Integration and Testing of a Wide-Band Airport Pseudolite

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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.

Mark R. Dickinson is a Senior Mathematician in the Navigation Branch of the William J. Hughes Technical Center. He has worked on the test and evaluation of satellite based communications and navigation systems since 1984. He is currently assigned to the LAAS program supporting development of the VDB, MLA antennas and Airport Pseudolite integration.

Don W. English has been involved with GPS development and testing for 15 years. Upon graduation from the University of Idaho in 1985, he went to work for Rockwell International as a member of the DoD GPS receiver development team. In 1990, Mr. English moved to San Diego to work for ARINC, Inc. While at ARINC has been involved in numerous GPS testing programs.

Jeffrey C. Liu has 20 years of experience in survey and geomatics engineering with over 12 years of direct GPS experience. Mr. Liu has masters in Geomatics and Survey Engineering from the Universities of Calgary and Tongji. Prior to joining ARINC earlier this year, Mr. Liu worked at Interstate Electronics Corporation on various GPS development projects.

ABSTRACT

The Federal Aviation Administration (FAA) baseline architecture for the Local Area Augmentation System (LAAS) includes Airport Pseudolites (APLs) as the preferred method for augmenting Differential Global Positioning System (DGPS) to achieve the availability required to support Category II/III operations.

The FAA utilized a Cooperative Agreement with the Air Transport Association (ATA) to procure and test a prototype APL system. The specification for procurement of the APL system was the most current design specification developed by RTCA working group 4A. Key parameters in the APL signal in space format were implemented to be variable in the prototype unit to allow refinement of the standards.

This paper first describes APL interference testing performed for the FAA by the ARINC SITE Laboratory. Tests were conducted on a selection of military and commercial GPS receivers. These interference tests explored the effects of the specified APL signal on the performance of standard GPS receivers. Additional tests were done while the APL parameters were varied over a wider range to allow flexibility during field tests. The interference tests concluded that the APL had minimal or no effect on the ability of GPS receivers to acquire and track the GPS satellite signal.

Upon completion of the interference testing, the APL system was integrated into the LAAS Test Prototype (LTP). The FAA William J. Hughes Technical Center (WJHTC) is the primary test location for FAA LAAS testing and home to the LTP. This paper describes the integration of the APL system into the LTP.

The paper provides initial results of a series of flight tests conducted using the LTP/APL system. United Parcel Service (UPS) provided a Boeing 767 to be used as a test vehicle that would represent a typical LAAS platform. A total of 39 precision approaches were conducted at the Atlantic City International Airport (ACY) using the LTP for guidance.

Initial results have shown that the specified APL signal format required some modification before the APL could provide sufficient average power to allow the tested GPS receivers to acquire and track the signal in space. The APL signal was received by the top mounted antenna of the Boeing 767, but the expected coverage range was about half of what was expected. The body of the aircraft

did at times prevent APL signal acquisition by blocking and attenuating the APL signal.

BACKGROUND

The FAA Joint Resource Council (JRC) has approved the full-scale development (FSD) of the Local Area Augmentation System as a replacement system for the current Instrument Landing Systems (ILS). The current limited budget precludes the classic approach to FSD. The FAA GPS Product team, AND-730, is currently tasked with directing the development of the standards for LAAS. Actual system development will be funded by industry in accordance with government standards through a Government/Industry Partnership (GIP) [1].

The FAA financially supports the approval process and also performs research and development to ensure the developed standards are valid. The FAA has also entered two GIPs that provide a channel for LAAS manufacturers to participate in standards development as well as to become familiar with the FAA LAAS approval process.

The WJHTC leads the LAAS Ground Facility (LGF) Performance Type 1 (PT 1) specification development effort. This specification, FAA-E-2937, was written with the participation of Raytheon and Honeywell through the GIP, and was baselined in September 1999. Concurrently, RTCA developed the LAAS PT 1 MOPS, which was sent out for ballot in September 1999.

Although LAAS will augment the Global Positioning System and provide all categories of precision approach capability for individual airports, current standards development to date has focused on LAAS PT 1 requirements to support Category I (CAT I) approach capability. The system architecture requires that all categories of LAAS equipment be compatible. Additional research is required to fully define the PT 3 requirements to support Category II/III operations. This will provide timely information to CAT I manufacturers to permit sound design decisions to facilitate compatibility with CAT III LAAS.

One major difference between PT 1 and PT 3 is system availability. Availability of the existing GPS constellation is insufficient to support CAT III operations. Airport Pseudolites are the preferred method for augmenting LAAS to achieve the required availability.

APL SYSTEM CONCEPT

An APL is a ground-based transmitter configured to emit in-band GPS-like signals. The reception and inclusion of an APL range in the user solution is intended to be as transparent as the use of additional satellites. To support this concept, information pertaining to the APL installed with a particular ground station will be included in the LAAS VHF data broadcast (VDB). When an aircraft penetrates the coverage volume of the LAAS VDB, it will receive the APL message type, defining the APL source ID. LAAS receivers capable of using the APL can then automatically assign the APL to an available channel and begin acquisition. LAAS receivers without APL capability will simply ignore the message.

As with all other LAAS equipment, the APL will be installed on airport property. At most airports, a single APL should sufficiently increase LAAS availability to the required level [2]. Although the LAAS PT 3 standards definition is just beginning, it is assumed that the maximum number of APLs required to support PT 3 on a given runway would be two [3]. Additional APLs, with a maximum of four APLs per airport, may be required to accommodate coverage restrictions.

APLs installed with an LGF will be positively monitored by each of the LGF ground station receivers. The APL will be treated exactly as an additional SV would in terms of integrity processing. Information on the health of the APL will be included in the APL VDB message. The LGF also provides a correction for each APL.

The APL signal-in-space (SIS) is being designed to support a 10 nmi operation range to a typical aircraft receiving the broadcast on a standard top-mounted GPS antenna. LAAS receivers should be capable of acquiring the APL in a standard GPS channel, without hardware modifications peculiar to the signal format. The airborne system is required to advise the pilot if the system does not meet the required level of performance based on actual signals received within 5 nmi. Therefore, the APL range information must be received and sufficiently smoothed by that point for inclusion in the LAAS solution.

INDUSTRY DEFINITION

RTCA Special Committee 159 Working Group 4 is currently tasked to develop LAAS criteria based on the FAA baseline architecture. A subgroup within this group was formed to develop a standard for the APL component of LAAS. The result of this work was a preliminary APL signal specification published in the current LAAS ICD, RTCA/DO-246. [4]. The goal of the working group was to define the ranging signal characteristics and signal data structure for the APL. This paper design could then be implemented and evaluated.

Several parameters were critical in defining the APL standard. A brief discussion of each parameter and the design decisions relating to that parameter are detailed below. A full discussion of the APL signal development can be found in [5].

The potential accuracy of the APL transmitted pseudorange was a primary design consideration. Previous testing had determined that ground reflections were difficult to suppress with C/A code APL systems [6]. Selecting a high chipping rate signal format for the APL broadcast mitigated this error source. The subgroup selected the existing wide-band P-Code modulation technique, as most existing GPS receivers are compatible with it. The wide-band code also allowed the signal to be spread across a wider spectrum and added to the interference margin. Therefore, a time-modified version of an existing PRN was selected, with 72 distinct increments identified for APL code definition.

Another critical requirement was that the APL broadcast not interfere with GPS Standard Positioning Service (SPS) signals. The challenge was that the APL power level at the maximum desired reception range must be at least as high as the satellite signal level. This would generate high power signal levels near the APL transmit antenna exceeding the dynamic range of current GPS receivers. The requirement that the APL be received and decoded in standard GPS hardware precluded an off L1 frequency selection. The design selected was similar to previous APL transmit solutions, to use a low duty cycle, pulsed signal [7]. The RTCA signal format defined a new pseudorandom transmission pattern that utilized very short duration pulses, with sufficient density to create a 2.7% duty cycle. The intent of the design was to create a signal with enough average power for a standard GPS receiver to track, while causing only a slight increase in receiver noise.

APL PROTOTYPE DESCRIPTION

The FAA utilized a cooperative agreement with the Air Transport Association to procure a prototype APL system. Two prototype APL transmitters and five APL capable receivers were delivered to the FAA in January 1999. IntegriNautics of Palo Alto, CA built the APL transmitters, model IN500A, which were used for all testing described in this paper.

The specification used for procurement of the APL system was the most current specification developed by RTCA. Key parameters in the signal in space format were required to be variable in the test prototype to allow necessary sensitivity analysis in interference testing, as well as variation in the broadcast parameters in response to test results. The APL transmitter is capable of broadcasting at any duty cycle from 0-100% and at peak power levels to +40 dBm. The unit can be set to broadcast in the specified RTCA pulse mode, in static and swept pulsing modes, in the previously tested RTCM pseudorandom mode, and a modified version of the RTCM mode which produces narrow pulsing similar to the RTCA mode.

Additional modes were added to the design specification to allow for repetition of previous FAA testing [8]. These modes included C/A broadcast capability and simultaneous C/A-wide-band broadcast. Further information on the APL transmitter can be found in [9].

Three dual front end, 24 channel, ground receivers and two 12 channel airborne receivers all capable of receiving the APL broadcast were delivered with the APL transmitters. The receivers were matched to transmitter specification and compatible with all transmitter modes. The receivers were built using a standard Trimble receiver module and loaded with custom designed software that would enable tracking of non-GPS PRNs. No specific APL hardware modifications were made to the basic module. The receivers operate using a 0.5 chip correlator spacing. The FAA LGF specification requires 0.1-chip correlator to comply with PT 1. While the receivers do not meet the current LGF specification, they are useful in determining the ranging capability of the APL.

APL INTERFERENCE TESTING

Both aviation and non-aviation GPS users not requiring or desiring the APL transmissions may be within the coverage area. In order to determine if the APL transmissions contributed only a small amount of noise to non-participating receivers, the effects of the APL broadcast on typical GPS equipment were characterized. The ARINC SITE Laboratory in San Diego executed a series of interference tests for the FAA to estimate APL interference characteristics on a suite of available civil and military receivers. The test receivers included: Rockwell MAGR – PPS Rockwell MAGR – SPS, Rockwell PLGR – PPS, Rockwell PLGR – SPS, Trimble TA-12, Rockwell Zodiac, Novatel 3951RM, Novatel Millenium, Garmin 155, Ashtech Z-XII, Canadian-Marconi Allstar, and Motorola Oncore.

The system used to execute these tests consisted of two GPS satellite simulators, the FAA prototype APLs, GPS receivers, ancillary support equipment, and personal computers. One GPS simulator provided both SPS and PPS signals for up to eight simulated SVs. The APL simulators were configured in accordance with RTCA/DO-246. The second GPS simulator was manipulated to provide an "APL-like" signal to provide additional APL emulation. APL power levels and duty cycles were manipulated to determine the effects on the GPS receivers under test. Each test included a control receiver and a receiver under test to verify baseline performance of each receiver type.

In each configuration, every attempt was made to ensure that the GPS and APL signals were subjected to common or comparable paths, and thus, the same amount of gain or attenuation. Therefore, the test signals presented to the receiver at the 'fictional' antenna output (pre-amplifier input) would be comparable to "live" signals. The GPS path losses to the test and control receiver were equalized via a manual variable attenuator. Since the test receiver experienced more loss due to the 3:1 combiner and additional cabling, the variable attenuator was set to a corresponding amount (5 dB) to insert additional loss in the control receiver's signal path. Thus, the observed signal levels were approximately the same, generally within +/- 0.5 dB.

Calibration of the various configurations was done with a spectrum analyzer prior to testing to account for cable and insertion losses. Output signal levels from the APL and satellite simulator were adjusted accordingly to account for the cumulative losses. A typical test configuration is shown in figure 1.

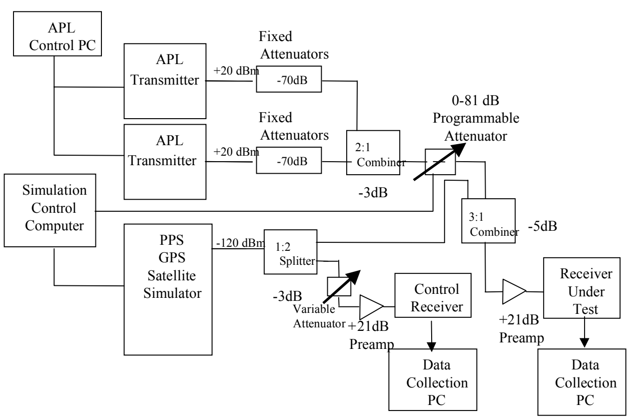

Figure 1. Dual APL Interference Test Setup

The interference tests were divided into four major test groups. Each test group is described below.

The Peak Power Test group was designed to determine the effect of APLs as a function of output power. This testing was accomplished by inserting a software controlled, variable attenuator on the APL's output. The input signal strength to the GPS receiver's pre-amplifier was then increased from –140 dBm to –65 dBm at a rate of 1 dB per 30 seconds. The testing was done with one and two APLs at the nominal RTCA output duty cycle of 2.733%.

The Duty Cycle Test group was designed to determine the effect of APLs as a function of their duty cycle. This testing was accomplished by manually setting the APL(s) duty cycle alternately to 1%, 2%, 4%, and 10%. The input signal strength to the GPS receiver's pre-amplifier was –70 dBm. The testing was done with one and two APLs.

The Acquisition /Reacquisition Test group was designed to determine the effect of APLs on the acquisition and reacquisition of GPS satellites. During these tests, a single APL was configured with signal strength (at the GPS receiver pre-amplifier input) of –70 dBm, and a duty cycle of 2.733%. During this testing, the initial acquisition of satellites was observed. Also, during this test, the GPS satellite simulator was used to turn satellites off and on to determine the reacquisition time of lost satellites.

The Dynamic Test group was designed to determine the effect of APLs on participant receivers in a realistic dynamic scenario. The dynamic scenario, as executed on the GPS Satellite simulator, emulated an aborted landing attempt and immediate re-routing to a nearby alternate airport. This scenario took the receiver from its starting point to one APL pair and then another. This testing was executed with a single APL, a pair of APLs, and two pair of APLs. Since ARINC had only one pair of APLs, the second APL pair was emulated by pulsing the output of a NorTel GPS satellite simulator. The APLs' were configured as per RTCA specifications, while signal strength control was accomplished via software controlled attenuators.

INTERFERENCE TEST RESULTS

The primary evaluation method for this testing was comparison of plots of the C/N_0 for the control receiver and receiver under test. Figure 2 and 3 show results from the Trimble TA-12 receiver.

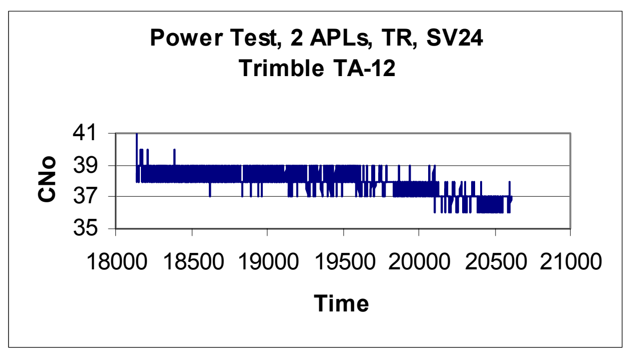

Figure 2. Dual APL Interference Result: Test Receiver

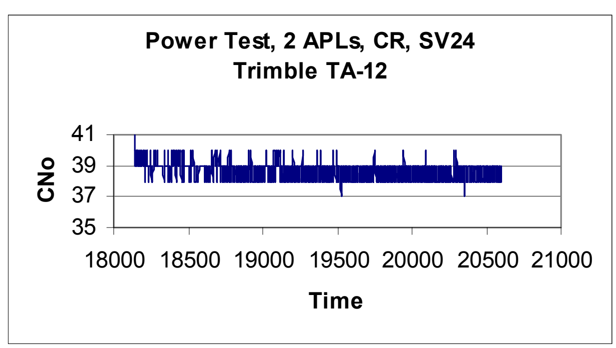

Figure 3. Dual APL Interference Result: Control Receiver

This receiver exhibited the greatest response to the APL broadcast in terms of reduction in C/N_0. The receiver subjected to the dual APL broadcast, shown in figure 2, reported a 1.5 dB less C/N_0 than the control receiver when the APLs were at full power. A more typical result is shown in figures 4 and 5, which show the results from the Novatel Dual L1 Beeline Millennium.

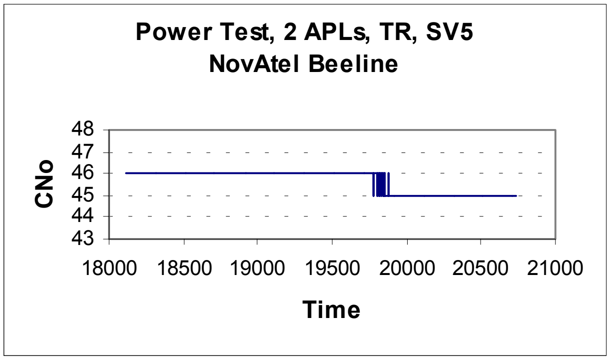

Figure 4. Dual APL Interference Test Receiver C/N_0

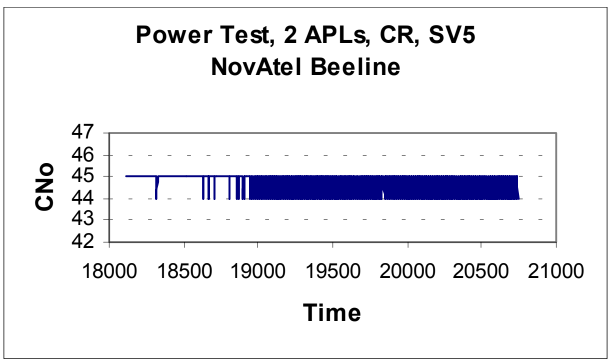

Figure 5. Dual APL Interference Control Receiver C/N_0

The Novatel Beeline receiver control receiver showed a slightly lower C/N_0 when compared to the receiver under test at the onset of the test when there was virtually no APL signal present. This small calibration error should be neglected. The C/N_0 of the receiver under test drops 1 dB when the APL signal reaches approximately –90 dBm. The control receiver reported C/N_0 is dropping in accordance with the simulated SV profile. Based on these simultaneous results, the total C/N_0 loss in the Novatel Beeline control receiver was just under 1 dB when subjected to the dual APL broadcast at maximum power.

A second evaluation parameter for the APL interference testing was measurement noise. Plots of receiver measurement noise were created and evaluated. The methods of estimating receiver measurement noise varied among the various receivers under test and are detailed in [10].

Figures 6 and 7 again show the Trimble TA-12 test and control receiver respectively. These figures show the collected pseudorange measurement noise as a function of time as the APL power is increased. This data in these figures was collected at the same time the C/N_0 data from figures 2 and 3.

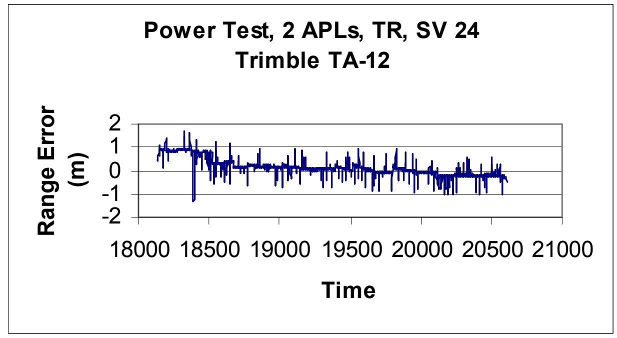

Figure 6. Dual APL Interference Test Receiver Noise

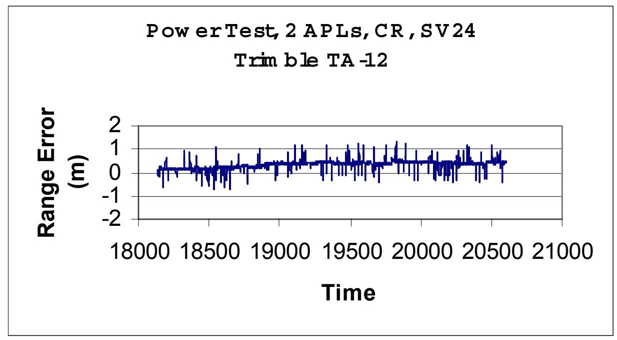

Figure 7. Dual APL Interference Control Receiver Noise

The data show little difference between the measurement noise of the test and control receiver. There is a difference in the measured bias between the test and control receiver, but it is within the expected test error and is considered insignificant.

Figures 8 and 9 show the Novatel Beeline test and control receiver respectively. These figures show the collected pseudorange measurement noise as a function of time as the APL power increased. Data in these figures were collected simultaneously with the C/N_0 data from figures 4 and 5.

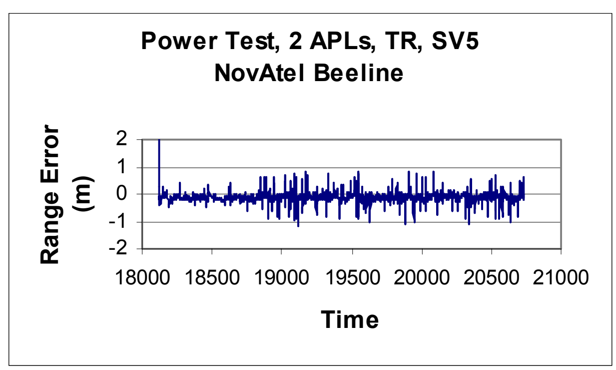

Figure 8. Dual APL Interference Test Receiver Noise

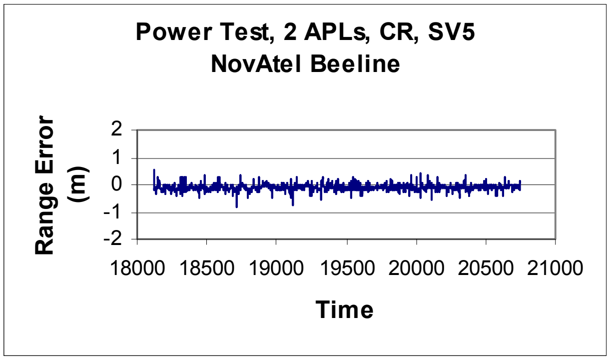

Figure 9. Dual APL Interference Control Receiver Noise

The measurement noise markedly increased as the APL power was increased above –100 dBm, as shown in figure 8, while the measurement noise of the control receiver remains constant. The noise remains constant for the remainder of the exercised power range of the APL, suggesting the test receiver increased its automatic gain control (AGC) in response to the APL broadcast.

The overall result of the APL interference tests was that the APL(s) had minimal or no effect on the ability of GPS receivers to acquire and track the GPS satellite signal, given the ranges of power and duty cycles tested. Several of the test receivers did report lower signal strength for GPS satellites during the APL peak power tests. Signal strength was reported by all tested GPS receivers as the ratio of signal to noise, C/N_0. Reduction in this ratio is not unexpected, as the APL signal should appear as noise to the non-participating receiver. The slight increase in measurement noise exhibited by some of the test receivers is still well within the bound of typical GPS receiver measurement noise and is considered insignificant

Test results were forwarded to FAA Spectrum Policy and Management, ASR-100, and the WJHTC was granted approval to transmit the APL SIS during coordinated test periods.

WIDE-BODY-FLIGHT TESTS

When initial results of the interference testing looked favorable, the FAA and ATA began seeking available test vehicles. Target aircraft were those which would be typical LAAS CAT III platforms. United Parcel Service (UPS) and Federal Express (FedEx) each agreed to provide revenue aircraft for short duration tests. A test schedule was drafted based on aircraft schedule. The overall objective of the wide-body testing would be to validate that APL could be included into the LAAS CAT II/III architecture.

An initial flight test period was scheduled for August 14-15 when UPS agreed to provide a Boeing 767. A second flight test period is scheduled for November 5-8, when FedEx agreed to provide an MD-10 aircraft undergoing certification.

The objective of the initial flight period with UPS was to demonstrate that the APL broadcast could be received and accurately tracked on a wide-body aircraft. A secondary objective was to demonstrate that the APL broadcast would not interfere with the operation of the LAAS. Final inclusion of the APL ranging signal in the real time solution would not be demonstrated in real time during the short duration flight tests, as the ranging characteristics of the APL had not been determined.

The initial phase of testing was conducted at the WJHTC using the LTP as the LAAS reference. The LTP system as deployed for the tests described in this report consisted of separate ground and airborne subsystems and was intended to provide CAT III approach capability. In addition to providing the LAAS service, the system also collected and stored all raw data for future simulation processing. The site was selected because it provided a known low interference environment with good SV geometry. Similar APL/LTP siting had also been used during previous FAA tests, and provided a baseline power budget.

The second series of flight tests to be conducted in November will be used to demonstrate real-time APL ranging at an operational airport. The collected data will also provide an additional data set on APL ranging performance in a second wide-body aircraft.

Ground Reference System

The ground system consisted of a ground processor, a data link, and three 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 10.

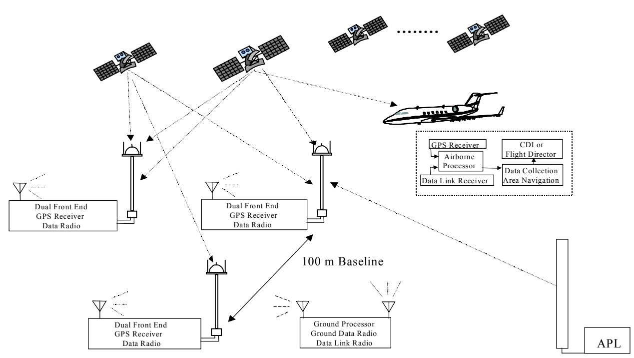

Figure 10 LTP System Block Diagram

Each reference station collects measurements from all GPS SPS SVs in view as well as the APL broadcast. 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 carrier smoothed, corrected for the known geometric range differences, and compared. 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.

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

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 the reference under test excluded. The b-value, $B_{pr}(n,m)$, is formed by subtracting the two averages, and represents the estimate of the bias in the measurement of the n^{th} ranging source as 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 or the APL 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 [11].

A key feature of the current LTP is the Multipath Limiting Antenna (MLA), first described in 1994 [12]. The MLA is a two-part antenna system designed to receive GPS SPS SVs from all elevation angles between 5 and 90 degrees. A detailed description of the MLA and its operation within the LTP, as well as the baseline performance of the LTP can be found in [13].

During the APL tests, the LTP used the dual 12 channel, 0.5 chip, correlator IntegriNautics GPS receivers to accommodate the two element MLA. At each reference station the high zenith array (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. Although the APL was received through both the HZA and the dipole elements of the MLA, the APL was not used for the hardware bias calibration.

Ground System Installation

The APL and LTP were located in an open area of the ACY airport as depicted in figure 11.

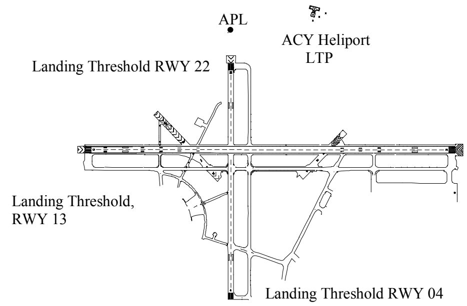

Figure 11. APL/LTP Installation at ACY

The APL transmit power was calculated using:

$$P_T = P_R - G_T + 20\log(4\pi d/\lambda) - G_A - G_P \quad \textbf{(2)}$$

where:
P_T = the required transmitter Power
P_R = the power required at the receiver input
G_T = the ground antenna gain at the approach angle
d = the required distance in nmi
λ = the wavelength in nmi
G_A = the aircraft antenna gain
G_P = the pulsing gain, $20\log_{10}$(Duty Cycle)

The transmitted power, +26 dBm, 400 mW, was adjusted for operation to 10 nmi, using a nominal aircraft antenna gain of –2 dB in the direction of the APL. The APL signal was transmitted using an existing precision distance measuring equipment (DME/P) antenna that had been used in previous testing. The expected combination pattern loss and frequency mismatch in the DME/P antenna was –12 dB.

The APL siting, with the transmitter installed near the landing threshold of RWY 22, allowed several approaches of interest with respect to the APL. Runway 13, the primary test runway, allowed approaches with an offset APL reference, which provided rapid geometry changes during the final segment of the approach. RWY 04 allowed approaches with the APL reference directly ahead of the final approach. RWY 22 provided similar approach criteria to RWY 04, but also provided an overflight of the APL transmitter.

Ground Integration Results

When the APL was initially powered up for ground system checkout, it was found that the reference receivers at the LTP ground station required several hundred seconds to acquire and track the APL signal. This result was not consistent with observed laboratory performance with similar power and duty cycle setting. It was determined that the ground station receivers were calculating C/N_0 values which were lower than the minimum required by the receiver to determine that the signal was valid. The discrepancy with the laboratory result was a result of increased noise. The pulse duty cycle was adjusted from the specified 2.7% to 5.4%, or to the interference equivalent of two APL transmitters, compensate for the reduced signal ratio. This value was supported by the dual APL interference tests, and also provided tracking margin at the reference antennas.

A final coding error in one of the ground station receivers prevented that receiver from acquiring the wide-band code. The error was not detected until the ground system checks on the first day of testing. This limited the number of ground reference measurements for the APL to two.

APL Ranging Error PRE_{G_APL} was calculated using equation 3 below as an initial check on the received APL range.

$$PRE_{G\_APL} = PR_{ref} - TD_{ref\_to\_APL} - C_{bias\_ref} \quad (3)$$

The true distance from the reference to the APL $TD_{ref\_to\_APL}$ was calculated using the known survey locations. Receiver clock bias, C_{bias_ref}, was calculated for each reference antenna without the APL included, precluding any potential APL bias from skewing the result.

The APL measurements were passed directly into the LTP SV processing routines. B-values, which are intended to represent the uncorrectable errors at each reference, were calculated for the APL. A sample of observed b-value data from the ground station during the wide-body flight tests is shown in figure 12.

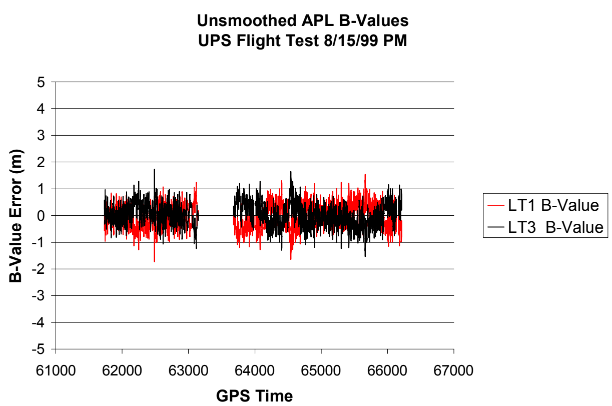

Figure 12. Observed APL B-value Performance

This particular data set was selected because it spans several over-flights of the APL by the test aircraft as well as a complete system reset and reacquisition. The data shows that the APL ranges received at each LTP reference antenna did not contain reference dependent errors. Errors of this type, such as standing multipath caused by the fixed APL/LTP geometry, or power related biases were shown to have caused errors in previously conducted tests and would cause the b-values to diverge.

Airborne System

The airborne system consisted of a 12 channel, 0.5 chip, APL capable receiver, 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 and the APL 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 provided ILS-like deviations to the aircraft flight instrumentation system. The DCAN also performed accurate time tagging and recording of the aircraft body state data from the inertial reference unit.

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 (ILS-VOR band). This VDB radio was under development and was not available for inclusion in LTP at the time of these tests. A commercially available data transceiver was utilized during these tests.

The truth source was an Ashtech Z-XII Time Space Position Information (TSPI) system, which consisted of ground and airborne receivers. The ground station receiver was installed at a surveyed location. The airborne receiver was mounted in the FAA equipment rack and connected to the test GPS antenna using a splitter. Based on the SV coverage during the flight tests, the TSPI system accuracy was approximately 0.1 m.

Airborne Installation

GPS and APL pseudorange were received using a standard top-mounted antenna located at aircraft station 600, as shown in figure 13.

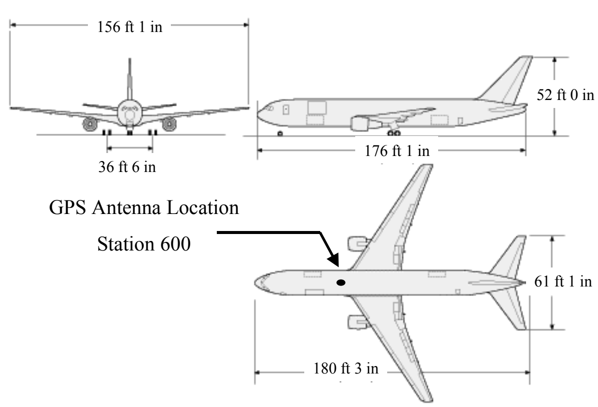

Figure 13. Aircraft Dimensions and Antenna Locations

The APL receiver used during the flight tests was equipped with two independent RF front ends, each with different input bandwidths. The bandwidth on the first input was set based on the GPS SPS bandwidth. The bandwidth on the second input was set based on the wide-band signal. The signal from the test antenna was split and fed into both receiver inputs to allow simultaneous evaluation.

Flight Test Profiles

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 pilot.

Flight Test Results – APL Tracking

A total of 39 approaches were completed by the UPS Boeing 767 at the ACY airport during the APL tests. Table 1 summarizes the number of runs completed to each runway end and the ranges at which the signal was tracked.

Runway	Number of Approaches	Acquisition Range (nmi)		
		Maximum	Minimum	Average
RWY 04	11	11.1	3.3	5.5
RWY 13	23	14.8	4.2	7.6
RWY 22	5	12.3	4.5	6.7

Table 1. APL Tracking Range

The Boeing 767 pitch attitude on the downwind and base approach legs during the flight profiles was fairly constant at 5-6° positive pitch. This orients the GPS antenna toward the APL as the aircraft flew away from the transmitter. The receiver was able to maintain lock on the APL during these procedures, at times up to 18 nmi from the transmitter. In these cases the aircraft antenna gain in the direction of the APL was close to the budgeted –2 dB. As the aircraft turned to the final approach course toward the APL, the 767 pitch remained at 5-6° positive pitch, but the angle with respect to the APL changed from positive to negative. At these times, the expected antenna gain, based on the typical patterns, could be as low as –20 dB. During 17 of the completed approaches, the APL receivers were able to maintain lock on the signal until the procedure was completed. During 8 of the remaining 22 approaches, the receivers did not acquire the APL until the aircraft was established on final approach and the aircraft pitch attitude dropped to nominally 0-1°, where the airborne antenna had a clear line of sight toward the transmitter.

APL Ranging Error, PRE_{APL}, was calculated using equation 4 below:

$$PRE_{APL} = PR_{user} - TD_{user\ to\ APL} - C_{bias\_air} - PRC_{APL} \quad (4)$$

The aircraft true distance, $TD_{user\ to\ APL}$, was calculated using the Ashtech Z-XII Time Space Position Information (TSPI) system truth position and the known location of the APL transmitter. The applied APL pseudorange correction, PRC_{APL}, was the correction that was calculated and broadcast along with the SV corrections in the data link message.

Airborne receiver clock bias, C_{bias_air}, was calculated along with the position solution. This clock bias, intended to represent only the receiver oscillator drift estimate and a fixed delay, was found to contain a rate term that corresponded to the aircraft vertical velocity. This effect was ultimately traced to a drift estimate calculated by the receiver and used to correct the raw pseudorange and carrier phase measurements. Modifications to the LTP airborne software to re-calculate and apply a corrected drift estimate for all completed procedures were not completed at the time of this writing. A representative plot of raw APL pseudorange error using a corrected clock bias term, as well as the aircraft pitch and roll, is shown in figure 14.

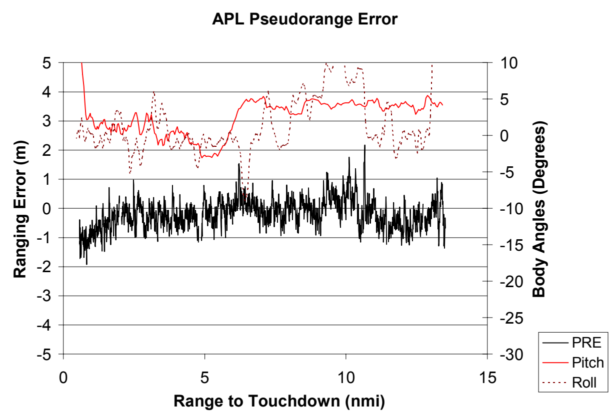

Figure 14. APL Pseudorange Error

The figure shows that APL ranging error not does not appear to strongly correlate with the aircraft pitch attitude. Data from this typical approach shows that the raw pseudorange error increased with aircraft roll, but these errors are of brief duration and would be effectively eliminated with carrier smoothing.

Vertical and Cross-Track Navigation Sensor Errors (NSE) were used to evaluate 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). 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. Figure 15 provides a ensemble plot of the post-processed Horizontal NSE of the APL included solution.

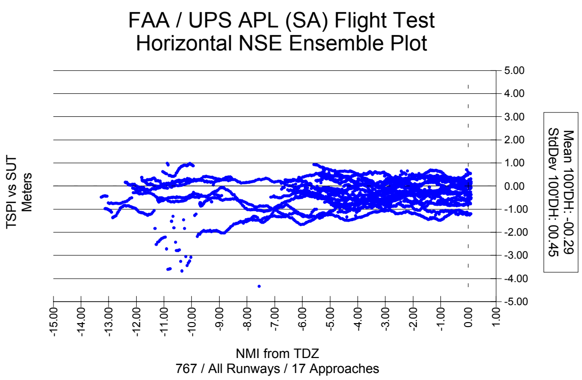

Figure 15. LTP/APL Horizontal NSE

CONCLUSIONS

The wide-band APL prototype, when operated within the parameters selected for the interference testing, has minimal or no effect on GPS reception and tracking. Additional changes in the APL SIS, if required, will necessitate additional interference testing.

The received APL ranges can be processed as GPS SPS SVs in the current LAAS test prototype ground facility. The LTP reference receivers were able to accurately track the transmitted APL SIS. The range comparisons, or MRCC, utilizing calculated b-values, were applied to the APL range using the same thresholds as the live SVs and did not cause exclusion of the APL range.

Airborne reception of the APL signal via a standard top-mounted antenna was demonstrated. Initial analysis shows a correlation between APL signal acquisition and tracking, but not with pseudorange error. The operational range was over 5 nmi on most approaches, but several approaches fell short of this range. Modifications to the APL SIS or APL receiver tracking parameters are required to provide for effective ranging.

The final APL ranging accuracy analysis will be completed when a new algorithm to compute an accurate receiver drift is completed. This algorithm is being completed as part of the real-time LTP/APL system integration to be tested during the next APL flight test period scheduled with FedEx in November of this year.

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