LORAN PERFORMANCE IN A GPS NON-PRECISION APPROACH ENVIRONMENT

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BIOGRAPHY

Dave Diggle is the Associate Director Emeritus of the Avionics Engineering Center at Ohio University in Athens, Ohio. In addition to his former duties as Associate Director, he lead the LORAN Support Team at the Avionics Engineering Center. Dave is a member of the Institute of Navigation (ION) and the International LORAN Association (ILA), and has received the RTCA's William C. Jackson Award for outstanding contributions in the field of avionics. He received his Ph.D. in Electrical Engineering from Ohio University and holds a private pilot certificate.

Chris Bartone is an Associate Professor at Ohio University with over 25 years of professional experience in communications, navigation, and surveillance (CNS) systems. He received his Ph.D. in EE from Ohio University in 1998, an MSEE from the Naval Postgraduate School in 1987, and a BSEE from The Pennsylvania State University in 1983. He previously worked for the Naval Air Warfare Center, performing RDT&E on CNS systems. Chris received the RTCA William E. Jackson Award in 1998 for his outstanding contribution to aviation in the area of DGPS. At Ohio University, Dr. Bartone has developed and teaches a number of GPS, radar, wave propagation, and antenna classes. His research concentrates on all aspects of CNS systems. He is a senior member of the IEEE, and a member of the ION and ILA. He is Chair of the ION Outreach Committee and Editor of the ION Virtual Navigation Museum. Chris is a licensed professional engineer in the state of Ohio.

Mitch Narins is the Chief Systems Engineer with the FAA's Navigation Services Group. He leads the FAA/USCG/Academic/Industry Team evaluating whether the LORAN C system can provide benefits for the aviation, maritime, and timing and frequency communities. Mr. Narins has held a number of program-manager and lead-engineer positions at the Naval Electronic Systems Command and at the Federal Communications Commission. He holds a Bachelor of Engineering (BE) degree from the City College of New York and a Masters of Engineering Administration/Management degree from the George Washington University.

ABSTRACT

The U.S. Federal Aviation Administration (FAA) has been investigating the capability of LORAN C (and soon to be eLORAN) to meet Required Navigation Performance (RNP) 0.3 requirements for accuracy, availability, integrity, and continuity. This level of accuracy is paramount if LORAN is to be used for GPS non-precision approach procedures, especially in light of the fact that eLORAN has been designated as the official backup for GPS in the United States.

The Avionics Engineering Center (AEC) at Ohio University has been collecting LORAN C data for the past five years at one airport situated in the United States' Midwest and at five airports located along the U.S. East Coast. To achieve RNP 0.3 accuracy levels in an airport terminal area, where approach procedures are flown, requires the use of locally measured and/or calculated LORAN C Additional Secondary Factors (ASFs). Flights to the six airports have been conducted semiannually (late winter and late summer) in an effort to determine and characterize the behavior of ASFs as a function of seasonal variations and to determine if a single set of ASFs can cover the entire terminal area for an airport.

This paper will present flight-test results showing LORAN accuracy performance during the execution of published GPS approach procedures. LORAN navigation data is adjusted using local ASF values for each airport and the procedures are hand flown with a Beechcraft King Air (C90) using a GNS-480 IFR-certified receiver for aircraft navigation. The paper will document available cross-track and along-track accuracies (LORAN versus GPS truth) as a function of altitude in the terminal area for each of the airports while flying representative GPS non-precision approach procedures. In addition, information on eLORAN and ASFs, as well as background on GPS non-precision approach procedures, will be included in the interest of completeness.

LORAN OVERVIEW

The LORAN-C (LOng RAnge Navigation) System is a hyperbolic radio-navigation system with precise time and frequency capability. The system is organized by chains consisting of a master and up to five secondary stations. The time difference (TD) measured by a user between the time-of-arrival of the master and two secondary transmissions yields the user's position.

Over the past 10 years, the U.S. Congress has appropriated $160 million to modernize the LORAN system infrastructure and funded research concerning the applicability of the system for land, maritime, aviation, and timing users [1]. All continental U.S. LORAN and northeast Canadian stations now have solid-state transmitters; U.S. stations have new timing and frequency equipment and electrical power backup using uninterruptible power supplies (UPSs) and local power generation equipment. Research, past and present, continues to support the premise that LORAN can provide valuable positioning, navigation, and timing (PNT) services to all users and function as a viable backup for GPS. Response to a January 2007 request for comment issued by the US Department of Transportation resulted in over 1000 responses, the vast majority of which supported the continuation of LORAN PNT services. **Figure 1** shows the current state of the North American LORAN System modernization [11].

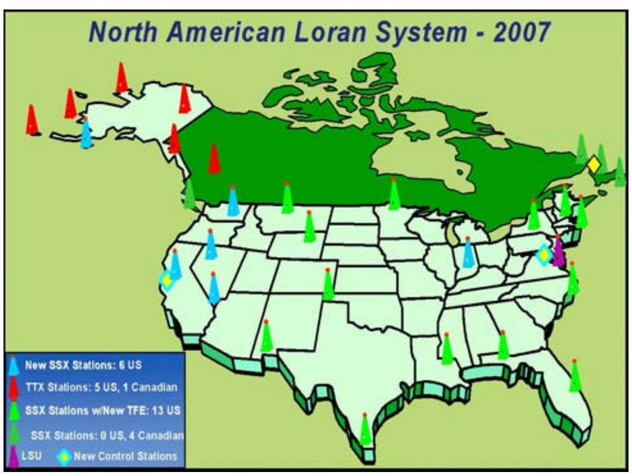

Figure 1

On the horizon is an enhanced LORAN System known as eLORAN [2]. Conceptually, eLORAN will incorporate a data channel for transmission of system (navigation) information, all LORAN transmitters will be synchronized to UTC, and user equipment will include *all-in-view* receivers.

Attributes of eLORAN include:

- 8-10 meters for harbor entrance/harbor approach,
- 0.3 nmi (307 m cross track) for non-precision approach (supports RNP 0.3 requirement),
- availability -- 0.999-0.9999,
- integrity -- $1x10^{-7}$ per hour
- continuity -- 0.999-0.9999 (150 sec approach),
- timing -- 50 ns recovery of UTC, and
- frequency -- Stratum 1 ($1x10^{-11}$).

LORAN C SIGNAL PROPAGATION

The LORAN C signal at 100 kHz propagates both as a ground wave and a sky wave but only the former is used for navigation since the latter can be a source of problems. Precise calculation of a user's position using LORAN C is accomplished through the use of a series of ground-based transmitters and knowledge of their precise location and the timing relationships among the signals which are transmitted from each. Consequently, it is extremely important that one has accurate knowledge of the speed at which the LORAN C signal propagates through the atmosphere between the transmitter and the user. Furthermore, the conductivity and permitivity of the medium over which the signal travels have an additional impact on the speed of propagation. For ship-borne users in an off-shore environment, the calculations for speed of signal propagation are reasonably straightforward; however, for a land-based user or an aircraft overflying terrain, the problem of determining the speed of propagation becomes more difficult. In the former situation, a seawater path between the user and the transmitters represents a homogeneous and predictable medium; but, in the latter case, terrain between the user and the transmitters as well as varying soil moisture content and temperature provide a far less homogeneous medium.

Calculation of the speed of propagation is broken down into three components, called phase factors, to account for the effects of the atmosphere as well as the medium underlying the propagation path. These phase factors are referred to as the Primary Factor (PF), the Secondary Factor (SF), and the Additional Secondary Factor (ASF). The reader is referred to Reference 3 for a detailed description of the phase factor parameters.

ASF CALCULATION

Millington's method [3, Appendix F] is the method generally applied to calculate ASFs. Overall, the method is straightforward, but to produce meaningful ASF values at a particular geographic point, or over a defined area surrounding such a point, becomes computationally intensive. Recent work in this field has been done by the University of Wales, Bangor, UK and Illgen Simulation Technologies, Goleta, CA. Software completed under contract to the FAA by the University of Wales forms the basis for the current LORAN Propagation Model (LPM) in development at Ohio University [12]. The LPM code, now being validated, should be capable of generating ASF values for all locations at or around a specific point of interest, e.g., an airfield.

On-site calculation of ASFs using a LORAN C receiver at the point of interest is the option which has been used exclusively over the past three and one-half years to compile the ASF databases used for this research. This method, too, presents some problems in that the data that are measured at the location of interest contain a number of unknown factors along with the desired ASF data. These factors include: LORAN C transmitter timing offset from UTC, processing delays within the LORAN C receiver/antenna system, and the receiver clock offset (bias). The ground system used to produce the ASFs in this study was built by Locus, Inc. of Madison, WI and was the subject of a paper presented at ION GPS 2004 [4].

The system consists of two LORAN C SatMate 1030 receivers, one connected to an E-field LORAN antenna, the other to an H-field antenna. A NovAtel OEM-4 GPS WAAS receiver and an accompanying airborne GPS antenna are used to provide truth reference information. Ground data from the three receivers are collected for approximately one hour at a suitable location–a series of airfields for the purposes of this paper. The LORAN C receivers are operated in a TOA rather than a TD mode and the processed data yields a "quasi-ASF" for each LORAN C transmitter in range, within the bounds of the GPS receiver accuracy and the unknown factors previously listed. Each TOA is represented as follows:

$$TOA_{GRI}^{N} = PF * d + SF(d) + ASF_{GRI}^{N} + UTC_{off} + \tau_R + \tau_B \quad (1)$$

where: N denotes master or one of the associated secondary transmitters
GRI is the LORAN C chain of interest
d is the known distance between the reference site and transmitter of interest
ASF is the unknown additional secondary factor
UTC_{off} is the unknown offset from UTC of the transmitter
τ_R is the unknown processing delay of the receiver/antenna system
τ_B is the receiver clock bias term

In the eventual world of eLORAN, the offset from UTC will either be eliminated or, as with GPS, UTC offset information will be a part of a navigation message. For the present, the well known stability of the LORAN C system will be relied upon and it will be assumed that the master and associated secondary transmitters remain *well behaved* over time. In the TOA mode, the frequency of the internal clock in the LORAN C receiver is locked to a composite frequency of all the stations being tracked, weighted according to various criteria such as distance and/or signal strength. In this manner, the receiver clock is stabilized by virtue of the fact that the overall LORAN C system attempts to maintain a *close* relationship to UTC. In addition, τ_B can be removed since it is a term common to all the TOAs. The "quasi-ASF" which results can be represented as follows:

$$ASF^{*N}_{GRI} = ASF_{GRI}^{N} + UTC_{off} + \tau_R \quad (2)$$

Eventually, the ASF* will converge to a true ASF when the LORAN C system is moved to a system where all transmitters are synchronized to UTC (currently underway) and each manufacturer of LORAN receivers characterizes their respective receiving systems and thus defines τ_R. In this research, the receiver used aboard the aircraft during flight testing is a SatMate 1030; thus, the LORAN C airborne TOAs which are processed include a nearly identical delay as the ground system except for a slight difference in antenna cable length. For the time being, then, errors associated with these two elements of equation (2) are considered to be small with respect to the actual ASF values. Thus the ASF, and ASF* values which are generated by the Locus ASF measurement system, while not identical, are extremely close in value.

REQUIRED NAVIGATION PERFORMANCE [5]

The term Required Navigation Performance (RNP) generally includes the term Area Navigation or RNAV because the RNP concept is essentially a complete statement of the navigation performance for operations within a defined airspace. Consequently, included in the RNP RNAV concept is not only the necessary accuracy, but the integrity, availability, and continuity-of-service required in a particular flight regime under consideration [5]. In the case of non-precision approach, and flight operations within the terminal area, the accuracy requirement for LORAN C would be RNP (0.3) RNAV which then places LORAN C in the same category as a standalone GPS non-precision approach.

Under the conditions of RNP (0.3) RNAV, the maximum cross-track error is ±0.3 nmi, or ±1820 ft, either side of the desired flight track. This specification is for total system error (TSE), at the 95% level, over the duration of the phase of flight, which in this case would be the time required for an aircraft to fly between the final approach fix (FAF) and the missed approach point (MAP) of the approach procedure. Clearly, the duration of flight for different aircraft and different approach procedures will vary and at some point in time must be defined for LORAN C non-precision approach.

Another condition inherent with RNP (0.3) RNAV is the overall containment of the cross-track error. Under the RNP RNAV definition, this value is twice the RNP accuracy or 0.6 nmi either side of the desired flight track. In this instance, the probability that the TSE of the aircraft exceeds this value is specified with a probability of missed detection at or less than 10^{-5} during the duration of flight. **Figure 2** illustrates the various constraints on accuracy and containment. Not illustrated is the along-track error which is also required to be within 0.3 nmi at the 95% level.

For the purposes of this paper, consideration will be given to the accuracy achievable for the LORAN C cross-track and along-track error. Further, only the portion of TSE attributable to the navigation sensor error (NSE) is available to be presented. NSE is derived using the difference between the LORAN C SatMate 1030 receiver position (corrected in real time using locally measured ASF* data) and that of a NovAtel OEM-4 WAAS enabled GPS receiver (i.e., truth). At present, NSE for an RNP (0.3) non-precision approach using LORAN C has been defined as approximately 1000 ft either side of the desired flight path. Other components which make up TSE, e.g., flight technical error, path following error, etc., have yet to be assigned values. For the airports addressed in this paper, cross-track NSE for stabilized approaches conducted under visual meteorological conditions (VMC) will be shown to be less than 30% of the 1000 ft (|mean| plus two sigma) allocated for NSE under the RNP (0.3) definitions.

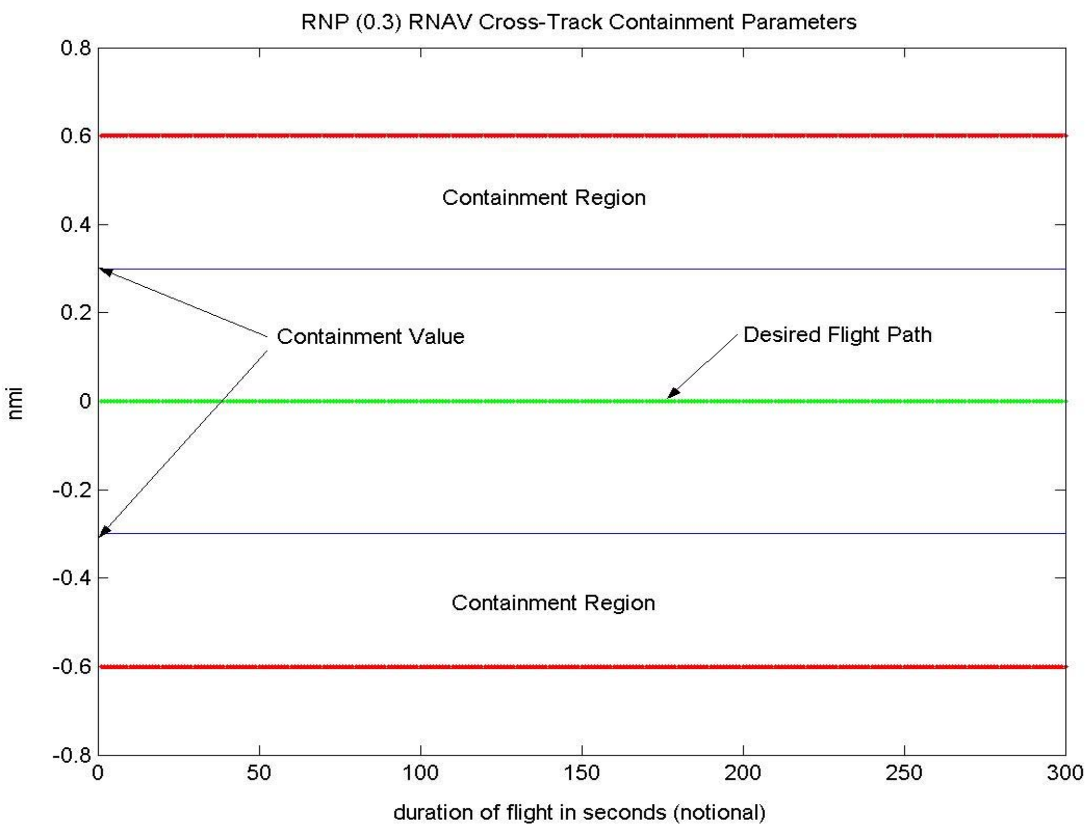

Figure 2

GPS Approach Architecture [10]

The basic GPS approach is "T" shaped in structure (see **Figure 3**). At either end of the top of the "T" is an initial approach fix (IAF). Centered between the two endpoints is an IAF combined with the initial fix (IF) for the approach. This point joins the vertical part of the "T" which is along the runway centerline extended. About midway along this line is the final approach fix (FAF). The FAF is generally 5 nmi from the runway threshold and 5-6 nmi from the IF/IAF. Distances between the IAFs and the IF are generally 3-6 nmi. All fixes associated with the approach are designated with five letter pronounceable names. Prior to runway threshold, there is the missed-approach point (MAP), a point at which the approach can be safely aborted and the missed-approach procedure executed. This point is determined based upon minimum descent altitude (MDA) or decision altitude (DA) dependent upon the vertical guidance used for the approach procedure.

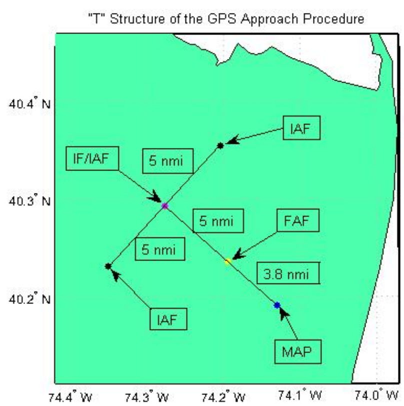

Figure 3

The GPS approach "T" structure is located within a 30 nmi terminal arrival area (TAA) centered approximately on the approach IF. The nature of the "T" allows for direct entry into the GPS approach depending upon the relative arrival bearing, i.e. no procedure turns are required. **Figure 4** is the FAA published Runway 25 GPS approach procedure used at the Ohio University Airport (UNI) in Albany, Ohio. Aircraft approaching HOPAX, the IF, from the east, enter the procedure directly; those aircraft arriving from the north and west, fly the portion of the "T" from CISBO, the northern IAF, to HOPAX and then proceed inbound on the approach heading; and, those aircraft arriving from the south and west, use DEVAY, the southern IAF, to HOPAX before proceeding inbound on the approach heading. The FAF, TACOY, is 6 nmi from the IF and 5.5 nmi from runway threshold. The MAP is shown prior to threshold and the missed approach procedure is a climb to 3000 ft msl direct CIMIX where a hold is entered.

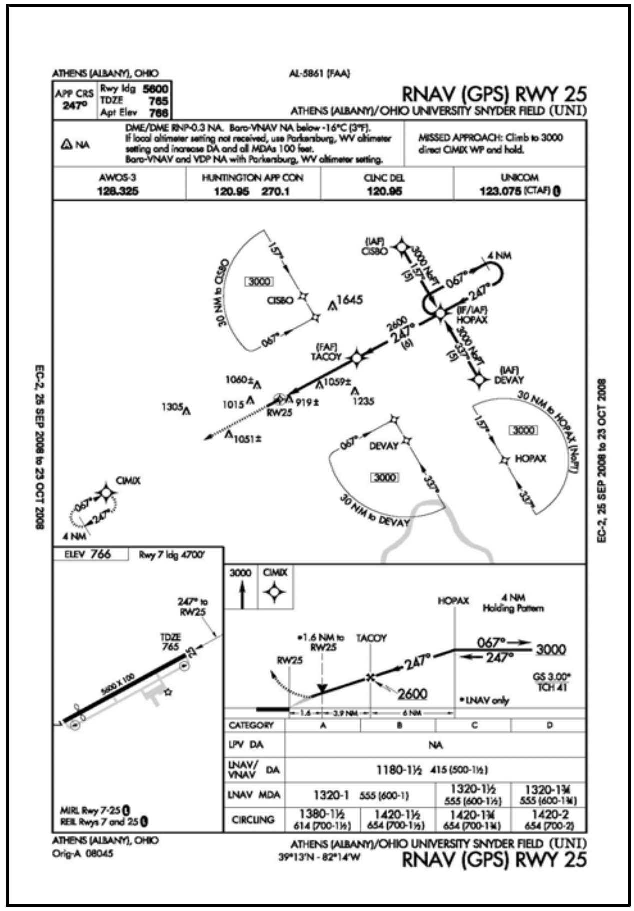

Figure 4

GPS receivers which are certified for instrument flight rules (IFR) use an integrity scheme known as receiver autonomous integrity monitoring (RAIM). RAIM algorithms require that the receiver track additional satellites beyond the minimum four required for GPS 3-D positioning. RAIM allows for detection, and sometimes exclusion, of satellites which may be transmitting hazardously misleading information. If the RAIM algorithm operating within the GPS receiver is satisfied, the selected GPS approach can be armed and execution can begin. The receiver output is coupled to a course deviation indicator (CDI) or similar device and displays guidance left or right of the desired course to the appropriate waypoint. The pilot flies the aircraft such that the needle in the CDI stays centered. Once inside the TAA, the CDI sensitivity changes from ±5 nmi to ±1 nmi (i.e., RNP 5 to RNP 1). This sensitivity is maintained throughout the approach procedure until the aircraft is on final approach and within 2 nmi of the FAF. At this point in time, the CDI sensitivity changes to ±0.3 nmi (RNP 0.3). This sensitivity is maintain to the MAP at which point the sensitivity returns to ±1 nmi. At the MAP, the pilot either has the field in sight and lands or executes the missed approach procedure.

All of the GPS approach procedures flown during this flight testing were under visual flight rules (VFR) conditions but the GNS-480 IFR certified receiver operated and was used as though IFR conditions were in affect. On each approach the aircraft either landed or overflew the runway at a nominal altitude of 100 ft.

FLIGHT TEST RESULTS

Results will be presented for five of the six airports used for this study. These include: Norwalk-Huron County Airport (5A1), Norwalk, Ohio; Atlantic City International Airport (ACY), Atlantic City, NJ; Monmouth Executive Airport (BLM), Belmar-Farmingdale, NJ; Bay Bridge Airport (W29), Stevensville, MD; and, Portland International Jetport (PWM), Portland, ME. The Jacksonville/Craig Municipal Airport (CRG), Jacksonville, FL., has been omitted since no standard GPS approach is available at this airport.

The spreadsheet in **Table 1** shows ground-measurement information from 2004 through early 2008 for BLM. The periods corresponding to the end of winter are 3/25/2004, 4/6/2005, 4/4/2006, 4/10/2007and 4/17/2008; those corresponding to the end of summer are 8/13/2004, 8/24/2005, 9/6/2206,and 9/6/2007. Comparison of the individual values for master and secondary LORAN stations (LorSta's) in each of the chains visible at BLM indicates strong repeatability season-to-season and year-to-year despite the fact that the data are measured using the SatMate 1030 LORAN C receiver clock. This clock is synchronized to a composite frequency of all the stations being tracked; note that master stations, for the last 18 months, have been synchronized with respect to UTC. The end of summer corresponds to the driest period of the year and one would expect to see some change in ASF* values from late winter which corresponds to the wettest period of the year. ASF* data for 5A1, ACY, and PWM are contained in the appendix.

Table 1 ASF* Values for Monmouth Executive Airport (BLM), Belmar-Farmingdale, NJ

	BELMAR-FARMINGDALE AIRPORT (BLM) NEW JERSEY (values in microseconds)															
Chain	8970				9960					7980				5930		
Station	M	W	X	Y	M	W	X	Y	Z	M	W	Y	Z	M	X	Y
3/25/2004	1.97	4.91	0.92	4.82	0.85	1.99	-1.80	1.29	2.26	3.96		-0.78	0.92	2.43	-1.90	-0.89
4/6/2005	1.98	4.90	0.87	4.73	0.79	2.10	-1.75	1.26	2.36	4.03	-3.78	-0.88	0.86	2.55	-1.85	-0.76
4/4/2006	2.13	5.01	0.82	4.59	0.75	1.99	-1.65	1.18		4.05		-0.93	0.80	2.46	-1.76	-0.62
4/10/2007	2.23	5.06	0.93	4.43	0.87	2.21	-1.77	1.27	2.25	4.06	-4.20	-0.82	0.87	2.42	-1.87	-0.79
4/17/2008	2.50	5.17	1.17	5.07	1.10	2.20	-1.87	1.18	2.50	4.07	6.32	-0.96	0.78	2.39	-1.97	-0.86
Mean	2.16	5.01	0.94	4.73	0.87	2.10	-1.77	1.24	2.34	4.03	-0.55	-0.87	0.85	2.45	-1.87	-0.78
Sigma	0.22	0.11	0.14	0.24	0.14	0.11	0.08	0.05	0.12	0.04	5.96	0.07	0.06	0.06	0.08	0.11
8/13/2004	1.92	4.87	0.88		0.80	2.09	-1.68	1.26	2.27	4.00		-0.91	0.82	2.55	-1.79	-0.71
8/24/2005	2.04	4.85	0.86		0.79	2.14	-1.68	1.24	2.41	3.79		-1.15	0.82	2.58	-1.79	-0.62
9/6/2006	2.02	4.77	0.92	4.89	0.84	2.10	-1.70	1.19	2.42	3.99	6.31	-0.89	0.75	2.54	-1.81	-0.64
9/6/2007	2.43	5.11	1.15		1.12	2.26	-1.87	1.31	2.50	3.95		-0.92	0.78	2.44	-1.98	-0.87
Mean	2.10	4.90	0.95	4.89	0.89	2.15	-1.73	1.25	2.40	3.93	6.31	-0.97	0.79	2.53	-1.84	-0.71
Sigma	0.22	0.15	0.13		0.16	0.08	0.09	0.05	0.10	0.10		0.12	0.04	0.06	0.09	0.11
Total Mean	2.13	4.96	0.95	4.81	0.88	2.12	-1.75	1.24	2.37	3.98		-0.92	0.82	2.49	-1.86	-0.75

Approaches Using Measured ASF* Values.

Figure 5 shows the location of the Monmouth Executive Airport at Belmar-Farmingdale, NJ. The site is near the New Jersey Shore south of New York City and approximately 20 miles south of the LORAN Monitor (LorMon) site at Sandy Hook, NJ. The ASF measurement system was set up in the ramp area of the airport and data collected for an hour. The measurement system allows the user to view a scatter plot comparing the GPS-receiver position output with that of the LORAN C receiver position output. The LORAN data collected using the H-field antenna were used to generate the local ASF* data which is the norm. H-field derived data appear to yield a more balanced pattern about the GPS-derived position.

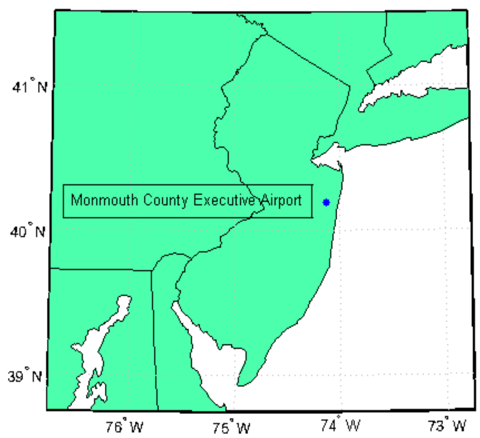

Figure 5

The 4/17/2008 ASF* values (see **Table 1**) were loaded into the SatMate1030 receiver aboard the aircraft and three GPS approaches shown in **Figure 6** were flown at the Monmouth Executive Airport before departing the area. The northeasterly IAF (BUBAL) was selected as the entry point for each GPS approach to Runway 14. Using the guidance from the GNS-480 receiver, the turn onto final for each approach occurs inside the IF (DANSE). From there, the path is directly over the FAF (FEGAN) and through the MAP. Each approach concludes with a low approach over the complete length of the field followed by a return to the IAF except for the third, which concludes with area departure following the low approach.

Figure 7 is a plot of the LORAN cross-track and along-track error as determined using a WAAS-augmented NovAtel OEM-4 GPS receiver as truth reference during the three GPS approaches at BLM on 4/17/2008. Altitude scaled by 10 is also shown in **Figure 7**. Each approach begins with the arrival at the IAF (black dot) at pattern altitude. The IF is shown with a magenta dot. Turns are involved at both of these fixes and a buildup in cross-track error is evident. The error build-up is primarily due to a five-second TOA integration time in the Satmate 1030 receiver. The LORAN and GPS data are aligned in such a manner as to remove most of this integration time but residual effects remain. Fortunately, these effects on the cross-track error diminish once the aircraft stabilizes on the final approach course. This is apparent as the aircraft approaches the FAF (yellow dot). The low approach over the airfield is indicated by the blue dot after which the cross-track error increases due to the turn back to the IAF.

Similar effects can be seen in the along-track error which is both speed and heading dependent. With the aircraft traveling nominally at 250 ft/sec (150 kts), the approximately 1250 ft of along-track error due to TOA integration has been removed before the along-track data is displayed. With this taken into account, the along-track error seldom exceeds 600 ft. In general, along-track error on a stabilized approach due to receiver averaging could be easily removed since the LORAN receiver calculates aircraft heading and velocity. Considering the entire sequence of approaches at BLM, the 95% along-track error (|mean| plus two sigma), with receiver averaging effects removed, was between 660 and 700 ft. **Table 2** summarizes the LORAN performance for the three GPS approaches completed at BLM using measured ASF* values. Data for each approach was analyzed beginning 15 sec prior to the IAF and ending during the low approach at the point of minimum altitude. In addition, a composite, starting with the first approach and continuing until the end of the final approach, is included. The composite numbers trend slightly lower since the return from the low approach to the IAF is generally a direct path with minimal turns.

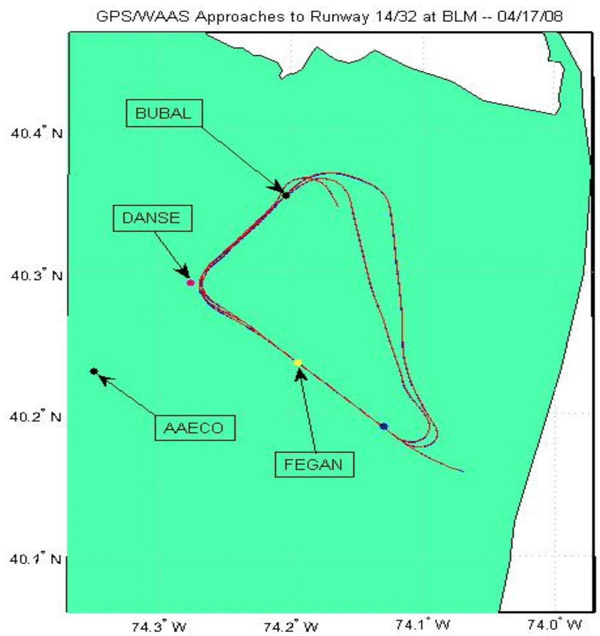

Figure 6 GPS Runway 14 Approach at BLM

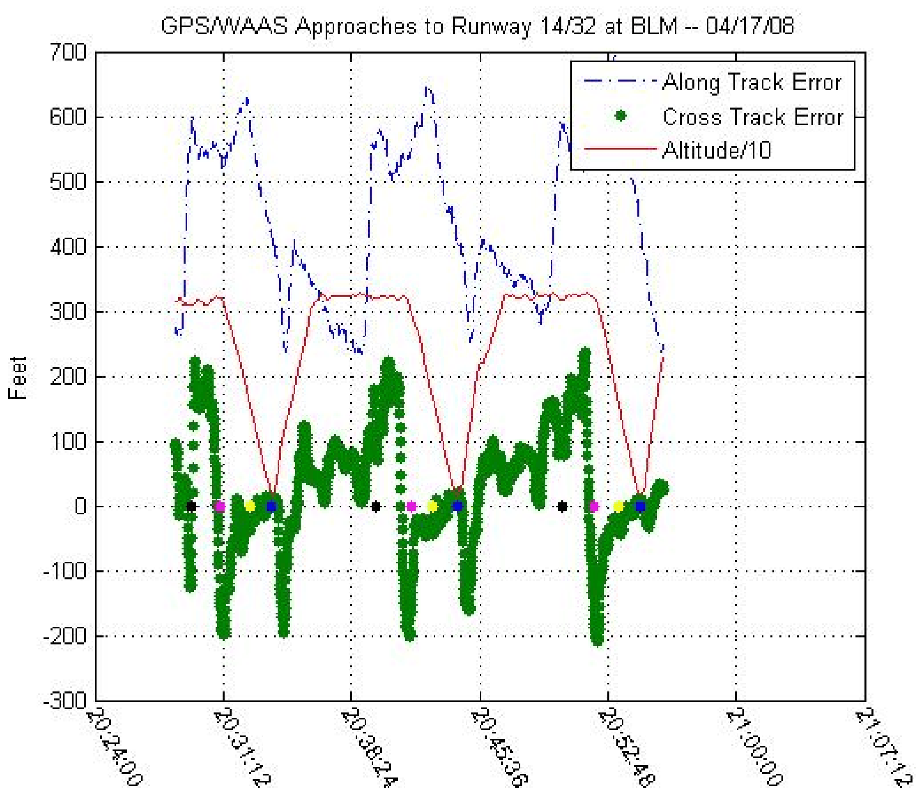

Figure 7 LORAN Error Performance (Measured ASF*) at BLM with Scaled Altitude

Table 2 LORAN Performance Summary for GPS Approaches

Date	Airport	Runway	Cross-track Error (ft)			Along-track Error (ft)		
			|Mean| (ft)	Sigma(ft)	95% (ft)	|Mean| (ft)	Sigma (ft)	95% (ft)
4/17/2008	BLM	14	78.8	102.6	284.0	529.4	64.9	659.2
4/17/2008	BLM	14	80.6	105.8	292.2	534.2	64.0	662.2
4/17/2008	BLM	14	82.6	107.2	297.0	558.0	67.9	693.8
Composite	BLM	14	75.5	93.4	262.3	455.6	120.3	696.2
4/14/2008	5A1	7	94.2	24.3	142.8	471.9	16.0	503.9
4/17/2008	ACY	13	95.2	93.2	281.6	758.2	251.9	1262.0

Also included in **Table 2** are single GPS approaches completed at 5A1 and ACY; details are in the appendices. The approach at 5A1 is a direct on-course entry at the IF with minimum turns. This is reflected in the lower 95% containment numbers for cross-track and along-track error. The excellent results at 5A1 can be attributed to the flat local terrain, the multiplicity of LorSta's in view, and the excellent geometry at Norwalk with respect to the network of LorSta's in view. The approach at ACY begins with an IAF entry; thus, the turns during the approach are evident in the higher 95% containment numbers. The excessive along-track error resulted from a repetitive timing condition which caused the TOA smoothing to vary between five and six seconds thereby adding an extra aircraft-velocity along-track segment of 250 ft on virtually every other measurement. This is evident in the LORAN error performance plot contained in Appendix A.

Approaches Using Averaged ASF* Values.

Over the past three and one-half years, sufficient ASF* information has been collected at the six airports used in this study, to begin to notice clear trends in the data. For this case, the Bay Bridge Airport, Stevensville, MD has been used (see **Figure 8**). Bay Bridge Airport is located about 30 miles east of Washington, D.C. A close look at **Table 3** indicates strong repeatability for the various observed LorSta transmitters from season-to-season and year-to-year. Based upon these observed ground-measurement trends, it was decided to create an averaged ASF* value for each of the six airports prior to conducting the late-summer 2006 flight work. The outcome showed favorable accuracy results for non-precision approach. The exercise was again repeated for the late-winter and late-summer 2007 flights and again the 2008 late-winter flight tests. For example, the mean of the four late-winter ASF* values at W29 for each of the LorSta transmitters were averaged with the mean of the four late-summer ASF* values. In the case of the 8970 Master, this value was 1.42 microseconds (see **Table 3**). Averaged values were generated for each LorSta transmitter historically observed at W29 and were subsequently loaded into the SatMate 1030 receiver prior to arrival at the airport on 4/17. In this case, the averaged ASF* values for W29 were loaded enroute following a brief refueling stop in Denton, MD, approximately 30 nmi from W29. Two GPS non-precision approaches were undertaken using the northerly IAF (AGARD).

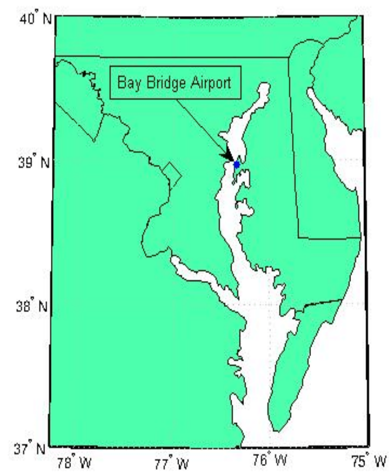

Figure 8

Table 3 ASF* Values for Bay Bridge Airport, Stevensville, MD

	BAY BRIDGE AIRPORT (W29) MARYLAND (values in microseconds)																				
Chain	8970					9960					7980				5930			9610			
Station	M	W	X	Y	Z	M	W	X	Y	Z	M	W	Y	Z	M	X	Y	M	V	Y	Z
3/24/2004		3.40	0.37	3.43		0.40	1.93	-1.30	0.12	1.65	2.93	5.23	-0.29	0.10	2.50	-1.61	-0.88	1.75			1.34
4/26/2005	1.35	3.29	0.34	3.55	4.13	0.34	2.52	-1.27	0.11	1.83	2.96	5.12	-0.26	0.09	2.84	-1.49	-0.59	0.15	-0.51	1.33	1.40
4/3/2006	1.46	3.47	0.40	3.55	4.17	0.39	2.52	-1.38	0.10	1.80	2.94		-0.31	0.07	2.77	-1.65	-0.77	0.22		1.38	1.43
4/9/2007	1.53	3.50	0.35	3.05		0.35	2.61	-1.38	0.13	1.63	2.96	5.05	-0.30	0.09	2.68	-1.65	-0.81	0.22	2.59		1.40
Mean	1.45	3.42	0.37	3.40	4.15	0.37	2.40	-1.33	0.12	1.73	2.95	5.13	-0.29	0.09	2.70	-1.60	-0.76	0.59	1.04	1.36	1.39
Sigma	0.09	0.09	0.03	0.24	0.03	0.03	0.31	0.06	0.01	0.10	0.01	0.09	0.02	0.01	0.15	0.08	0.12	0.78	2.19	0.04	0.04
8/12/2004	1.26	3.21	0.38	3.69		0.40	2.59	-1.28	0.10	1.75	2.90		-0.29	0.09	2.09	-1.43	-0.50	0.01	1.59	1.21	1.43
8/31/2005	1.34	3.25	0.37		4.25	0.37	2.62	-1.26	0.08	1.84	2.94	5.33	-0.29	0.06	2.87	-1.41	-0.42			1.28	1.27
9/13/2006	1.27	3.29	0.38	3.60		0.37	2.60	-1.33	0.14	1.76	2.99		-0.20	0.12	2.83	-1.62	-0.73				1.33
9/5/2007	1.70	3.55	0.46	3.65		0.48	2.64	-1.47	0.11	1.80	2.94	5.09	-0.29	0.09	2.67	-1.74	-0.87	0.55			1.46
Mean	1.39	3.33	0.40	3.65	4.25	0.40	2.61	-1.34	0.11	1.79	2.94	5.21	-0.27	0.09	2.62	-1.55	-0.63	0.28	1.59	1.25	1.37
Sigma	0.21	0.15	0.04	0.05		0.05	0.02	0.09	0.03	0.04	0.04	0.17	0.04	0.03	0.36	0.16	0.21	0.38		0.05	0.09
Total Mean	1.42	3.37	0.38	3.52	4.20	0.39	2.50	-1.33	0.11	1.76	2.95	5.17	-0.28	0.09	2.66	-1.58	-0.70	0.43	1.32	1.30	1.38

Figure 9 shows the entry for the GPS 29 approach. After the completion of the approach, a tight teardrop turn follows, followed by a low approach to Runway 11, and then a repeat of the GPS 29 approach. **Figure 10** depicts the LORAN performance for both of the GPS approaches as well as the intervening low approach to Runway 11. **Table 4** summarizes the LORAN performance for the two GPS approaches completed at W29 using averaged ASF* values. Data for each approach was analyzed beginning 15 sec prior to the IAF and ending during the low approach at the point of minimum altitude. All of the GPS approaches in **Table 4** originated at an IAF and contain the effects of aircraft turns. The composite along-track error at W29 reflects the tight teardrop turn prior to the low approach to Runway 11. Also included in **Table 4** are the results from single GPS approaches conducted at 5A1, ACY, and PWM. The cross-track and along-track performance are in keeping with values seen historically at these airports [6, 7, 8, 9] The excessive along-track error at 5A1 is indicative of the repetitive timing condition noted previously. Plots associated with the LORAN performance at 5A1, ACY, and PWM are located in Appendix A, B, and C.

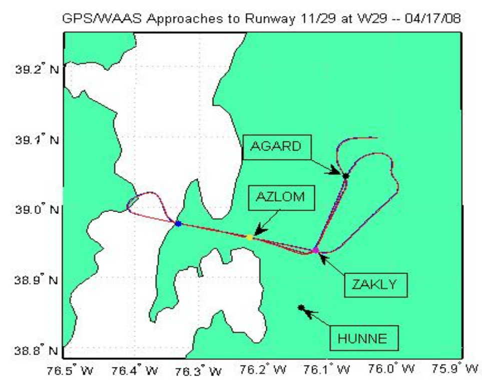

Figure 9 GPS Runway 29 Approach at W29

Table 4 LORAN Performance Summary for GPS Approaches–Averaged ASF* Values

Date	Airport	Runway	Cross-track Error (ft)			Along-track Error (ft)		
			|Mean| (ft)	Sigma(ft)	95% (ft)	|Mean| (ft)	Sigma (ft)	95% (ft)
4/17/2008	W29	29	202.1	120.8	443.7	461.1	187.5	836.1
4/17/2008	W29	29	215.9	127.5	470.9	420.4	180.3	781.0
Composite	W29	29	207.8	230.2	668.2	411.5	178.3	768.1
4/14/2008	5A1	7	86.1	86.6	259.3	533.6	176.7	887.0
4/17/2008	ACY	13	67.5	87.2	241.9	424.6	186.5	797.6
4/17/2008	PWM	36	148.4	71.2	290.8	415.2	83.7	582.6

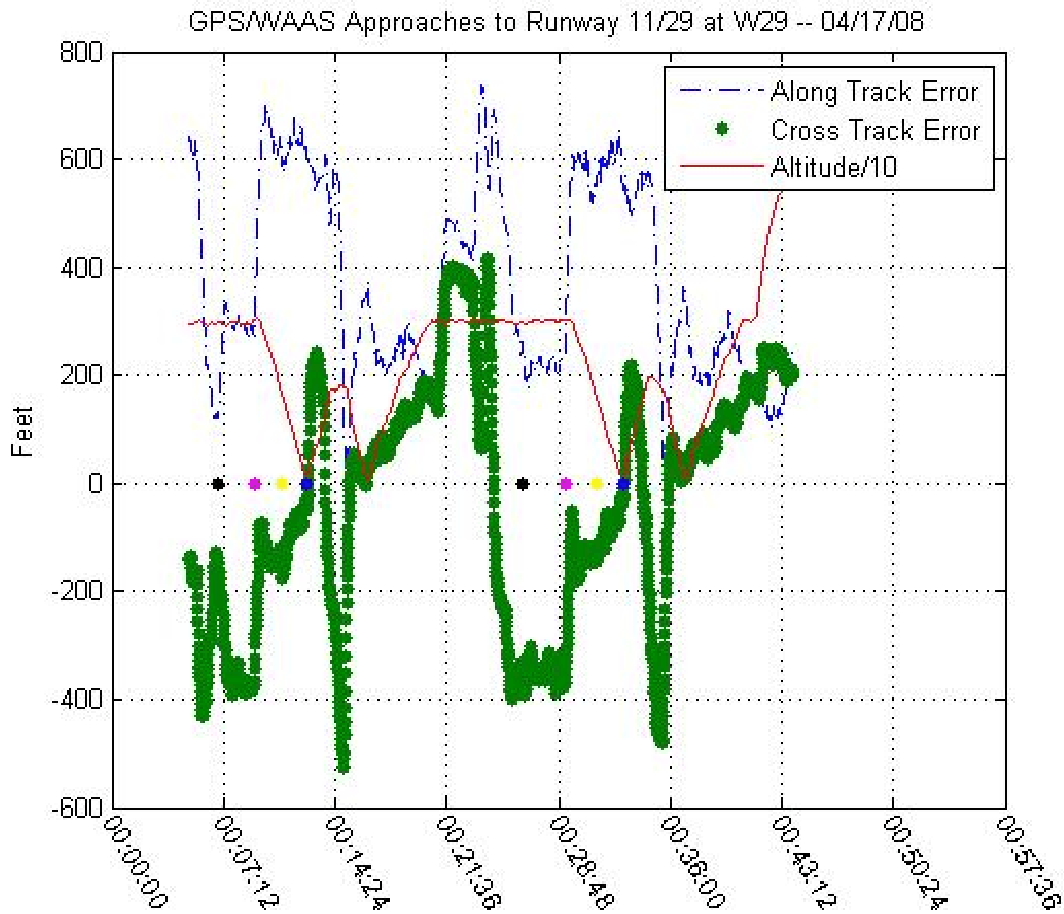

Figure 10 LORAN Error Performance (Averaged ASF*) at W29 with Scaled Altitude

SUMMARY AND CONCLUSIONS

Locally generated ASF* measurements demonstrate season-to-season and year-to-year (temporal) consistency, i.e., late winter 2004 to late winter 2008 and late summer 2004 to late summer 2007, for all six airport locations, five of which are shown in this paper. There have been exceptions, particularly in the last 18 months, as various LORAN chains have shifted to UTC time-of-transmission (TOT) control and the monitor-station concept abandoned, but on balance, accuracy has been maintained.

The analysis of flight measurements for late winter 2008 shows that the LORAN cross-track and along-track error are well behaved over the GPS non-precision approaches flown at the four east-coast and the one mid-west airport. **Figures 11** and **12** are composite plots of cross-track and along-track error for all of the 14 GPS non-precision approaches analyzed for this paper. LORAN performance for both

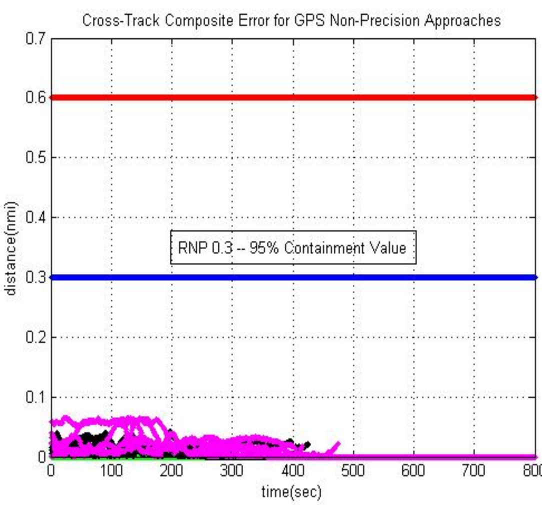

Figure 11 Cross-Track Composite Error

measured ASF* values (black traces) and averaged ASF* values (magenta traces) is shown with respect to the RNP 0.3, the 95% total system error (TSE) containment value. Cross-track error is generally somewhat less that 0.1 nmi and decreases significantly to below 0.05 nmi once aircraft turns required by the procedure are completed and the aircraft approaches the Final-Approach-Fix (FAF). Along-track error is somewhat greater but still well within the RNP 0.3 containment value. If one anomalous trace with known timing errors is eliminated, along-track error is contained between 1.5 and 1.0 nmi, and tends toward the lower value as the aircraft approaches the FAF.

Clearly, if one examines the ASF* data collected over the past four years, the consistency of the data is quite apparent and yields a strong qualitative conclusion that use of LORAN TOA measurements locally corrected with averaged ASF* data is definitely viable for non-precision approach at a great majority of the airports in the U.S. National Airspace System (NAS). While at this point in time, the sets of averaged ASF* values examined to date are limited, it appears that a single set of averaged ASF* values will be sufficient to meet the navigation sensor error (NSE) cross-track requirements (1000 ft or less) for LORAN RNP (0.3) non-precision approach. There will obviously be some locations where this is not true due to widely varying environmental conditions, all-in view geometry limitations, etc., so in those cases twice annual updates may be needed. Taken as a whole, the airports surveyed to date are representative of those east of the Rocky Mountains, but airports in the intra-mountain west and west-coast areas need to be studied since ASF* gradients in those areas can be steep.

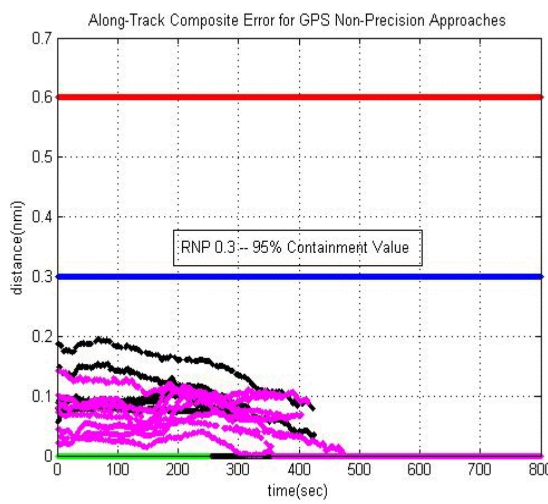

Figure 12 Along-Track Composite Error

Overall, with new time and frequency equipment (TFE) installed at all CONUS LorSta locations, and the move to TOT-control completed, locally generated ASF* values, and ultimately the true ASF values, should prove to be more stable than those currently available, thus yielding even greater LORAN cross-track and along-track accuracies than those presently shown. The over-riding conclusion from the material presented in this paper is that the current LORAN navigation system in operation in the United States is more than capable of providing the National Airspace System accuracy requirements imposed upon it for GPS-equivalent non-precision approach. The LORAN system operating today is the result of significant infrastructure improvements including solid-state transmitters, new TFE, *no-break* LorSta power, etc. In addition, all-in-view LORAN C receivers using

H-field antennas are also an important part of the equation. As the LORAN community moves into the age of eLORAN, which includes a data channel capability with navigation messages encoded on the LORAN pulses, and time-of-transmission control for each LorSta, achieved accuracies for aviation application will continue to improve.

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ACKNOWLEDGMENTS

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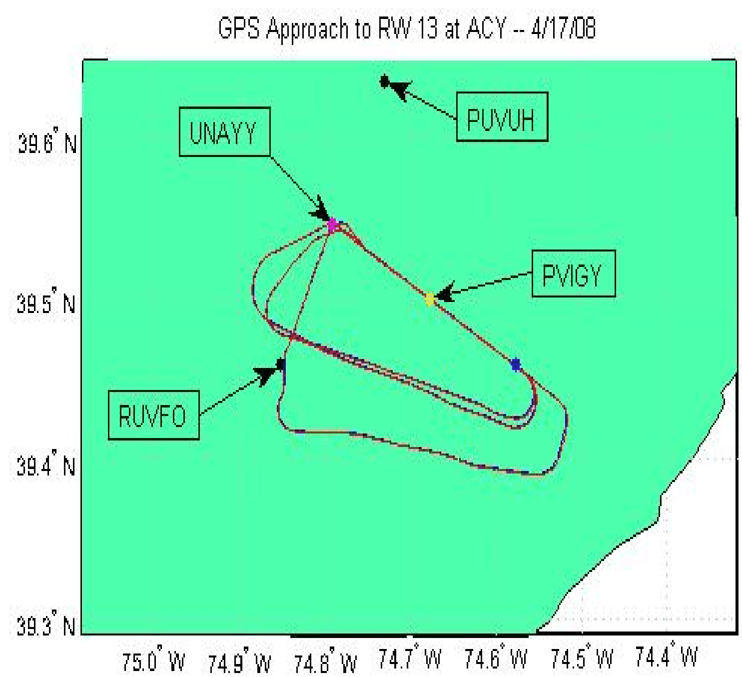
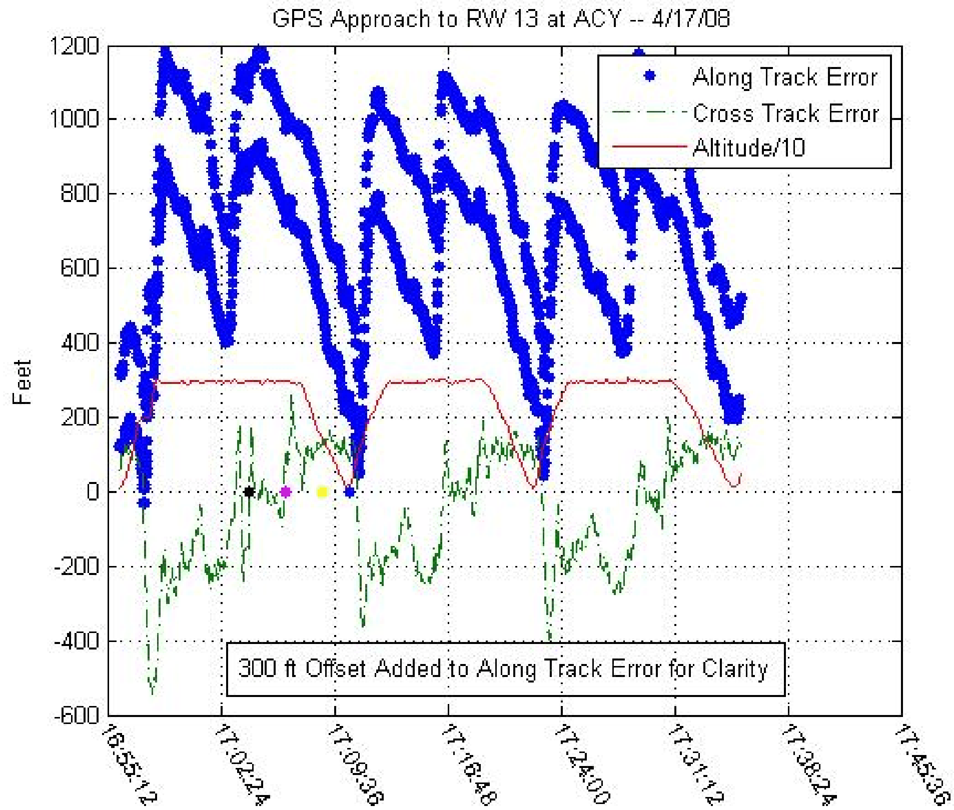
APPENDIX A: ATLANTIC CITY INTERNATIONAL AIRPORT, NJ

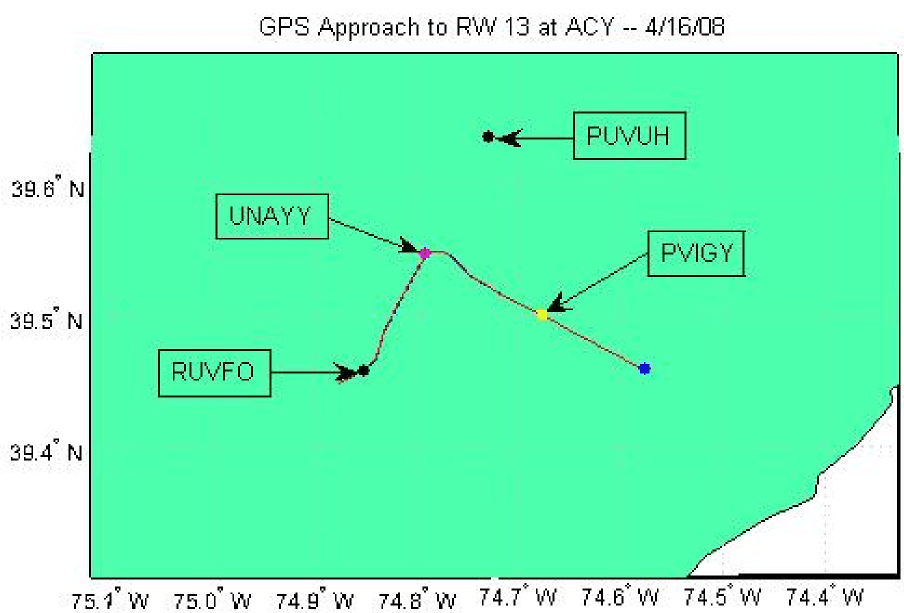
ASF* Values for Atlantic City International Airport (ACY)

	ATLANTIC CITY INTERNATIONAL AIRPORT (ACY) NEW JERSEY (values in microseconds)																
Chain	8970					9960					7980				5930		
Station	M	W	X	Y	Z	M	W	X	Y	Z	M	W	Y	Z	M	X	Y
3/26/2004	2.39	4.11	1.16	5.11		1.12	2.42	-1.63	0.61	2.69	3.54	6.15	-1.05	0.52	2.80	-1.76	-1.41
4/5/2005	2.41		1.27	5.28		1.19	2.48	-1.60	0.62	2.81	3.51		-1.11	0.46	2.89	-1.72	-1.31
4/3/2006	2.37	4.20	1.13	4.99	5.19	1.10	2.41	-1.64	0.59	2.68	3.61	5.99	-1.07	0.54	2.84	-1.76	-1.35
4/9/2007	2.49	4.26	1.18			1.14	2.60	-1.68	0.63	2.55	3.62	6.05	-0.98	0.55	2.77	-1.81	-1.43
4/17/2008	2.41	4.34	0.97			0.93	2.63	-1.82		2.45	2.33	4.66	-2.39		2.80	-1.94	-1.50
Mean	2.41	4.23	1.14	5.13	5.19	1.10	2.51	-1.67	0.61	2.64	3.32	5.71	-1.32	0.52	2.82	-1.80	-1.40
Sigma	0.05	0.10	0.11	0.15		0.10	0.10	0.09	0.02	0.14	0.56	0.70	0.60	0.04	0.05	0.09	0.07
8/12/2004	2.51	4.21	1.51	5.19		1.20	2.48	-1.73	0.52	2.61	3.42	6.10	-1.13	0.44	2.94	-1.86	-1.35
8/23/2005	2.33	4.03	1.20			1.15	2.54	-1.61	0.59	2.74	3.59		-1.02	0.53	2.95	-1.74	-1.28
9/5/2006	2.33	4.04	1.15	5.21		1.10	2.54	-1.59	0.59	2.77	3.61	6.18	-1.02	0.51	2.94	-1.73	-1.26
9/5/2007	2.61	4.51	1.13	5.01	5.57	1.09	2.77	-1.73	0.72	2.66	3.75	6.25	-0.95	0.64	2.90	-1.87	-1.42
Mean	2.45	4.20	1.25	5.14	5.57	1.14	2.58	-1.67	0.61	2.70	3.59	6.18	-1.03	0.53	2.93	-1.80	-1.33
Sigma	0.14	0.22	0.18	0.11		0.05	0.13	0.08	0.08	0.07	0.14	0.08	0.07	0.08	0.02	0.08	0.07
Total Mean	2.43	4.21	1.19	5.13	5.38	1.12	2.55	-1.67	0.61	2.67	3.46	5.94	-1.18	0.52	2.88	-1.80	-1.36

Plots are from measured ASF* values followed by averaged ASF* values




GPS Approach to RW 13 at ACY -- 4/17/08
Feet
Along Track Error
Cross Track Error
Altitude/10
300 ft Offset Added to Along Track Error for Clarity
1200
1000
800
600
400
200
0
-200
-400
-600
16:55:12
17:02:24
17:09:36
17:16:48
17:24:00
17:31:12
17:38:24
17:45:36


GPS Approach to RW 13 at ACY -- 4/16/08
PUVUH
UNAYY
PVIGY
RUVFO
39.6° N
39.5° N
39.4° N
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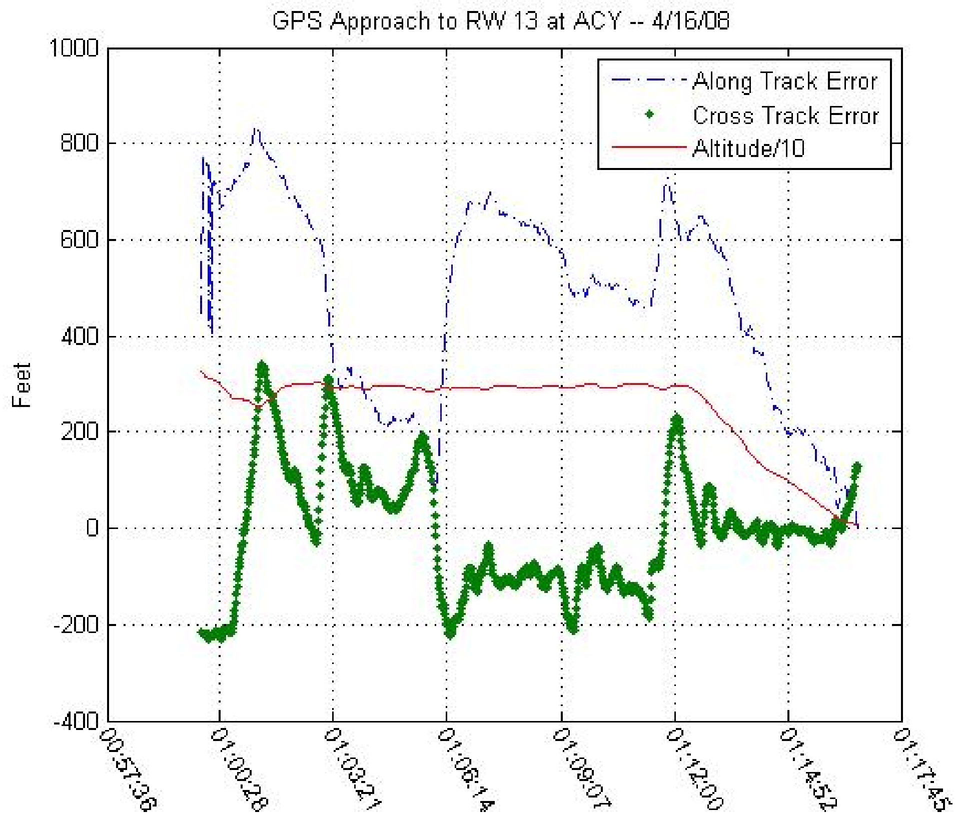
75.0° W
74.9° W
74.8° W
74.7° W
74.6° W
74.5° W
74.4° W



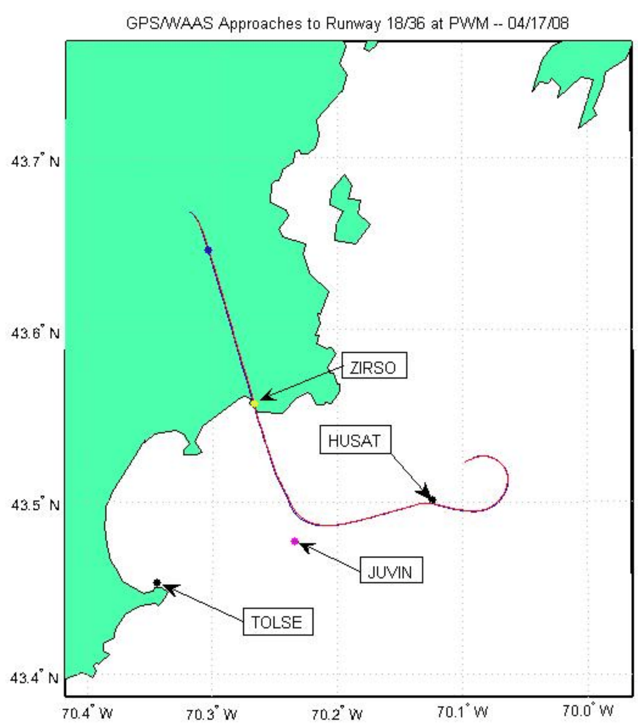
GPS Approach to RW 13 at ACY -- 4/16/08
Along Track Error
Cross Track Error
Altitude/10
Feet
1000
800
600
400
200
0
-200
-400
00:57:36
01:00:28
01:03:21
01:06:14
01:09:07
01:12:00
01:14:52
01:17:45

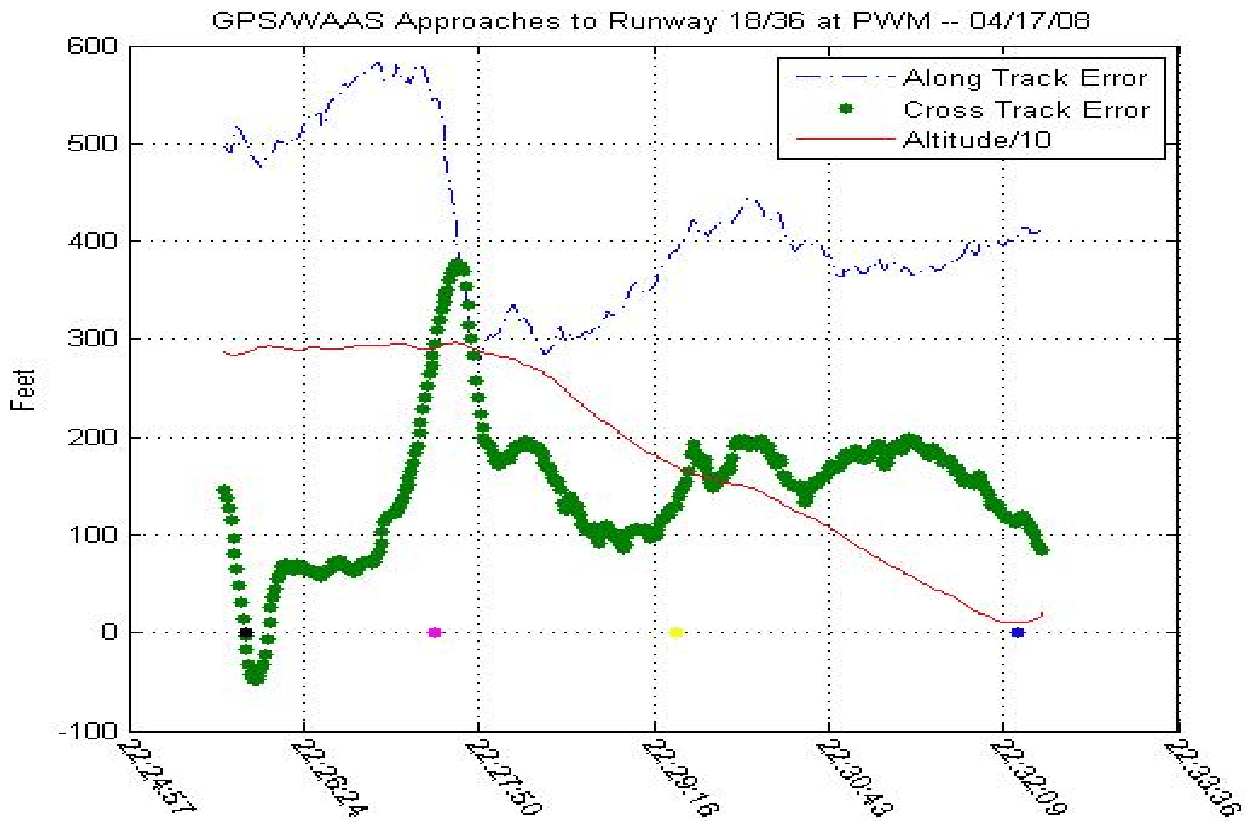
APPENDIX B: PORTLAND INTERNATIONAL JETPORT, ME

ASF* Values for Portland International Jetport (PWM)

	PORTLAND INTERNATIONAL JETPORT (PWM) MAINE (values in microseconds)															
Chain	8970				9960					7980			5930			
Station	M	W	X	Y	M	W	X	Y	Z	M	Y	Z	M	X	Y	Z
3/25/2004	3.39	1.89	1.60	0.67	1.62	0.46	-1.84	1.16	3.65				0.82	-1.98	-0.07	
4/25/2005	3.15		1.48		1.46	0.53	-1.83	1.21	3.53		-1.90	-0.40	0.93	-1.99	0.06	
4/5/2006	3.09		1.49		1.48	0.45	-1.86	1.12	3.26		-1.86	-0.37	0.85	-2.00	0.05	2.35
4/10/2007	3.19		1.56		1.52	0.64	-1.91	1.19	3.43				0.85	-1.99	0.05	
4/18/2008	3.58	6.77	1.63		1.62	0.61	-2.02	1.14	3.63	4.43	-2.08	-0.64	0.84	-2.11	-0.02	
Mean	3.28	4.33	1.55	0.67	1.54	0.54	-1.89	1.16	3.50	4.43	-1.95	-0.47	0.86	-2.01	0.01	2.35
Sigma	0.20	3.45	0.07		0.08	0.09	0.08	0.04	0.16		0.03	0.02	0.04	0.05	0.06	
8/11/2004	3.20	-2.40	1.46	5.33	1.45	0.57	-1.88	1.25	3.68		-1.96	-0.45	0.96	-2.05	0.10	2.71
8/30/2005	3.22		1.46		1.44	0.59	-1.74	1.21	3.64					-1.74	0.30	
9/7/2006	3.25	6.56	1.50		1.49	0.57	-1.92	1.24	3.67	4.31	-2.13	-0.69	0.95	-2.07	0.13	
9/7/2007	3.78		1.72		1.71	0.62	-2.02	1.23	3.77	4.39	-2.03	-0.58	0.73	-2.13	0.00	2.48
Mean	3.36	2.08	1.54	5.33	1.52	0.59	-1.89	1.23	3.69	4.35	-2.04	-0.57	0.88	-2.00	0.13	2.60
Sigma	0.28	6.34	0.12		0.13	0.02	0.12	0.02	0.06	0.06	0.09	0.12	0.13	0.18	0.13	0.16
Total Mean	3.32	3.21	1.54	3.00	1.53	0.56	-1.89	1.20	3.60	4.39	-1.99	-0.52	0.87	-2.01	0.07	2.47

Plots are from averaged ASF* values only



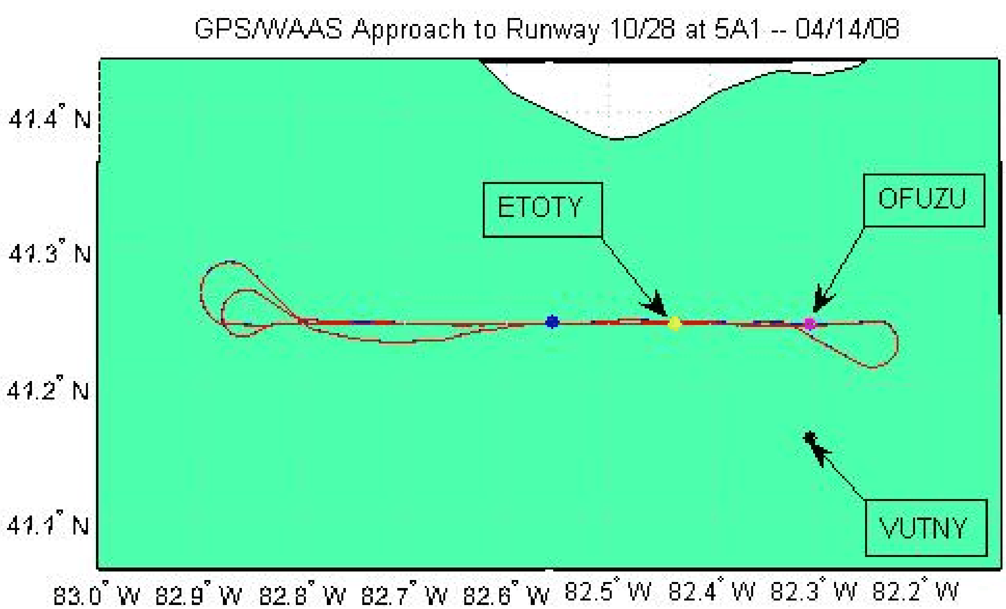

GPS/WAAS Approaches to Runway 18/36 at PWM -- 04/17/08
Along Track Error
Cross Track Error
Altitude/10
Feet
600
500
400
300
200
100
0
-100
22:24:57
22:26:24
22:27:50
22:29:16
22:30:43
22:32:09
22:33:36

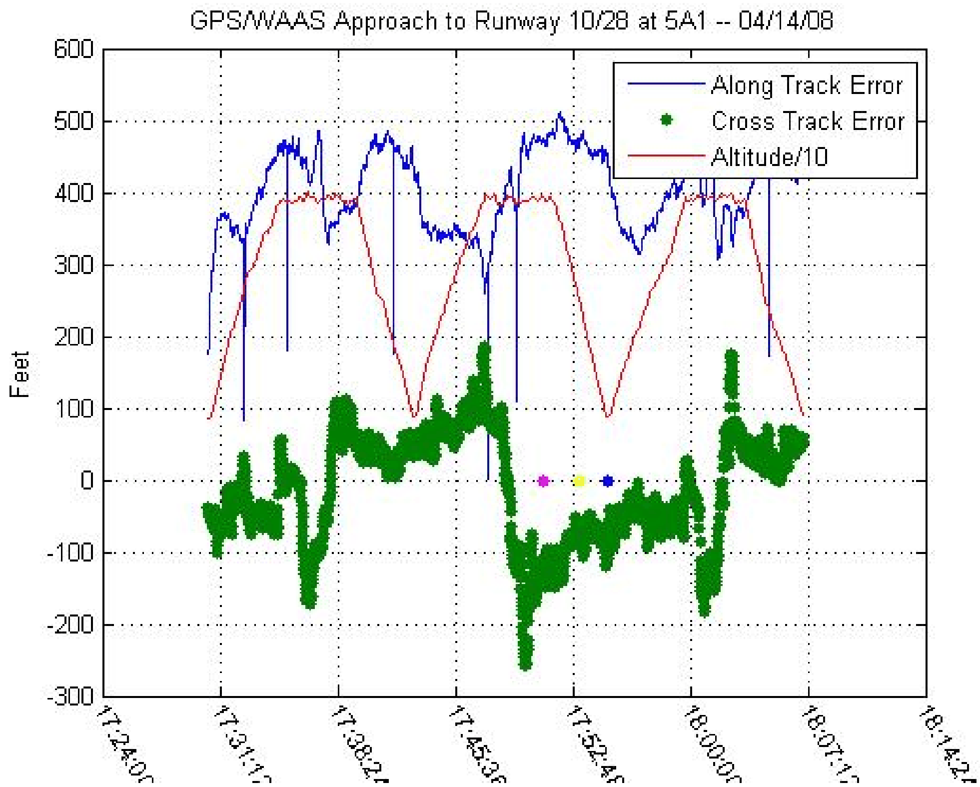
APPENDIX C: NORWALK-HURON COUNTY AIRPORT, OH

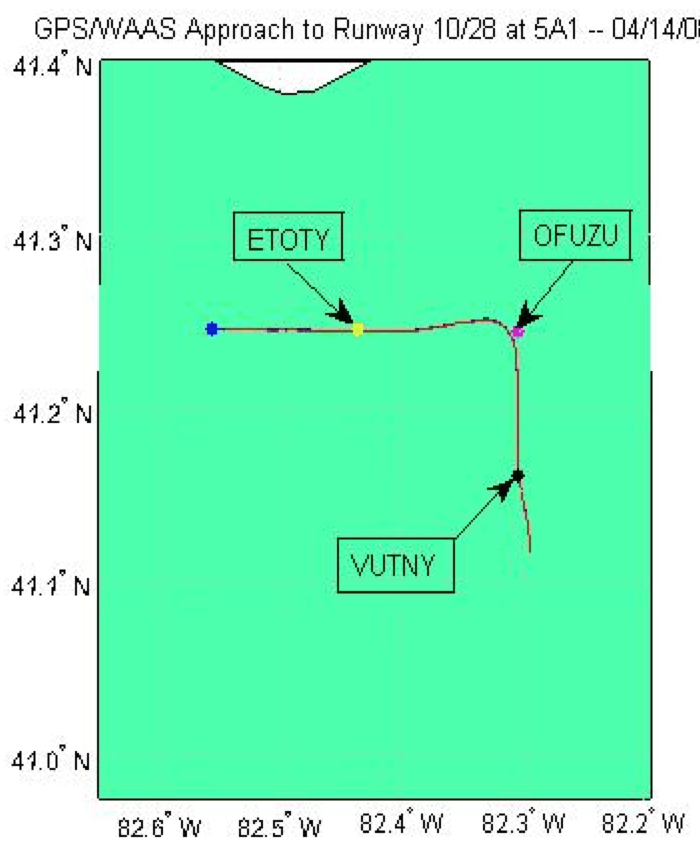
ASF* Values for Norwalk-Huron County Airport (5A1)

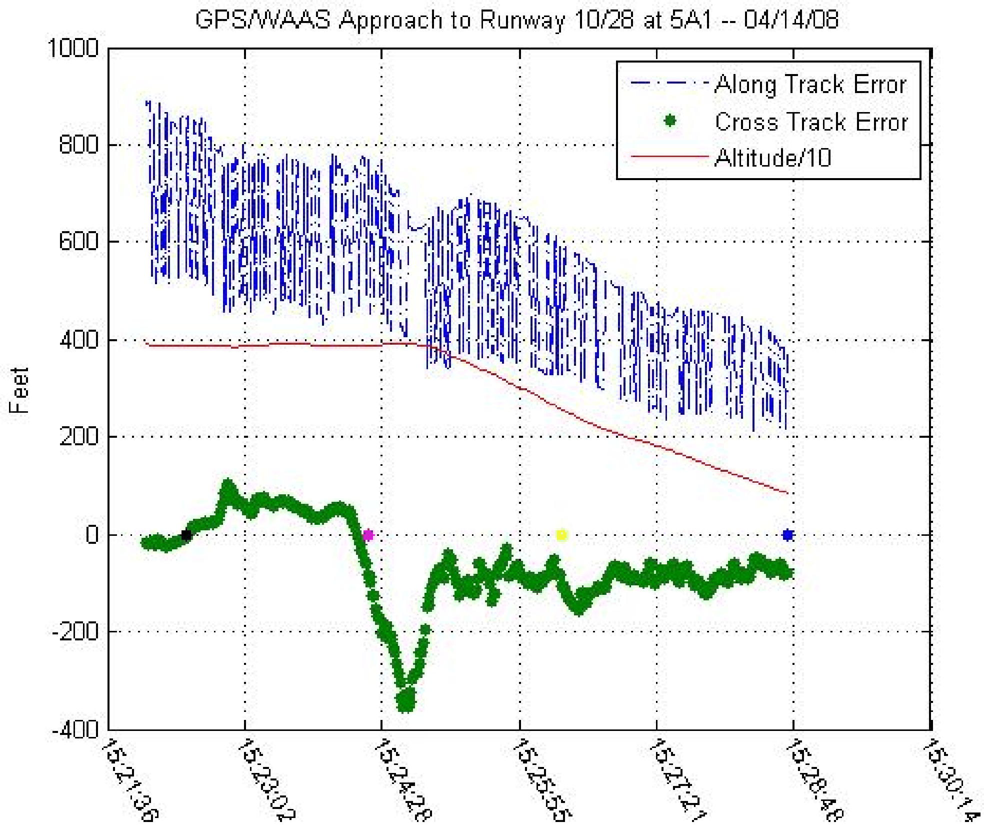
	NORWALK-HURON COUNTY AIRPORT (5A1) OHIO (values in microseconds)																						
Chain	8970					9960					7980					8290			9610				
Station	M	W	X	Y	Z	M	W	X	Y	Z	M	W	X	Y	Z	M	W	X	M	V	X	Y	Z
3/26/2004	-0.88	4.42	0.56	1.75	0.86	0.44	2.02	2.52	2.27	-0.60	3.10	2.61	2.25	1.89	1.54	-1.92	-2.20	-2.64	-2.05	-1.15	0.29	0.00	0.89
4/5/2005	-0.84	4.41	0.59	1.84	0.82	0.45	1.93	2.49	2.31	-0.61	3.07	2.56	2.12	1.89	1.54	-1.98	-2.20	-2.75	-2.06	-1.20	0.18	-0.07	0.87
3/29/2006	-0.83	4.27	0.56	1.67	0.80	0.46	1.94	2.45	2.18	-0.60	3.02	2.58	2.10	1.79	1.43		-2.10	-2.59	-2.02	-1.23		-0.24	0.85
4/4/2007	-0.80	4.35	0.55	1.18	0.83	0.58	2.01	2.39	2.33	-0.70	3.07	2.58	2.09	1.94	1.64	-1.92	-2.27	-2.53	-1.97	-1.18		-0.04	0.89
4/14/2008	-0.82	4.14	0.53	1.50	0.84	0.55	2.02	2.33	2.11	-0.72	2.01	1.56	1.17	0.86	1.39	-1.99	-2.26	-2.66	-1.92	-1.15		-0.17	0.84
Mean	-0.83	4.32	0.56	1.59	0.83	0.49	1.98	2.44	2.24	-0.65	2.85	2.38	1.95	1.67	1.51	-1.95	-2.21	-2.63	-2.00	-1.18	0.23	-0.10	0.87
Sigma	0.03	0.12	0.02	0.26	0.02	0.06	0.05	0.08	0.09	0.06	0.47	0.46	0.44	0.46	0.10	0.04	0.07	0.08	0.06	0.03	0.08	0.10	0.02
8/20/2004	-0.93	4.27	0.65	1.72	0.89	0.48		2.70	2.29	-0.63	3.04	2.63	2.28	1.85	1.51	-1.87	-2.21	-2.64	-2.04	-1.23		-0.04	0.82
8/24/2005	-0.93	4.25	0.66	1.89	0.92	0.49	1.88	2.68	2.31	-0.65	3.02	2.63		1.89	1.51	-1.92	-2.19	-2.66	-2.03	-1.18	0.30	-0.12	0.80
8/30/2006	-0.94	4.26	0.67	1.73		0.49	1.82	2.64	2.21	-0.64	3.01	2.58	2.16	1.86	1.47		-2.16	-2.57	-2.03	-1.27		-0.24	0.81
8/29/2007	-0.82	4.42	0.56	1.63	0.95	0.58	1.93	2.44	2.29	-0.72	3.07	2.67	2.27	1.94	1.53	-2.05	-2.21	-2.80	-2.00	-1.33	0.34	0.03	0.84
Mean	-0.91	4.30	0.63	1.74	0.92	0.51	1.88	2.62	2.28	-0.66	3.04	2.63	2.24	1.89	1.51	-1.95	-2.19	-2.67	-2.03	-1.25	0.32	-0.09	0.82
Sigma	0.05	0.08	0.05	0.11	0.03	0.05	0.06	0.12	0.04	0.04	0.03	0.04	0.07	0.04	0.03	0.09	0.02	0.10	0.02	0.06	0.03	0.12	0.02
Total Mean	-0.87	4.31	0.60	1.67	0.88	0.50	1.93	2.53	2.26	-0.65	2.94	2.50	2.09	1.78	1.51	-1.95	-2.20	-2.65	-2.01	-1.22	0.27	-0.10	0.84

Plots are from measured ASF* values followed by plots of averaged ASF* values




GPS/WAAS Approach to Runway 10/28 at 5A1 -- 04/14/08
Along Track Error
Cross Track Error
Altitude/10
Feet
600
500
400
300
200
100
0
-100
-200
-300


GPS/WAAS Approach to Runway 10/28 at 5A1 -- 04/14/08
ETOTY
OFUZU
VUTNY
41.4° N
41.3° N
41.2° N
41.1° N
41.0° N
82.6° W
82.5° W
82.4° W
82.3° W
82.2° W


GPS/WAAS Approach to Runway 10/28 at 5A1 -- 04/14/08
Along Track Error
Cross Track Error
Altitude/10
Feet
1000
800
600
400
200
0
-200
-400
15:21:36
15:23:02
15:24:28
15:25:55
15:27:21
15:28:48
15:30:14

APPENDIX D

GPS Non-Precision Approach Waypoints

AIRPORT	WAYPOINT							LATITUDE	LONGITUDE	DISTANCE
5A1	VUTNY	41	9	37.702	82	18		41.160	-82.300	
	OFOZU	41	14	37.88	82	18		41.244	-82.300	5.0
	ETOTY	41	14	39.87	82	26		41.244	-82.433	6.0
ACY	PUVUH	39	38	6.53	74	43		39.635	-74.717	
	UNAYY	39	32	48.05	74	47		39.547	-74.783	6.1
	PVIGNY	39	29	59.3	74	40		39.500	-74.667	6.1
ACY	RUVFO	39	27	29.45	74	51		39.458	-74.850	
	UNAYY	39	32	48.05	74	47		39.547	-74.783	6.1
	PVIGNY	39	29	59.3	74	40		39.500	-74.667	6.1
W29	HUNNE	38	51	25.24	76	8		38.857	-76.133	
	ZAKLY	38	56	17.92	76	7		38.938	-76.117	4.9
	AZLOM	38	57	25.26	76	13		38.957	-76.217	4.8
W29	AGARD	39	2	36.89	76	4		39.044	-76.067	
	ZAKLY	38	56	17.92	76	7		38.938	-76.117	6.7
	AZLOM	38	57	25.26	76	13		38.957	-76.217	4.8
BLM	AAECO	40	13	49.62	74	20		40.230	-74.333	
	DANSE	40	17	31.26	74	16		40.292	-74.267	4.8
	FEGAN	40	14	11.26	74	11		40.236	-74.183	5.1
BLM	BUBAL	40	21	14.28	74	12		40.354	-74.200	
	DANSE	40	17	31.26	74	16		40.292	-74.267	4.8
	FEGAN	40	14	11.26	74	11		40.236	-74.183	5.1
PWM	HUSAT	43	30	4.86	70	7		43.501	-70.117	
	JUVIN	43	28	38.68	70	14		43.477	-70.233	5.3
	ZIRSO	43	33	26	70	16		43.557	-70.267	5.0
PWM	TOLSE	43	27	11.86	70	20		43.453	-70.333	
	JUVIN	43	28	38.68	70	14		43.477	-70.233	4.6
	ZIRSO	43	33	26	70	16		43.557	-70.267	5.0