Validation of the FAA LAAS Specification Using the LAAS Test Prototype (LTP)

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BIOGRAPHY

John Warburton is a Senior Electronics Engineer in the Airborne Systems Technology Branch at the William J. Hughes Technical Center. He has worked in the test and evaluation of precision landing systems, including ILS, MLS, and GPS since 1983. He is currently the project manager for development and operation of the FAA's Local Area Augmentation System test bed, the LAAS Test Prototype.

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ABSTRACT

The FAA Satellite Navigation Office, AND-730, is currently developing a specification for the Local Area Augmentation System (LAAS) Ground Facility. The FAA William J. Hughes Technical Center has been tasked with validation of that specification. As part of the validation, the LAAS Test Prototype (LTP) was used in a series of tests to evaluate LAAS performance at operational airports selected from the LAAS Requirements Document (RD).

This paper summarizes the LTP ground and flight tests conducted in Pennsylvania at the Philadelphia International Airport, in Alaska at the Fairbanks International and Cold Bay Airports, and in Minnesota at the Minneapolis International Airport.

Over 240 approaches were conducted using the system described in this report. Approaches were completed in both an FAA-owned Boeing 727, and a Falcon 20 owned by the National Research Council of Canada.

The results of the LTP tests have shown that the current LAAS architecture is capable of providing the level of service required by the LAAS RD.

BACKGROUND

The FAA Joint Resource Council (JRC) has approved the full-scale development (FSD) of the Local Area Augmentation System (LAAS) as a replacement system for the current Instrument Landing Systems (ILS). LAAS will augment the Global Positioning System (GPS) and provide precision approach capability at individual airports.

The FAA Satellite Navigation Office, AND-730, has supported and directed a wide variety of efforts [1] intended to demonstrate the feasibility of using augmentations of GPS to meet the accuracy and integrity requirements for all categories of precision approach and landing. These demonstrations have yielded excellent results and have been the principal source for definition of the LAAS architecture [2].

The first full-scale testing of the LAAS architecture was completed in August 1997 at the WJHTC using a system built by Ohio University (OU)[3]. The testing proved the architecture was sound and could provide the required level of service in a test environment.

The LAAS group of the Navigation Branch, ACT-360, in conjunction with AND-730, MITRE, OU, Stanford University, and Naval Air Warfare Center Aircraft Division (NAWCAD) selected three test airports for LAAS specification validation. The selection criteria included varying multipath environments, difficult or confined siting, strong radio frequency (RF) environments, and inclusion of the airport in the LAAS Requirements Document (RD) as a LAAS candidate.

ACT-360 reconfigured its existing LAAS Test Prototype (LTP)[4], a government-owned suite of equipment, to include the changes implemented by OU, implement new receivers and antenna optimizations, and reflect the current specification requirements. Further modifications were made to increase the system's siting flexibility.

TEST OBJECTIVE

The primary objective of these flight tests was to establish the system performance of the current LTP at the selected airports. The LTP is compliant with the most current version of the FAA's LAAS specification, and confirmation that the LTP can achieve the intended performance will validate the LAAS specification. A secondary objective of the tests was to gather data to support the development of LAAS siting criteria.

LTP SYSTEM DESCRIPTION

The LTP system as deployed for the tests described in this paper consisted of separate ground and airborne subsystems and was intended to provide Performance Category 3 capability, as defined in the RD. In addition to providing the LAAS service, the system also collects and stores all raw data for future simulation processing. By collecting Performance Category 3 data, all category systems can be simulated.

A separate Time Space Position Information (TSPI) truth system was used to gauge the system performance.

Ground Reference System

The ground system consisted of a ground processor, a data link, and four reference stations, each consisting of a GPS receiver and a specially designed antenna. Multiple reference stations are required to provide the accuracy, integrity, and continuity needed to support CAT III operations. The configuration is shown in Figure 1.

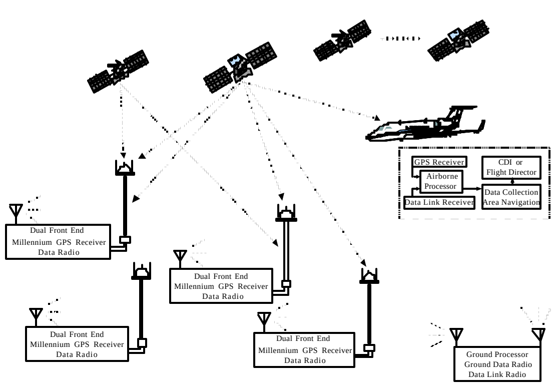

Figure 1. LTP System Block Diagram

Each reference station collects measurements from all GPS standard positioning service (SPS) satellite vehicles (SVs) in view. These measurements are sent to the ground processor, via wireless modem, where they are compared to the expected measurements, based on the geometry of the satellite and the precisely surveyed reference station antenna locations only. The measurements are then translated to a single reference point and a preliminary range correction is calculated for cross-comparison. The comparison, or Multiple Reference Consistency Check (MRCC), is the basis for the ground system integrity. The comparison is quantified by calculating a bias or B-value given by equation 1.

$$B_{PR}(n,m) \equiv PR_{corr}(n) - \frac{1}{M(n)-1} \sum_{\substack{i \in S_n \\ i \neq m}} PR_{sca}(n,i) \quad (1)$$

The average pseudorange correction for the n^{th} ranging source, $PR_{corr}(n)$, is calculated using information from all available references. The average correction for the same ranging source is then calculated with m^{th} reference excluded. The B-value, $B_{pr}(n,m)$, is formed by subtracting the two averages, and is intended to represent an estimate of the uncorrectable error in the measurement of the n^{th} ranging source measured by the m^{th} reference.

The resulting value is compared to the integrity threshold, which is based on the continuity requirement. The ground system calculates correction data for an individual SV only if the B-values from at least two references are below the integrity threshold. A detailed description of the LAAS integrity method can be found in [5].

This error estimation and measurement exclusion is valid only if errors measured at the individual reference locations are independent. Correlated errors will decrease the accuracy of the estimation and can potentially degrade system integrity and continuity. Development of proper LAAS siting requirements will ensure reference independence.

A key feature of the current LTP is the Multipath Limiting Antenna (MLA). This antenna system, first described in 1994[5], was reintroduced to the LAAS community by OU in 1996. The MLA is a two-part antenna system designed to receive GPS SPS SVs from all elevation angles between 5 and 90 degrees.

The most critical part of the MLA system is a dipole array that is used to receive SVs at elevation angles between 5 and 30 degrees. Signals from SVs at these elevation angles are generally lower in power and more susceptible to multipath interference from ground reflections, which can enter conventional GPS antennas from beneath the desired reception pattern. The measurement error caused by the multipath reflection is proportional to the ratio of the signal strength of the desired direct transmission to the undesired multipath reflection signal strength. The dipole array in the MLA was designed with a high gain lobe in the direction extending from 5 to 30 degrees elevation, which increases the received power level of low elevation SVs. The gain begins to sharply decrease at 5 degrees, and is reduced by 35dB at –5 degrees, providing a strong desired to undesired ratio. The goal of this antenna design was to limit pseudorange measurement errors at the ground station reference antennas to 0.3m. Coverage for SVs at elevation angles from 30 to 90 degrees is provided by a high zenith array (HZA) which is physically mounted on top of the dipole array. The HZA provides at least 20dB of direct to indirect pattern isolation throughout its coverage volume.

The LTP employs dual 12 channel, ultra-narrow, 0.05 chip correlator spacing Novatel Millennium GPS receivers to accommodate the two element MLA. At each reference station the HZA was connected to the primary 12 channels and the dipole array was connected to the secondary 12 channels. The SV measurements were collected at precisely the same time in both the primary and secondary channels, eliminating potential clock errors between the antenna elements. A final calibration using an SV that is common to each MLA element is performed to remove remaining hardware biases.

The current FAA LAAS specification requires a Very High Frequency (VHF) data broadcast (VDB) which operates in the assigned navigation band from 108.00 MHz to 117.975 MHz. This VDB radio was under development and was not available for inclusion in LTP at this time of these tests.

The LTP as deployed for these tests transmitted pseudorange and carrier correction message types 1 and 6 as defined in the current LAAS Interface Control Document (ICD)[7]. A Freewave spread spectrum data transceiver, operating in the commercial wireless telephone band of 903-927 MHz was used to transmit the required data to the aircraft at data rate of 1 Hz. The end-to-end cyclic redundancy check was not transmitted, and will be incorporated with the specified VDB.

Airborne System

The airborne system consisted of a 12 channel, narrow correlator, Novatel 3951RM GPScard receiver housed in a PC, and standard aircraft GPS patch antenna, a data transceiver, and an airborne processor. The airborne processor received pseudorange measurements at a 5 Hz rate from the GPS receiver and corrections for each live GPS SV at a 1 Hz rate from the ground system. The airborne processor computed the aircraft position through differential techniques. The differential position was sent to the FAA Data Collector/Area Navigation Computer (DCAN), which calculated the desired approach path and output ILS-like deviations to the aircraft Course Deviation Indicator (CDI). The DCAN also provided accurate time tagging and recording of all available analog and digital information. An ultra-narrow correlator Novatel Millennium receiver, identical to the receivers utilized in the ground system, was connected to the airborne antenna for simultaneous data collection and post-process simulation.

TSPI System

The truth source was an Ashtech Z-XII TSPI system, which consisted of a ground and airborne receiver. The ground station receiver was installed at a surveyed location. The airborne receiver was mounted in the FAA equipment rack connected to the LTP project GPS antenna. Raw truth data was processed using Ashtech Precise Differential GPS Navigation (PNAV) Trajectory software. This software package performed post-processing of the Z-XII raw data collected to provide precise GPS positioning between ground station and airborne receiver. With proper SV coverage, TSPI system accuracy is approximately 0.1 m. Ashtech PRISM mission-planning software was run prior to the scheduling of the flight test approaches to ensure adequate GPS constellation availability

FLIGHT TEST PROCEDURES

The flight profiles for the subject flight tests consisted of multiple straight in ILS, or ILS-like 3-degree approaches. The approaches began at approximately 10 nmi from the runway threshold where a 3-degree glidepath was intercepted at 3000 ft above ground level (AGL). All flights were conducted under Visual Flight Rules (VFR) conditions using the LTP position to calculate ILS-like deviations that were displayed in the cockpit for reference. Approaches were flown either manually or with the LTP guidance signal coupled to the flight director, at the discretion of the project pilot.

A goal at each airport was to complete at least 40 approaches utilizing LTP guidance. A second goal was to complete at least three sets of approaches with the same SV constellation in order to demonstrate consistency. Additional approaches were completed, when possible, with varied SV constellations to better statistically represent the installations.

LAAS was designed so that a single installation could provide precision approach capability to all runway ends. To the extent possible, approaches were equally divided among all available runway ends. At all test airports LTP procedures were designed by the ACT-360 test team to exactly overlay existing landing aids. This was done to provide the aircraft test pilots with a crosscheck of the LTP guidance, and for the collection of comparison data when possible.

EQUIPMENT SETUP

The current specified requirement is that the reference antennas should be independently sited. As stated above, LAAS siting requirements are still under development. To minimize the potential for correlated multipath errors during the validation flight tests, a goal at each LTP installation was to provide at least 100m separation between each reference antenna.

In addition to the LTP, a second GPS data collection system was installed at one reference location at each test site. This equipment consisted of two 3951RM GPSCards which were connected to the MLA, and an Ashtech Z-XII which was connected to an Ashtech survey antenna. This equipment was used to collect data for 24-hour periods to more fully analyze the multipath environment.

Philadelphia

The Philadelphia International Airport (PHL) is built along the Delaware River on relatively flat ground, with 3 runways, two of which are parallel to the river. The airport property is well-developed, with five terminals, a busy cargo area, a large United Parcel Service hangar, and current construction of a fourth runway.

Suitable siting for the LTP was found between the approach areas of runways 9L and 9R. Two reference antennas were located in an open field adjacent to a lighting and power distribution center just off the approach end of runway 9L. The two remaining antennas were located between a drainage pool and the taxiway for runway 9R. The distance between the two sets of antennas was approximately four-hundred meters.

PHL was selected as a test site for the LTP because it is listed in the RD as a candidate airport for LAAS. It is a high volume airport, serving as an eastern hub for US Airways. The radio frequency (RF) environment was challenging, with several television broadcast towers located in the city of Roxborough, only 8 miles to the north. The proximity of the airport to the river also provided for a consistent ground water level estimate for ground multipath calculations, as well as several approaches over water.

Fairbanks

The Fairbanks International Airport (FAI) is located in north central Alaska. The airport is located on a fairly level area surrounded by mountainous terrain. The airport is lightly developed, with one main terminal building, an Alaskan Airlines facility with one large hangar, and several small general aviation hangar areas.

The most suitable area for the LTP was found just off the approach end of runway 19R. The antennas were located in a somewhat confined area of open ground adjacent to the localizer. Three antennas were sited in an approximate equilateral triangle with 80m sides, and the fourth reference was located in line with one side of the triangle that was approximately perpendicular to the runway.

FAI was selected as a test site for the LTP because it is listed in the RD as a candidate airport for LAAS. It also provided a challenging environment for a DGPS system due to is high latitude and preponderance of low elevation SVs. The site has a high ground water level, as evidenced by a 6000 foot water runway parallel to the main runway, 1L. FAI has a CAT III ILS allowing the recorded LPT performance to be compared to an operational high category commissioned facility.

Cold Bay

The Cold Bay Airport (CDB) is located at the end of the Alaskan Peninsula, in southeast Alaska. The airport is sparsely developed, with a small terminal and several support buildings. There is significant terrain located on three sides of the airport, including one peak at 12000 feet, which blocked reception of SVs under 6 degrees in that direction. The RF environment of CDB was quiet, as evidenced best by the excellent operation of the wireless datalink.

A suitable area for the LTP was found 3000 feet from the approach end on RWY 32. Three of the antennas were place in a triangle located in a marshy area behind an installed Microwave Landing System (MLS). The fourth antenna was placed on a hilltop that was within 150m of the center of the triangle. The surveyed elevation of the fourth reference was about 10m higher that the first three.

CDB was selected as a test site for the LTP because of is fairly high latitude, and high number of low elevation SVs. The mountainous terrain and ocean surrounding also provided test conditions not previously characterized. CDB has both a CAT I ILS and MLS allowing the LTP performance to be compared to those traditional systems.

Minneapolis

The Minneapolis-St Paul International airport provided a busy mid-continent location. The airport is well developed with one large main terminal located between two parallel runways, 12L and 12R, and several large cargo hangers to the south.

The LTP was installed between the approach ends of runways 12L and 12R a remote transmitter (RTR) communications site collocated with the Airport Terminal Radar (ASR-9). This site was not the best available, but was selected to allow evaluation of system performance in a complex multipath environment.

Minneapolis-St Paul was selected as a test site for the LTP because it is a high volume airport, serving as a hub for Northwest Airlines. Previous FAA flight test experience at the airport and with the air traffic personnel provided additional benefit.

VALIDATION METHODS

B-Value Validation and Site Multipath Analysis

B-values are intended to represent the uncorrectable errors at each reference. The primary components of this error are code phase multipath and receiver noise. Standard code minus carrier (CMC) techniques [8] were employed to produce a multipath and receiver noise 'truth' which was compared against the B-value estimates. The ionospheric divergence was removed using the L1 and L2 carrier phase measurements of the Ashtech Z-XII. CMC was calculated for both the LTP Millenium receiver data and the 3951 GPSCard data.

In addition to the B-value analysis, CMC processing was used to produce color-coded multipath plots of all satellites in view over 24-hour periods for antenna sites of particular interest. These plots utilized 360-degree digital photograph onlays of the local environment to identify potential multipath reflectors and signal obstructions.

MLA Validation

The current LGF specification places a bound on the maximum broadcast correction error (BCE) that can be included in LAAS corrections. This quantity, however, is not directly verifiable, as correction truth is unavailable. Relative performance of an individual reference can be determined by comparing its measurements to the composite measurement of the approved references. This comparison is numerically described by the calculated B-values, as defined by equation 1.

To properly represent the observed errors, system data was collected during each test in continuous blocks between twelve and fifteen hours in length. The collected data was sorted into one-degree elevation bins for all SV measurements below 10 degrees and five-degree elevation bins for all other observations. The mean and standard deviation for each bin was calculated, scaled, and plotted with the BCE curve in order to evaluate MLA performance.

Although the LGF specification identifies the RMS error in the average correction, the performance of each reference was individually plotted. The RMS correction error should lie within the scaled reference performance.

In the MLA analysis, when the real-time B-value exceeded the integrity threshold, a recalculated B-value was included in the statistics. This B-value of the excluded reference was calculated using the average correction of the remaining approved SVs.

Sigma Monitor Considerations

The sigma monitor concept considers the variations in the day-to-day measures of the standard deviation of each elevation bin. Variations should be small, except in cases where the siting or measurements have been corrupted. The function is designed to detect variation of a calculated short-term sigma from a site's established sigma performance. To explore this concept, measured B-values statistics were compared on successive days.

NSE Analysis Method

Vertical and Cross-Track NSE were the primary means for evaluating LTP system performance. NSE is defined as the difference between the navigation solution provided by the system under test and the TSPI determined truth position. The NSE was calculated for each approach from the aircraft turn onto the final course to 50-ft height above touchdown (HAT). NSE individual plots and ensemble statistic plots for individual runways as well as the composite of all approaches to all runways were generated. Estimation statistics were computed to characterize the data. These statistics included calculation of ensemble means (μ), standard deviations (σ), and 95% error estimates ($\mu \pm 2\sigma$) of the NSE at 100 ft HAT.

RESULTS

MLA Measurement Performance

Philadelphia was the first LTP test site. The siting selected for this location was conservative, using large available areas of open ground with reference locations separated by at least 100m. The performance of each reference location is shown in Figure 2.

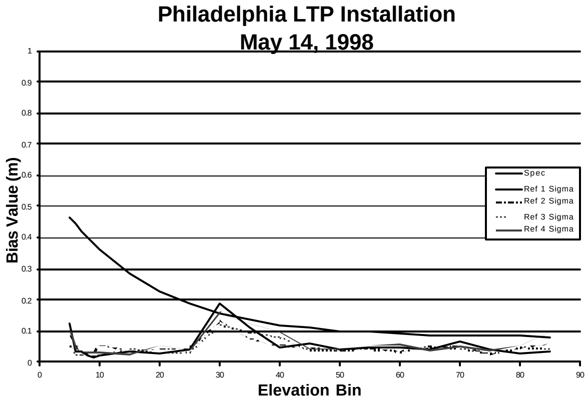

Figure 2. PHL Reference performance

The dipole portion of the MLA, used for all elevation angles less than 30 degrees, provided measurements with considerable margin under the specified BCE curve. The HZA, which provided the remaining coverage, did not meet the specified curve at the lowest portion of its coverage. This result was consistent with other test locations.

Fairbanks, the second LTP test installation, employed slightly less conservative siting than Philadelphia in that the reference locations were placed only 80m apart in a flat open location. Measurement performance is shown in Figure 3.

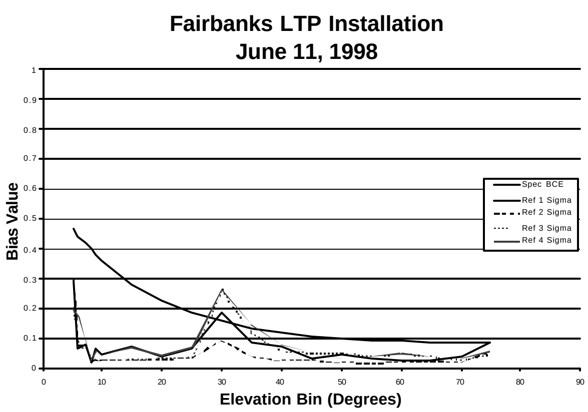

Figure 3. FAI Reference performance

Degraded performance is shown in the 5-degree elevation bin. This result was consistent throughout the Fairbanks tests. It was later found that a special receiver command was inadvertently issued that reduced the dynamic range of the ground station receivers. This slightly delayed acquisition of SVs in two of the references and caused some of the corrections in the 5 degree elevation bin to be based on only 2 references.

Signals in the GPS band generally pass through soil, where they are attenuated, and reflect from the ground water. In Cold Bay, the third test site, the LTP reference antennas were installed in an area with very high ground water as well as standing surface water. This was done to subject the MLAs to strong ground multipath. It was anticipated that signal reflections would come directly from the surface and the have little attenuation due to local soil. The achieved performance is shown in Figure 4.

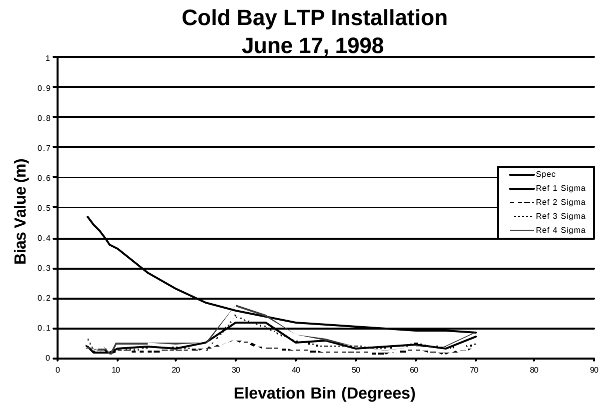

Figure 4. CDB Reference performance

A very aggressive site was selected for the fourth LTP installation in Minneapolis. Two references were located on open, clear ground. A third reference was located on top of a small hill. The fourth reference, Ref 3, was placed in the center of four 30ft communications towers. It was expected that signal reflections from the towers would produce high elevation angle multipath that would not be attenuated by the pattern of the MLA and pass into the system, to be handled by the integrity system. The performance at this location is shown in Figure 5.

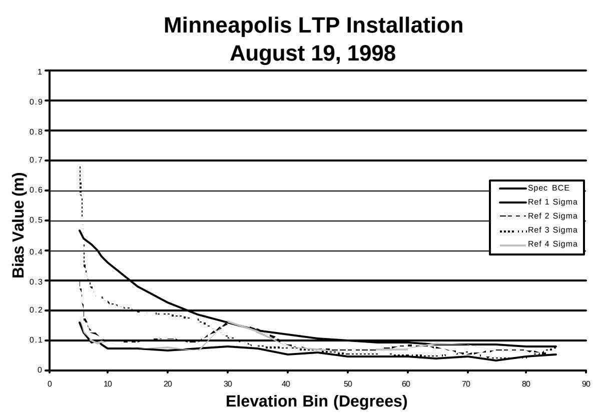

Figure 5. MSP Reference performance

Figure 5 shows that the installed performance of Ref 3 did not meet the specified BCE performance of the LGF specification. It is important to note that the system only utilizes measurements that have passed the integrity tests discussed earlier. During system operation, the integrity algorithm at times did exclude low elevation measurements from Ref 3 and prevented corruption of the actual broadcast corrections.

Site Multipath Analysis

Figure 6, included at the end of the paper, shows CMC binned by azimuth and elevation (0.5° azimuth bins, 0.25° elevation bins) for the dipole antenna at the Ref 3 site. These plots normally present multipath data that is color-coded into four multipath amplitude bands. Due to the poor translation of the multi-color plot to black and white, only multipath greater than 1 meter is shown in the figure.

The amount of multipath greater than 1 meter is not surprising since this antenna was purposefully located in a stressful environment. As can be seen from the plot, there is a significant amount of multipath in three azimuth regions: 25-45°, 150-270°, and 310-330°. The 360 degree photo onlay shows a building and two antenna towers in line with the first region, an antenna tower in line with the third region, but does not show many potential reflectors in the second region. However, if the photo is shifted by 180 degrees as shown in Figure 7, included at the end of the paper, there are a multitude of reflectors (including buildings and antenna towers) which undoubtedly contribute to the observed multipath.

Sigma Monitor Analysis

Performance plots were produced for each day the LTP was installed at each test location. A second day's data from Minneapolis is shown in Figure 8 as a demonstration of the repeatability of the measured sigma performance.

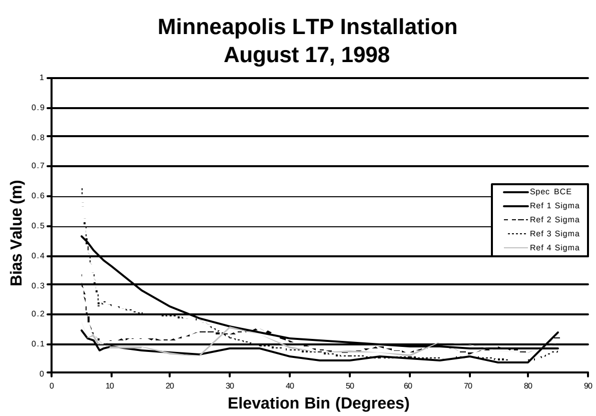

Figure 8. MSP Reference performance

B-Value Comparison to Code minus Carrier

Real-time B-values were compared to post-processed code minus carrier measurements at each test location on an individual SV basis. A representative plot of the agreement between the two quantities for one SV is shown in Figure 9.

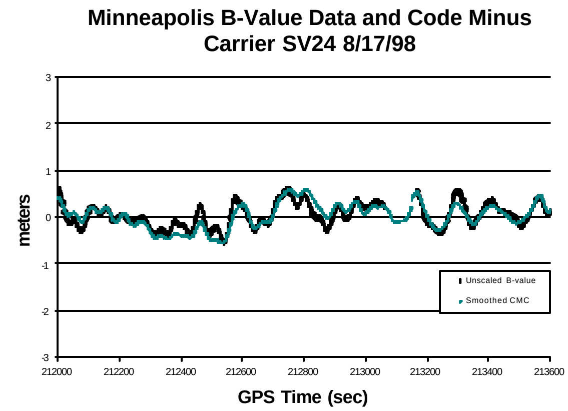

Figure 9. Minneapolis B-value Data

Flight Test

Flight test results provided a final end-to-end test that the LAAS system corrections were accurate and could be used to calculate a real-time position solution.

An initial flight test at the WJHTC was used verify the correct phase center characteristic of the dipole and HZA elements of the MLA. This initial testing suggested the manufacturer's measurement of the HZA phase center was incorrect. A surveyed location was used for that measurement during all LTP flight tests. The vertical NSE flight test results from the PHL tests are shown in Figure 10.

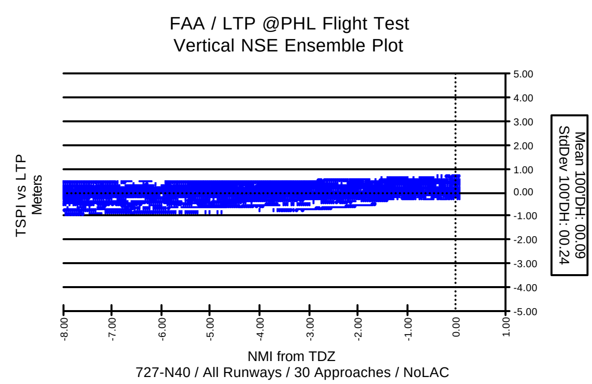

Figure 10. PHL Vertical NSE

This result suggested the antenna parameters were correct, with only a slight vertical bias. This result, however, was not consistent with later tests, which each showed a negative vertical bias, and example of which is shown in Figure 11.

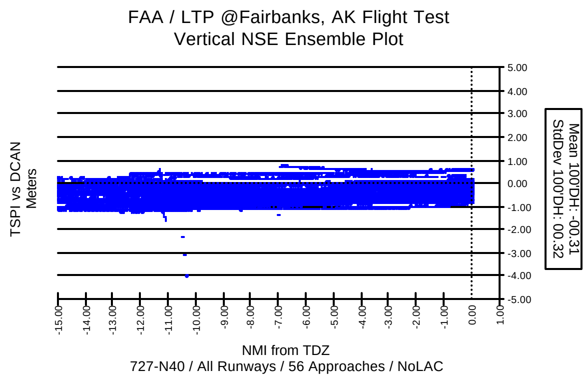

Figure 11. FAI Vertical NSE

Post-processing of available test data suggests the HZA element's phase center is not fixed.

Final ensemble plots of the vertical and horizontal performance for all completed approaches is shown in Figures 12 and 13.

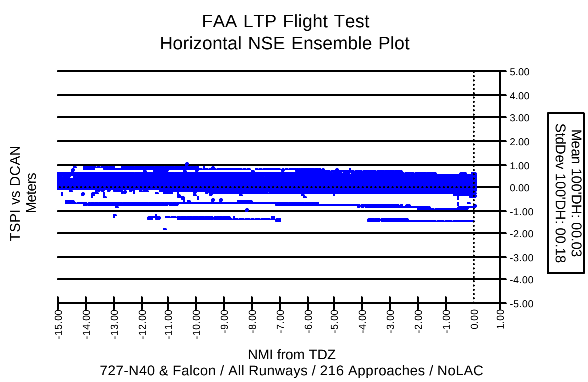

Figure 12. Horizontal NSE

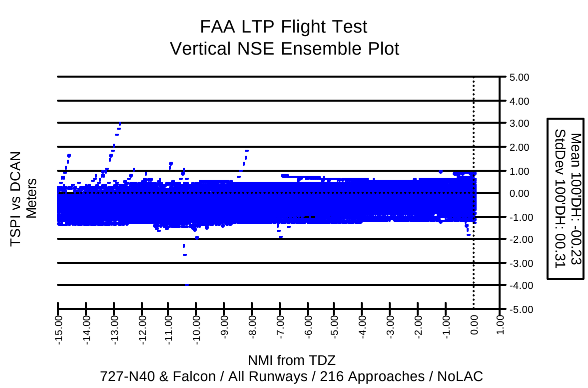

Figure 13. Vertical NSE

CONCLUSIONS

The dipole portion of the MLA, when properly sited, is capable of providing signals with errors that are much lower than the values specified in the LGF specification. The HZA portion of the MLA did not meet the not-to-exceed broadcast correction error requirements of the LGF specification in all cases. Resolution of the phase center location and phase stability of the current HZA is required to fully characterize the element's performance. Alternate HZA elements are currently under development.

The MLA antenna was shown to be very effective at mitigating the effects of ground multipath. The system results observed in Cold Bay, where the ground multipath was the most severe, were well within the specified limits. Although the dipole antenna was shown to be very effective at mitigating ground multipath, the antenna was vulnerable to reflections from objects above the antenna base. Careful siting will be required to ensure that the dipole performance falls within the specification requirements.

The sigma monitor concept is valid over short duration. Successive calculations of elevation bin standard deviations agree. Further investigation, including verification of the long-term variations are planned

B-values were shown to agree with independent code-carrier results, and provide a proper representation of reference errors.

The LTP end-to-end flight test results demonstrated that the system provided accurate corrections to the airborne system. The measured 95% NSE results at the 100-foot decision height of 0.39m horizontal and 0.85m vertical are well within the performance category 3 levels specified in the current LAAS RD. A significant portion of the total vertical NSE was due to the uncertainty with the HZA location, and will be resolved in future tests. Several approaches contained data dropouts that can be observed in the ensemble plot. These are particularly evident when the system has coasted for more than a few seconds. The coasting period in the LTP was extended during these tests to accommodate the sensitivity of the data link utilized for these tests.

The tests also showed that the LTP system provides a robust baseline system to validate LAAS concepts. The system was operated continuously during the one-week deployments at each designated operational airport without failure. The system is currently installed and operational at the WJHTC.

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REFERENCES

1. Braff, R., et al., "FAA's CAT III Feasibility Program: Status and Accomplishments," Proceeding of ION GPS-95, The Satellite Division of the Institute of Navigation, Palm Springs, California, September 1995.
2. Braff, R. "Description of the FAA's Local Area Augmentation System (LAAS)," NAVIGATION, Journal of The Institute of Navigation, Vol. 44, No. 4, Winter 1997-98, pp. 411-24.
3. VanGraas, F., et al., "Ohio University/FAA Flight Test Demonstration Results of the Local Area Augmentation System (LAAS)," Proceeding of ION GPS-97, The Satellite Division of the Institute of Navigation, Kansas City, Missouri, September 1997.
4. Warburton, J., et al., "Flight Test Results of the FAA Local Area Augmentation System Test Prototype", ION 53rd Annual Meeting proceedings, July 1997.
5. Lui, F., et al., "Ohio University/FAA Flight Test Demonstration Results of the Local Area Augmentation System (LAAS)," Proceeding of ION GPS-97, The Satellite Division of the Institute of Navigation, Kansas City, Missouri, September 1997.
6. Braasch, M., "Optimum Antenna Design for DGPS Ground Reference Stations," Proceeding of ION GPS-94, The Satellite Division of the Institute of Navigation, Salt Lake City, Utah, September 1994
7. GNSS Based Precision Approach Local Area Augmentation System (LAAS) Signal-in-Space Interface Control Document (ICD), Final Draft, February 20, 1998.
8. Braasch, M., "Isolation of GPS Multipath and Receiver Tracking Errors," NAVIGATION: Journal of The Institute of Navigation, Vol. 41, No. 4, Winter 1994-95.

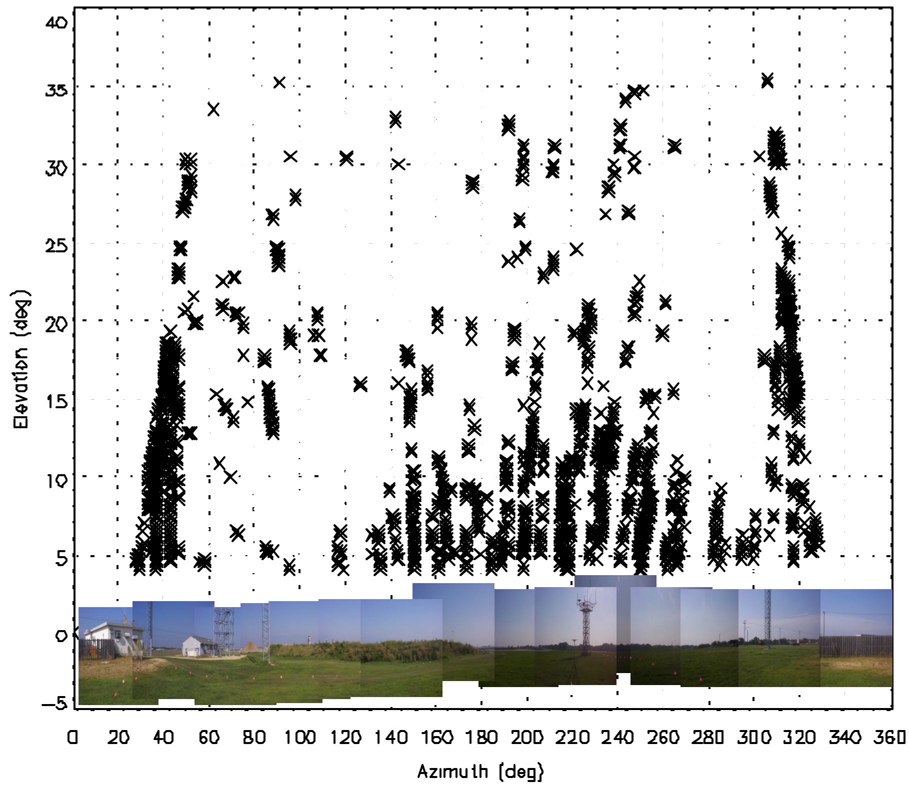

Figure 6. Minneapolis Site Ref 3 Multipath Plot

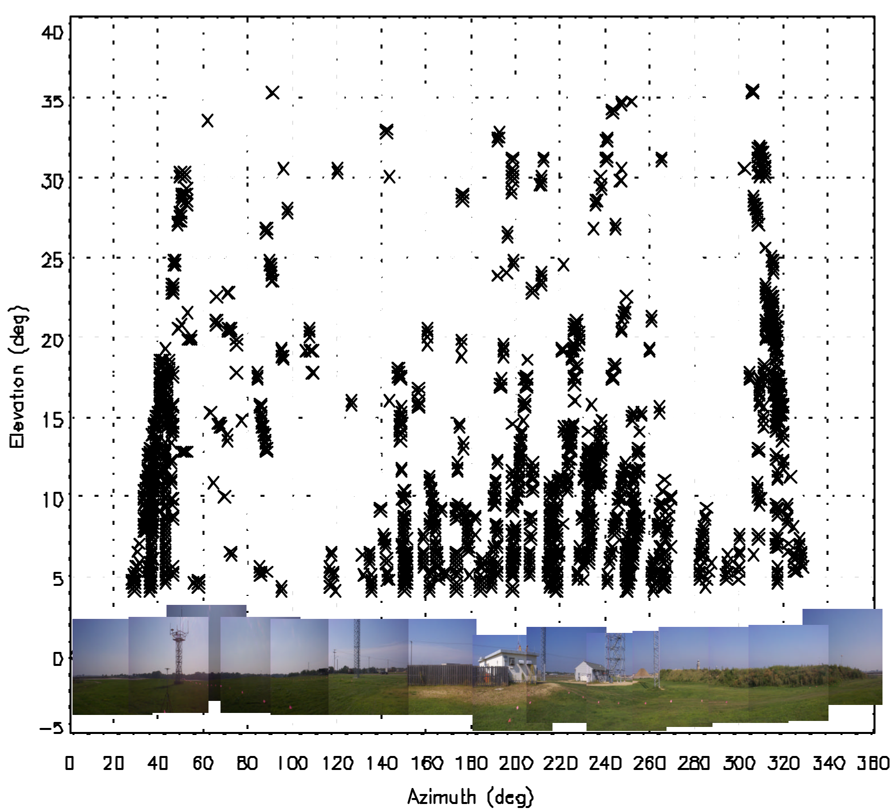

Figure 7. Site Ref 3 Multipath Plot - 180° Photo Shift