Technical and Programmatic Features of the FAA's LAAS

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The US Federal Aviation Administration (FAA) is developing and planning to field the Local Area Augmentation System (LAAS). LAAS is a Ground-Based Augmentation System (GBAS) to GPS, and is designed to serve all categories of precision approach. The purpose of this paper is to provide the latest technical and status information on the LAAS programme. The technical aspects of the LAAS specification are discussed, followed by a description of specification validation field testing and results. Institutional and programmatic aspects are then summarized along with a chronology of events leading up to the Government Industry Partnership (GIP) for the initial development and fielding of LAAS.

1. INTRODUCTION.

This paper is a sequel to a paper presented two years ago and published in *The Journal*.[1] Since that time the specification for the Local Area Augmentation System (LAAS) ground system has matured, related activities at RTCA (formerly the Radio Technical Commission for Aeronautics) Working Group (WG) 4A and the International Civil Aviation Organization (ICAO) are well underway, and the FAA LAAS prototype has been tested at several airports. This paper provides a summary and discussion of these activities.

The LAAS system design and its specified performance are discussed. Next, the LAAS test prototype (LTP) is described, and its tests at several airports are summarized. The last part of the paper contains a history of LAAS, its status at RTCA and ICAO, and a discussion of the Government Industry Partnership (GIP) to field the first LAAS.

2. LAAS SYSTEM DESIGN AND SPECIFICATION.

The FAA LAAS architecture has been previously described,[2] and this paper will not re-visit every aspect but will provide an update and status of the FAA specification and validation activities. The LAAS ground facility (LGF) specification is written to be compliant with the RTCA *LAAS Minimum Aviation System Performance Standards* (*MASPS*) *DO-245* and RTCA *LAAS Interface Control Document* (*ICD*) *DO-246*. The LGF is intended to be compatible with the RTCA LAAS Minimum Operating Performance Standard (MOPS). A clear division of integrity between the LGF and the airborne receiver subsystem is critical to the achievement of interoperability of various manufacturers' equipment.

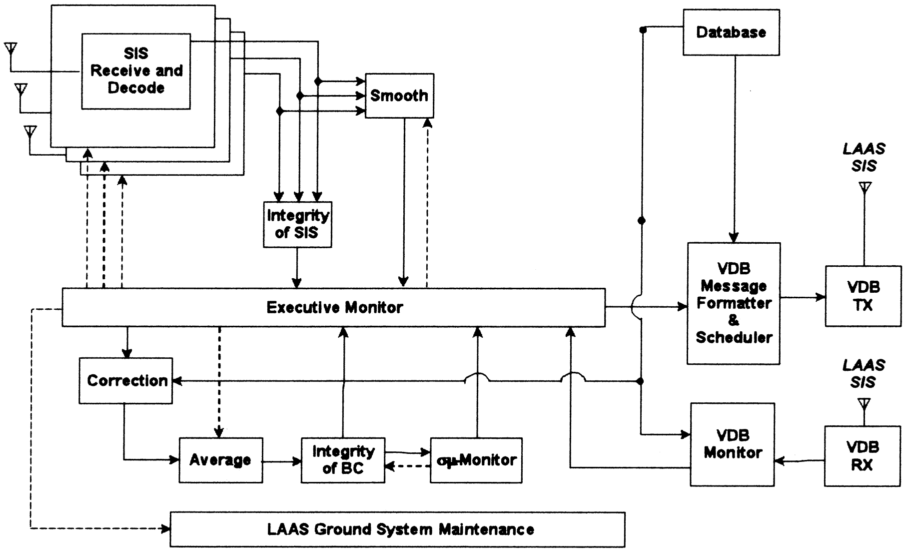

Figure 1. LAAS ground facility design, performance Type 1.

The FAA specification team consists of a ‘core group’ of experts familiar with FAA and RTCA requirements. Working in parallel to the Core Group is a team of government and university experts, known as the FAA Key Technical Advisors (KTAs). One of the first challenges for the KTA team was to identify the critical design parameters necessary to assure interoperability. The KTA team produced a detailed block diagram of a LAAS describing inputs and outputs throughout the system architecture. Figure 1 is a representation of the LGF architecture detailing all of the critical elements described in the KTA analysis.

An important system feature depicted in Figure 1 is the requirement for three reference receivers (RRs). Each RR is required to track all rangeing sources in view on GPS L1, at 1575·42 MHz. There are several benefits obtained from requiring multiple RRs. First, multiple RRs provide an increase in long-term service availability. In the LAAS architecture, RR measurements are averaged for each rangeing source to improve accuracy by reducing the effects of non-correlated error sources. Secondly, the LGF can perform fault exclusion; with two RRs, a faulty RR cannot be isolated.

The FAA LGF specification requires 18 channels to provide for all-in-view tracking. With the current GPS constellation, 14 satellites have been observed at high latitude locations, e.g., Fairbanks, Alaska. Four additional channels allow for Space Based Augmentation System (SBAS) rangeing sources or Airport Pseudolites (APLs). Additionally, there is some margin in the system to accommodate the possibility of an increase in the current GPS constellation to include 30 satellites.

The LGF specification requires carrier-smoothed code measurements for each rangeing source, using a standard filter. The LGF specification requires 100 seconds smoothing, consistent with the RTCA MASPS. The smoothing time must be specified to ensure interoperability with the airborne receiver. If the smoothing time were not specified, it is possible that code/carrier divergence, a common effect on the signal as it propagates through the ionosphere, could affect the RR differently than the airborne receiver and cause undetected, misleading information in the avionics. The LGF specification also requires that each RR use identical processing techniques, e.g., correlator spacing and tracking loop characteristics. This is necessary since the error estimates (B-values) broadcast to the aircraft are based on comparisons among the RRs. A comparison must be made with the fewest number of variables so that any significant errors, such as multipath, are easily detectable. Each RR must output independent measurements at a minimum 2 Hz rate.

The characteristics of the RR antenna are not specified in terms of gain and desired to undesired ratio of the signal. This was done to allow manufacturers maximum flexibility in their respective designs. Instead, the system was viewed in terms of the error characteristics of the broadcast corrections. The broadcast correction error (BCE) for Performance Type 1 (PT 1), suitable for Category I approaches, is given in Figure 2. 'M' represents the number of independent measurements per rangeing source. The RMS curve in Figure 2 assumes a narrow correlator (0·1 chip width) for each RR. To meet this requirement, other aspects of the RR must be taken into account, including the antenna selection. Correction accuracy improves as the number of averaged independent measurements increases.

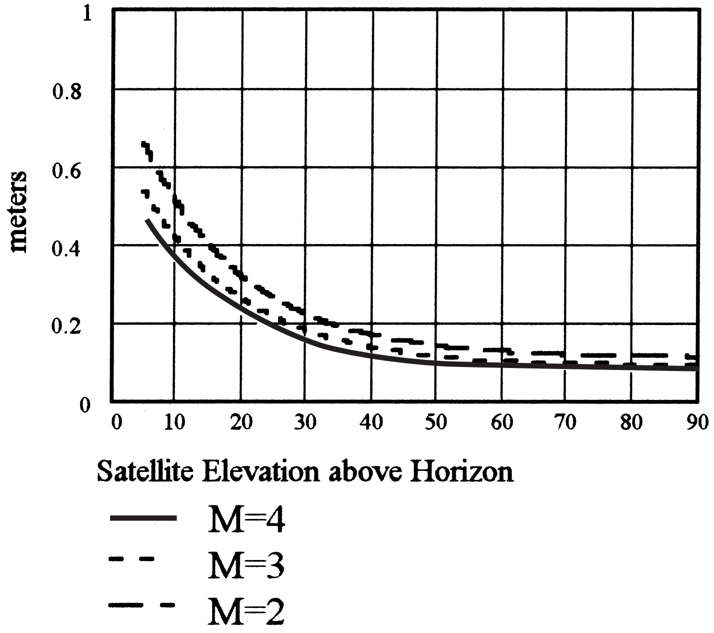

Figure 2. Accuracy of corrections for LAAS performance Type 1.

The transmission of each rangeing source correction is accomplished through a VHF Data Broadcast (VDB). The VDB specified in the LGF specification is consistent with the RTCA LAAS ICD, which requires a differentially encoded 8-phase shift keying (D8PSK) modulation format with a Time Division Multiple Access (TDMA) capability. The TDMA allows for multiple transmissions on a single frequency. For PT 1, only two of eight slots, each 0·0625 seconds long, will be required. There are two sets of eight slots allocated in each 1-second time frame. The designated band for the VDB is 108·000 MHz to 117·975 MHz, which is within the ILS and VOR bands.

Adherence to the RTCA LAAS ICD in the LGF specification maintains interoperability among various manufacturers' equipment. Each parameter to be broadcast is described in detail and divided logically into message types. For PT 1, the essential messages are Type 1, Type 2, and Type 4. The Type 1 message, broadcast every 0·5 seconds, includes the pseudorange corrections, error estimates, and modified Z-count. The Type 2 message, broadcast every ten seconds, contains site-specific variables, such as local magnetic variation and vertical ellipsoid offset. However, critical in the Type 1 message is the number of measurements field. It informs the airborne user there has been an LGF alarm, and the system cannot be used. The Type 4 message contains specific information about the final approach path and will be broadcast every ten seconds.

The primary function for decision making within the LGF is in the Executive Monitor (EM). The EM determines when the system is in alarm or alert. An alarm indicates that the system should not be used for any level of service until all systems have been checked out and returned to a normal state. An alert indicates that there was a fault detected that could be isolated and still allow the system to remain in a normal state.

3. LAAS GROUND FACILITY PERFORMANCE.

The LAAS performance will be discussed in terms of required performance for the LGF RRs, and not the expected performance on the aircraft. Those allocations are presented in the RTCA LAAS MASPS and will not be repeated here.

3.1. *LGF Accuracy*.

The LGF correction accuracy, as presented in the MASPS, is defined by a family of curves that are modelled based on current and expected receiver and antenna technology, and the number of RRs. The analysis was done for Seattle, which is a relatively high latitude airport. Similar analyses at Chicago, New York, Dallas, Anchorage, and Miami produced comparable results.

The 'A' curves represent the lowest allowable accuracy performance. The LAAS MASPS assumes a correlator spacing of 0·2 chip and choke-ring antenna as the minimum technology employed to meet this performance. Based on long-term service availability analysis (Table F-1 LAAS MASPS), this configuration would give less than 95 percent availability for PT 1 with two RRs (based on Seattle). The FAA LAAS Requirements Document (RD) requires a minimum of 99·9 percent availability. This is necessary since one LGF provides service to an entire airport, which is not true for an ILS. With three or four RRs, 99·7 percent availability is possible at the PT 1 level. For PT 2 and 3, representing higher levels of approach capability, less than 72 percent availability would be possible.

The 'B' accuracy curves assume a correlator spacing of 0·1 chip and choke-ring antenna as the minimum technology employed to meet this performance. The 0·1 chip spacing provides sufficient improvement in performance over 0·2 chip spacing, so that 99 percent availability for PT 1 is achieved with two RRs (based on Seattle). Three RRs are needed to achieve 99·9 percent availability for PT 1, as required in the FAA LAAS RD. With three RRs, 98 percent availability is possible for PT 2 and PT 3. With four RRs, 99 percent availability is possible for PT 2 and PT 3.

The 'C' family of accuracy curves assumes a correlator spacing of 0·1 chip and a Multipath Limiting Antenna (MLA) in combination with a choke-ring antenna as the minimum technology employed to meet this performance. The MLA is specified for satellites below 35 degrees in elevation and the choke ring antenna covers 35 degrees to the zenith. In Level C, 99·9 percent availability for PT 1 is achievable with only two

RRs (based on Seattle). The best availability achievable for PT 3 (suitable for Category III service) is 99·8 percent. This indicates that either APLs or some other form of augmentation is needed to increase availability for PT 3.

To increase availability, the FAA is sponsoring research into a wide-band APL that has a duty cycle of 2 percent. This concept has gained some consensus within RTCA Working Group (WG) 4A, but conclusive flight tests have not been conducted. In addition, the type and number of RRs and respective antennas also limit availability. Extensive research has been focused on the design of advanced antenna technology. Several key aspects, which could affect availability, must still be considered. A short discussion of these aspects is presented here.

3.2. *Antenna Considerations Affecting Availability*. Curve C is easily distinguished from curves A and B by examining the performance below 10 degree elevation. The A and B curves both degrade considerably in performance, while the C curve demonstrates the ability of the MLA to limit this degradation. To date, the performance of the A and B curves have not been consistently demonstrated below 10 degrees[3] in such a way that the modelling of these curves has been validated. Conversely, there has been considerable research into the MLA to demonstrate that the performance in the model is achievable.[3–5] This is a key consideration since lack of performance at low-elevation angles will significantly reduce availability as fewer satellites are used in the position solution.

Two primary factors may cause degradation of the signals from satellites at elevation angles below 10 degrees. The first is the thermal noise. Thermal noise can significantly reduce the received signal level of low-elevation satellites and degrade accuracy. The choke-ring antenna, with reduced gain at low elevation angles, does not improve reception. The second factor is multipath ground reflections. Ground reflections can enter a sidelobe of the antenna at considerable strength. The direct signal enters the antenna through the main lobe, but at reduced power due to the pattern of the choke ring. Under these conditions, the direct to indirect signal ratio will approach 1.

The FAA LGF specification for PT 1 cites the B3 curve as the minimum accuracy performance. Difficulty in achieving the required performance at low elevation angles (below 10 degrees) with a modified choke antenna, may force manufacturers to look at technologies similar to the MLA. A high availability airport (99·99 or higher) will require the MLA, even for Category I.

3.3. *LGF Integrity*. A major role of the LGF is to detect rangeing source errors and RR errors that can corrupt the broadcast differential corrections. The LGF specification defines five failure classes that must be detected *prior* to the generation of a particular rangeing source correction:

(a) Signal deformation.
(b) RF interference.
(c) Rangeing source below specified signal levels.
(d) Code/carrier divergence.
(e) Excessive acceleration of code and carrier phases.

Signal deformation is a failure class that occurs when the correlation peak of a given rangeing source is non-symmetric. The magnitude of this failure is a function of the receiver correlator spacing. Therefore, the LGF must monitor each possible airborne receiver implementation where the correlator spacing is different than at the LGF. Because this monitoring is potentially complicated and costly, the FAA and RTCA SC-159 WG-4A are discussing acceptable constraints for the airborne receiver to provide for a limited set of correlator spacing to monitor, thus reducing complexity.

RF interference is an obvious threat to obtaining a usable rangeing source measurement. Because the satellite signal may begin to degrade before it is deemed unusable, the rangeing source must be flagged with an indication to the airborne receiver that the source is unusable. A satellite transmitting below specified levels of signal strength is also flagged.

If undetected, code/carrier divergence and excessive satellite clock acceleration rangeing source failures can result in large aircraft position error. While each failure class may appear similar to the airborne user, dissimilar tracking loops between the ground RRs and the airborne receiver can result in an error that is not easily correctable.

Six conditions must be *true for a pseudorange correction to be declared free of errors*:

1. Continuous lock has been maintained for 200 seconds on the rangeing signals used in determining the correction, or the filters are determined to have converged.
2. The magnitude of the associated estimated error on the correction does not exceed a predefined threshold.
3. The magnitude of the pseudorange correction does not exceed 327·67 metres.
4. Under fault-free conditions, the distribution of the broadcast correction error is overbounded for all values greater than or equal to $+/-$ 3 sigma by a Gaussian distribution function.
5. The cross correlation coefficient between any two RR measurement errors is kept small through proper siting and selection of antennas.
6. When there is a fault, the resulting error in the pseudorange correction is overbounded in the tails by a normal distribution.

When continuous lock is not maintained, the filter smoothing the raw pseudoranges must be reset. The time required for the filter to converge is twice the smoothing time constant of the specified filter ($2 * 100$ seconds). In condition 2, there is an estimate of the error on each pseudorange correction that is compared to a threshold on the ground before it is transmitted to the aircraft. The error estimate is used in an airborne algorithm to bound the vertical and lateral navigation sensor errors (NSEs). These bounds are compared to alert limits. Condition 3 requires that the broadcast correction also be compared against the allowed broadcast message length of 327·67 metres to ensure it can be properly encoded in the message stream or there is not a large satellite ephemeris error. Condition 4 requires that the broadcast correction exhibit characteristics consistent with the H_0 hypothesis described in the RTCA LAAS MASPS. Condition 5 ensures that the RRs are sited in such a way to prohibit common multipath sources from corrupting any two RRs in a similar way. Condition 6 requires that a fault in any single RR that corrupts the pseudorange correction must be covered under the H_1 hypothesis of a single RR fault.

To show that the LGF is meeting the requirement in 4–5 above, a Sigma/Mean Monitor will be employed at each ground station. Samples over the previous hours

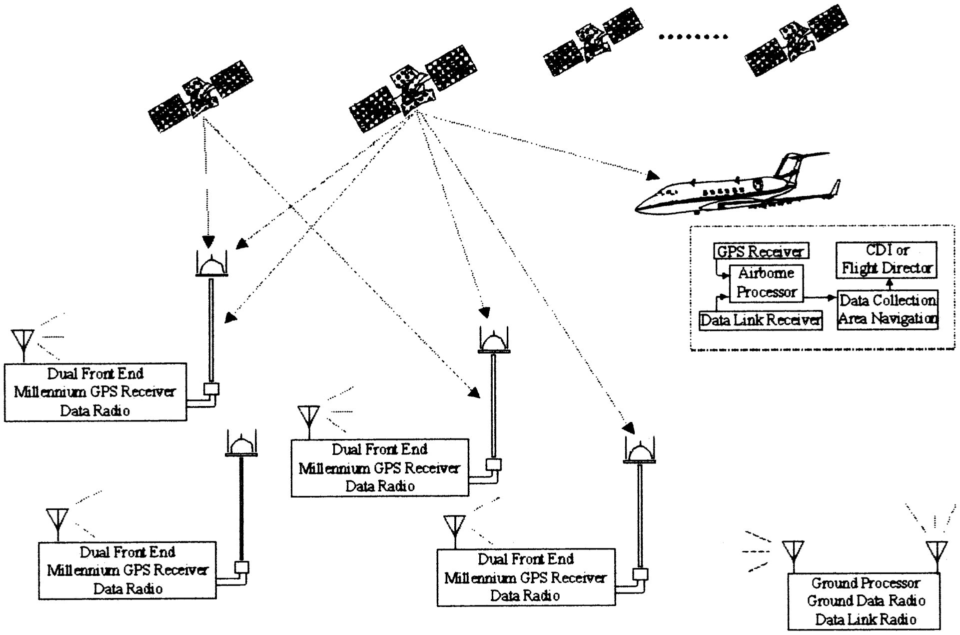

Figure 3. LTP System block diagram.

and days will be collected and analysed to determine if the condition in which statistical de-correlation between RR errors and the overbounding of the RMS continues to hold true.

4. LAAS TEST PROTOTYPE. The LAAS test prototype (LTP) was established in 1996, as a government-owned platform on which potential elements of the LAAS architecture could be integrated and evaluated.[5] The first full-scale testing of the LAAS architecture was completed in August 1997 at the FAA's William J. Hughes Technical Center (WJHTC) using a system designed and built by Ohio University (OU).[4,5] The testing proved the architecture was sound and could provide the required level of service in a test environment. The WJHTC personnel then reconfigured their existing LTP to include evolutionary changes implemented by OU, new receivers and antenna optimizations, and specific current specification requirements. Further modifications were made to increase the system's siting flexibility.

Philadelphia International Airport, Minneapolis/St. Paul International Airport, and Fairbanks International Airport were selected 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.

A series of flight tests was performed to validate concepts of the LAAS specification at the selected airports. These tests were intended to confirm that the LTP, a system representative of the current specification requirements, could achieve the intended performance and thus demonstrate specification validity. Data was also collected to support the development of LAAS siting criteria. A description of the tests and their results are presented later in the paper.

5. 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 PT 3 capability for Category III approaches, as defined in the LAAS RD. In addition to providing the LAAS service, the system also collected and stored all raw data for future analysis. All category systems can be analysed using subsets of the raw data. A separate Time Space Position Information (TSPI) truth system was used to measure the system accuracy.

5.1. *Ground Reference System.*

The ground system consisted of a processor, a data link, and four RRs, each having a GPS receiver and a specially designed antenna. The configuration is shown in Figure 3.

Each RR collects range measurements from all GPS standard positioning service (SPS) space vehicles (SVs) in view. Each measurement is sent to the ground processor, via wireless modem, where it is compared to the expected range that is based on the position of the SV and the precisely surveyed RR antenna location.

A preliminary range correction is calculated using the measurements from each RR, and a cross comparison between RRs is performed. This comparison, or Multiple Reference Consistency Check (MRCC) is a primary test statistic for ground system integrity. The comparison is quantified by calculating an error estimate, called a B-value, given by equation 1.

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

The average pseudorange correction for rangeing source n, $PR_{\mathrm{corr}}(n)$, is calculated using information from all available RRs. The average correction for the same rangeing source n is then calculated with RRm excluded. PR_{sca} is the smoothed and clock-adjusted pseudorange correction. The B-value, $B_{\mathrm{PR}}(n,m)$, is formed by subtracting the two averages, and represents the estimate of the error in the average correction for rangeing source n as contributed by RRm. The resulting value is compared to a pre-determined threshold. Individual range measurements are excluded from the final broadcast correction if their B-value exceeds the threshold. A further description of this LAAS integrity method can be found in Reference 2 and its citations.

Another key feature of the current LTP is the MLA. This antenna system, first described in 1994,[6] was reintroduced to the LAAS community by OU in 1996. The MLA is a two-component antenna system designed to receive GPS SPS SVs from all elevation angles between 5 and 90 degrees. The most critical component of the MLA is a dipole array that was used in the LTP 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 undesired multipath reflection to the desired direct 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 to decrease at 5 degrees, and is reduced by 35 dB at -5 degrees, providing a strong desired-to-undesired ratio. The goal of this antenna design was to limit pseudorange measurement errors caused by single reflection ground multipath at the ground station reference antennas to 0·3 metres (two sigma). In the LTP, coverage for SVs at elevation angles from 30 to 90 degrees was provided by a high-zenith array (HZA) which is physically mounted on top of the dipole array. The HZA provides a minimum of 20 dB of direct to indirect pattern isolation throughout its coverage volume.

The LTP employs dual 12-channel, ultra-narrow correlator, 0·05 chip correlator spacing, Novatel Millennium GPS receivers to accommodate the two-element MLA. At each RR, 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, thus eliminating potential clock errors between the antenna elements. A final calibration using an SV that is common to each MLA component is performed to remove remaining hardware biases.

The LTP as deployed for these tests transmitted pseudorange and carrier correction message Types 1 and 6 as defined in the current LAAS ICD.[7] The specified VDB radio was under development and not available for inclusion in the LTP at this time of these tests. A 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 1 Hz data rate. The end-to-end cyclic redundancy check was not transmitted and will be incorporated with the specified VDB.

5.2. *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 signals to the aircraft deviation indicators. 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 analysis.

5.3. *TSPI System.* The truth source was an Ashtech Z-XII TSPI system, which included both a ground and airborne GPS 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 carrier-phase data collected to provide precise GPS positioning between ground station and airborne receiver. With proper SV coverage, TSPI system accuracy is approximately 0·1 metres. Ashtech PRISM mission-planning software was run prior to the scheduling of the flight test approaches to ensure adequate GPS constellation availability.

6. FLIGHT TEST PROCEDURES.

The flight profiles for the subject flight tests consisted of multiple, straight-in, ILS-like, 3-degree approaches. The approaches began at approximately 10 nm from the runway threshold where a 3-degree glide path 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. Approaches were flown either manually or with the LTP guidance signal coupled to the flight director, at the discretion of the project pilot.

At each airport, the goal was to complete at least 40 approaches utilizing LTP guidance and 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 better to 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 WJHTC test team to overlay existing landing aids. This provided the aircraft test pilots with a cross-check of the LTP guidance, and for the collection of comparison data when possible.

7. EQUIPMENT SITING. The current specified requirement is that the RRs 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, each LTP installation was to have at least 100 metres separation between each RR antenna.

In addition to the LTP, a second GPS data collection system was installed at one RR 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 analyse the multipath environment more fully.

7.1. *Philadelphia.* The Philadelphia International Airport (PHL) is located along the Delaware River on relatively flat ground. It has three runways, two of which

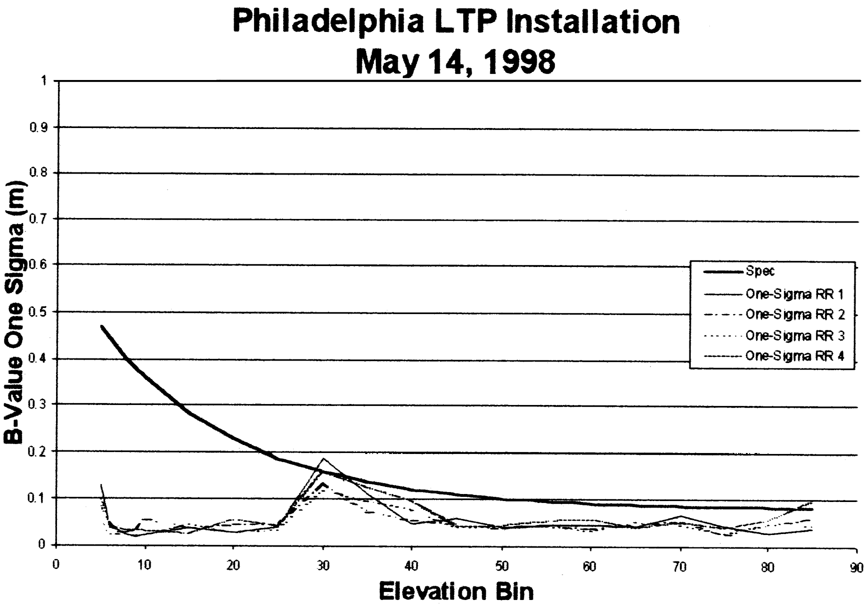

Figure 4. Philadelphia (PHL) reference receiver performance.

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 RRs were located in an open field adjacent to a lighting and power distribution centre just off the approach end of runway 9L. The two remaining RRs were located between a drainage pool and the taxiway for runway 9R. The two sets of RRs were approximately 400 metres apart.

PHL was selected since 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 eight 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.

7.2. *Minneapolis.* Minneapolis-St Paul was selected since it is a high-volume mid-continent airport serving as a hub for Northwest Airlines. Previous FAA flight test experience at the airport and cooperation with the air traffic personnel also influenced the selection. The airport is well developed with one large main terminal located between two parallel runways, 12L and 12R, and several large cargo hangars to the south.

The LTP was installed between the approach ends of runways 12L and 12R near 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.

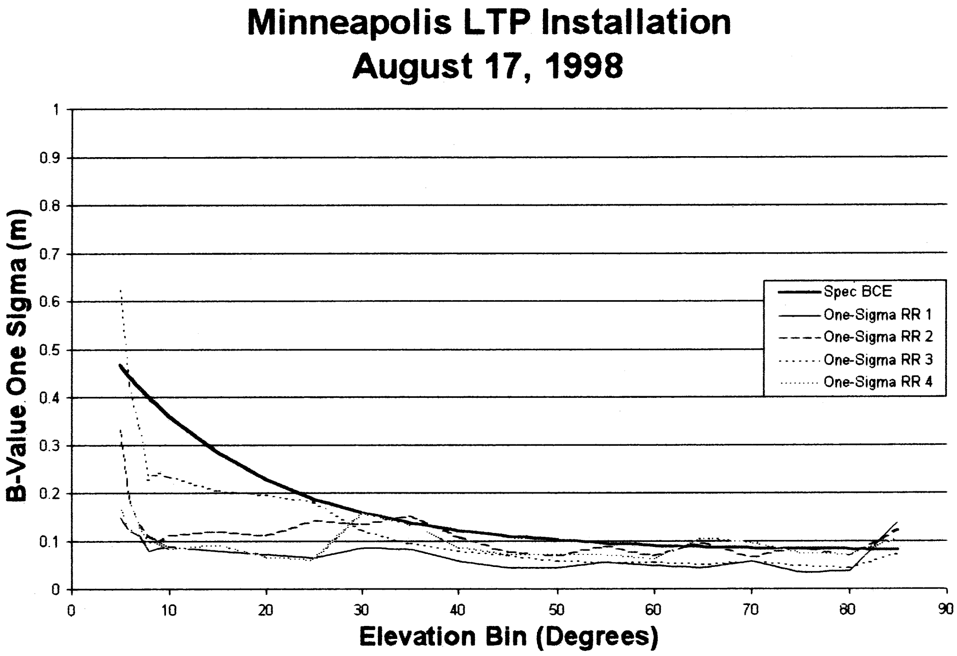

Figure 5. Minneapolis (MSP) reference receiver performance.

8. RESULTS.

8.1. *Multipath Limiting Antenna Performance.* Philadelphia was the first LTP test site. The performance accuracy of each RR is shown in Figure 4.

The dipole portion of the MLA, used for all elevation angles less than 30 degrees, provided measurements with considerable margin under the specified PT 1 RMS curve. The HZA, which provided the remaining coverage, did not meet the specified curve at the lowest portion of its coverage. This result was observed at all test locations and is the subject of further investigation. Alternate HZA elements are currently under development.

A non-optimal site was selected for the LTP installation in Minneapolis. Two RRs were located on open, clear ground. A third RR was located on top of a small hill. The fourth RR 'RR 3' was placed in the centre of a cluster of four 10-metre communications towers. It was expected that signal reflections from the towers would produce multipath that would not be attenuated by the pattern of the MLA and the resulting errors would pass into the system, and then be processed by the integrity function. The performance at this location is shown in Figure 5.

Figure 5 shows that RR3 did not meet the specified RMS performance of the LGF specification. It is important to note that the system only broadcasts corrections that have passed the integrity tests discussed earlier. Thus, during system operation, the integrity algorithm did at times exclude low elevation measurements from RR3 and prevented corruption of the actual broadcast corrections.

These results show that 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 for the B curve. The HZA portion of the MLA did not meet the not-to-exceed broadcast correction error requirements of the LGF specification

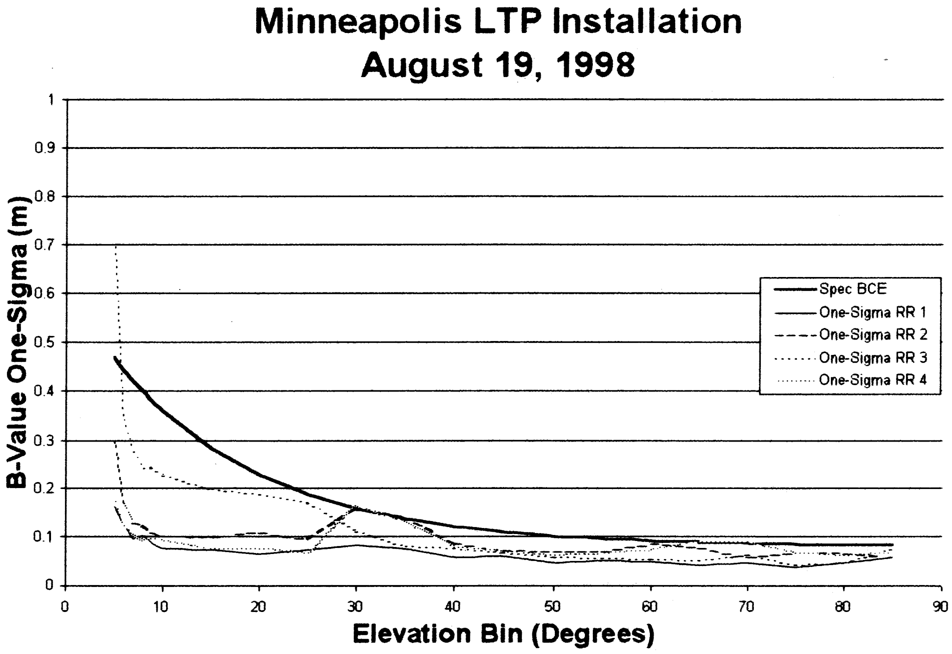

Figure 6. Minneapolis (MSP) reference receiver performance on second day.

in all cases. Resolution of the phase centre location and phase stability of the current HZA is required to characterize fully the element's performance.

The MLA antenna was shown to be very effective at mitigating the effects of 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 is within the specification requirements.

8.1. *Sigma/Mean Monitor Analysis.* The Sigma/Mean Monitor concept considers the variations in the hour-to-hour and day-to-day error statistics of each elevation bin. Variations are expected to be small, except in cases where the siting or measurements have been corrupted. The function is designed to detect significant variations of sigma, mean and correlation of errors from a site's established statistical performance. To explore this concept, measured B-values sigmas were compared on successive days. 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 6 as a demonstration of the repeatability of the measured sigma performance.

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

8.2. *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. This technique is described in Reference 8. A representative plot of the agreement between the two quantities for one SV is shown in Figure 7.

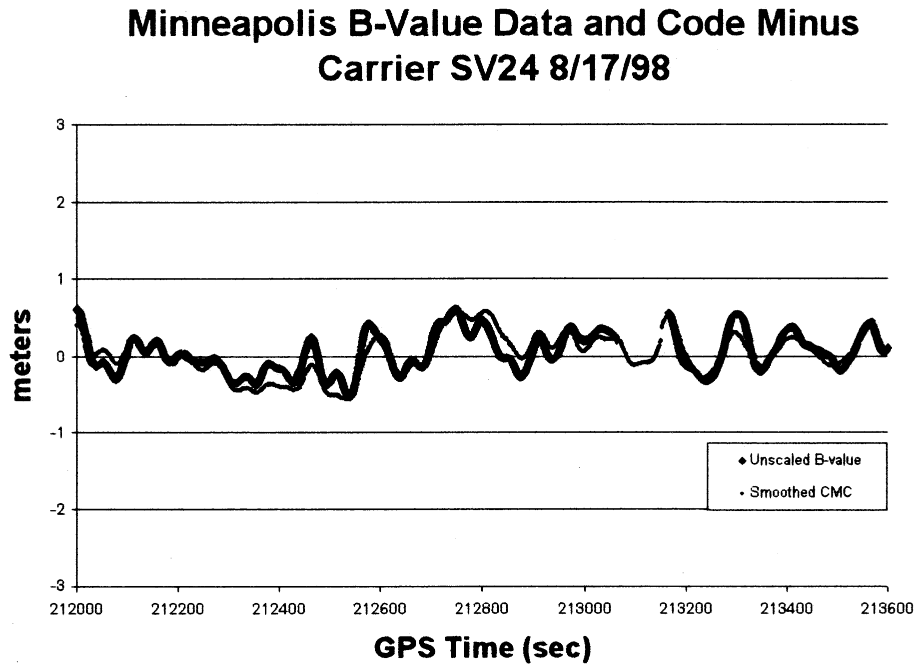

Figure 7. Minneapolis B-value data.

This example demonstrates that B-values agree with independent code-carrier results and, therefore, provide a proper representation of RR errors.

8.3. *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

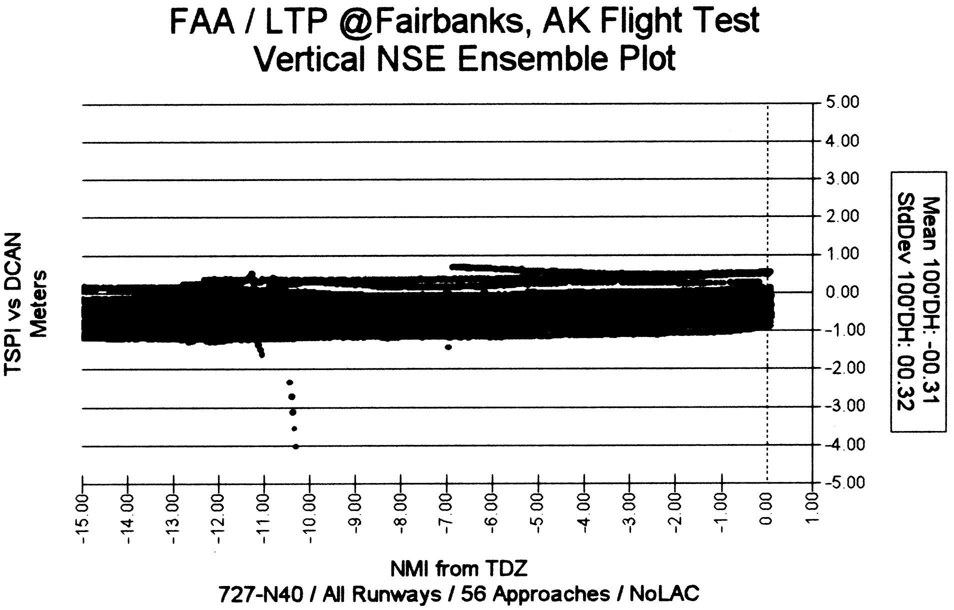

Figure 8. Philadelphia (PHL) Vertical Navigation Sensor Error (NSE).

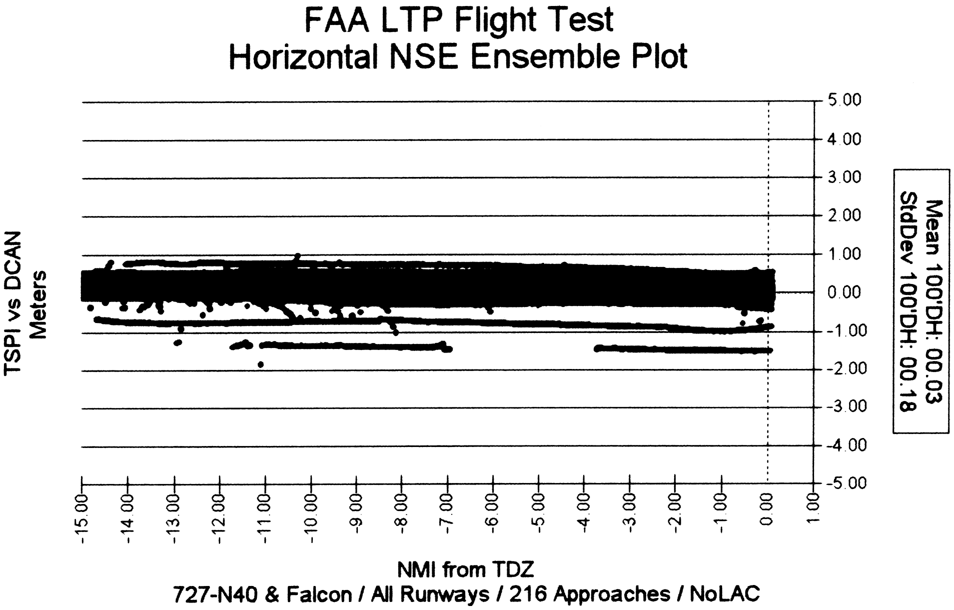

Figure 9. Navigation System Error (NSE) from all approaches.

position solution. An initial flight test at the WJHTC was used to verify the correct phase centre characteristic of the dipole and HZA elements of the MLA. This initial testing suggested the manufacturer's measurement of the HZA phase centre was incorrect. A surveyed location was used for that measurement during all LTP flight tests. The vertical navigation sensor error (NSE) flight test results from the PHL tests are shown in Figure 8.

This result suggested that the antenna parameters were correct, except for a slight vertical bias. This result, however, was not consistent with the results of the remaining airports, which each showed a negative vertical bias on the order of 0·3 metres. Final ensemble plots of the vertical and horizontal performance for all completed approaches are shown in Figures 9 and 10, including any observed bias.

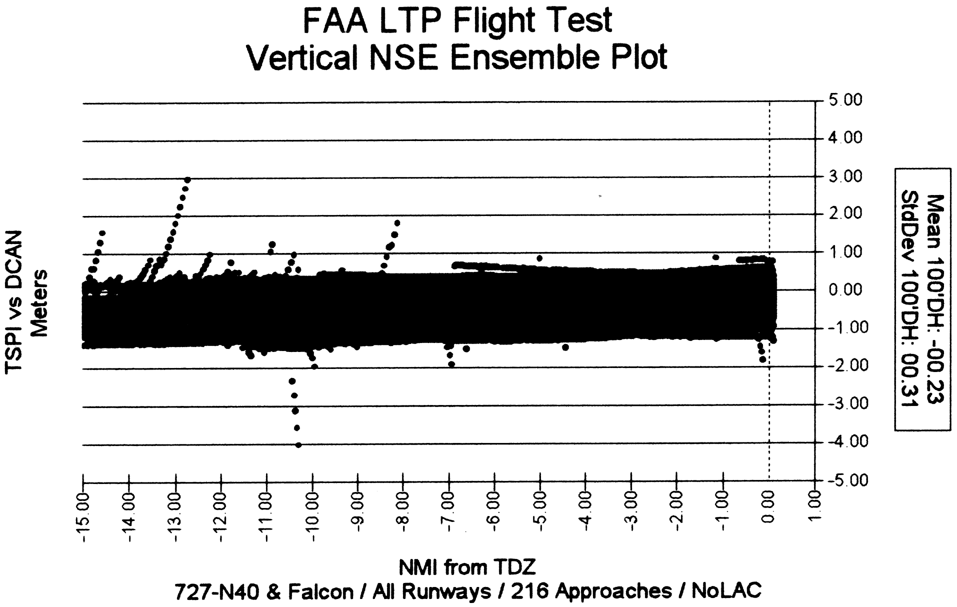

Figure 10. Vertical Navigation System Error (NSE) from all approaches.

The end-to-end flight test results demonstrated that the LTP provided accurate corrections to the airborne system. The measured 95 percent NSE results of 0·39 metre lateral and 0·85 metre vertical a the 100 ft decision height are well within PT 3 levels specified in the current LAAS RD. The observed bias contributed a significant portion of the total vertical NSE. The most probable cause is the uncertainty with the HZA phase-centre 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 several 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 a hardware or integrity failure. The system is currently installed and broadcasting prototype corrections at the WJHTC.

9. LAAS HISTORY AND STATUS. This section provides a short summary of the history of the LAAS program to document the 6-year effort that has resulted in a procurement program for installation in the National Airspace System (NAS). The history is followed by a summary of the status of the activities in RTCA and ICAO, and a description of a non-standard initial procurement program.

9.1. *LAAS History*. The impressive results achieved to date in LAAS technology, prototyping, and tests, have their roots in the extensive FAA-funded LAAS research program that began in 1992. The technical highlight of the program was the successful completion of the Category III landing feasibility flight tests in 1995.[9,10] These flight tests involved both industry and university-developed local area differential GPS (DGPS) systems. The completion of over 400 successful approaches indicated that a local area DGPS can provide the consistent performance to meet Category III accuracy and continuity requirements. Concurrently, industry was sponsoring its own trials and developing local area DGPS systems for Special Category I (SCAT-I) approaches. SCAT-I systems are developed for private use. Their requirements are contained in RTCA document DO-217, *Minimum Aviation System Performance Standards for DGNSS Instrument Approach System: Special Category I*. Although the requirements of DO-217 and the various approaches industry took to satisfy those requirements fell short of FAA-derived operational requirements, valuable lessons were learned. Moreover, the FAA approval process for DO-217-based equipment, although cumbersome and lengthy, was a valuable experience for FAA regulators. That process can be found in FAA Order 8400.11.

In February 1996, FAA management directed the LAAS program team to begin developing the specification for the LGF and work with RTCA to develop the Minimum Operational Performance Standards (MOPS) for the airborne segment, and complete both documents by the end of 1998. The US delegate to ICAO requested that they begin developing the Standards and Recommended Practices (SARPS) to ensure worldwide interoperability of Ground Based Augmentation Systems (GBAS). This was followed by formal presentation of the LAAS architecture to RTCA and ICAO.

In November 1996, the FAA LAAS Project Office met with RTCA, Inc. to present their objectives and concepts for the LAAS and to enlist support for the development of the MOPS. RTCA SC-159 WG 4A undertook the task, beginning with the development of the MASPS for LAAS. The MASPS developed the allocation of requirements between the ground facility and the aircraft receiver. In addition the LAAS ICD, detailing the signals, corrections, and other data transmitted to the aircraft by the ground system, was established. The LAAS MASPS and ICD were officially approved by RTCA on 28 September 1998. The RTCA MOPS for Category I is expected to be sent to ballot in February 1999, and the Category III MOPS is expected to be completed by the end of 1999. Following each MOPS approval, the FAA will use the MOPS to produce the appropriate Technical Standard Order (TSO) for airborne receiver requirements.

In 1997 the LAAS architecture was presented to ICAO. ICAO has been developing GBAS SARPS that will allow for the use of LAAS for CAT I by the international community. The Global Navigation Satellite System Panel (GNSSP) is presently planning on a full Panel meeting to approve the CAT I GBAS SARPS in April 1999.

The LGF specification work was started by the FAA, but it became clear that the ground facility manufacturers proposing systems should have greater involvement in the specification development process. As part of the GIP, the FAA is working together with participating manufacturers and also benefiting from an RTCA review of the specification. To date, this arrangement has proved valuable in identifying additional requirements and refined many of the concepts not initially considered in the MASPS and ICD. Furthermore, as the operational concept and maintenance requirements have matured they have also brought about necessary changes in the specification to comply with the operational use of LAAS in the NAS.

In January 1998, the FAA Joint Resources Council (JRC) approved LAAS for full-scale development (FSD) and acquisition. In approving the program, the JRC recognized the budget realities made it impossible to fund completely the initial equipment and operational implementation of LAAS. Therefore, they encouraged the use of the 'Other Transaction Authority (OTA)' as means for a GIP for the initial phase of LAAS. The OTA permits 'agreements' with industry that do not mandate strict reporting and oversight requirements of a formal contract, and involves a cost-sharing arrangement with the industry partners.

9.2. *Government Industry Partnership.* Through the GIP, the FAA obtains the benefit of its industry partners' developmental investment in SCAT-I and can incrementally develop an operational LAAS. Industry obtains the means for a more efficient approval process for their LAAS systems, thereby providing earlier marketing opportunities. The FAA will principally provide in-kind resources for technical oversight and operational approval of industry-developed fielded LAASs. Industry partners will build LAASs, install them at airports and in aircraft of their choosing, and test those installations.

The FAA is currently negotiating with two SCAT-I manufacturers. Each manufacturer's team is required to include a receiver manufacturer, airport authority and aircraft operator. The GIP agreements are expected to result in operational LAAS approvals for Category I installations by the summer of 2000. Subsequently, LAAS will undergo additional definition for Category III, with operational approvals expected two years later. Finally, with the success of Category III LAAS via the GIP, the FAA will be in the position to purchase, field, and approve LAAS for use throughout the US NAS.

The FAA intends to purchase and install 143 ground LAAS CAT I and CAT II/III systems. These systems are designated to replace existing CATII/III Instrument Landing Systems (ILSs), provide for newly qualified CAT II/III airports, and provide CAT I services at airports where availability requirements cannot be met with WAAS or the airport is outside the footprint of the WAAS satellites. The FAA intends to begin its purchase of LAAS ground systems in 2003.

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KEY WORDS

1. Air. 2. Electronics. 3. GNSS. 4. Augmentation.