port circular-polarization L1-L2-L5 coverage of the upper hemisphere
- Sharp antenna pattern cutoff on the horizon for mitigation of ground multipath at low elevation angles
- 30 dB sidelobes in the lower hemisphere for mitigation of ground multipath at higher elevation angles
- Very high quality carrier delay (antenna phase center) and code (group) delay characteristics
- Circular polarization at low elevation angles for mitigation of lateral multipath

This antenna has been under development since 1999, and is now entering the initial phase of field deployment. The prototype ARL-1900 antenna was built under contract to the FAA. After successful testing by the FAA, in December of 2005, 17 additional antennas were built and tested. Ten additional antennas are currently being built.

This paper reviews the ground multipath issue and describes a means for enhanced mitigation of the ground multipath problem. The variability of the ground reflectivity is quantified and its impact on the possible variation of the ground multipath error is described. Siting recommendations are made which enhance the multipath performance

INTRODUCTION

The ARL-1900 ground reference antenna is shown in Figure 1 installed at the William J. Hughes FAA Technical Center, Atlantic City, NJ. It is a 19-element collinear array antenna designed specifically for the LAAS/GBAS application. Figure 2 shows the array antenna with the radome removed.

ARL-1900 Differential GPS Ground Reference Antenna

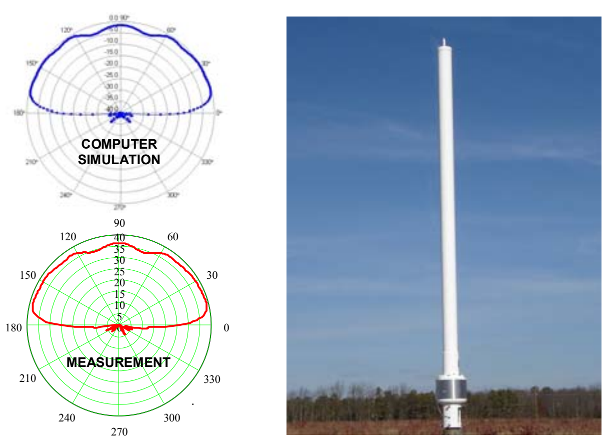


Figure 1

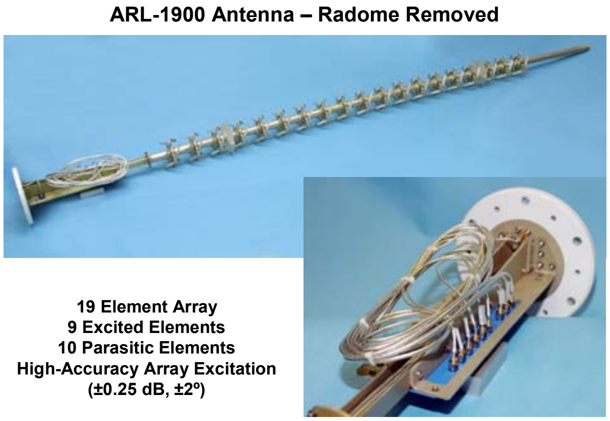


Figure 2

The array antenna comprises 19 radiating elements and a 9-way-power-divider and cabling assembly as shown in Figure 2. The cabling assembly has 9 equal-length coaxial cables that connect to (counting from the bottom) elements numbers 3, 5, 7, 9, 10, 11, 13, 15, and 17. These elements are excited directly; the remaining elements are excited parasitically (indirectly via mutual coupling).The ARL-1900 is a very simple but a very high precision antenna.

The key features of the ARL-1900 antenna are:

- One-port, circular polarization, L1-L2-L5 coverage of the upper hemisphere
  - One port – one receiver, no satellite handover problem
  - Full GNSS band, 1150-1600 MHz
- Sharp antenna pattern cutoff on the horizon for mitigation of ground multipath at low elevation angles
  - 2.5 dB/º slope on horizon
  - 30 dB antenna Up/Down gain ratio down to 6º elevation
- 30 dB sidelobes in the lower hemisphere for mitigation of ground multipath at higher elevation angles
  - 30 dB antenna Up/Down gain ratio
- Very high quality carrier delay (antenna phase center) and code (group) delay characteristics
  - Carrier delay variation ±1cm (unit-to-unit ±1mm)
  - Code delay variation ±2.5cm (unit-to-unit ±3mm)
- Circular polarization at low elevation angles for mitigation of lateral multipath [5-6]
  - Taxing aircraft, hangers, etc.
- Unit-to-unit de-correlated sidelobes in the lower hemisphere
  - Enhances ground multipath de-correlation amongst ground reference receivers
- Integral air terminal for lightning protection
  - Non-scattering air terminal configuration, no performance degradation

The initial concept for the ARL-1900 was developed in 1993 and the first patent was issued in 1996 [1]. The initial concept was very narrow band and there were problems with the implementation. An improved wideband version was developed in 1999 with an associated patent issued in 2001 [2]. This second version had the same basic architecture as the ARL-1900 [3] but it had one significant problem, excessive code delay variation with azimuth angle at high elevation angles [4]. The solution to the problem associated with the second version became apparent in 2003. The ARL-1900 antenna is the embodiment of this solution. Measurements in December of 2005, at the William J. Hughes FAA Technical Center [7] (see Figure 3) demonstrated excellent performance for the ARL-1900 antenna.

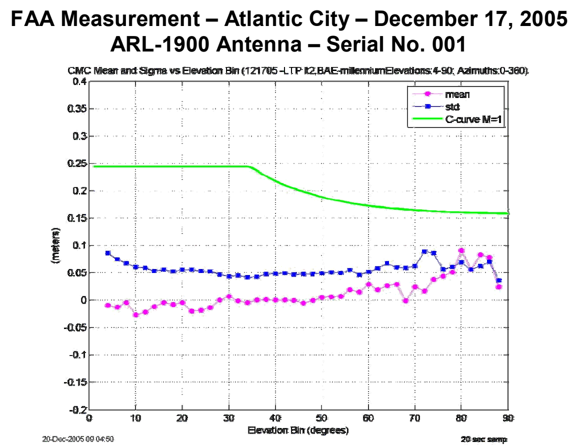


Figure 3

RANDOM SIDELOBES ENHANCE MULTIPATH DE-CORRELATION AMONGST REFERENCE RECIEVER STATIONS

The requirement for coverage of the upper hemisphere results in an inherently low-gain antenna. Ideally, with no antenna dissipative loss, the highest gain possible is 3 dBi. It is very difficult to design a low-gain antenna with low sidelobes (30 dB). The design strategy for achieving low sidelobes for a low gain antenna was presented in [3]. The basic concept is to set the systematic (zero array-excitation error) peak sidelobe level substantially below the desired peak sidelobe level (30 dB), and then to specify the error tolerance on the array excitation such that the combined 2-sigma value for the peak systematic and error sidelobes is less than 30 dB.

Figure 4 presents the basic approach for the design of the ARL-1900 antenna. The array excitation tolerances of ± 0.2 dB and ± 2º require high precision components for the collinear array antenna. The elevation patterns for 20 random-error trials presented in Figure 4 show the predominant random nature of the unit-to-unit sidelobe levels

ARL-1900 Random Sidelobe level

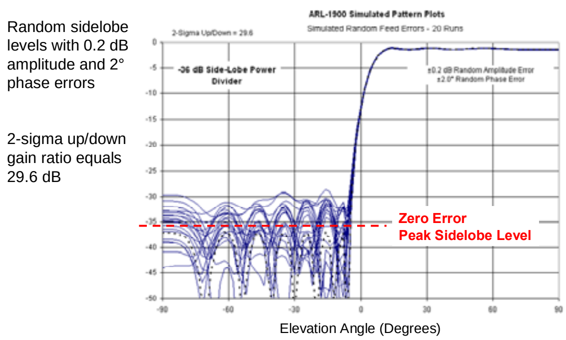


Figure 4

One significant benefit for the ARL-1900 antenna is provided by the random nature of the unit-to-unit sidelobe level. Four reference receiver stations are typically utilized to suppress multipath. The four stations are located with respect to each other to provide de-correlation of the multipath signals. The random nature of the ARL-1900 antenna unit-to-unit sidelobe level enhances the de-correlation of the ground multipath signals.

GROUND MULTIPATH CHARACTERISTICS

The basic geometry for ground multipath is shown in Figure 5. At the antenna phase center the direct signal and a ground reflected (multipath) signal are combined. The polarization of the ground reflected signal experiences a transformation upon reflection. The Fresnel formulas quantify this transformation and are presented below.

Ground Multipath Geometry

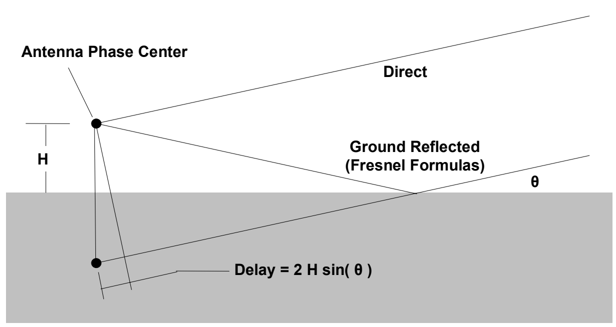


Figure 5

The Fresnel formulas for the reflection factor for vertical polarization, Γ_{VP}, and for horizontal polarization, Γ_{HP}, are given by:

$$\Gamma_{VP}(\theta) = \frac{\left(\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}\right)\sin(\theta) - \sqrt{\left(\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}\right) - \cos^2(\theta)}}{\left(\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}\right)\sin(\theta) + \sqrt{\left(\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}\right) - \cos^2(\theta)}}$$

$$\Gamma_{HP}(\theta) = \frac{\sin(\theta) - \sqrt{\left(\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}\right) - \cos^2(\theta)}}{\sin(\theta) + \sqrt{\left(\varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0}\right) - \cos^2(\theta)}}$$

ε_0 = Free space dielectric constant

ε_r = Relative dielectric constant

σ = Conductivity

ω = Radian frequency

θ = Elevation angle

Ground Parameters

Ground Type	Relative Dielectric Constant, ε_r	Conductivity, σ (S/m)
Smooth Sea	81	4
Fresh Water	81	0.01
Wet Ground	16	0.002
Very Dry Ground	4	0.001

Figure 6

Ground Reflection Factor – Linear Polarization

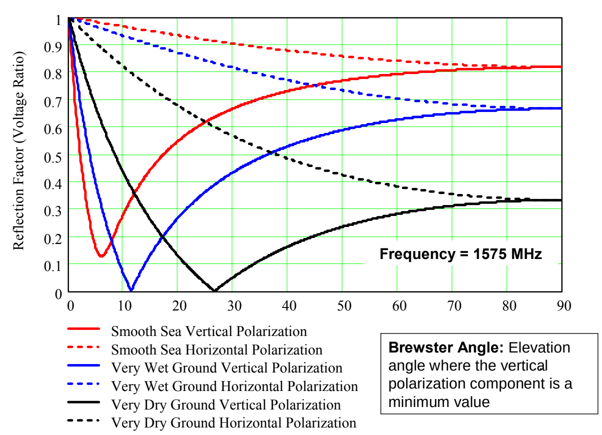


Figure 7

The ground reflection characteristics are quantified by two parameters in the Fresnel formulas, the relative dielectric constant, ε_r and the conductivity, σ. Figure 6 presents a table that lists these parameters for four different types of grounds ranging from a smooth sea to a very dry ground.

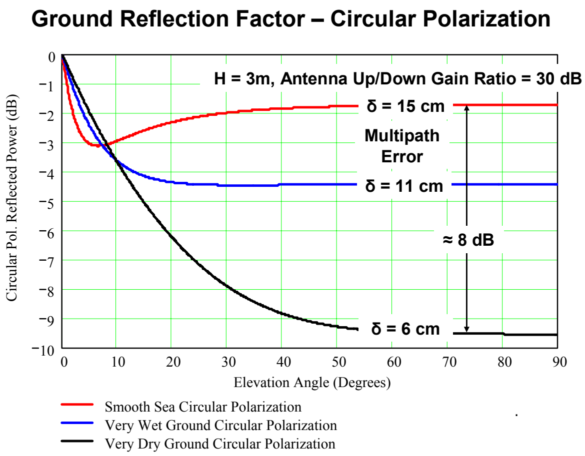


Figure 8

The reflection factor magnitude versus elevation angle for vertical and horizontal linear polarization components of an incident signal are presented in Figure 7. The Brewster angle is defined as the elevation angle where the magnitude of the vertically polarized component is a minimum. The reflection phase for the vertically polarized component varies 180º across the Brewster angle. The handedness for a reflected circularly polarized incident signal reverses across the Brewster angle. On the zenith side of the Brewster angle an incident right-hand circularly polarized incident signal is reflected with left-hand polarization.

Figure 8 presents the magnitude of the reflection factor for an incident circularly polarized signal. At angles near the horizon right hand circular polarization is reflected as right-hand circular polarization. At the Brewster angle the reflected signal is essentially horizontally polarized. At angles near zenith, an incident signal with right-hand circular polarization is reflected with left-hand circular polarization. (There have been cases where the antenna gain pattern has been measured with respect to right hand circular polarization, and the ratio of the gain in the zenith direction to the gain in the nadir direction has been reported as the desired-to-undesired ratio for the zenith direction. This, of course, was in error since the antenna has, inherently, left-hand circular polarization in the nadir direction.)

Figure 8 shows that for elevation angles below 10º the magnitude of the reflection factor is essentially independent of the type of ground. For elevation angles above 30º there is substantial variation of the reflection factor magnitude. In the zenith direction there can be an 8 dB difference in the reflection magnitude for smooth sea and a very dry ground. The corresponding variation in the multipath error could range from 15 cm for the case of a smooth sea to 6 cm for the case of very dry ground.

DEFINITION OF DESIRED-TO-UNDESIRED (D/U) SIGNAL RATIO

For a given satellite elevation angle and assuming a flat horizontal ground: The D/U ratio is defined as the ratio of the received direct signal to the received multipath (indirect) signal.

An approximate formula for D/U is given by:

$$\frac{D}{U}(\theta) \approx \frac{G(\theta)}{G(-\theta)}\frac{1}{\Gamma(\theta)} = \frac{\text{Up / Down Gain Ratio}(\theta)}{\Gamma(\theta)} \qquad (1)$$

$G(\theta)$ = Antenna gain with respect to an isotropic antenna (dBi, total radiated power)

$\Gamma(\theta)$ = Magnitude of ground reflection factor

θ = Elevation angle

Equation (1) assumes polarization match for both the direct and indirect signals. (The magnitude of the direct signal is proportional to the total power in the direct signal; the magnitude of the indirect signal is proportional to the total power in the reflected signal.) It is a conservative estimate for the D/U ratio.

An exact formula for D/U is given by:

$$\frac{D}{U}(\theta) = \left|\frac{G_{VP}(\theta) + jG_{HP}(\theta)}{G_{VP}(-\theta)\Gamma_{VP}(\theta) + jG_{HP}(-\theta)\Gamma_{HP}(\theta)}\right| \qquad (2)$$

G_{VP} = Antenna gain with respect to vertical linear polarization

G_{HP} = Antenna gain with respect to horizontal linear polarization

Γ_{VP} = Fresnel formula for vertical polarization

Γ_{HP} = Fresnel formula for horizontal polarization

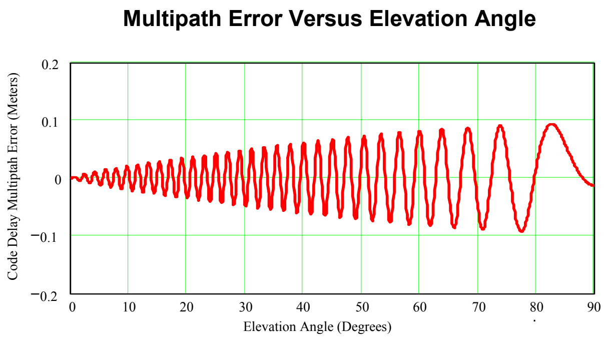
All the factors in Equation (2) are complex voltages.

MULTIPATH ERROR VERSUS ELEVATION ANGLE

The multipath error, $\delta(\theta)$, versus elevation angle is given by the approximate formula [8]:

$$\delta(\theta) \approx \frac{1}{D/U(\theta)} 2H\sin(\theta)\sin\left(\frac{4\pi H}{\lambda}\sin(\theta)\right)$$
$$\delta(\theta) \approx \frac{G(-\theta)}{G(\theta)}\Gamma(\theta) 2H\sin(\theta)\sin\left(\frac{4\pi H}{\lambda}\sin(\theta)\right) \qquad (3)$$

It is assumed that the ground is flat and horizontal. Equation (3) is valid for $H < 7.5$ m and $D/U >> 1$.



H = 3 m
D/U(θ) = 36 dB = Antenna Up/DownGainRatio/Γ(θ)
Antenna Up/DownGainRatio = 30 dB
Γ(θ) = - 6 dB

Figure 9

Multipath error versus elevation angle is presented in Figure 9. The interference pattern shown in Figure 9 is simply that of a source located 3 m above the ground surface and its image 3 m below the surface. It is noted that if the antenna were located above a pool of water, the peak error would be near 0.15 m.

GENERAL SITING CONSIDERATIONS

As indicated in Equation (3), the peak multipath error is directly related to the antenna height above the local ground. One would tend to locate the antenna as close to ground as possible, but it is soon recognized that this location would be overly sensitive to local transient objects that can produce substantial multipath effects. Experience to date has indicated that an antenna phase center height of 3 m is suitable for airport environments. It is recommended that the phase center height should not be less than 2 m.

The variability of the peak multipath error associated with the water content of the local ground leads to the following recommendations:

- Avoid a site with a local bowl-shaped (concave) terrain feature
  - Concave ground can amplify the ground reflection factor
  - Concave ground can also accumulate rain water at the base of the antenna
  - Location at the apex of a convex surface is the ideal location
- Stabilization considerations
  - Grade the local site (4 m radius) to minimize the possibility of a water saturated local ground or pools of water near the antenna base
  - Add a layer of crushed stone (or other suitable materials) to provide a stable electrically-rough surface with a reflection factor ranging between -6 and -9 dB

SUMMARY

This paper:

- Presented an overview of the ARL-1900 ground reference antenna performance and history. This antenna is unique with near ideal characteristics
- Presented a detailed description of ground multipath characteristics, which highlighted the possible variability of the local ground reflectivity. This impacts the multipath performance, especially at high elevation angles
- Made recommendations for the siting of the antenna and possible treatment of the local ground surface for control of the variability of the local ground reflectivity

ACKNOWLEDGEMENTS

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REFERENCES

[1] A.R. Lopez, U.S. Patent No. 5,534,882, "GPS Antenna Systems," Jul. 9, 1996

[2] A.R. Lopez, R.J. Kumpfbeck, E.M. Newman, U.S. Patent No. 6,201,510, "Self-Contained Progressive-Phase GPS Elements and Antennas," Mar. 13, 2001

[3] A.R. Lopez, "GPS Ground Station Antenna for Local Area Augmentation System, LAAS," ION NTM 2000, 26-28 January 2000, Anaheim, CA

[4] A.R. Lopez, "Calibration of LAAS Reference Antennas," ION GPS 2001, 11-14 September 2001, Salt Lake City, UT

[5] A.R. Lopez, "LAAS Reference Antennas – Circular Polarization Mitigates Multipath Effects," ION 59th Annual Meeting/CIGTF 22nd Guidance Test Symposium, 23-25 June 2003, Albuquerque, NM

[6] A.R. Lopez, "LAAS Reference Antennas – Key Siting Considerations," ION GNSS 17th International Meeting of the Satellite Division, 21-24 Sept. 2004, Long Beach, CA

[7] FAA Navigation/LAAS T&E Team, "Local Area Augmentation System Performance Analysis / Activities Report, Report #9, Reporting Period: January 1 to March 31, 2006," April 30, 2006, pp. 43-45

[8] C.C. Counselman, "Multipath-Rejecting GPS Antennas," Proceedings of the IEEE, Vol. 87, No. 1, Jan 1999