LORAN C ADDITIONAL SECONDARY FACTORS: IMPLICATIONS FOR MEETING REQUIRED NAVIGATION PERFORMANCE (RNP) 0.3 – AN UPDATE

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BIOGRAPHY

Dave Diggle is the Associate Director of the Avionics Engineering Center at Ohio University in Athens, Ohio. In addition to his duties as Associate Director, he leads the Loran Support Team at the Avionics Engineering Center. Dave is a member of the Institute of Navigation and the International Loran Association, 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.

Curt Cutright is a Research Engineer with the Avionics Engineering Center at Ohio University. Curt's research deals with navigation systems including INS, Loran C, GPS, and GPS software receiver development. He has a B.S. in Electrical Engineering from Ohio University.

Linn Roth is President of Locus, Inc., a Madison, WI company that specializes in high-performance digital Loran receivers for navigation and timing applications. Linn is a member of the Institute of Navigation and a Fellow of the Royal Institute of Navigation. He is President of the International Loran Association, and has received the ILA's Medal of Merit and President's Award. He received a B.A. from the University of California-Berkeley and a Ph.D. in Physiology from the University of California-San Francisco.

Chad Schweitzer is a Project Engineer at Locus, Inc. where he has worked for nearly five years. His duties include software development and support for the SatMate line of Loran C receivers. Chad holds an M.S. in Electrical Engineering from Minnesota State University at Mankato and an M.S. in Electrical Engineering from the University of Wisconsin-Madison.

Mitch Narins is the Senior System Engineer with the FAA's Navigation and Landing Product Team who has led 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 Federal Aviation Administration (FAA) has been investigating the ability of Loran C to meet Required Navigation Performance (RNP) 0.3 requirements for accuracy, availability, integrity, and continuity. The use of locally measured and/or calculated Loran C Additional Secondary Factors (ASFs) is key to Loran meeting those accuracy requirements for non-precision approach and landing guidance. The Ohio University Avionics Engineering Center (AEC) has been collecting Loran C data for the past two years at five airports situated along the United States East Coast and one in the Midwest. Flights to these 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 approach area for an airport.

At each airport, Loran C data are collected on the ground using all-in-view Loran C receivers with H-field and E-field antennas. WAAS-augmented GPS position data are collected simultaneously for use as a truth reference.

Following the collection of data, a number of stabilized approaches (using ILS when possible) are performed at the airfield. These flight paths commonly extend beyond the approach perimeter for the airport due to Air Traffic Control considerations.

In the initial stages of this program, all data collected were post-processed to: 1) generate airfield-specific ASFs, 2) produce ASF-corrected Loran C tracks, and 3) determine lateral error information showing the difference between the ASF-corrected Loran C tracks and GPS truth–the latter provided by a WAAS-augmented GPS airborne receiver. More recently, the ground and air data-collection systems have been upgraded to allow ASFs to be calculated immediately after the ground data have been collected. These ASFs are then loaded into the all-in-view Loran C receiver aboard the aircraft, the Loran C position data are corrected in real-time, and both raw and real-time ASF corrected data are logged along with WAAS-augmented GPS truth data.

This paper will provide a background on Loran C ASFs, and present results showing ASF stability for the various airports over the past two years. The paper will also document measured cross-track accuracies at each of the airports and give initial estimates of the coverage provided by a single set of ASFs for a given airport. Originally, this paper was presented at the ION 61st Annual Meeting in June 2005 [1]. Data available as of April 2005 was used as the basis for that paper. This paper has been updated and includes data that was collected in August and September 2005.

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. 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 user and the transmitter. In addition, 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 represent 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, the Secondary factor, and the Additional Secondary factor [2].

Primary Factor (PF): Since the speed of radio frequency (RF) propagation through the atmosphere is slightly less that in a vacuum, the Primary factor adjusts for this difference using the index of refraction for the atmosphere, **ν**. A value of 1.000338 is representative of the index of refraction of the atmosphere.

$$PF = \nu/c \qquad \text{where } c = 6.17936\ \mu\text{sec/nmi} \qquad (1)$$

Secondary Factor (SF): The speed of Loran C signal propagation is further slowed as the signal travels over seawater. The Secondary Factor reflects the fact that seawater is not as good a conductor as the atmosphere. As the ground wave propagates over such a path, part of the RF energy penetrates the seawater slowing the propagation speed of the signal. As such, the SF is defined as the additional amount of time by which the signal is retarded by travel over a seawater path as compared to a path purely through the atmosphere. There is no closed-form calculation for SF but several equations have been proposed. Presented here are the Harris Polynomials.

$$SF = -0.01142 + 0.00176d + 0.510483/d \qquad (2)$$
$$\text{where } d \leq 100 \text{ statute miles}$$

$$SF = -0.40758 + 0.00346776d + 24.0305/d \qquad (3)$$
$$\text{where } d \geq 100 \text{ statute miles}$$

Additional Secondary Factor (ASF): Use of the PF and SF account for the propagation delays through the atmosphere and over an all-seawater path but generally the propagation path is more complex; more representative is a combination of seawater and land over which the signal passes. The ASF is used to account for the added amount of time by which the signal is retarded when propagated over a land path. The ASF varies depending upon such items as terrain, temperature, and soil water content. ASFs can be determined in several ways. One approach is to segment the path between the user and each transmitter of interest and calculate the delay contribution based upon the properties of the segment. This is known as Millington's method. Another approach is to calculate the ASFs using a Loran C receiver at a particular point of interest. This latter approach along with some preliminary results will be discussed later in this paper [2].

ASF CALCULATION

Reference 2 contains an excellent presentation on Millington's method given in Appendix F. Overall, the method is straightforward, but to produce meaningful ASF values at a particular geographic point, or better still, over a defined area surrounding such a point, quickly 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, is currently under evaluation by the FAA Loran C ASF Working group. The BALOR (BAngor LORan Software Suite) code, once 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 will be investigated in the remainder of this paper. 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 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 [3].

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 antenna are used to provide truth reference information. 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:

$$TOA_{GRI}^{N} = PF * d + SF(d) + ASF_{GRI}^{n} + UTC_{off} + \tau_R + \tau_{\mathrm{B}} \quad (4)$$

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 E-Loran, 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:

$$ASF^{*N}_{GRI} = ASF_{GRI}^{N} + UTC_{off} + \tau_R \quad (5)$$

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 and each manufacturer of Loran C receivers characterizes their respective receiving systems and thus defines τ_R. Further, the receiver used aboard the aircraft in this flight testing is also a SatMate 1030 so the Loran C airborne TOAs which are processed also include a nearly identical delay except for a slight difference in antenna cable length. For the time being, then, errors associated with these two elements of equation (5) 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 [4]

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, and continuity of service required of a particular flight regime under consideration [4]. In the case of non-precision approach, the desired designation using 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 about 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 than10^{-5} during the duration of flight. **Figure 1** 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 only to the accuracy achievable for the Loran C cross-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 capable GPS receiver. 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, NSE for stabilized approaches conducted under visual meteorological conditions (VMC) will be shown to be less than 25% of the 1000 ft allocated for NSE under the RNP (0.3) definitions.

FLIGHT TEST RESULTS

Results will be presented for four 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; Portland International Jetport (PWM), Portland, ME; and Jacksonville/Craig Municipal Airport (CRG), Jacksonville, FL. The two airports omitted are Belmar Farmingdale Airport (BLM), Monmouth, NJ and Baybridge Airport (W28), Stevensville, MD. Both of these fields are reasonably close to Atlantic City and the results have not been completed due to time constraints.

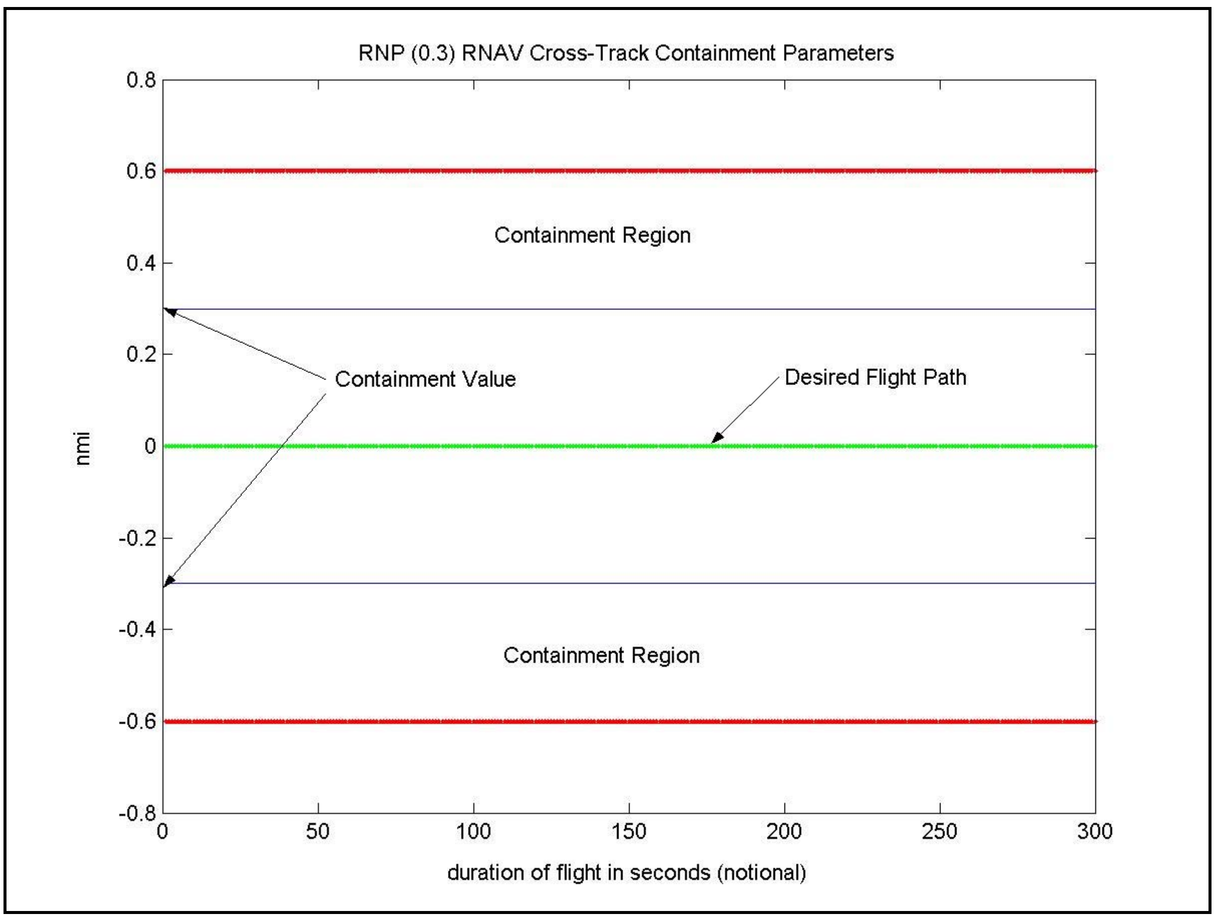

Figure 1

Figure 2 shows the location of the airport at Norwalk, Ohio. The site is approximately 5 miles south of the Loran Monitor (LorMon) site at Plumbrook, Ohio. 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 C 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 balanced pattern about the GPS-derived position, while the E-field derived data generally yield a position with a large bias value.

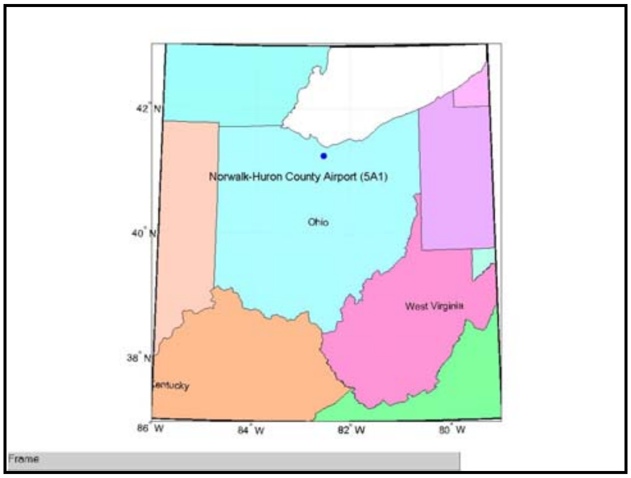

Figure 2

ASF* data have been generated with the measurement system since the early spring of 2004 at the airports in this study. The spreadsheet in **Table 1** shows information from 2004 and 2005 for 5A1. The periods corresponding to the end of winter are 3/26/2004 and 4/5/2005; those corresponding to the end of summer are 8/20/2004 and 8/24/2005. Comparison of the individual values for master and secondary Loran stations (LorSta's) in each of chains visible at Norwalk indicates strong repeatability year-to-year despite the fact that the data are measured using the Loran C receiver clock. This clock is synchronized to a composite frequency of all the stations being tracked; note that master stations are managed relative to rather than 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 early spring which corresponds to the wettest period of the year.

The 8/24/2005 ASF* values were loaded into the SatMate1030 receiver aboard the aircraft and the approaches shown in **Figure 3** were flown at the Norwalk-Huron County Airport (5A1) before departing the area. In most cases, the final-approach fix (FAF) for a given approach is located approximately 5 nmi from runway threshold. At a recent meeting of the Loran C ASF Working Group (March 2005) there was interest in extending that distance to 10 nmi in order to cover all eventualities regarding RNP (0.3) approaches. Since 5A1 is an uncontrolled airfield with little traffic, three 10 nmi approaches were flown to each runway end. Note that 3-degree climb-outs were counted as reverse direction approaches in the interest of saving time. The flight tracks are shown in **Figure 3** starting with a slow-climb takeoff to the east simulating an approach to Runway 28, a tear-drop turn, with a true approach to Runway 28 and a slow climb-out simulating an approach to Runway 10. This cycle is flown once more with a final approach to Runway 28 completing the airwork.

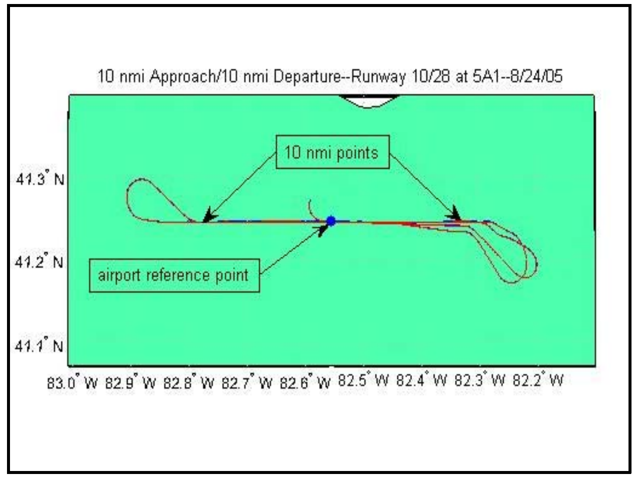

Figure 3

Figure 4 has been retained from the June 2005 ION paper since it is illustrative of the data presented in the figures throughout the paper. It shows a full 10 nmi approach/departure on Runway 10. The approach commences 10 nmi from the Runway 10 threshold and ceases 10 nmi from Runway 28 threshold. The altitude at the beginning of the approach is approximately 4000 ft msl. On a three-degree glideslope, this represents 3000 ft AGL with respect to the field elevation at 5A1 which is about 900 ft msl. The approach continues to approximately 100 ft AGL for a low pass over the airport and subsequent three-degree climb-out simulating the approach to Runway 28. Shown on the plot are the altitude scaled by 10 for fit, the along-track error, and the cross-track error. Throughout the approach, the cross-track error remains below150 ft, well within the navigation sensor error (NSE) accuracy requirement of RNP (0.3). The along-track error on the plot has less meaning since a five-second integration of the Loran C TOAs is used in the SatMate 1030 receiver processing. This five-second delay has been removed when comparing GPS-derived and Loran C-derived positions to derive the NSE. It has no effect on the cross-track error since a stabilized published approach is used (generally either ILS, when available, or GPS); however, with the aircraft traveling at 250 ft/sec, the approximately 1250 ft of along-track error due to TOA integration has been removed before the along-track data is displayed. Even with this taken into account, the along-track error is still under 1920 ft which is the RNP (0.3) limit on accuracy.

With the exception of the airwork at 5A1, only 5-nmi approaches (no simulated departure) will be flown at the other airports to approximately 100 ft AGL for a low full-length approach over the runway followed by an immediate climb to pattern altitude and return for the next approach. Three approaches will be flown at each of those airports.

Table 1. 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
Mean	-0.86	4.42	0.58	1.80	0.84	0.44	1.98	2.51	2.29	-0.60	3.09	2.59	2.19	1.89	1.54	-1.95	-2.20	-2.70	-2.06	-1.18	0.23	-0.03	0.88
Sigma	0.03	0.01	0.02	0.06	0.03	0	0.06	0.02	0.03	0.01	0.02	0.04	0.09	0	0	0.04	0	0.08	0.01	0.04	0.08	0.05	0.02
8/20/2004	-0.9	4.27	0.65	1.72	0.89	0.48		2.7	2.29	-0.6	3.04	2.63	2.28	1.85	1.51	-1.9	-2.2	-2.6	-2	-1.2		-0	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
Mean	-0.93	4.26	0.65	1.81	0.91	0.48	1.88	2.69	2.3	-0.64	3.03	2.63	2.28	1.87	1.51	-1.9	-2.2	-2.65	-2.04	-1.21	0.30	-0.08	0.81
Sigma	0	0.01	0.00	0.12	0.02	0.01		0.01	0.01	0.01	0.01	0		0.03	0	0.04	0.01	0.01	0.00	0.04		0.05	0.01

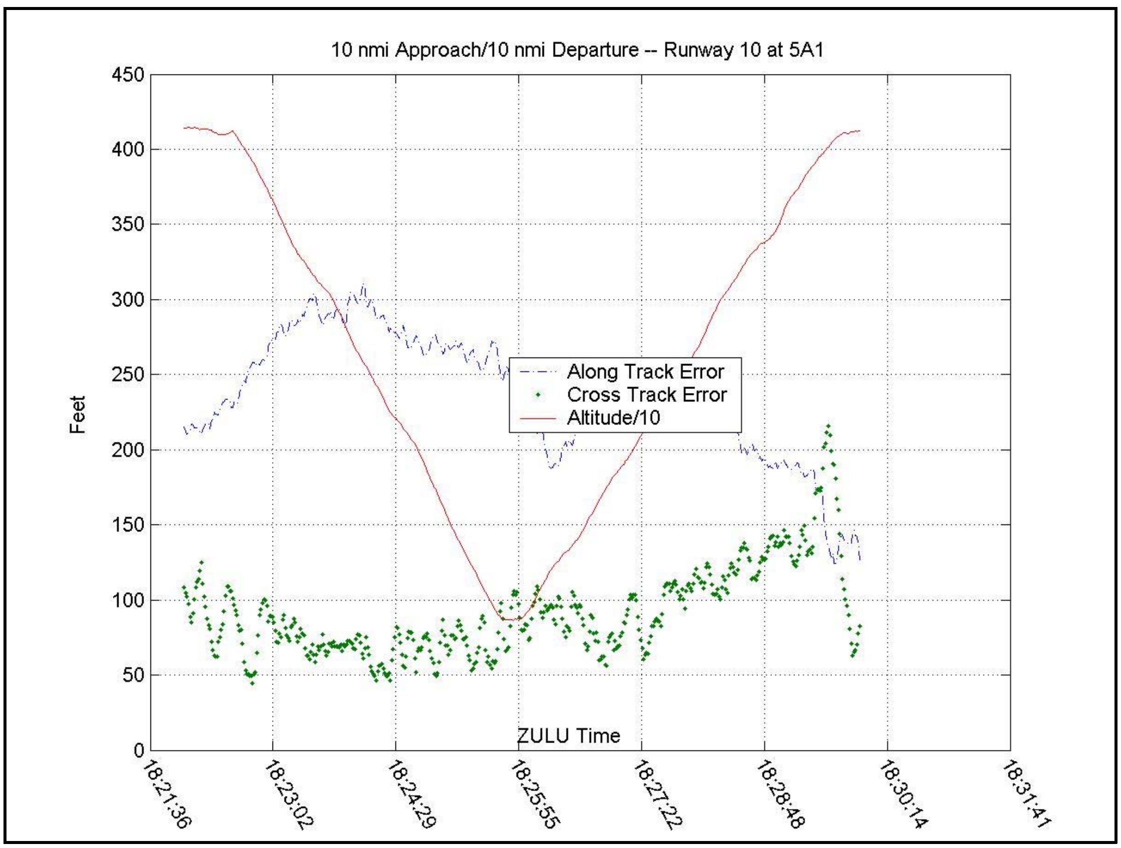

Figure 4

Figure 5 is a plot of all of the approaches completed at 5A1. The cross-track error is well behaved on all of the approaches (under 150 ft). The airwork ends with a final approach on Runway 28 with a break-off at midfield and area departure.

Figure 6 shows the general location of the airport at Atlantic City. The ASF* measurements were generated at ACY following arrival at 2:00 PM on 8/23/2005. The data were collected at the edge of the general aviation ramp. Atlantic City International Airport is not in the immediate vicinity of a LorMon station, the closest being about 75 miles away at Sandy Hook, New Jersey. The ASF* values are shown in **Table 2**. As with the ASF* values for Norwalk-Huron County Airport, there is excellent repeatability year-to-year, spring 2004 to spring 2005; summer 2004 to summer 2005 is reasonably close, as well. Three approaches to Runway 13 were flown that same afternoon. All approaches were 5-nmi stabilized approaches commencing at 1500 ft AGL and terminating with a low pass at 100 ft over the full length of the runway.

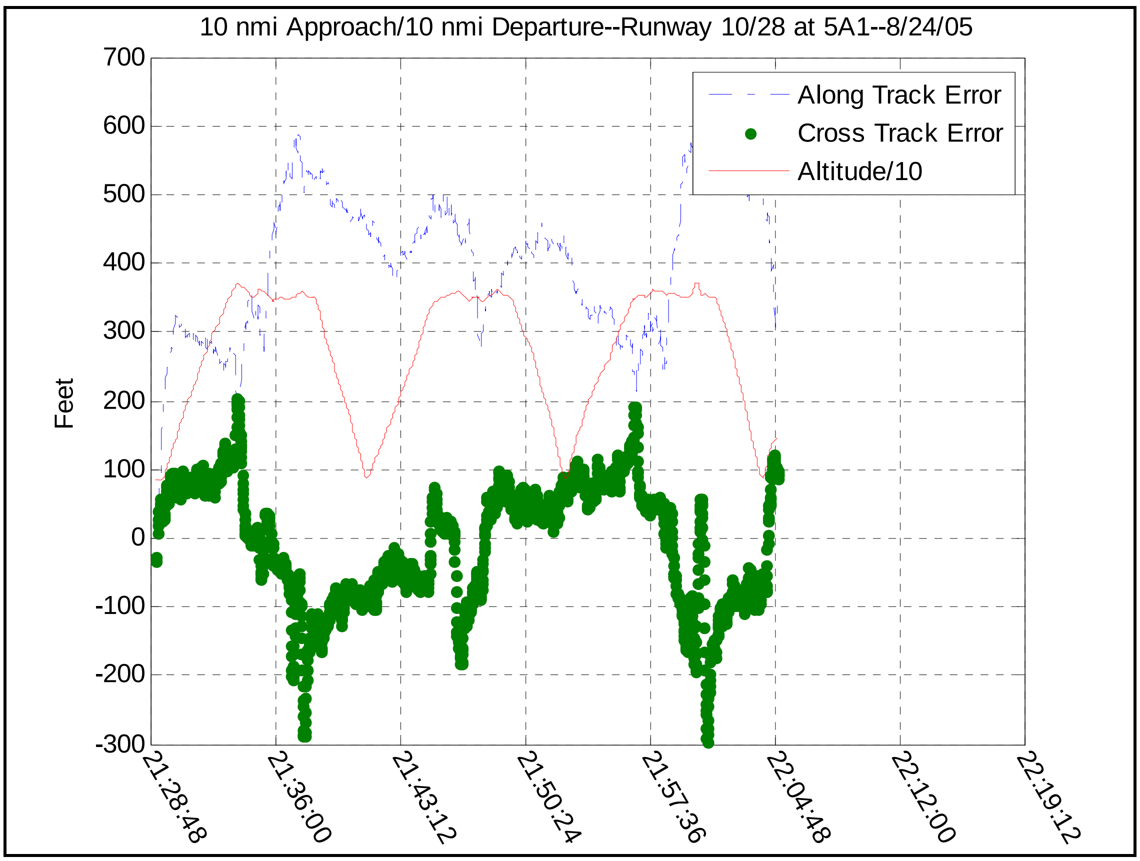

Figure 5

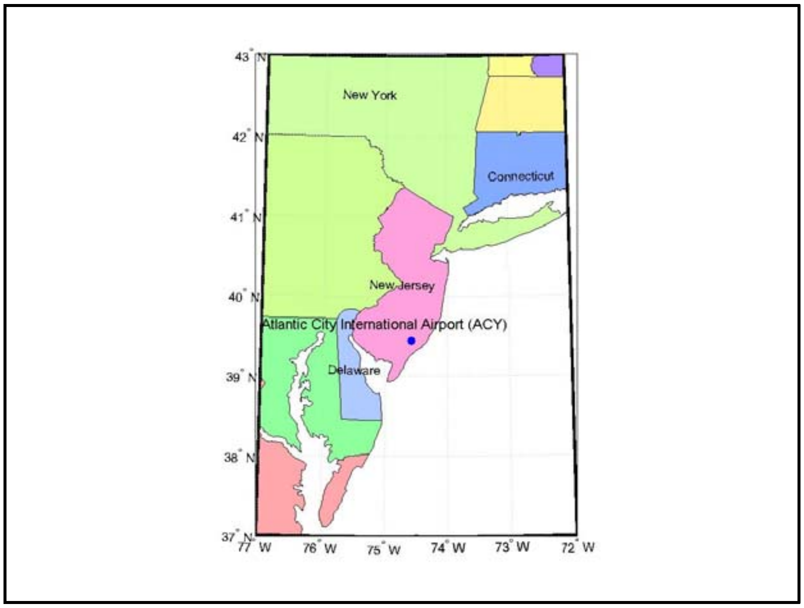

Figure 6

Table 2. ASF* Values for Atlantic City International Airport (ACY)

	ATLANTIC CITY INTERNATIONAL AIRPORT (ACY) NEW JERSEY (values in microseconds)																					
Chain	8970					9960					7980					8290			5930			
Station	M	W	X	Y	Z	M	W	X	Y	Z	M	W	X	Y	Z	M	W	X	M	X	Y	Z
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		-1.42	8.58	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	3.50
Mean	2.40		1.22	5.20		1.16	2.45	-1.62	0.61	2.75	3.53			-1.08	0.49				2.85	-1.74	-1.36	
Sigma	0.01		0.08	0.12		0.05	0.04	0.02	0.01	0.08	0.02			0.04	0.05				0.06	0.03	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	
Mean	2.42	4.12	1.36	5.19		1.18	2.51	-1.67	0.56	2.68	3.51	6.10		-1.08	0.48				2.95	-1.80	-1.32	
Sigma	0.13	0.13	0.22			0.04	0.04	0.08	0.05	0.09	0.12			0.08	0.06				0.01	0.08	0.05	

Figure 7 shows the flight tracks flown in the course of completing the three approaches to Runway 13. The scaled-altitude and along- and cross-track error plots are shown in **Figure 8**. Cross-track error is within 100 ft during the last 5 nmi of the approach and barely exceeds 250 ft during the entire series of approaches.

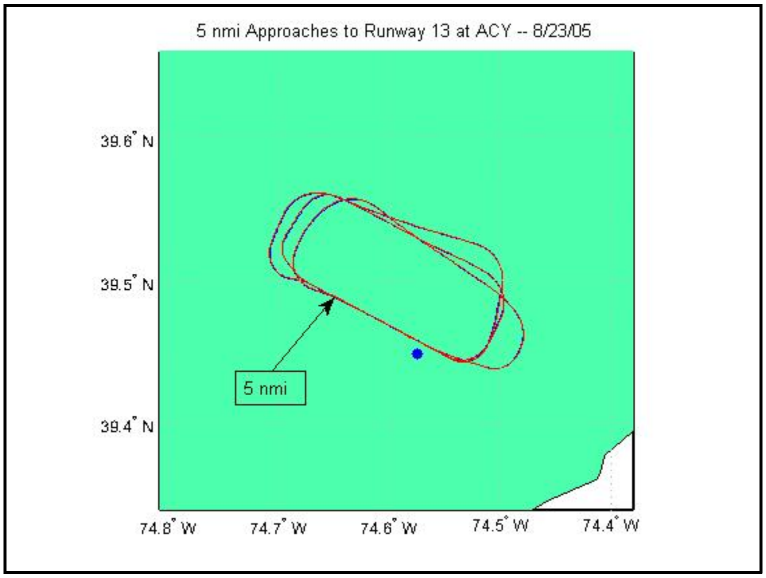

Figure 7

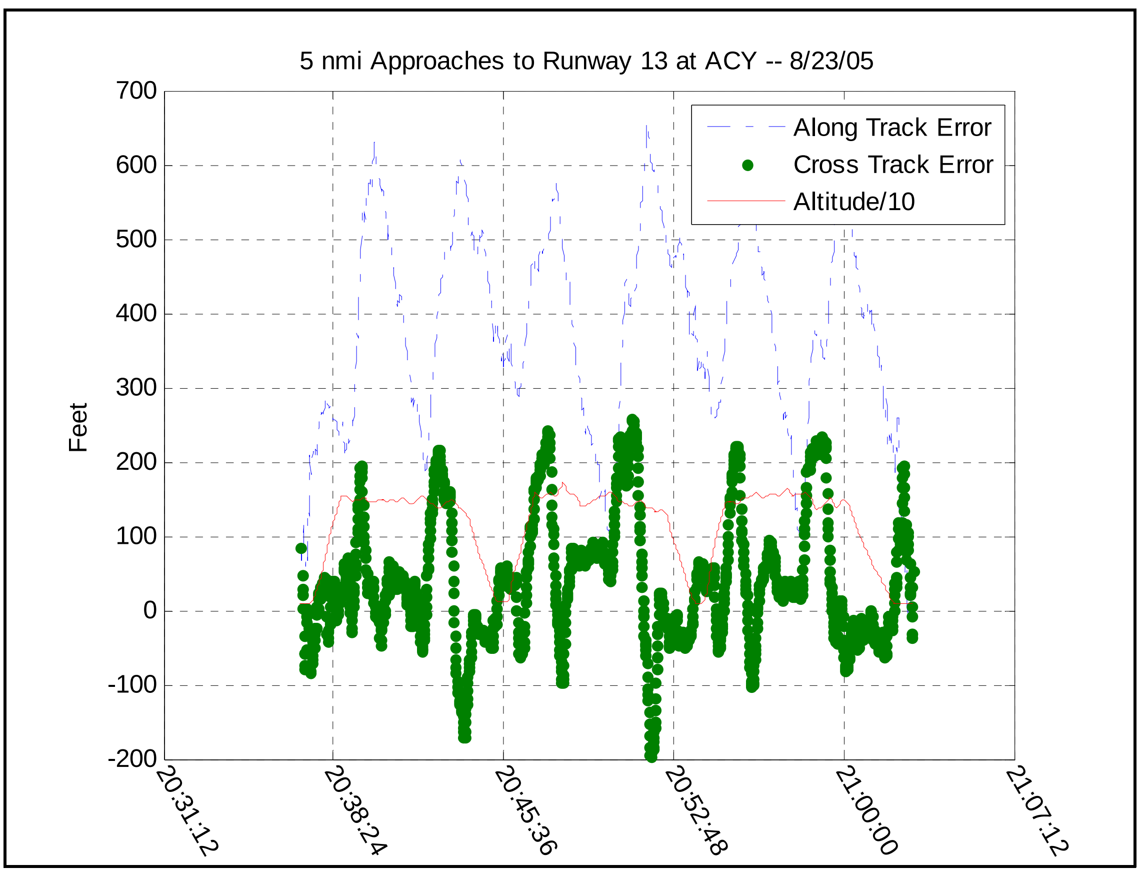

Figure 8

Figure 9 shows the general location of the airport at Portland, Maine. Old ASF* values from 4/25/2005 were loaded into the SatMate 1030 receiver prior to entering the local Portland area on 8/30/2005. The ground track is shown in **Figure 10** and the scaled-altitude and along- and cross-track error plots in **Figure 11**. Cross-track error is within 100 ft during the last 5 nmi of the approach and barely exceeds 300 ft during the entire 20-nmi arrival. This is indicative of excellent ASF* repeatability. The current set of ASF* measurements were generated at PWM on 8/30/2005 following arrival at 3:00 PM. The data were collected on the general aviation ramp next to the FBO–Northeast AirMotive. Portland International Jetport is located in the immediate vicinity of a LorMon station at Cape Elizabeth, Maine. ASF* values are shown in **Table 3**. The ASF* values for the end-of-summer period at PWM exhibit the repeatability seen at the previous two airports, i.e. ACY and 5A1, from a year-to-year standpoint. In fact, the spring 2005 ASF* values bear a closer resemblance to those collected in summer 2004 and summer 2005 rather than those collected in late spring 2004. Further, taking into consideration the dual rated LorSta transmitters, the "sticks-in-the-fix" are essentially those belonging to 9960, the Northeast Chain. Approaches were flown later that same day to Runway 11. All approaches were 5-nmi stabilized approaches with a starting altitude of 1500 ft AGL, ending with a low pass at 100 ft over the full length of the runway. The following morning, a 10-nmi slow climb departure from Runway 11 over seawater was performed before departing the area.

Figure 12 shows the flight tracks flown in the course of completing the three approaches to Runway 11. **Figure 14** is a plot of the three approaches to Runway 29 showing scaled altitude, along-track, and cross-track error. Cross-track error is within 150 ft during the last 5 nmi of the approach and remains under 300 ft during the entire series of approaches. **Figure 13** shows the flight path followed during the 10-nmi overwater departure from Runway 11; **Figure 15** is a plot of scaled altitude, along-track, and cross-track error for the same departure. Cross-track error slightly exceeds 150 ft in the vicinity of the land/sea interface and diminishes as the aircraft proceeds out over the ocean to the 10 nmi point.

Table 3. 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	Z	M	W	X	Y	Z	M	W	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	
Mean	3.27	1.89	1.54	0.67		1.54	0.49	-1.84	1.19	3.59			-1.90	-0.40	0.87	-1.99	-0.01	
Sigma	0.17		0.08			0.11	0.05	0.01	0.04	0.08					0.08	0.01	0.09	
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	
Mean	3.21	-2.40	1.46	5.33		1.45	0.58	-1.81	1.23	3.66			-1.96	-0.45	0.96	-1.90	0.20	2.71
Sigma	0.01		0.00			0.01	0.02	0.10	0.03	0.03						0.22	0.14	

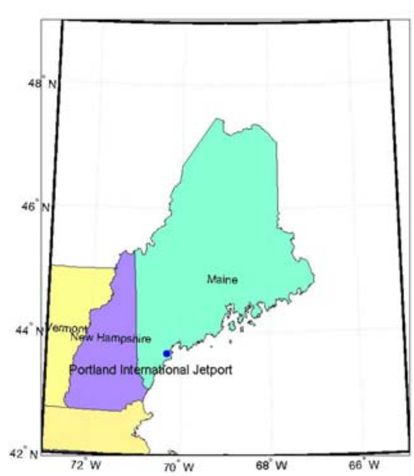

Figure 9

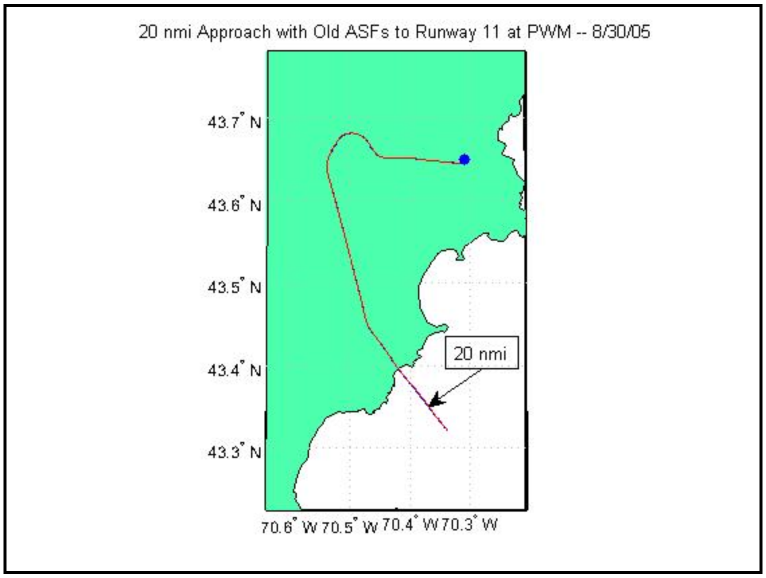

Figure 10

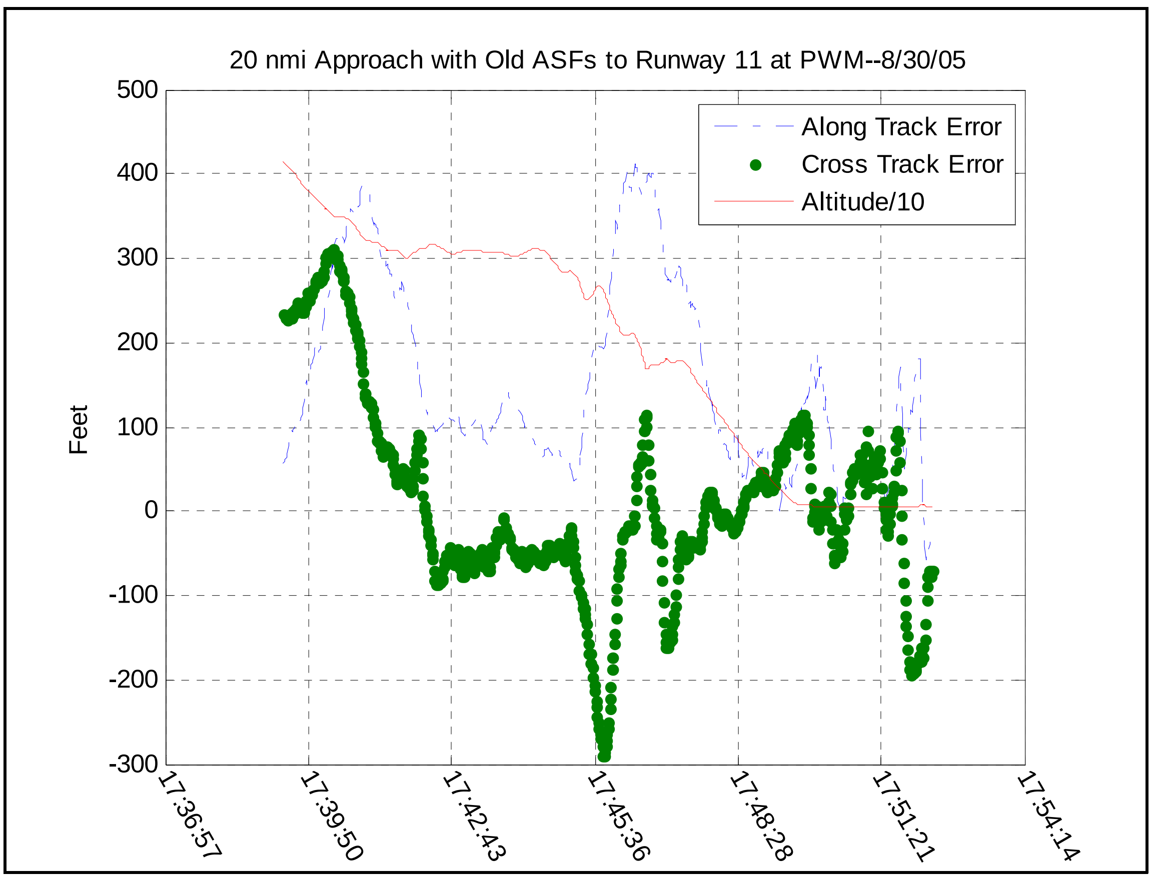

Figure 11

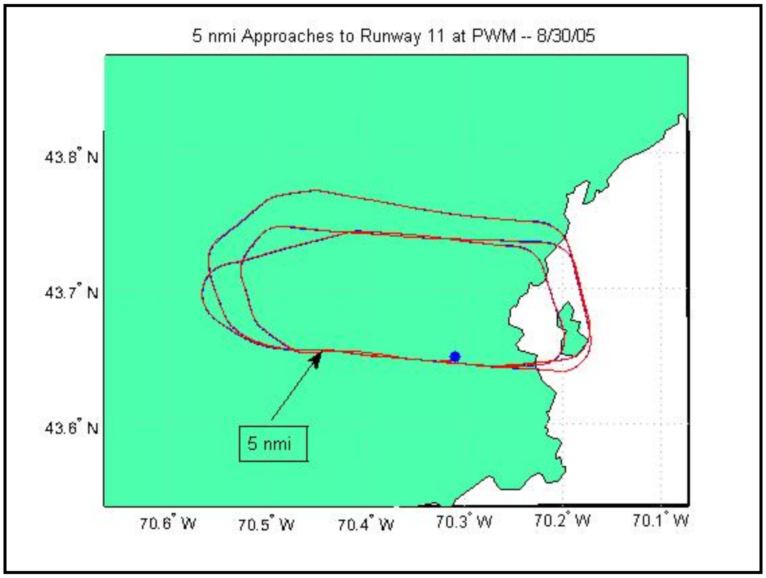

Figure 12

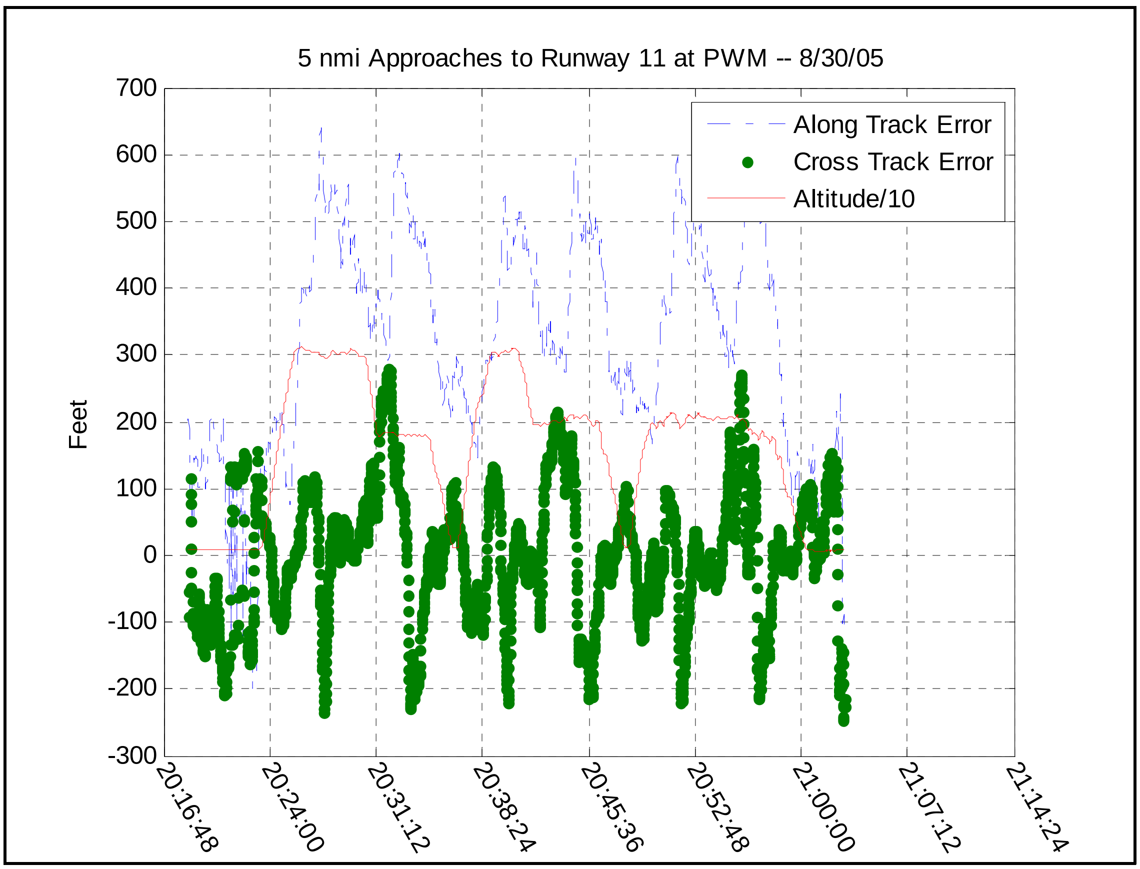

Figure 13

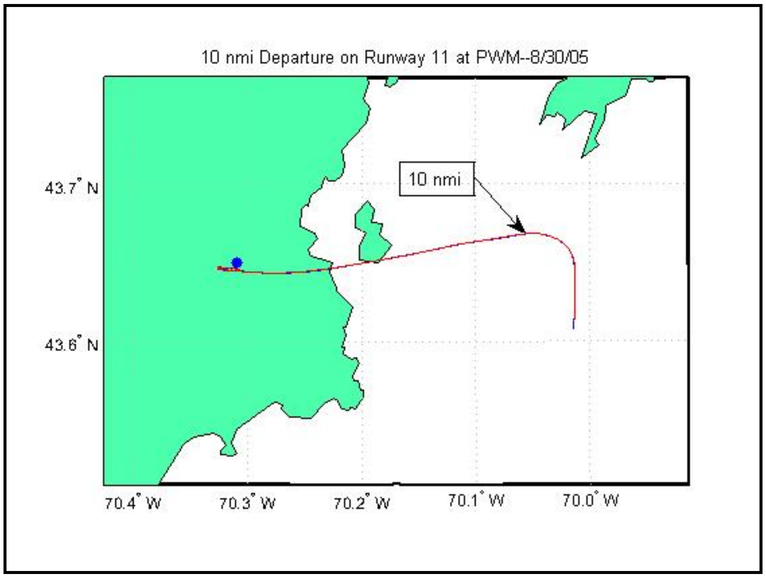

Figure 14

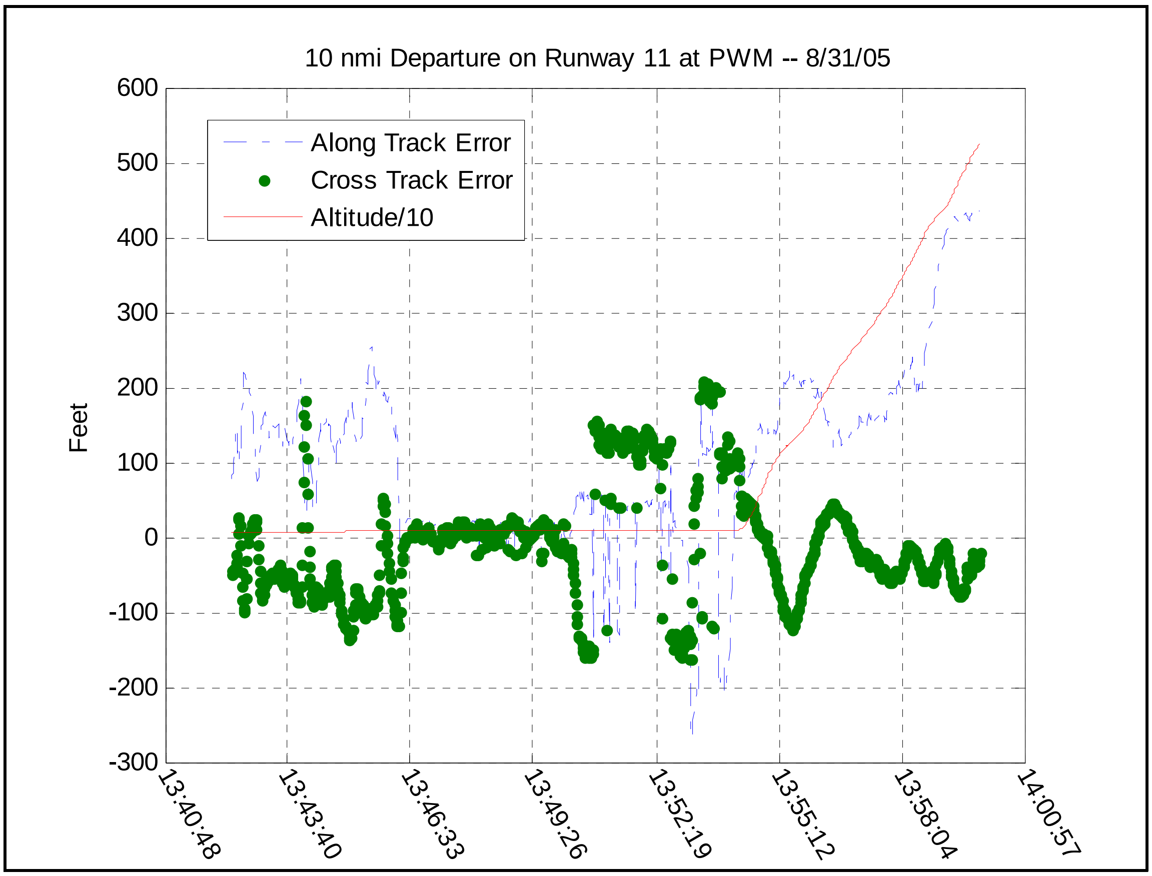

Figure 15

Figure 16 shows the general location of Craig Municipal Airport in the vicinity of Jacksonville, Florida. The ASF* measurements were generated at CRG on the morning of 9/1/2005. The data were collected beside the general aviation ramp next to the FBO–Craig Air Center. Craig Municipal Airport is located in the immediate vicinity of a LorMon station located on the Mayport Naval Base. ASF* values are shown in **Table 4**. The ASF* values for CRG exhibit the same repeatability seen at two of the previous airports, i.e. ACY and 5A1, from a year-to-year standpoint. The ASF* values for late summer 2004 and 2005 are also reasonable when compared with those for early spring of 2004 and 2005. Approaches were flown later that same morning to Runway 32. All approaches were vectored by air traffic control and pass over the coastline (outbound and inbound) before reaching the 5-nmi point from threshold at which the approach begins. All approaches were 5-nmi stabilized approaches with a starting altitude of 1500 ft AGL, ending with a low pass at 100 ft over the full length of the runway.

Figure 17 shows the flight tracks flown in the course of completing the three approaches to Runway 32. **Figure 18** is a plot of the three approaches to Runway 32 showing scaled altitude, along-track, and cross-track error. Cross-track error is within 100 ft during the last 5 nmi of the approach and remains under 500 ft during the entire series of approaches.

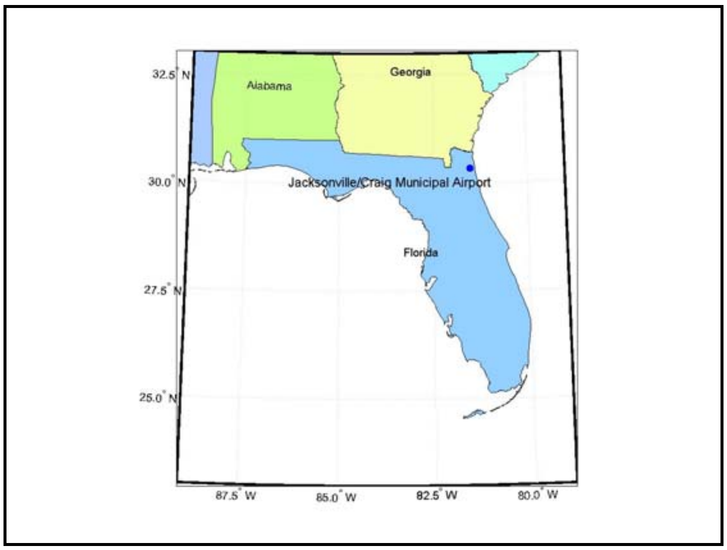

Figure 16

Table 4. ASF* Values for Craig Municipal/Jacksonville Airport (CRG).

	JACKSONVILLE/CRAIG MUNICIPAL AIRPORT (CRG) FLORIDA (values in microseconds)																			
Chain	8970					9960					7980					9610				
Station	M	W	X	Y	Z	M	W	X	Y	Z	M	W	X	Y	Z	M	V	X	Y	Z
3/23/2004	2.93	1.07	3.66	5.59	3.92	3.98	-5.69	-1.13	-1.24	3.41	1.00	3.49	-0.08	-0.06	-1.11	1.77	3.15	3.35	-2.82	1.29
4/27/2005	2.98	1.08	3.98		3.96	4.20		-0.98	-1.24	3.60	1.00	3.49	-0.13	-0.06	-1.11	1.80	3.15	3.28	-2.92	1.30
Mean	2.96	1.08	3.82	5.59	3.94	4.09	-5.69	-1.06	-1.24	3.51	1.00	3.49	-0.10	-0.06	-1.11	1.79	3.15	3.32	-2.87	1.30
Sigma	0.04	0.01	0.23		0.03	0.16		0.11	0	0.13	0	0	0.04	0	0	0.02	0	0.05	0.07	0.01
8/20/2004	3.14	1.10	4.20		4.22	4.32		-0.93	-1.23	3.73	1.02	3.58	-0.08	-0.03	-1.11	2.01		3.78	-2.84	1.32
9/1/2005	3.06	1.09	4.06		4.10	4.22		-0.96	-1.26	3.63	1.00	3.53	-0.09	-0.04	-1.11	2.06			-2.78	1.30
Mean	3.10	1.10	4.13		4.16	4.27		-0.95	-1.25	3.68	1.01	3.56	-0.08	-0.03	-1.11	2.04		3.78	-2.81	1.31
Sigma	0.06	0.01	0.10		0.08	0.07		0.02	0.02	0.07	0.01	0.04	0.00	0.00	0.00	0.04			0.04	0.01

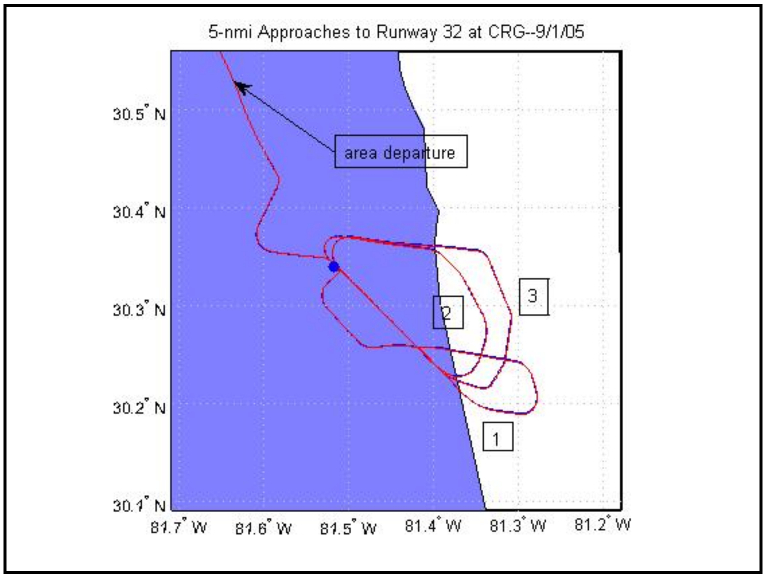

Figure 17

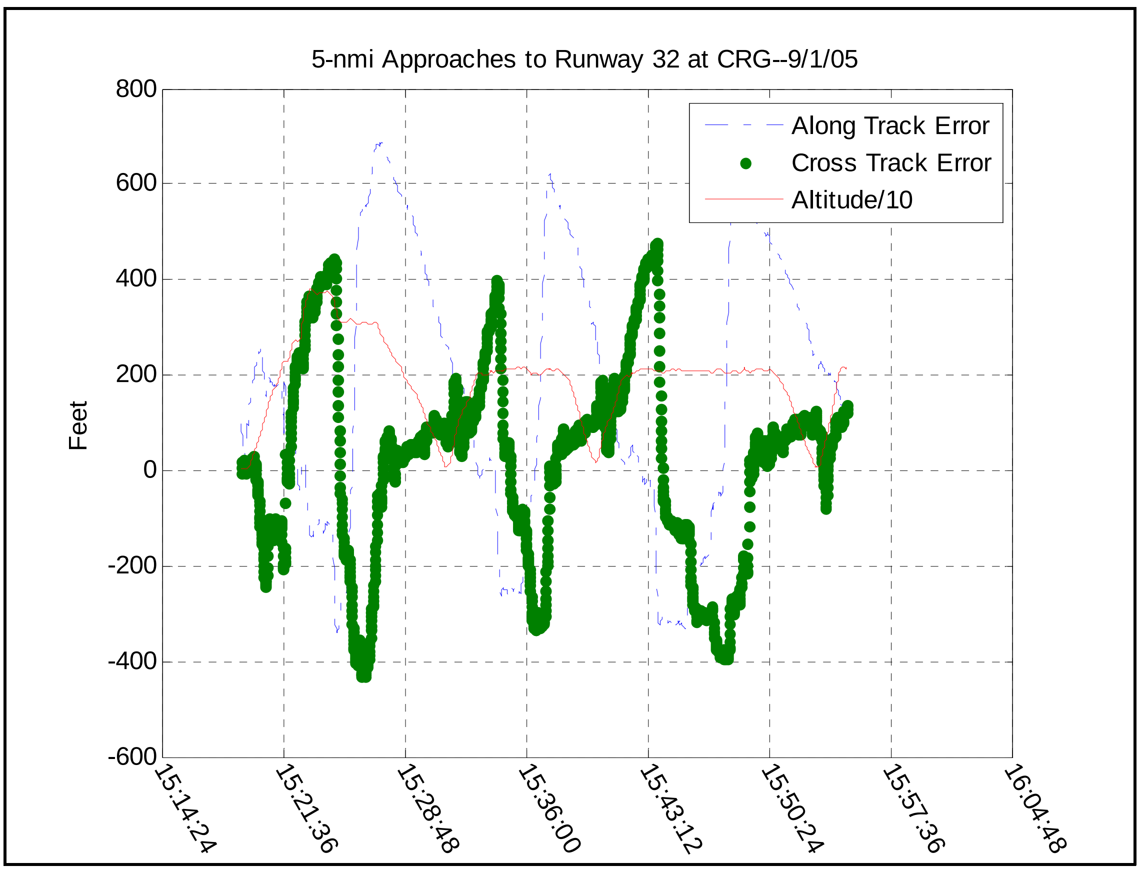

Figure 18

SUMMARY AND CONCLUSIONS

Locally generated ASF* measurements demonstrate year-to-year (temporal) consistency for all six airport locations, four of which are shown in this paper, early spring 2004 to early spring 2005 and late summer 2004 to late summer 2005. The exception to this is at Portland, Maine where the early Spring 2004 ASF* values do not compare well with any of the ASF* values collected thereafter. It is not known with certainty but the new timing-and-frequency equipment (TFE) upgrade at the Seneca, New York Master LorSta may have occurred sometime between spring and summer of 2004.

The analysis of flight measurements shows that the Loran C cross-track error is well behaved for 5-nmi stabilized approaches typical of those published by the FAA for non-precision approach. At one location, Norwalk-Huron County Airport (5A1), Ohio, 10 nmi stabilized approaches were conducted. Cross-track error at this airport, which is in close vicinity to the Plumbrook, Ohio LorMon station, showed 100-150 ft cross-track error over a series of three approaches which varied in altitude between approximately 3000 ft to 100 ft returning to 3000 ft AGL. At the four airports shown, cross-track error throughout the patterns flown in the vicinity of these airports remained below 500 ft throughout turns and variations in altitude. These results are consistent with similar airwork conducted over the past several years. Analysis in Reference 3 for ACY shows that Loran C cross-track error meets the RNP (0.3) NSE criteria for approaches flown with ASF* values collected several months prior but used as though they were current values. The approach into PWM on 8/30/2005 flown with ASF* values from 4/25/2005 (see **Figures 10** and **11**) also clearly supports the RNP (0.3) NSE criteria. The data in the four spread sheets (Tables 1 through 4) tend to support this analysis since the August 2004 and August/September 2005 data compare favorably to the March 2004 and April 2005 data with the noted exception at Portland, Maine for Spring 2004.

While the sets of ASF* values are limited, it appears that a single set of ASF* values will be sufficient to meet the NSE cross-track requirements (1000 ft or less) for Loran C RNP (0.3) non-precision approach. While previous analysis has indicated that the variation in temporal values throughout the year may be sufficiently bounded to limit the need for ASF* values to a single set for an entire year, it is likely that twice annual updates may be needed for some airports where all-in-view geometry is limited. 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. Overall, with new TFE installed at all CONUS LorSta locations and the upcoming move to time-of-transmission control, ASF* values, and ultimately the true ASF values, should prove to be more stable than those currently available, thus yielding even greater Loran C cross-track accuracies than those presently shown.

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ACKNOWLEDGEMENTS

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