LORAN C ACCURACY CONSIDERATIONS: TERMINAL AREA AND EN ROUTE

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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.

Mitch Narins is the Senior Systems Engineer with the FAA's Navigation and Landing Product Team who 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 Federal Aviation Administration (FAA) has been investigating the capability 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 in the terminal area for non-precision approach and landing guidance. More recently, the use of Loran C in the en-route environment, as a backup for the use of GPS in Automatic Dependent Surveillance-Broadcast (ADS-B), has become a topic of interest.

The Avionics Engineering Center (AEC) at Ohio University has been collecting Loran C data for the past three 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 terminal area for an airport. In addition, Loran C data have been collected during this time period while en route to and from each of these airports.

This paper will provide a background on Loran C ASFs and present results showing ASF stability for the various airports over the past three years. The paper will also document available cross-track accuracies as a function of altitude in the terminal area for each of the airports and show typical coverage provided by a single set of ASFs for a given airport. Results will also be presented showing cross-track accuracies as a function of altitude during the en-route phase between the airports under consideration. Information from three separate Loran receivers (an Apollo 618, a BFG-Jet 7201, and a Locus SatMate 1030) will be used for the en-route portion of the paper.

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. 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 1 for a detailed description of the phase factor parameters.

ASF CALCULATION

Millington's method [1,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 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 has been used exclusively over the past three 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 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 [2].

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. 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 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:

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

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 and each manufacturer of Loran C receivers characterizes their respective receiving systems and thus defines τ_R. In this research, the receiver used aboard the aircraft during flight testing is also a SatMate 1030 so 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 [3]

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 in a particular flight regime under consideration [3]. 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 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 than 10^{-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 enabled 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 30% of the 1000 ft (|mean| plus two sigma) allocated for NSE under the RNP (0.3) definitions.

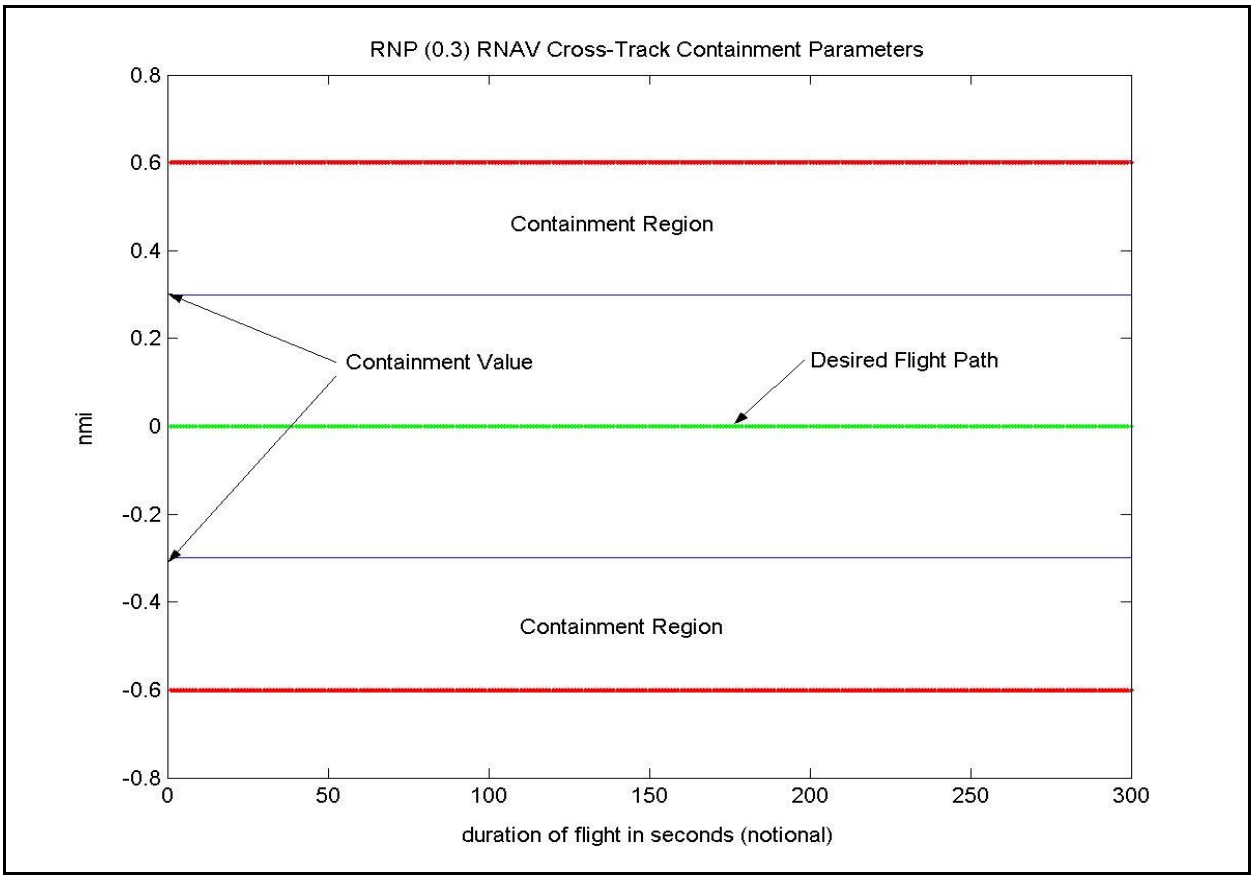


Figure 1

FLIGHT TEST RESULTS–TERMINAL AREA

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.

The spreadsheet in **Table 1** shows information from 2004, 2005, and 2006 for 5A1. The periods corresponding to the end of winter are 3/26/2004, 4/5/2005, and 3/29/2006; those corresponding to the end of summer are 8/20/2004, 8/24/2005, and 8/30/2006. Comparison of the individual values for master and secondary Loran stations (LorSta's) in each of the chains visible at Norwalk 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 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 late winter which corresponds to the wettest period of the year. Data for ACY, PWM, and CRG are contained in the appendix.

Table 1. ASF* Values for Norwalk-Huron County Airport (5A1) Ohio

	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
Mean	-0.85	4.37	0.57	1.75	0.83	0.45	1.96	2.49	2.25	-0.60	3.06	2.58	2.16	1.86	1.50	-1.95	-2.17	-2.66	-2.04	-1.19	0.23	-0.10	0.87
Sigma	0.02	0.08	0.02	0.09	0.03	0.01	0.05	0.04	0.07	0.01	0.04	0.03	0.08	0.06	0.06	0.04	0.06	0.08	0.02	0.04	0.08	0.12	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
Mean	-0.93	4.26	0.66	1.78	0.91	0.48	1.85	2.67	2.27	-0.64	3.02	2.61	2.22	1.87	1.50	-1.90	-2.19	-2.62	-2.03	-1.23	0.30	-0.13	0.81
Sigma	0.01	0.01	0.01	0.10	0.02	0.01	0.04	0.03	0.05	0.01	0.02	0.03	0.08	0.02	0.02	0.04	0.03	0.05	0.01	0.05		0.10	0.01
Total Mean	-0.89	4.31	0.61	1.78	0.87	0.47	1.92	2.59	2.28	-0.62	3.05	2.61	2.22	1.86	1.51	-1.92	-2.18	-2.66	-2.04	-1.20	0.26	-0.09	0.84

Approaches Using Measured ASF* Values.

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.

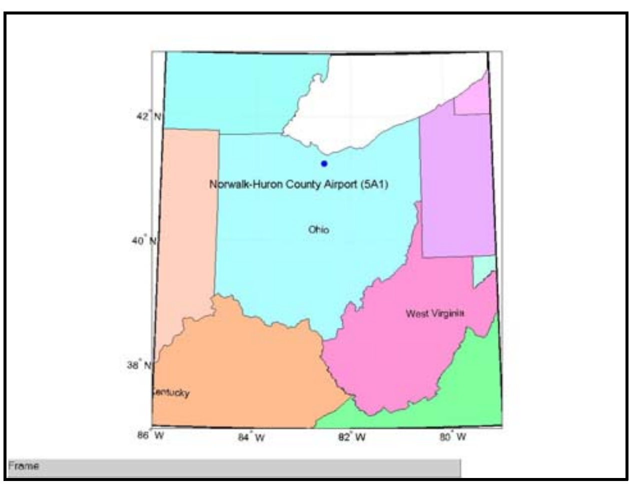


Figure 2

The 8/30/2006 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. For the vast majority of non-precision approaches, the final-approach fix (FAF) for a given approach is located approximately 5 nmi from runway threshold. At a 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, four 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 west simulating an approach to Runway 10, a tear-drop turn, with a true approach to Runway 10 and a slow climb-out simulating an approach to Runway 28. This cycle was flown twice more with a final approach to Runway 28 completing the air work. A combination of eight approaches (four actual and four simulated) were flown this day at 5A1. Following these approaches, the aircraft landed at Mansfield Lahm Regional Airport (MFD), Mansfield, OH, some 25 nmi distant. The ASFs loaded into the SatMate 1030 receiver prior to take off at 5A1 were retained for the entire flight including the landing at MFD.

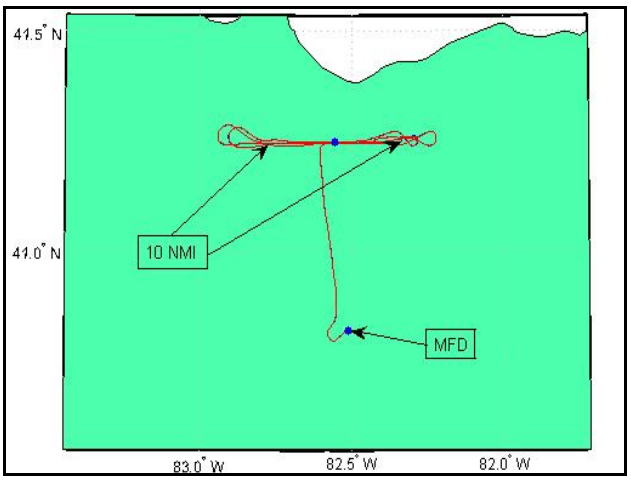


Figure 3

Figure 4 is a plot of all of the approaches completed at 5A1 on 8/30/2006. They begin with the 10-nmi slow-climb departure on Runway 28 (simulating a three-degree approach to Runway 10) climbing to approximately 4000 ft msl. The 4000 ft msl altitude, on a three-degree glideslope represents 3000 ft AGL with respect to the field elevation at 5A1 which is about 900 ft msl. This is followed by an actual approach to Runway 10 commencing 10 nmi from threshold and continuing to approximately 100 ft AGL for a low pass over the airport. This is followed by a 10-nmi slow-climb departure (simulating an approach to Runway 28) climbing to 2000 ft msl. Air traffic control (ATC) restrictions with the Cleveland Air Route Traffic Control Center would not permit higher altitudes to the east of 5A1 on this particular day. The approach/departure sequences were continued until a total of eight were completed. Shown on the plot are the altitude scaled by 10 for fit, the along-track error, and the cross-track error. Throughout the approaches, the cross-track error remains at or below 100 ft peaking to between 200 and 300 ft in the tear-drop turns due to receiver averaging and H-field antenna effects. For the entire sequence of approaches at 5A1, including tear-drop turns and the landing at MFD, the 95% cross-track error (|mean| plus two sigma) was under 200 ft (193.8 ft).

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. 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. 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 can be easily removed since the receiver calculates aircraft heading and velocity. For the entire sequence of approaches at 5A1, including tear-drop turns and the landing at MFD, the 95% along-track error (|mean| plus two sigma), with receiver averaging effects removed, was slightly greater than 650 ft (655.9 ft).

With the exception of the air work at 5A1, only 10-nmi approaches (with no departures simulating approaches) were flown at the other airports. Each approach commences at approximately 3000 ft AGL and is flown to approximately 100 ft AGL for a full-length low approach over the runway. This is followed by an immediate climb to pattern altitude and return for the next approach. Three such approaches were flown at each of these airports–ACY, PWM, and CRG. These figures are contained in the appendix grouped with the corresponding ASF* table. **Table 2** summarizes the results of the approaches at all of the four airports. While the results for the airport at Norwalk, OH (5A1) are the best overall, the other three airports are more representative of the typical 95% values for along- and cross-track errors on non-precision, 10-nmi stabilized approaches. The excellent results at Norwalk 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. Some, but not all, of these attributes are enjoyed by the other airport locations.

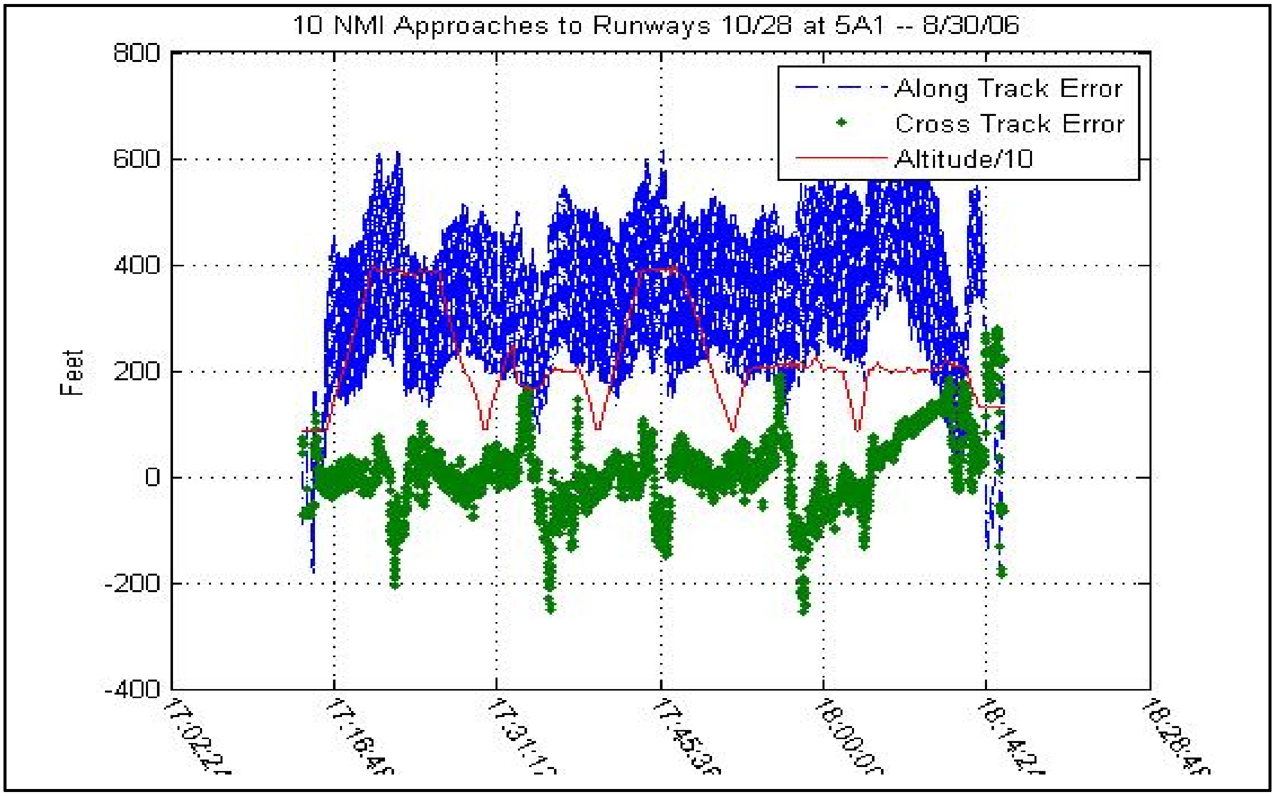


Figure 4

Table 2. Non-Precision Approach Accuracy Using ASF* Values–Late Summer 2006

Date	Airport	Runway	Cross-track Error (ft)			Along-track Error (ft)		
			|Mean| (ft)	Sigma(ft)	95% (ft)	|Mean| (ft)	Sigma (ft)	95% (ft)
8/30/2006	5A1	10 & 28	51.8	71.0	193.8	312.5	171.7	655.9
9/5/2006	ACY	13	178.2	213.6	605.4	308.5	235.5	779.5
9/7/2006	PWM	11	110.0	135.3	380.6	301.3	202.8	706.9
9/12/2006	CRG	32	142.5	178.9	500.3	268.1	331.8	931.7

Approaches Using Averaged ASF* Values.

Over the past three years, sufficient ASF* information has been collected at the six airports used in this study, to begin to notice clear trends in the data. A close look at **Table 1** indicates strong repeatability for the various observed LorSta transmitters from season-to-season and year-to-year. Based upon these observed 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. For example, the mean of the three late-winter ASF* values at 5A1 for each of the LorSta transmitters were averaged with the mean of the two late-summer ASF* values (the 8/30/2006 data was not yet in hand). In the case of the 8970 Master, this value was -0.89 microseconds (see **Table 1**). Averaged values were generated for each LorSta transmitter historically observed at 5A1 and were subsequently loaded into the SatMate 1030 receiver prior to arrival at the airport. In this case, the averaged ASF* values for 5A1 were loaded shortly following the departure from the Ohio University Airport (UNI), i.e., about 100 nmi distant from the Norwalk airport. **Figure 5** shows the flight path taken from UNI to 5A1 and **Figure 6** shows the along-track and cross-track errors plus the altitude scaled by a factor of 10. For the entire 100 nmi flight to 5A1, the 95% along-track error (|mean| plus two sigma), with receiver averaging effects removed, was slightly greater than 1450 ft (1450.9 ft). Likewise, for the entire 100 nmi flight to 5A1, including the approach to Runway 28, the 95% cross-track error (|mean| plus two sigma) was under190 ft (187.8 ft). The along-track and cross-track error values for 5A1 are included in **Table 3**. Over the course of the flight, altitude varied from a maximum of approximately 12,000 ft at the onset, to field altitude of about 900 ft at conclusion. Aircraft ground speed varied over the course from approximately 250 kts at onset to 120 kts on approach to landing. The effect of aircraft ground speed is most notable in the along-track error.

Over the course of the late-summer 2006 flight work, the same sequence of events was conducted at ACY, PWM, CRG. The approach paths and error plots are shown respectively in **Figures 7** and **8** for ACY, **Figures 9** and **10** for PWM, and **Figures 11** and **12** for CRG. Except for the flight and approach to 5A1, all approaches were under ATC auspices and vary according to local conditions present upon arrival in the terminal area. A summary of the results of these approaches in the terminal area is also included in **Table 3**.

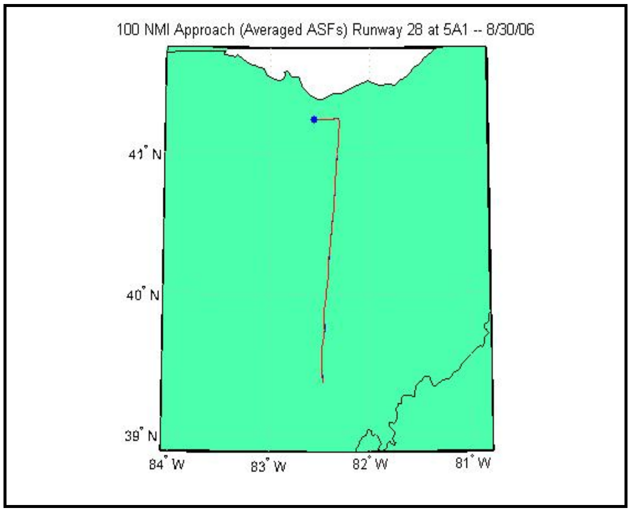


Figure 5

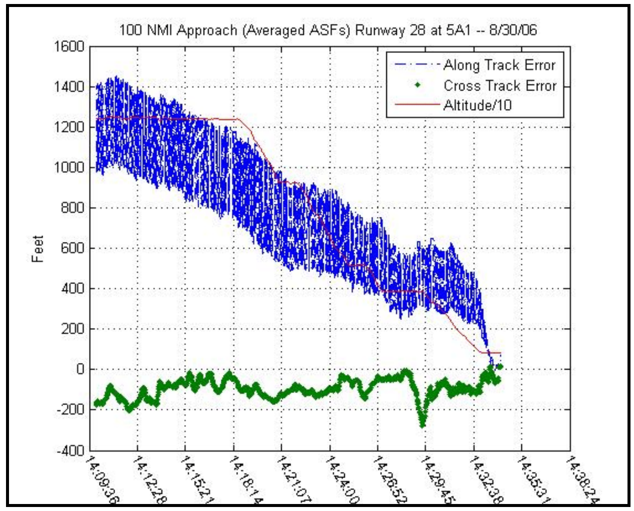


Figure 6

Table 3. Non-Precision Approach Accuracy Using Averaged ASF* Values

Airport	Distance (NMI)	Runway	Cross-track Error (ft)			Along-track Error (ft)		
			|Mean|	Sigma	95%	|Mean|	Sigma	95%
5A1	100	28	95.2	46.3	187.8	727.5	361.7	1450.9
ACY	22	13	80.0	111.5	303.0	434.5	330.6	1095.7
PWM	22	11	83.1	101.1	285.3	406.4	244.3	895.0
CRG	10	32	91.8	106.9	305.6	430.0	235.4	900.8

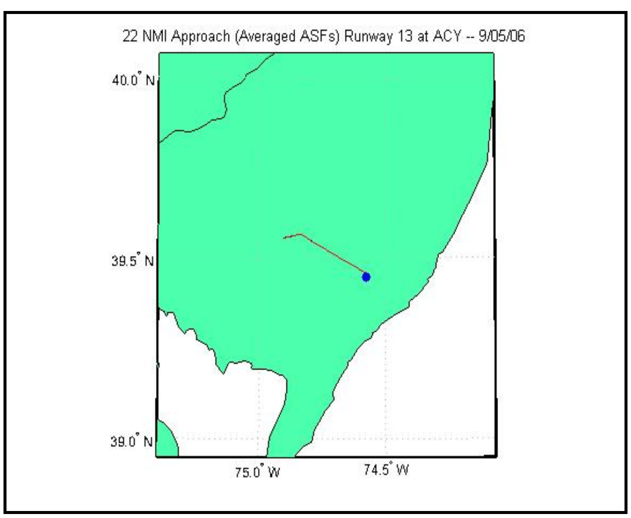


Figure 7

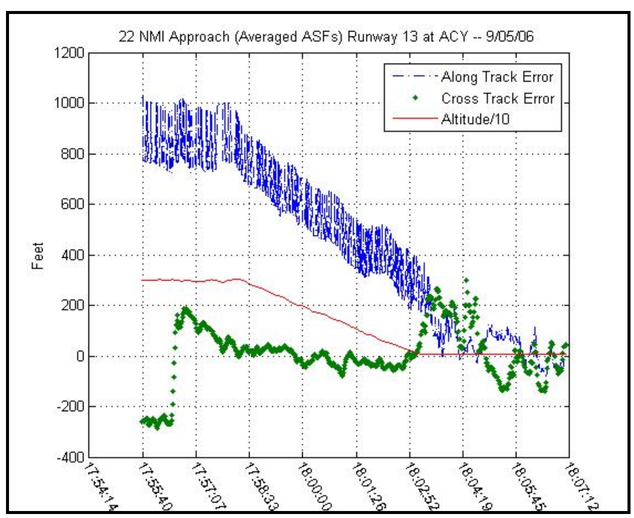


Figure 8

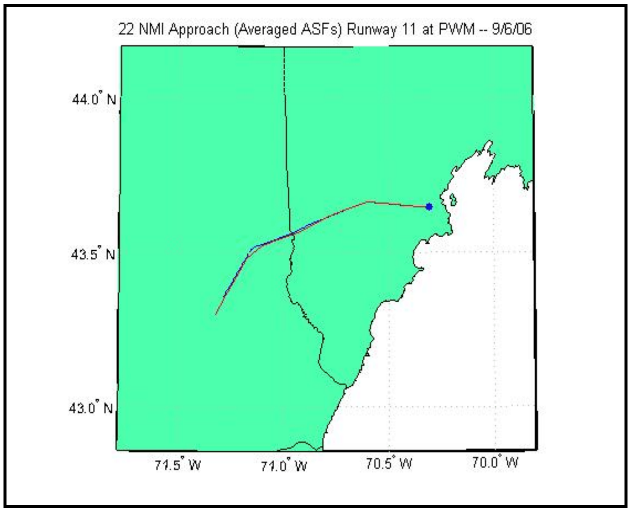


Figure 9

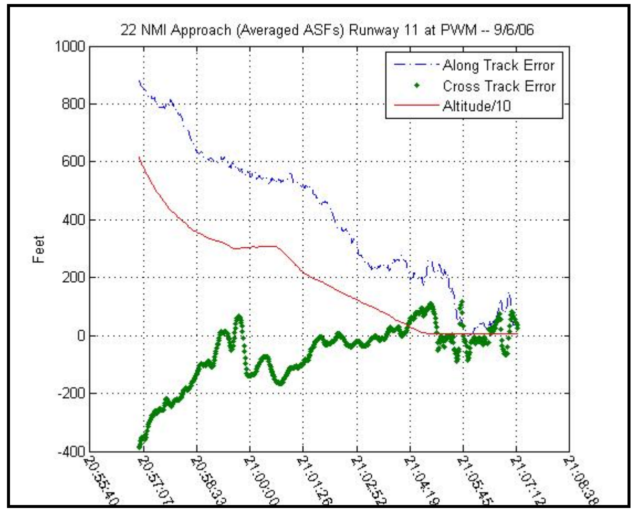


Figure 10

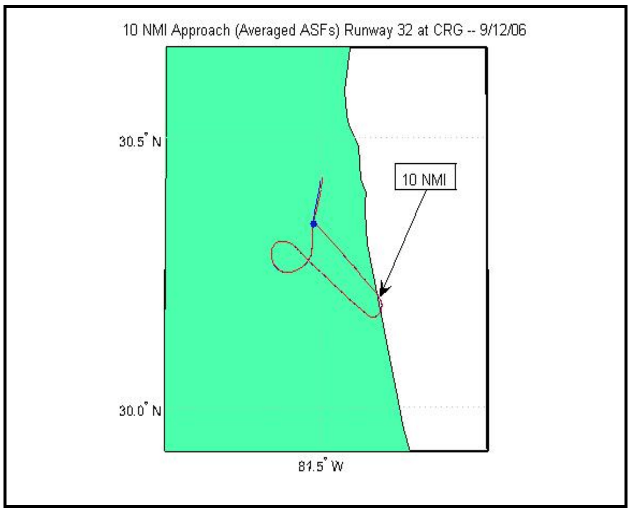


Figure 11

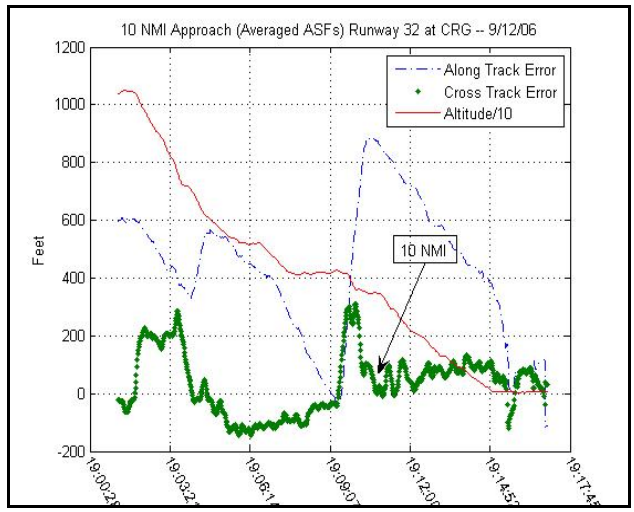


Figure 12

FLIGHT TEST RESULTS – EN ROUTE

The use of Loran C for navigation during the en-route phase of flight has been certified by the FAA since the late 1980s. More recently, there has been renewed concern due in large part to FAA interest in introducing the Automatic Dependent Surveillance-Broadcast (ADS-B) system into the NAS. ADS-B is currently operated in portions of Alaskan airspace and in CONUS areas along the east coast, and portions of Florida and Arizona. ADS-B uses GPS as its source for aircraft position and with that in mind, there is a need to provide a back-up source of position in the unlikely event that some sort of GPS outage might occur.

The data collection system carried on board the Ohio University Beechcraft King Air C-90 contains three Loran-C receivers–a Locus SatMate 1030, an Apollo 618, and a BF Goodrich/Jet 7201. The Satmate and the BFG/Jet are all-in-view receivers while the Apollo is a traditional triad-based receiver. In addition, the Apollo and Jet receivers are FAA certified. The Jet receiver takes things a step further in that it contains a database which provides some ASF correction to its Loran position. As regards the SatMate, there is no internal ASF database so only primary and secondary factors are used in the position calculation during en-route segments.

In the past, only the data collected with the SatMate 1030 has been used since the focus of this research has been precision approach and landing accuracy using Loran C data corrected with locally derived ASF* data. Even so, position data from all the receivers is collected and stored but has here-to-fore not been analyzed since en-route performance has not been a topic of interest. During late-summer 2006 flight testing, however, additional efforts were made to monitor all of the Loran-C receiver data collected during transit between the six airports where the ground data is collected for ASF* purposes. Much of the en-route data which was collected was done so at FL 180, an altitude which the ADS-B community felt would best demonstrate the possibility for Loran C to provide a meaningful GPS backup. Eight flight segments resulted and these are shown in **Figures 13** to **28**. Taken in pairs, the first figure shows the route of flight while the second figure is a plot of the cross-track accuracy for the three Loran-C receivers, plus the aircraft altitude scaled by a factor of 10. The accuracy results (|mean| plus two sigma) from the eight en-route segments are summarized in **Table 4**. No attempt has been made to remove any outliers in the Loran C position data due to receiver anomalies. A NovAtel OEM-4 dual-frequency WAAS-augmented GPS receiver was used as the truth source for aircraft position. A few comments are in order:

-The Apollo 618 receiver did not provide consistent performance during the en-route segments and its accuracy data is not included in **Table 4**.

-Considerable P-static was encountered during the initial stages of the transit between UNI and ACY (**Figures 13** and **14**). Both the Apollo and BFG/Jet receivers, which share a conventional E-field antenna, ceased navigation during the P-static encounter. This accounts for the poor accuracy performance of the BFG/Jet receiver. The SatMate 1030 uses an H-field antenna which essentially is not susceptible to P-static so it continued to navigate during the P-static encounter and its accuracy performance reflects the norm.

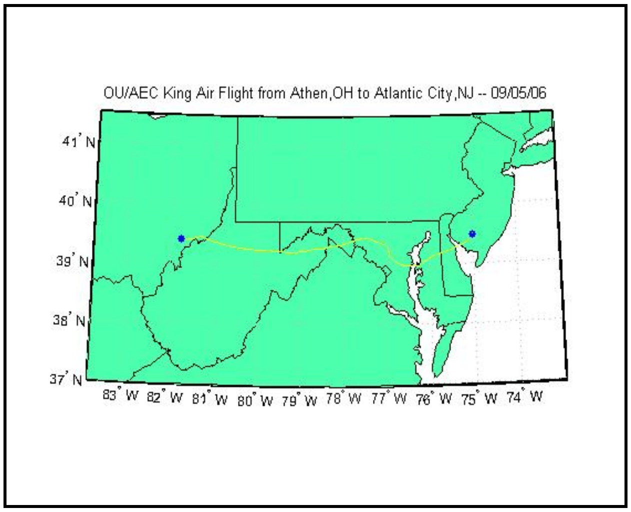
-During the flight segment from Wilkes-Barre, PA to UNI (**Figures 19** and **20**), the BFG/Jet receiver experienced LorSta acquisition problems late in the flight. This accounts for its poor (relatively speaking) accuracy performance.

-Between CRG and W28, a deliberate attempt was made to overfly the LorSta at Carolina Beach, NC. Both the SatMate and the Apollo were unable to maintain navigation due to what appears to be signal saturation in the receiver front end. The design of the BFG/Jet receiver apparently overcomes this problem (method not known) and the accuracy performance reflects the norm.

Table 4. Summary of En-Route Accuracy Results per Flight Segment

Date	Route	Time En Route (min)	Time @ Altitude (min)	Altitude	RX	|Mean| (ft)	Sigma (ft)	95% (ft)
9/5/2006	UNI-ACY	92	67	17,000 ft	SM	336.6	482.2	1301.0
					JT	1109.6	1988.1	5085.8
9/6/2006	BLM-PWM	130	49	17,000ft	SM	709.8	811.2	2332.2
					JT	274.9	381.4	1037.7
9/7/2006	PWM-AVP	96	35	FL 180	SM	662.9	843.9	2350.7
					JT	251.0	292.3	835.6
9/7/2006	AVP-UNI	96	70	FL 180	SM	652.4	367.4	1387.2
					JT	357.8	934.1	2226.0
9/12/2006	UNI-CAE	96	48	FL 180	SM	694.3	781.0	2256.3
					JT	451.8	523.3	1498.4
9/12/2006	CAE-CRG	74	30	FL 180	SM	1313.3	569.1	2451.5
					JT	166.7	143.4	453.5
9/13/2006	CRG-W29	146	91	FL 190	SM	2145.6	879.6	3904.8
					JT	454.3	361.8	1177.9
9/13/2006	EST-UNI	89	46	14,000	SM	334.7	442.5	1219.7
					JT	367.4	384.1	1135.6

Note: SM – Locus SatMate 1030; JT – BFG/Jet 7201



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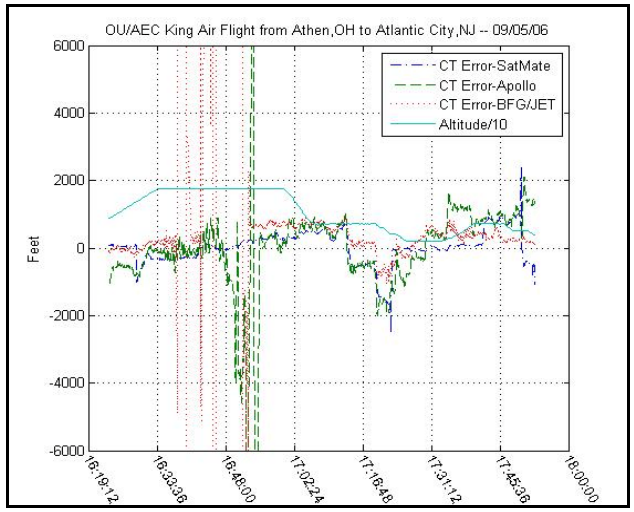

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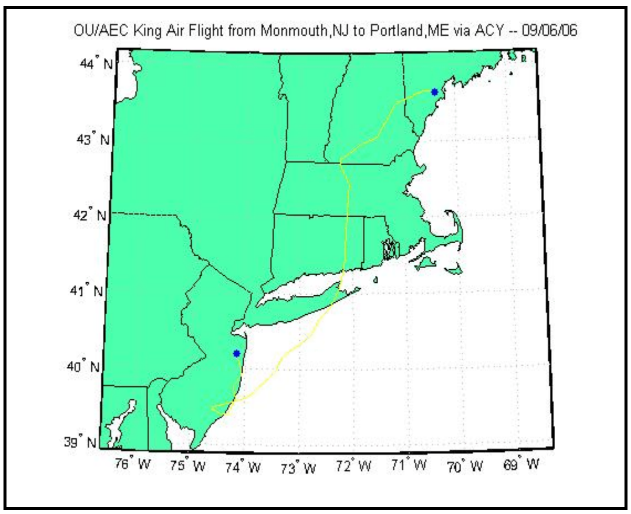

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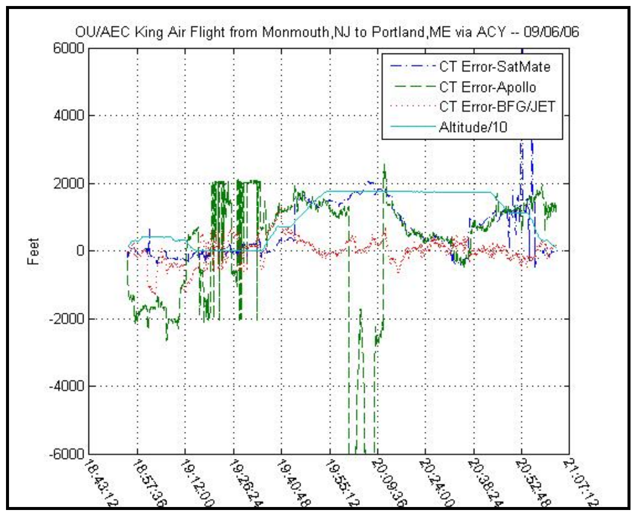

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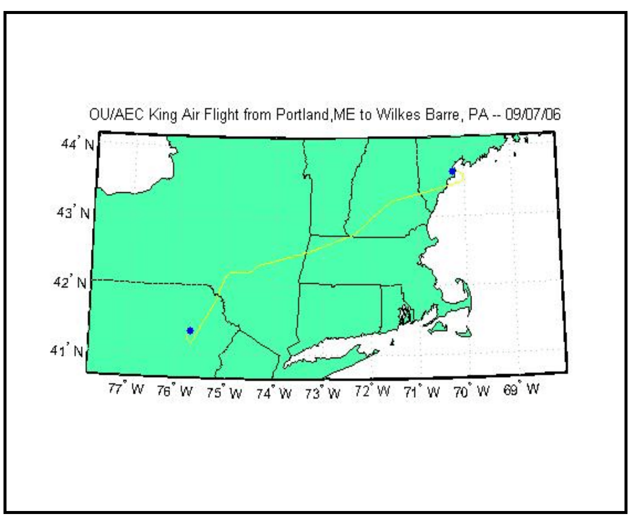

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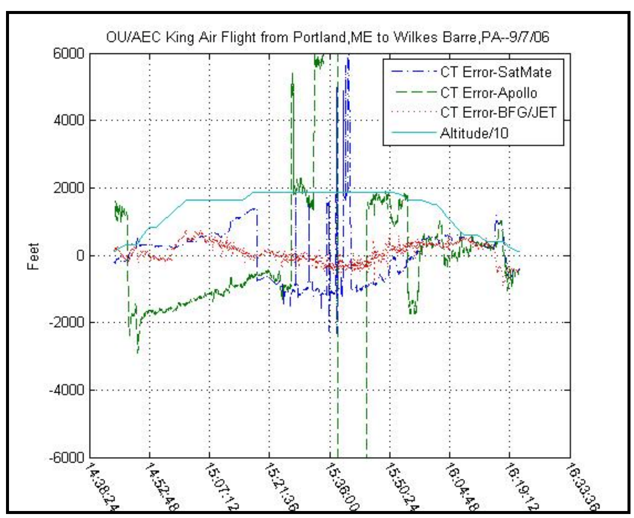

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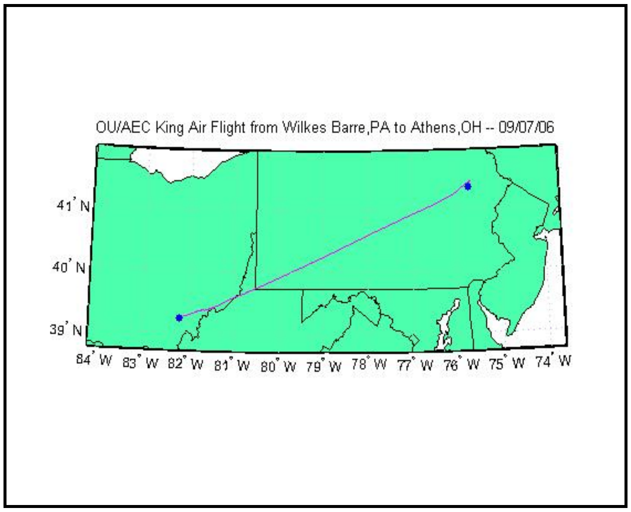

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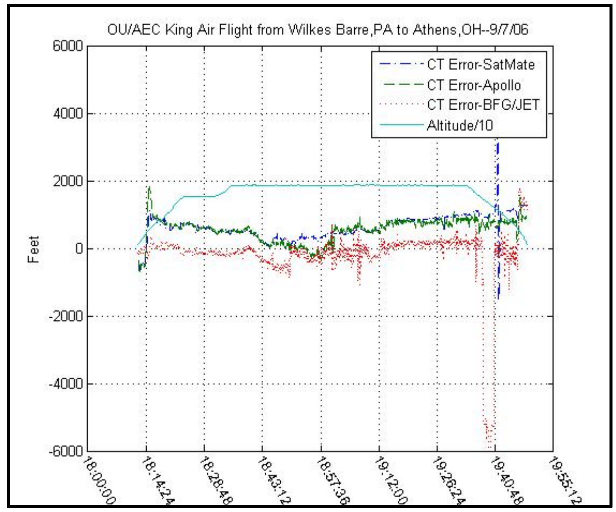

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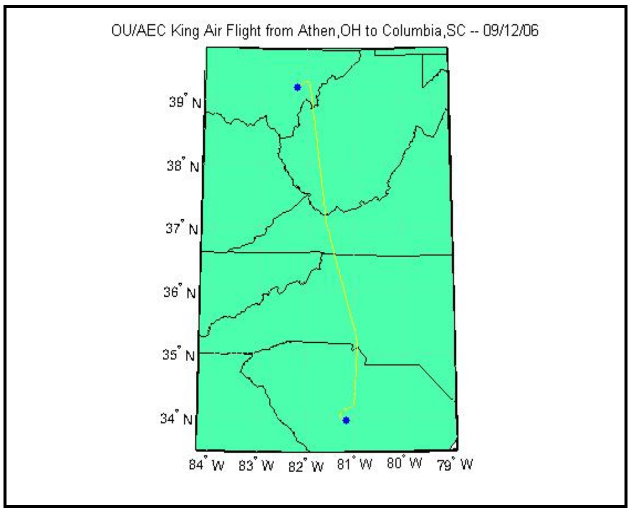

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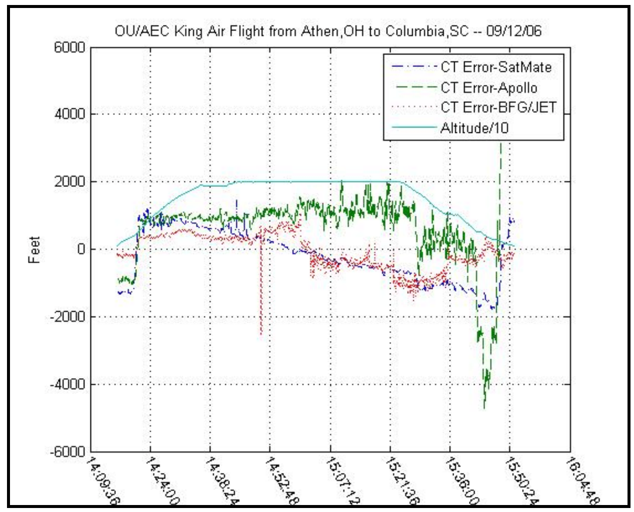

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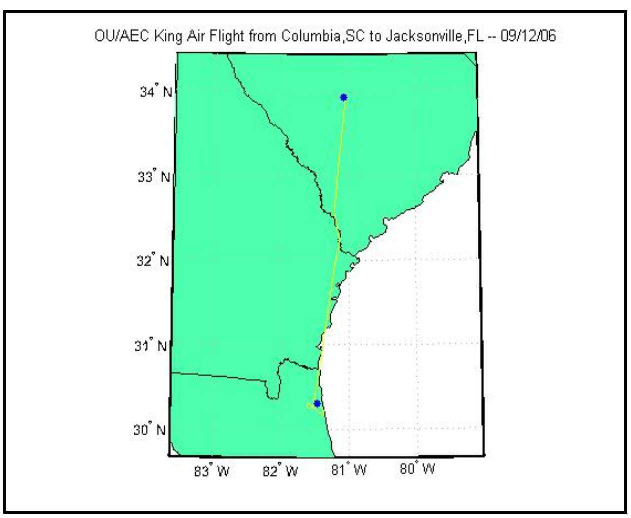

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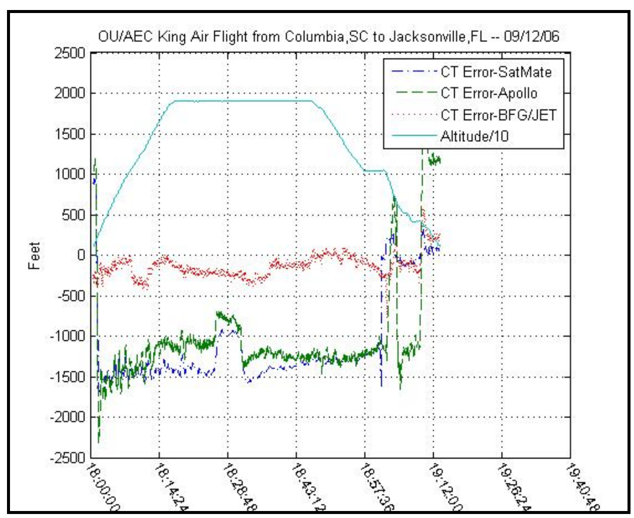

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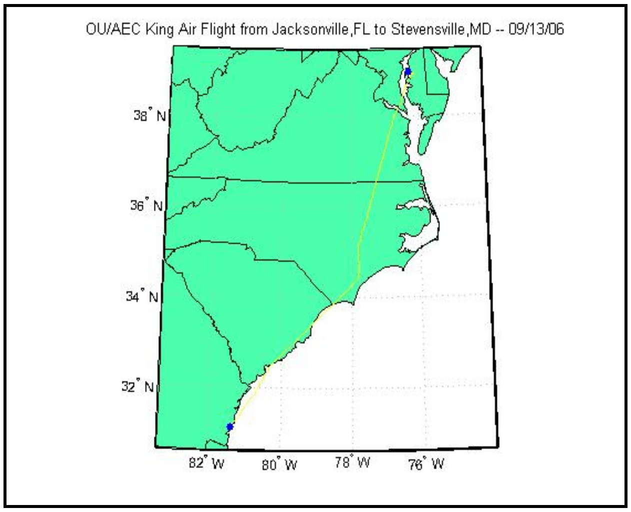

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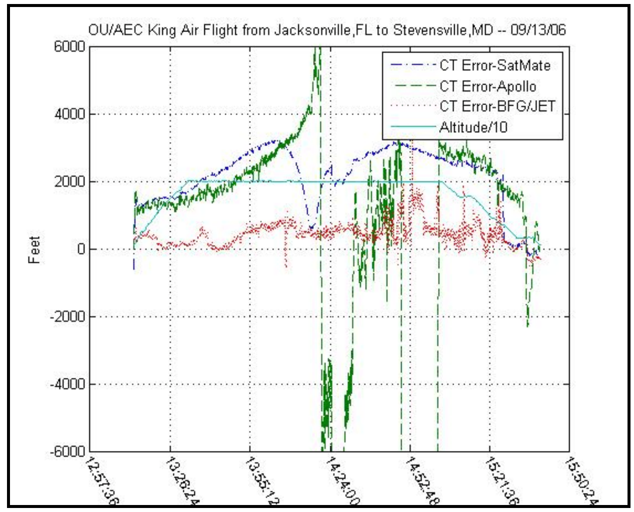

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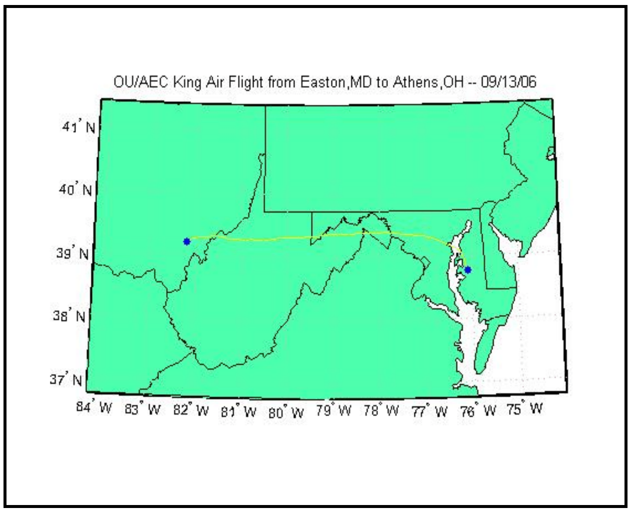

Figure 27

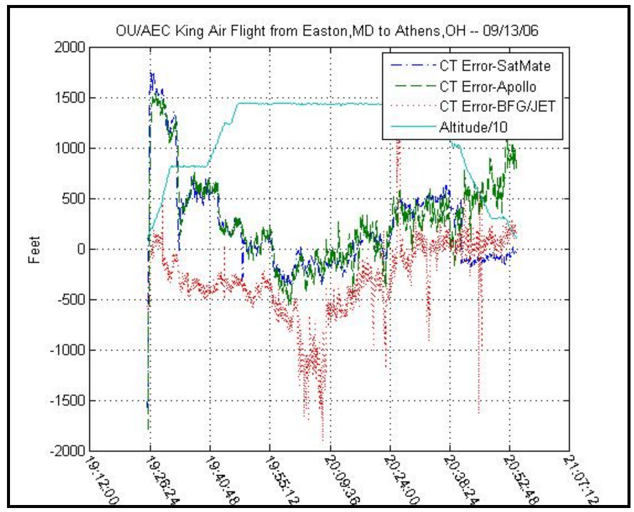

Figure 28

Of the three Loran receivers used in the AEC Loran C data collection system, clearly the BFG/Jet 7201 receiver out-performed both the Apollo 618 and the SatMate 1030. Little documentation is available regarding this receiver which was designed and built in the late 1980s. In the course of a conversation with the engineer who was responsible, in part, for the production of the BFG/Jet 7201 [6], it was learned that the receiver uses a linear front end, contains an ASF database believed to be based upon a quarter-degree grid covering CONUS and portions of Alaska and Canada (see **Figure 29**). In addition, the BFG/Jet 7201 was the OEM Loran module used in the Bendix/King KLN 88, an FAA certified receiver [7]. Upon inspection of the BFG/Jet 7201 circuit board, the following components were readily identified–an 8-bit microprocessor as well as a 64-K RAM chip and a 256-K ROM chip. The receiver itself was an ASIC which carried an ANI (Advanced Navigation, Inc.) 7200 designation.

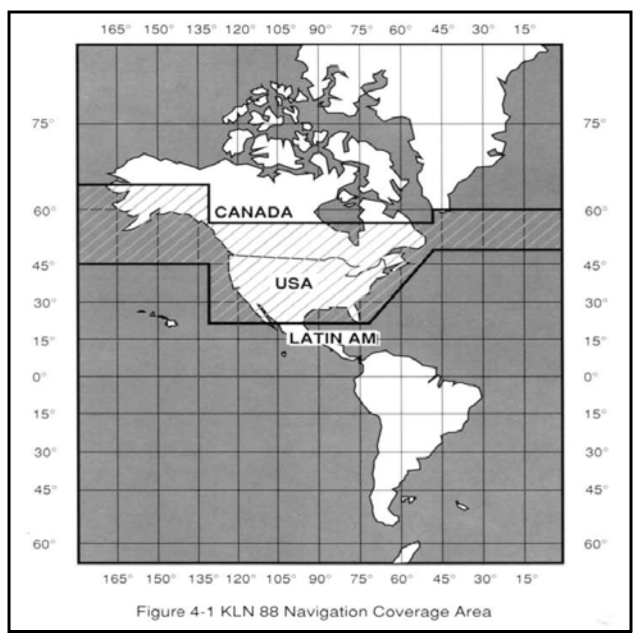

Figure 29

SUMMARY AND CONCLUSIONS

Locally generated ASF* measurements demonstrate season-to-season and 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 2006. 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 for late summer 2006 shows that the Loran C cross-track error is well behaved for 10-nmi stabilized approaches, twice the distance typical of that published by the FAA for non-precision approach. At one location, Norwalk-Huron County Airport (5A1), Ohio, 10-nmi stabilized departures/approaches were conducted. The 95% cross-track error value at this airport, which is in close vicinity to the Plumbrook, Ohio LorMon station, was shown to be less than 195 ft (|mean| plus two sigma) over a series of eight approaches which varied in altitude between approximately 3000 ft to 100 ft returning to 3000 ft AGL. At the four airports shown, the 95% cross-track error value throughout the patterns flown in the vicinity of these airports remained below 610 ft (|mean| plus two sigma) including turns and variations in altitude (see **Table 2**).

The averaged ASF* accuracy results are consistent with similar air work conducted over the past several years [2,4,5]. For example, analysis in Reference 2 for ACY showed that Loran C cross-track error was well below the RNP (0.3) NSE criteria (1000 ft) for approaches flown with ASF* values collected several months previously but used as though they were current values. Clearly, if one examines the ASF* data for 5A1 (see **Table 1**), the consistency of the data is quite apparent and yields a strong qualitative conclusion that using Loran C measurements locally corrected with averaged ASF* data is probably viable for non-precision approach at a great majority of the airports in the 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 NSE cross-track requirements (1000 ft or less) for Loran C RNP (0.3) non-precision approach. A summary of the data presented show that for the worst case observed, about 30% of the NSE cross-track error budget was expended (see **Table 3**). 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. Overall, 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 time and frequency equipment (TFE) installed at all CONUS LorSta locations, and the upcoming move to time-of-transmission control, 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 C cross-track accuracies than those presently shown for use in the terminal area and for non-precision approach.

The results for the en-route portion of this research are presented for the first time due to recent interest from the ADS-B community regarding use of Loran C as a backup to GPS. For the most part, the eight en-route segments analyzed show excellent accuracy results for cross-track error (see **Table 4**). If one discounts the en-route segments UNI-ACY and AVP-UNI, the former where P-static conditions were encountered and the latter where receiver problems occurred, the 95% cross-track error (|mean| plus two sigma) was less than 25% of an equivalent RNP (1.0) accuracy requirement. Currently, en-route segments are flown with a cross-track accuracy requirement equivalent to RNP (4.0). Several caveats should be added, however, when considering these results. First, the BFG/Jet 7201 receiver which yielded the best results, uses a combination SF/ASF correction-factor database stored internally. At present, it is believed that the correction factors are calculated for a quarter-degree grid covering the area of interest, CONUS in this case (see **Figure 29**). This receiver uses late 1980s technology and clearly a reduced grid size could be easily accommodated today. This would permit increased accuracy since the SF/ASF correction factors could better reflect the geographic area which they represent. Second, for Loran C to be viable in any geographic location (terminal or en-route), the receiver must be configured to use an H-field antenna vice the conventional E-field antenna (i.e., whip) to minimize P-static effects.

The over-riding conclusion from the material presented in this paper is that the current Loran C navigation system operation in the United States is capable of providing the National Airspace System (NAS) accuracy requirements imposed upon it for terminal, non-precision approach, and en-route segments of flight. The Loran C 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 E-Loran which includes 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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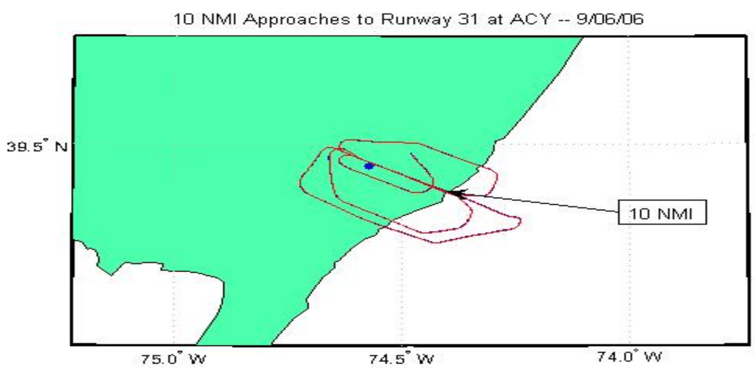
ACKNOWLEDGMENTS

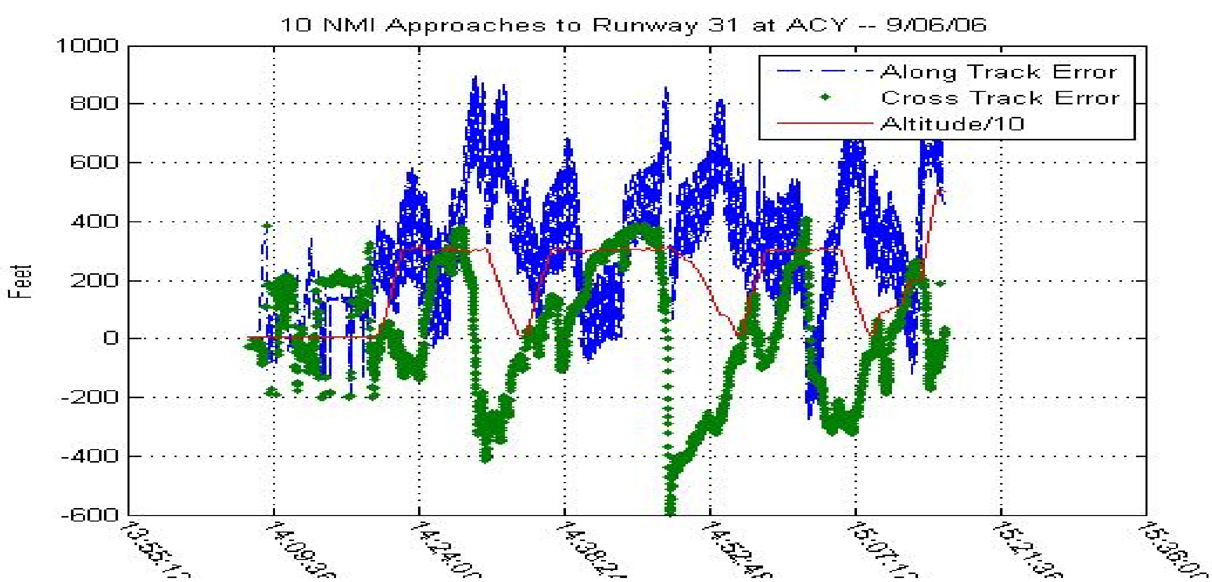
This work was supported by the FAA under Contract DTFA01-01-C-00071, Technical Task Directive 2.1.

APPENDIX

ASF* Values for Atlantic City International Airport (ACY)

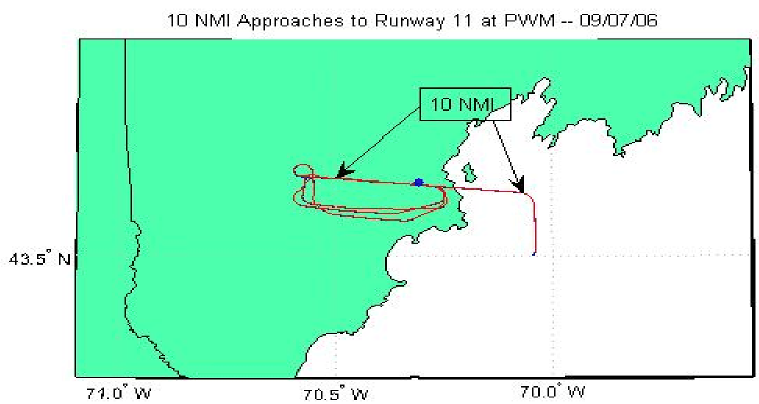
	ATLANTIC CITY INTERNATIONAL AIRPORT (ACY) NEW JERSEY (values in microseconds)																
Chain	8970					9960					7980				5930		
Station	M	W	X	Y	Z	M	W	X	Y	Z	M	W	Y	Z	M	X	Y
3/26/2004	2.39	4.11	1.16	5.11		1.12	2.42	-1.63	0.61	2.69	3.54	6.15	-1.05	0.52	2.80	-1.76	-1.41
4/5/2005	2.41		1.27	5.28		1.19	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
Mean	2.39	4.16	1.19	5.13	5.19	1.14	2.44	-1.62	0.60	2.73	3.55	6.07	-1.08	0.51	2.84	-1.75	-1.36
Sigma	0.02	0.06	0.07	0.15		0.05	0.04	0.02	0.02	0.07	0.05	0.11	0.03	0.04	0.05	0.02	0.05
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
Mean	2.39	4.09	1.29	5.20		1.15	2.52	-1.64	0.57	2.71	3.54	6.14	-1.06	0.49	2.94	-1.78	-1.30
Sigma	0.10	0.10	0.20	0.01		0.05	0.03	0.08	0.04	0.09	0.10	0.06	0.06	0.04	0.01	0.07	0.05
Total Mean	2.41	4.14	1.27	5.16		1.16	2.47	-1.65	0.58	2.70	3.53	6.09	-1.08	0.49	2.89	-1.77	-1.34

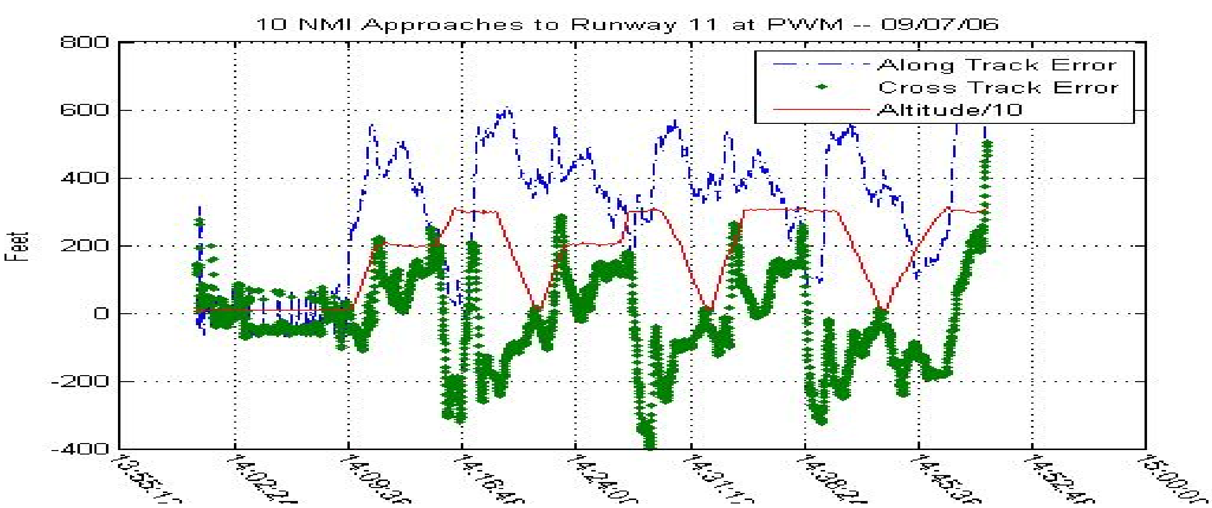




ASF* Values for Portland International Jetport (PWM)

	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
Mean	3.21	1.89	1.52	0.67	1.52	0.48	-1.84	1.16	3.48		-1.88	-0.38	0.87	-1.99	0.01	2.35
Sigma	0.16		0.07		0.09	0.04	0.02	0.05	0.20		0.03	0.02	0.06	0.01	0.07	
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	
Mean	3.22	2.08	1.47	5.33	1.46	0.58	-1.85	1.23	3.66	4.31	-2.05	-0.57	0.96	-1.95	0.18	2.71
Sigma	0.03	6.34	0.02		0.03	0.01	0.09	0.02	0.02		0.12	0.17	0.01	0.19	0.11	
Total Mean	3.21	-0.26	1.49	3.00	1.48	0.53	-1.83	1.20	3.57		-1.92	-0.42	0.91	-1.94	0.11	2.53





ASF* Values for Jacksonville/Craig Municipal 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
3/30/2006	3.07	1.08	3.82			4.00		-1.06	-1.23	3.59	1.00	3.39	-0.16	-0.05	-1.13				-2.95	1.28
Mean	2.99	1.08	3.82	5.59	3.94	4.06	-5.69	-1.06	-1.24	3.53	1.00	3.46	-0.12	-0.06	-1.12	1.79	3.15	3.32	-2.90	1.29
Sigma	0.07	0.01	0.16		0.03	0.12		0.08	0.01	0.11	0.00	0.06	0.04	0.01	0.01	0.02	0.00	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
9/12/2006	3.09	1.07	4.09		4.17	4.17		-1.03	-1.26	3.66	0.99	3.46	-0.04	-0.03	-1.12	2.08			-2.76	1.29
Mean	3.10	1.09	4.12		4.16	4.24		-0.98	-1.25	3.67	1.00	3.52	-0.07	-0.03	-1.11	2.05		3.78	-2.79	1.30
Sigma	0.04	0.02	0.07		0.06	0.08		0.05	0.02	0.05	0.02	0.06	0.02	0.00	0.01	0.04			0.04	0.02
Total Mean	3.05	1.09	3.98		4.05	4.17		-1.00	-1.24	3.61	1.00	3.51	-0.10	-0.04	-1.11	1.91		3.55	-2.85	1.30