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Positioning System Accuracy Assessment for the Runway Incursion Prevention System Flight Test at the Dallas/Ft. Worth International Airport

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December 2004

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CONTENT

Abstract

NASA/Langley Research Center collaborated with the Federal Aviation Administration (FAA) to test a Runway Incursion Prevention System (RIPS) at the Dallas Fort Worth International Airport (DFW) in October 2000. The RIPS combines airborne and ground sensor data with various cockpit displays to improve pilots' awareness of traffic conditions on the airport surface. The systems tested at DFW involved surface radar and data systems that gather and send surface traffic information to a research aircraft outfitted with the RIPS software, cockpit displays, and data link transceivers. The data sent to the airborne systems contained identification and GPS location of traffic. This information was compared with the own-ship location from airborne GPS receivers to generate incursion alerts. A total of 93 test tracks were flown while operating RIPS. This report compares the accuracy of the airborne GPS systems that gave the own-ship position of the research aircraft for the 93 test tracks.

Introduction

A Runway Incursion Prevention System (RIPS) was tested at the Dallas Fort Worth International Airport (DFW) in October 2000. The test was conducted jointly by NASA and the FAA to demonstrate the feasibility of using an airborne traffic alert system in an operational environment. The test consisted of flying NASA's Airborne Research Integrated Experiment System (ARIES) research aircraft through a series of test tracks with differing alerting algorithms and movement profiles. The aim was to demonstrate that RIPS could detect and provide alerting of incursions in operational scenarios that pilots encounter. RIPS is designed to prevent runway incursions by providing pilots with an enhanced awareness of surface traffic conditions. This is achieved through cockpit displays and audible alerts that are supported by an information infrastructure integrating ground surveillance and data systems, data link systems, airborne position systems, and incursion-alerting algorithms. An overview of the RIPS flight test is given in [1].

The ground based surveillance and data systems were developed by the FAA based on recommendations from the National Transportation Safety Board (NTSB) [2]. The main emphasis of the ground systems was to provide a Surface Traffic Information System Broadcast (STIS-B) service to airborne vehicles. This broadcast contained a list of the traffic that has been detected by ground sensors on the airport surface. The targets from these surface sensors were compiled using data fusion software developed by the United States Department of Transportation (DOT). A description of the ground based surveillance systems and their performance during the test are given in [3] and [4]. The STIS-B was the data link that delivered surface traffic information to the airborne systems. Once received on the airborne systems, the incursion-alerting algorithms compared the traffic locations to the own-ship position to determine if incursion conditions existed. The incursion alerting algorithms are described in more detail in [5] and [6]. The accuracy of the onboard positioning systems was central to the alert determination and is the central topic of this report.

The own-ship positioning systems contained both airborne and ground components. The onboard components included three Global Positioning System (GPS) receivers designed for the Local Area Augmentation System (LAAS), the Wide Area Augmentation System (WAAS), and the Ashtech receiver System (Ashtech). Ground components included a ground station for broadcasting the differential corrections to the Ashtech system and a ground station for broadcasting differential corrections to the LAAS system. During the flight test, positioning data, for all GPS systems, were recorded as the ARIES conducted maneuvers. After the flights were completed, the positioning data was correlated and compared with separately generated "Truth" data to characterize and compare the accuracy of each positioning system.

This report gives an overview of the GPS systems on board the research aircraft (ARIES), and the maneuvers made during the flight test. The data collected during the flight test are described. An analysis is given on the accuracy of each system along with some discussion of the comparison process and anomalies encountered during the analysis. Track comparisons for selected runs are given in the Appendices.

Positioning Systems

The positioning systems used during the DFW flight test were all differential-GPS systems with varying accuracy and beacon placements. The ARIES had three primary positioning systems onboard with each receiving its own differential corrections in addition to the standard signals from the GPS constellation. The positioning systems installed on the ARIES included a LAAS receiver and a WAAS receiver. This was in addition to ARIES's own Ashtech GPS receiver. A brief description of each system is given below.

The positioning systems received their signals from two GPS S67-1575 Series patch antennas mounted on top of the aircraft. The antennas were dual-frequencies (L1/L2) with low-noise amplifiers (LNA) at 1227.6 MHz and 1575.2 MHz. The antennas were mounted on top of the aircraft at station #690 as illustrated in Figure 1. Both antennas were about 12.7 cm (5”) from the centerline of the aircraft. As indicated in the figure, the LAAS receiver was wired to the right antenna while the WAAS and Ashtech receivers were connected to the left antenna. The LAAS system received its differential correction signal through an antenna located at the leading edge of the vertical stabilizer. The Ashtech differential corrections were received through a blade antenna mounted on the bottom left side of the aircraft aft of the left wing fairing. The WAAS GPS system received its differential correction signal through the same patch antenna which it receives GPS satellite signals.

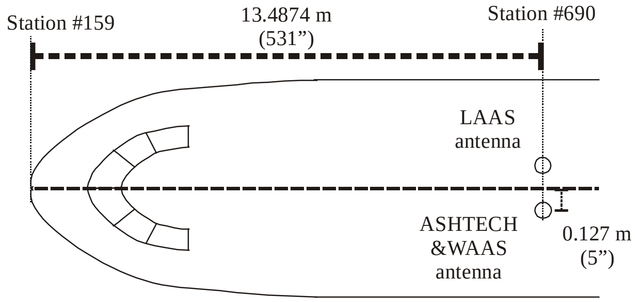


Figure 1: Location of GPS antennas.

Onboard the ARIES, the Ashtech, LAAS, and WAAS signals from the two antennas were wired to their respective receivers. Figure 2 gives an overview of the path for the position information from the antennas to the major components in the research aircraft. Note that the Onyx computer was the processing center that ran the flight and runway incursion software and was the destination of the GPS position information. The Data Acquisition System (DAS) was the data recording system that, at preset intervals, recorded positioning and other data from the Onyx. The Ashtech receiver outputs its data through a serial port connection to a FieldWorks laptop computer that further relayed the information to a VERSA Module Eurocard (VME) based computer which also interfaces to an experimental Flight Management System (FMS). The LAAS receiver also relayed its information through this VME computer. Data from the WAAS receiver as well as the Inertial Reference Unit (IRU) flowed though the IO Concentrator which functions as a data relay system. The IO Concentrator and FMS VME computer converted the position data from their source to a form that could be placed on a high speed shared memory network (ScramNet) ring that connected the four major components shown in bold boxes in Figure 2. The position data was delivered to the Onyx via the ScramNet ring (not illustrated in the figure).

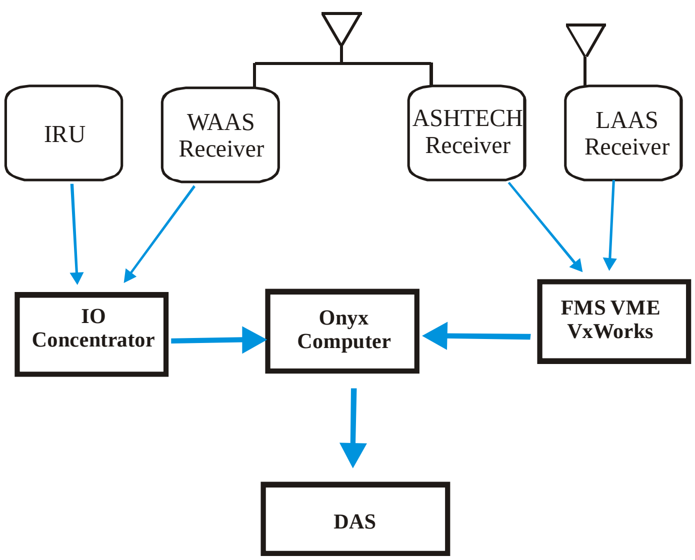


Figure 2: Data path for position data from receivers to DAS.

Ashtech System

The Ashtech is a GPS system installed on the ARIES and used as the reference positioning system on the ARIES for all missions. During deployment, this system was used along with a ground based differential beacon placed at a surveyed location to obtain very accurate positioning information onboard the ARIES. These positions were also used in a post flight process to separately generate a Truth data set that was then used as the basis against which position readings from other systems were compared. The Truth data was accepted as the "true" position of the ARIES during the DFW flight test.

The Truth data was derived from the Ashtech measurements using a carrier phase interferometric technique known as Kinematic Differential GPS. The post flight processed data was accurate to about 15cm from the antenna's phase center. For comparison, the raw Ashtech data was accurate to at most 3 meters; and, with differential correction, was accurate to approximately 1 meter. During the DFW tests, the Ashtech system was not always able to operate with differential corrections. A separate accuracy comparison of the Ashtech operating in the two modes was also performed for this report.

At DFW, the beacon antenna was installed on the roof of the nearby Harvey Hotel. The approximate location of the hotel is given in Figure 3. The exact coordinate of the Ashtech beacon is given in Table 1.

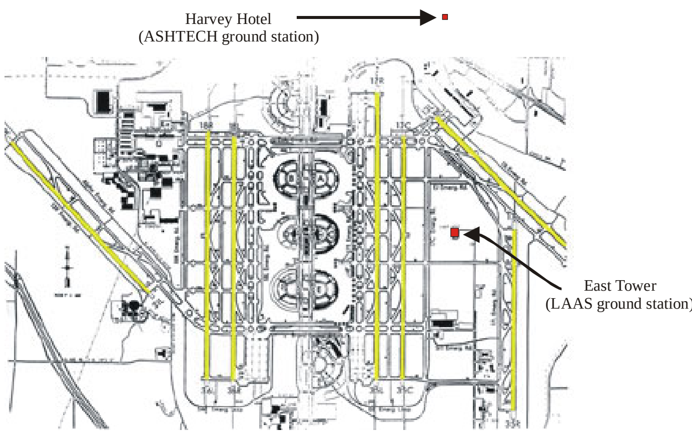


Figure 3: DFW map indicating Harvey Hotel location.

Table 1: Surveyed position of the Ashtech differential beacon antenna.

Latitude:		N 32° 55' 01.04792"	32.91695776°	32°55.0174653' N
Longitude:		W 97° 00' 32.50204"	- 97.00902834°	97°00.5417007' W
Elevation (MSL):	210.543 m	690.758 ft		
Ellipsoid height:	183.440 m	601.837 ft		
Geoid height:	- 27.103 m	-88.921 ft		
ECEF-	X: +654013.941,	Y: -5319586.210,	Z: +3446330.795 m	

Wide Area Augmentation System (WAAS)

WAAS is being developed by the FAA to improve the navigation capabilities of the National Airspace System (NAS). Its main objective is "*…to provide satellite-based navigation capability for all phases of flight within the National Airspace System (NAS) from en route through precision approach.*" [7]. WAAS is designed to provide sole means enroute, terminal, non-precision, and Category I precision approach capability throughout the WAAS coverage area (U.S. NAS). It provides additional accuracy, availability, and integrity for navigation systems and is slated to replace aging navigation aids such as the Non-directional Beacons (NDB), Very High Frequency (VHF) Omni-directional Radios (VOR), Distance Measuring Equipments (DME) and most Category I Instrument Landing Systems (ILS).

WAAS consists of an integrated system of approximately 25 precisely surveyed ground based reference stations and two geo-stationary satellites. These WAAS Reference Stations (WRS) are located throughout the continental US as well as Alaska, Hawaii, and Puerto Rico. WRS are installed nominally 500 to 1000 km apart. There are two WRS in Texas, one of which is located at DFW where the flight test was conducted. The

DFW WRS site has been in service since Feb. 18, 1999. The satellites rebroadcast precision differential corrections to WAAS users and are located above the continental east and west coasts. Operationally, the WRSs are "receive only" stations. Each WRS receives signals from the GPS constellation and forwards the data to a Wide area Master Station (WMS) where corrections are computed. The corrections are then relayed to several ground uplink stations where the differential corrections are packaged. The messages are then uplinked to one of two geo-stationary satellites that rebroadcast the corrections to aircraft in the service area. [8]

The WAAS augmented GPS signal corrects GPS signal errors caused by ionosphere disturbances, timing and satellite orbit errors. In near continuous broadcast since December of 1999, it is expected to improve the accuracy of basic GPS to about 7 meters vertical and horizontal. During the DFW tests, the differential signal was received from one of the 2 WAAS geo-stationary satellites.

Local Area Augmentation System (LAAS)

LAAS is a differential correction transmitter system being developed for the FAA for use primarily at airports. It is a public use system that will provide Category I/II/III precision approach capability and will be part of the future FAA NAS architecture. LAAS will operate independently from WAAS, while at the same time complementing WAAS, by providing additional GPS augmentation to support airports requiring Category II/III precision approach applications. LAAS will also provide a Category I capability at locations where WAAS cannot, and will provide a signal which could be used for surface navigation in the airport area. LAAS will have a higher availability requirement as needed at higher demand airports. More information about LAAS is available in [9].

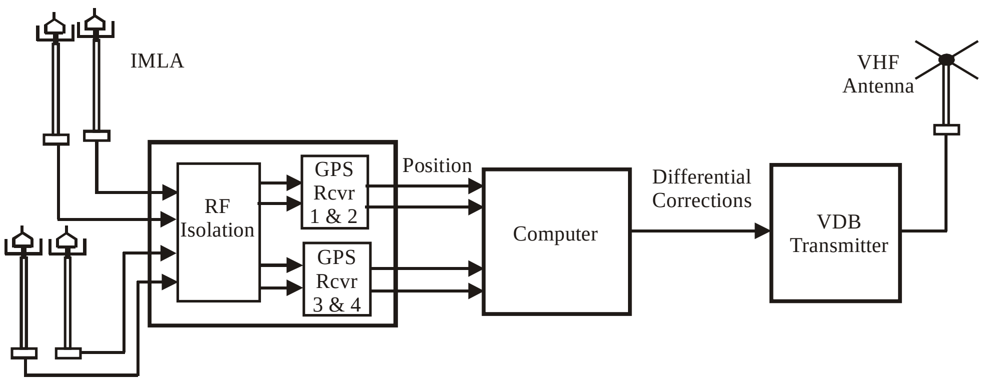


Figure 4: LAAS logical block diagram.

Figure 5: One of four receiver antennas at the LAAS ground station near the DFW East Tower.

The LAAS ground station (figure 4) tested at DFW was built by Ohio University and installed near the base of the East Control Tower (Figure 5). Four GPS receiver subsystems were used to obtain stationary position. Each receiver subsystem consisted of an Integrated Multipath Limiting Antenna system (IMLA) antenna connected to a Novetal Millennium GPS receiver. The IMLA was actually two separate antennas; one received GPS signals from satellites above 30 degrees while the other received signals below 30 degrees (Figure 4). The position information was sent to a computer, which calculated the differential corrections. The corrections were then forwarded to a VHF Data Broadcast (VDB) transmitter connected to a fifth antenna (Figure 6). Figure 7 shows the rack that housed all the LAAS electronics including the GPS receivers, the computer, and the VDB transmitter. Recall that the ARIES received this GPS correction signal through an antenna mounted on the forward edge of the vertical stabilizer. Rockwell-Collins provided the airborne LAAS receiver, which was an uncertified prototype. The LAAS as installed at DFW was reported to be accurate to about 1 meter. More details concerning the LAAS ground station may be found in [10].

Figure 6: VDB transmitter antenna.

Figure 7: LAAS electronics rack.

Aircraft Movement profiles

A total of 93 test tracks were flown during the DFW flight test. These tracks consisted of repetitions of seven basic movement profiles. Positioning data were collected during each movement profile. All the test runs were conducted around runway 35C/17C on the East side of DFW. Appendix A contains a map of the DFW airport. This section briefly describes the movement profiles of each of the test tracks. The descriptions are generic and germane to the GPS accuracy comparison for the aircraft movement. However, the classification of the movement profiles is based on the RIPS test matrix given in Requirements Documents for the Dallas Ft. Worth flight test. More information about the profiles including objectives of the activities are also given in [1].

Profile 1 (P1 - Aborted landing, go-around):
During this profile, the ARIES flew a standard approach and performed a go-around when the ARIES reached approximately 61meters (200 ft.) altitude above the terrain. The aircraft remained airborne during this entire profile. The data segment for this profile generally started at the base leg and finished when the ARIES reached cruise altitude after the go-around climb. The area covered by this profile was a box pattern about 25 kilometers northward and eastward of runway 35C/17C with a decent on the runway. Selected test tracks for this profile are given in Appendix B. Of particular interest in this profile is the flight over the runway and the descent and climb.

Profile 2 (P2 - Rejected takeoff):
During this profile, the ARIES taxied (generally along taxiway P) to the departure runway. When cleared for take-off, the ARIES executed a take-off roll but aborted the take-off usually before 120 knots (kts). The

aircraft remained on the airport surface during this entire profile. Its speed varied from taxi speeds (about 20 kts) to take-off speeds (about 100 kts). This profile gives a good assessment of surface accuracy. Selected tracks for this profile are found in Appendix C.

Profile 3 (P3 – Taxi to cross runway):
For this profile, the ARIES taxied to a runway but stopped before crossing the hold bar. Like Profile 2, the aircraft was on the airport surface for this entire track and only reached taxi speeds. This profile generally contained the shortest segment of data. Selected tracks for this profile are found in Appendix D.

Profile 4 (P4 - Landing on occupied runway):
This profile was very similar to Profile 1 with the aircraft conducting a standard approach and performing a go-around at approximately 61meters (200 ft) altitude. The aircraft's speed and ground coverage were also similar to Profile 1. Selected tracks for this profile are found in Appendix E.

Profile 5 (P5 – Ramp approach):
This profile entailed the aircraft to travel toward a gate at Terminal C. The aircraft turned away before pulling completely up to the gate; however, to avoid having to cut engines and push back from the gate. The aircraft speed range was taxi speeds. It is notable that there are periods during execution of this profile that the aircraft was stationary. These periods are useful for getting data for comparing the GPS systems while the aircraft is in a stationary position. Two samples of this profile is given in Appendix F

Profile 6 (P6 – Landing, stop on runway, runway exit):
The data segment for this profile includes flight, approach, landing, roll out to full stop on the runway, and taxiing off the runway. This profile covered the widest range in speed due to the range of activities involved. More information on the test objectives of this profile may be found in [11]. GPS coverage and accuracy was evaluated from the air to the surface. Selected tracks for this profile are found in Appendix G.

Profile 7 (P7 – Landing, runway turnoff):
For purposes of this report, this profile was almost identical to profile 6 except that the ARIES did not make a full stop on the runway. More information on this profile can also be found in [11]. The activity covered flight, approach, landing, rollout, and runway turnoff. Selected tracks for this profile are found in Appendix H.

Data Collection

For each positioning system installed onboard the ARIES, both position and status data were recorded at various sample rates by the DAS. The primary instruments generating position data included LAAS, WAAS, and Ashtech. The LAAS and WAAS data contained latitude, longitude, MSL height, Universal Time Clock (UTC) time, GPS signal quality and instrument status parameters. The GPS quality parameters include the position dilution factors for the vertical, horizontal axis (VDOP,HDOP) as well as time dilution(TDOP). The Ashtech system, in addition to the above parameters, also reported Earth Centered Earth Fixed (ECEF) XYZ coordinates. Other status information was also reported by the instruments – including differential mode operation. (See Table 2)

In addition to the LAAS, WAAS, and Ashtech primary instruments, algorithms running on the onboard Onyx computer combined the LAAS and Ashtech position reports with those from the Inertial Reference Units (IRU) to generate two additional positioning streams as illustrated in Figure 8. For the purposes of this report, IRU differences will not be considered. Hence, all IRU data were assumed to be identical. The LAAS/INS and Ashtech/INS blended solutions were computed at 50 Hz. During the test, system operators could select which IRU position stream to use in the Inertial Navigation System (INS) to blend with the LAAS or Ashtech; and also to select which blended solution (Ashtech/INS of LAAS/INS) to send to the RIPS software.

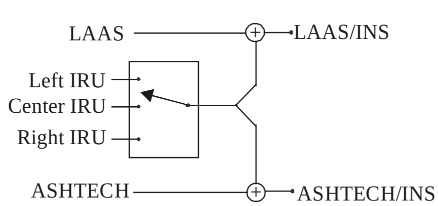


Figure 8: Data blending sources

This report will compare the accuracy of the following seven position data streams against the Truth data described earlier.

1) LAAS
2) LAAS with no differential corrections - available for one test day when the LAAS ground station was not operating
3) WAAS
4) Ashtech with no differential corrections (when available)
5) Ashtech with differential corrections
6) Differentially corrected Ashtech blended with IRU
7) Differentially corrected LAAS blended with IRU

Table 2, below, gives the parameters available from each of the GPS systems. For purposes of this analysis, the Truth data was accepted as the definitive position of the aircraft. It should be noted that this data was given in GPS time, which is 13 seconds ahead of UTC time. Alignment of the data took this into consideration.

Table 2: Recorded parameters

	Truth Parameters	**LAAS Parameters**	**LAAS/INS**	**WAAS Parameters**	**Ashtech Parameters**		**Ashtech/INS**
Time	GPS Time	LAAS UTC	DAS UTC	WAAS UTC	Ashtech UTC		DAS UTC
Position	Latitude Longitude Ellipsoid Height	Latitude Longitude Altitude MSL	Latitude Longitude Altitude MSL	Latitude Longitude Altitude MSL	Latitude Longitude Altitude MSL	ECEF X ECEF Y ECEF Z	Latitude Longitude Altitude MSL
Signal Quality	NSV PDOP	NSV EWP VVF HDOP VDOP		NSV EWP VVF HDOP VDOP	NSV TDOP PDOP HDOP VDOP		
Status	Flag	Status 1 Status 2		Status 1 Status 2	Differential flag Data Age		

Note in Table 2 that the Ashtech system generated two sets of position outputs. For each instance the ARIES position is given in both geodetic Latitude/Longitude (Lat/Lon) and the Earth Centered Earth Fixed (ECEF) coordinates. These coordinates are in theory the same, but bear a comparison of the two coordinates to confirm this assumption. The formulation used by the Ashtech instrument to convert between coordinate systems is not known. To arrive at congruent measures for this analysis, the ECEF coordinates were converted to geodetic form and plotted against the raw geodetic coordinates output by the Ashtech. Typical results for the horizontal axis are plotted in Figures 9, 10, 11, and 12 for four profiles. In the graphs, no interpolation is done for either the Lat/Lon or the ECEF XYZ coordinates.

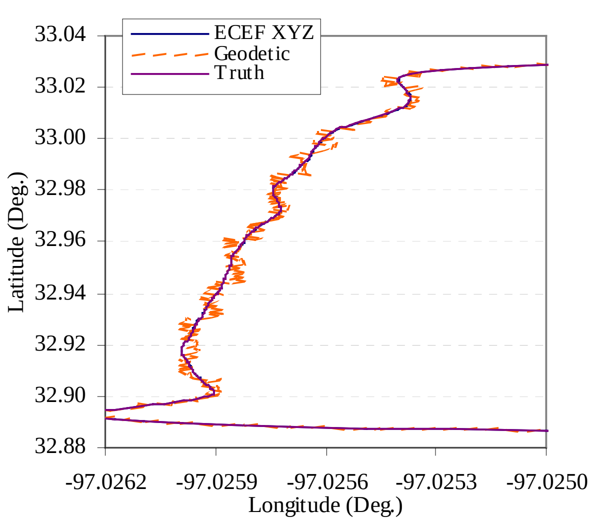


Figure 9: Profile 1 Ashtech ECEF versus geodetic coordinates

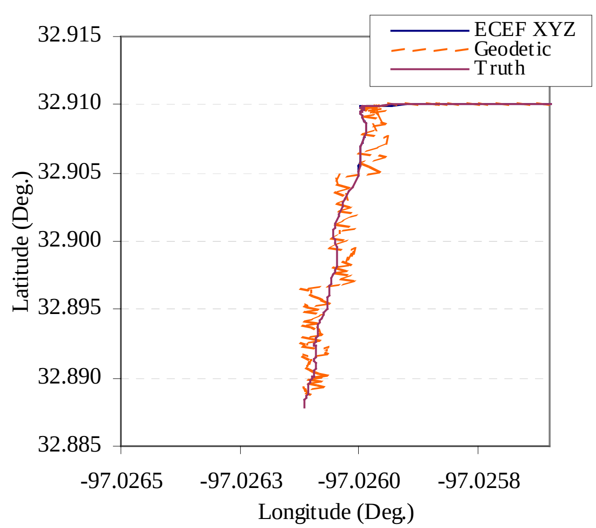


Figure 10: Profile 2 Ashtech ECEF versus geodetic coordinates

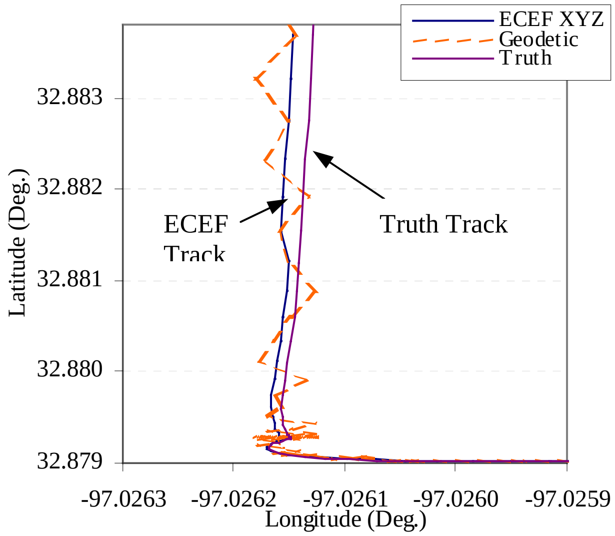


Figure 11: Profile 3 Ashtech ECEF versus geodetic coordinates

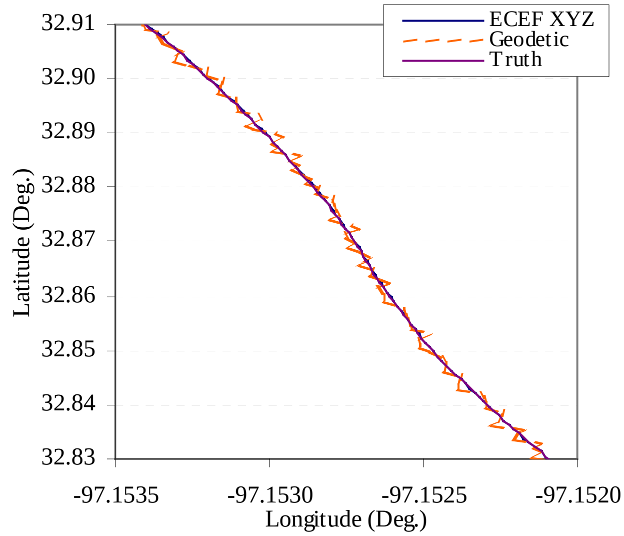


Figure 12: Profile 4 Ashtech ECEF versus geodetic coordinates

As may be seen from Figure 9 to 12, the geodetic form of the Ashtech ground track appears to be jittery. The ECEF XYZ form is closer to the Truth track. In Figure 9, 10, and 12, the ECEF track overlays the Truth track. Since the Lat/Lon data derived from the ECEF coordinates were more accurate and it is unclear how the instrument computes Lat/Lon from ECEF, comparisons in this report dealing with the Ashtech instrument used the ECEF derived Lat/Lon coordinates instead of the raw Lat/Lon coordinates provided by the instrument.

It is unfortunate that not all the data were available all the time. However, there were enough data from each of the six channels to make meaningful comparisons. It should be noted that all the data were recorded at different rates. To simplify the analysis, all the positioning system data were reduced to 2 Hz. Given that the Truth data were generated at 1 Hz, the truth data were interpolated to 2 Hz for comparisons with the other data.

Comparison Methodology

The accuracy of each GPS system was assessed by comparing the position reports with the post processed Truth data. Simplistically, this task involved correlating the data points to the Truth data and computing the difference. The error can then be put into a local frame of reference for verification and easier understanding. Plots of the ground track of the different GPS systems were used to check the error computations. Additionally, it was possible to estimate the error of each system by plotting reported positions of each system against the Truth data during periods when the aircraft was stationary.

Initially, track errors were computed by correlating reported positions by UTC time. This was a logical approach since UTC was reported by all systems and was a component of the GPS system. Unfortunately, this effort revealed sampling time issues as well as timing discrepancies among the positioning systems. These discrepancies complicated the process of aligning individual data points with the Truth data and yielded track errors much larger than those indicated by the stationary plots and ground track plots. The majority of the large errors were traced to sample rate mismatches between the GPS devices and the DAS. The sections below describe how this problem prevented a direct temporal alignment of the data and describe the spatial approach taken to compute track errors that more closely corroborate with stationary and ground track plots.

Sample rate mismatch:

The major impediment to temporal alignment of the data was the mix of data rates, sampling rates, and data reduction rates. The Ashtech, LAAS and WAAS instruments produced position reports at 1 Hz but were recorded by the DAS at 6.3 Hz. The Ashtech/INS and LAAS/INS blended data were generated by the Onyx and recorded by DAS at 25.4 Hz, and 50.7 Hz respectively. Recall that each instrument (LAAS, WAAS, and Ashtech) produced a UTC time representing the instance that the Lat/Lon data was valid. With each record, DAS also logged the UTC time representing the instance when the data was logged. The latency of the recording system was computed by taking the difference between the UTC times (Discussed later). The post processed Truth data was provided in 1-second intervals (1 Hz).

In order to reduce the volume of data, the recorded position data from DAS was extracted at approximately 2 Hz. While a vast majority of the data was given in two readings per second, it was common to have instances where three readings were extracted for a one second period and instances where only one reading was extracted for a one second period. This was because of the difference between the recording rates and extraction rates – more specifically that the extraction rate was not a harmonic of the recording rate. This was problematic owing to the nature of the over-sampling and caused readings to be taken where the Lat/Lon data was updated and recorded before its accompanying UTC updated. Sample data segments that illustrate this are given in Table 3 for LAAS and Table 4 for WAAS. This anomaly is found most often in the WAAS data and to a lesser extent in the LAAS, and Ashtech data.

Table 3: LAAS UTC update delay (S4/r170_02.xls)

DAS UTC	LAAS UTC	LAAS Lon (Deg)	LAAS Lat (Deg)	LAAS Alt MSL (m)
5:35:20.703000	05:35:20.097580	-96.9038125	32.8690646	1489.86538
5:35:21.198000	05:35:20.097580	-96.9038125	32.8690646	1489.86538
5:35:21.692000	05:35:20.097580	-96.9039265	32.8681678	1484.68377

Table 4: WAAS UTC update delay from raw data. (S4/r170_02.xls)

DAS UTC	WAAS UTC	WAAS Lon (Deg)	WAAS Lat (Deg)	WAAS Alt MSL (m)
5:46:51.520000	05:46:50.992172	-97.1510343	32.9452458	939.090678
5:46:52.014000	05:46:50.992172	-97.1510343	32.9452458	939.090678
5:46:52.509000	05:46:50.992172	-97.1515125	32.9445108	939.395479

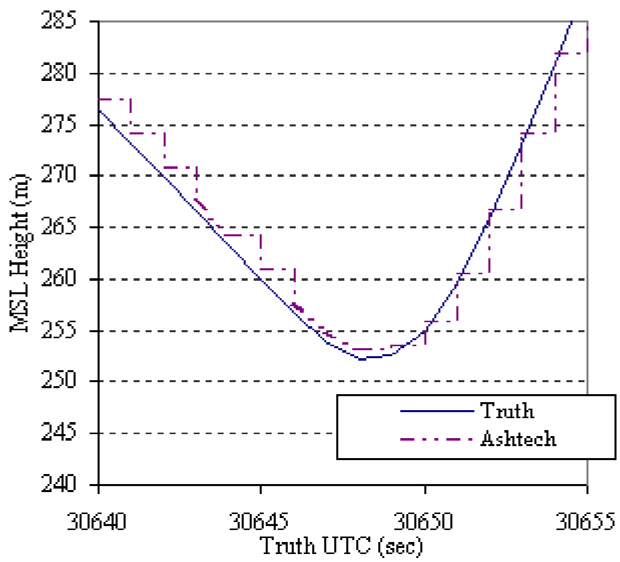


Figure 13: Height reported by Ashtech correlated to Truth data using UTC time.

This artifact of the DAS recording and post processing system distorted some of the error computations when the data was matched to the Truth data by time. The result is that for points where the Lat/Lon data was updated before the UTC, the error is large because that position is compared with a previous position based on the UTC match. While the vast majority of the data can be matched in a temporal sense, this problem occurred often enough to make the average disagree with that observed in the stationary plots. Furthermore, this error was exaggerated when the aircraft was flying because the movement rate was much higher in the air compared to on the surface. Because this artifact in the data occurred with no regular pattern, it precluded any easy time-based matching algorithms to correlate to the Truth data for computing track error. This is illustrated best in Figure 13 where the Ashtech vertical track shows a stair stepping effect instead of a smooth curve.

Spatial Comparison Method:

In light of the problems of matching the LAAS, WAAS, and Ashtech GPS position reports using only the UTC, an alternative method was devised to correlate the GPS position reports to the Truth data. This method combined the temporal alignment with a spatial computation in a two-step technique. The first step was to match a GPS position to the closest two Truth position points based on the UTC of the candidate point. The second step was to compute the error as illustrated in Figure 14. The error was computed as the perpendicular distance from the line connecting the two Truth points to the GPS point. This technique was purely geometric and did not consider any temporal alignment of the points. This technique was not exact but yielded error measurements that were most consistent with visual inspections of the ground tracks.

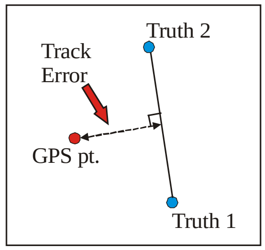


Figure 14: Error definition.

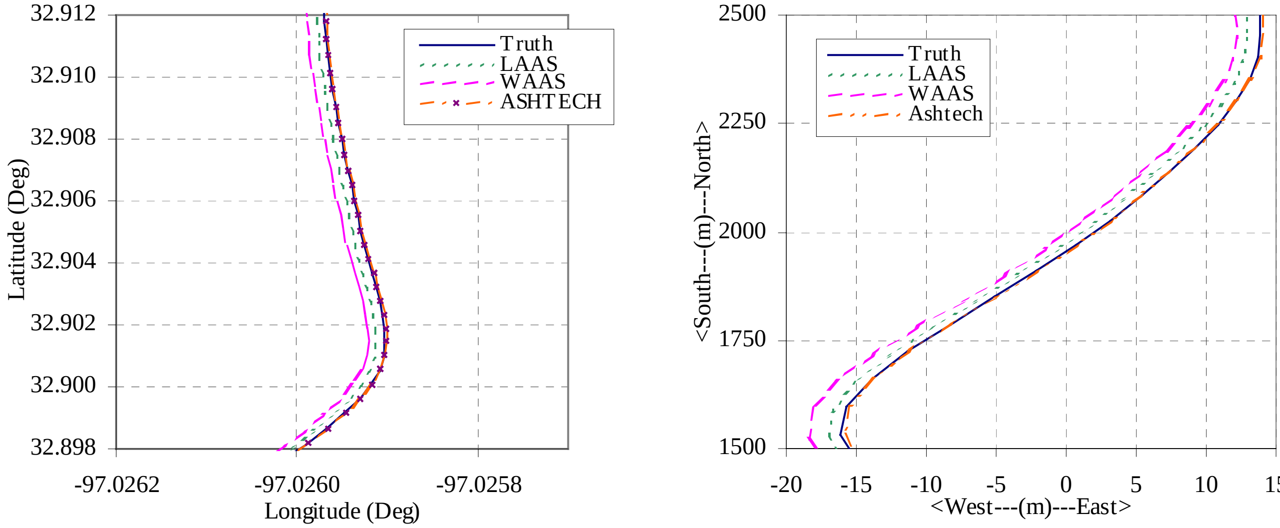
LAAS WAAS & Ashtech Results

Positioning system data was available from 93 test runs conducted at DFW. Studying the ground tracks in the spatial sense without any temporal considerations gave a qualitative assessment of the performance of each system while ignoring any timing irregularities between the systems. The comparisons of the seven positioning data streams were performed in two ways. Comparisons of the raw ground tracks for each system was made first. This was followed by statistical summaries of the data, which were computed using the method described above. The purpose of comparing the raw ground tracks for each positioning system was to provide a reality check on any conclusions drawn from statistical averages. Ground tracks for six of the movement profiles can be found in Appendices B-G.

This section presents typical ground tracks of the primary GPS systems. The blended systems were also compared to their respective primary systems. The ground track study was done based on the raw Lat/Lon coordinates recorded directly from DAS. It should be noted that the GPS system was optimized for horizontal positioning accuracy. Hence, the accuracy study was best achieved by examining the horizontal and vertical axis separately. Other system parameters such as DOPS and visible satellite counts were used to assess the availability of the systems.

Horizontal Accuracy

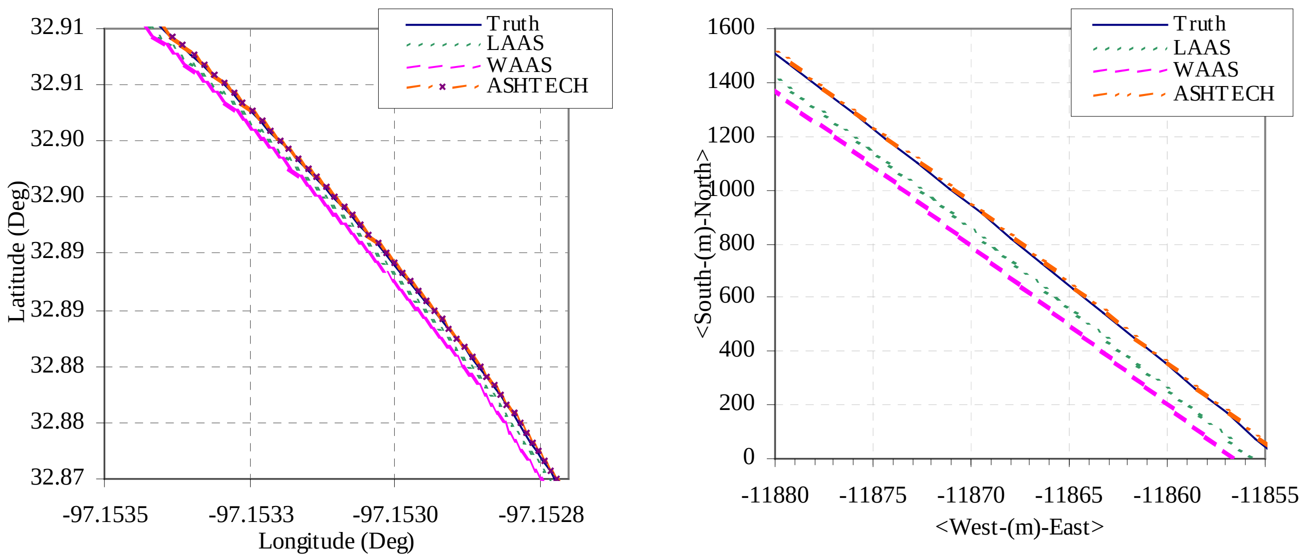
The horizontal tracks of the seven positioning data streams can be compared in numerous ways, each based on a different grouping of the data. Tracks from different locations or different elevations may be compared. To give a cross section of representative activities, comparisons are shown here for tracks on the ground as well as tracks in flight. A surface run along runway 35C is given in Figure 15. Tracks at flight elevation are shown in Figures 16-19. The flight paths were typical of the activities that the ARIES executed in the air during various test runs. Note in the lat/lon plots that either the latitude or longitude had to be greatly exaggerated to show the track error. This made the grids disproportionate between the two axes. To give a better sense of the magnitude of the track error, the Lat/Lon coordinates of the tracks are put into a local coordinate frame in the (b) portion of Figure 15-18. The local coordinate frame is based at the center of the threshold of runway 17C. This is a convenient base point because all the runs were conducted from this runway. Due to the volume of data generated, only selected runs are given in the Appendices.



(a)Track in Lat/Lon coordinates.

(b) Small section of track in runway coordinates.

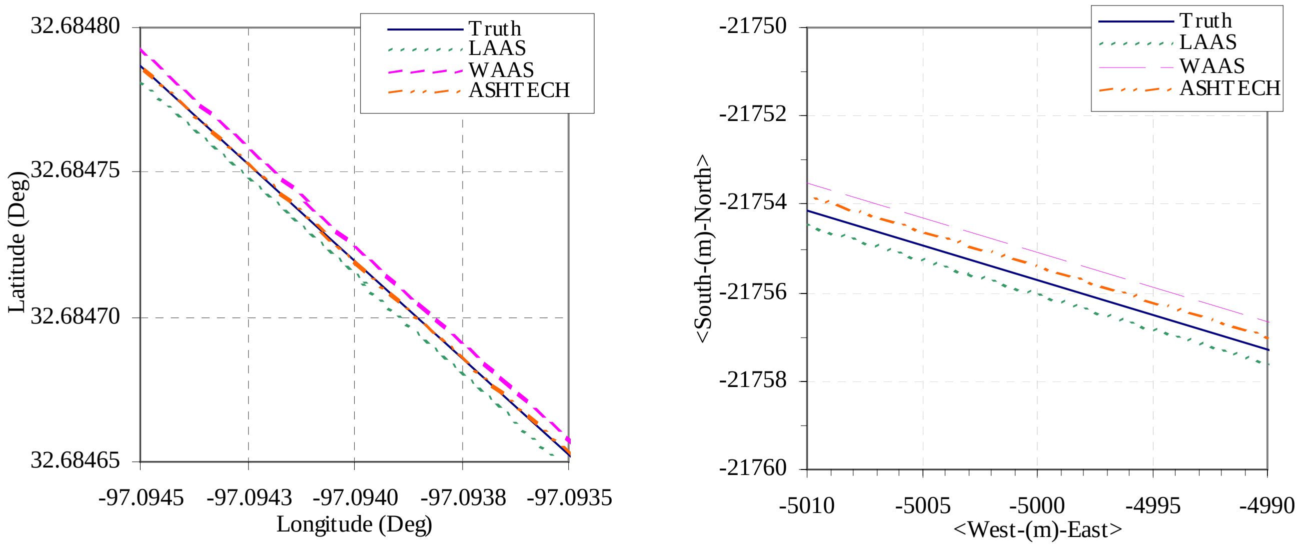
Figure 15: Runway 17C fly over, heading north. The east/west scale in (b) is greatly exaggerated to show track error.



(a) Track in Lat/Lon coordinates.

(b) Track in runway coordinates.

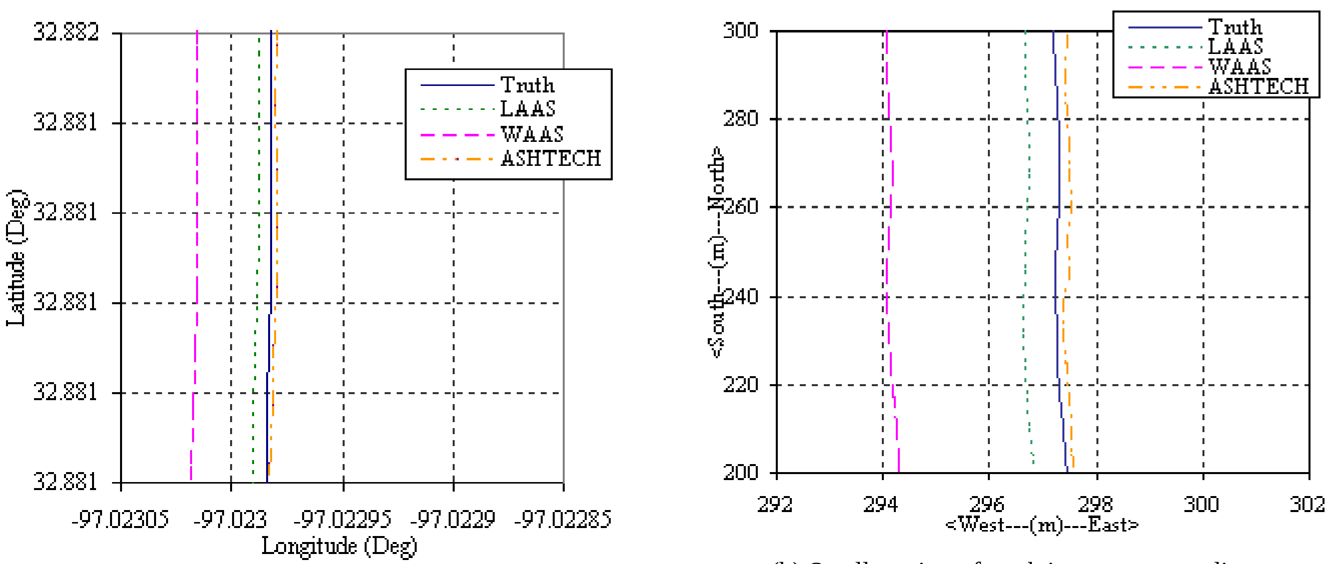
Figure 16: Flight path parallel to, but west of, runway 35C. The east/west scale in (b) is greatly exaggerated to show track error. (b) magnifies a small segment of (a).



(a) Track in Lat/Lon coordinates.

(b) Track in runway coordinates.

Figure 17: A segment of an east/west track flown south west of DFW. Flight path is perpendicular to runway 35C. The north/south axis scale in (b) is greatly exaggerated to show track error. (b) magnifies a small segment of (a).

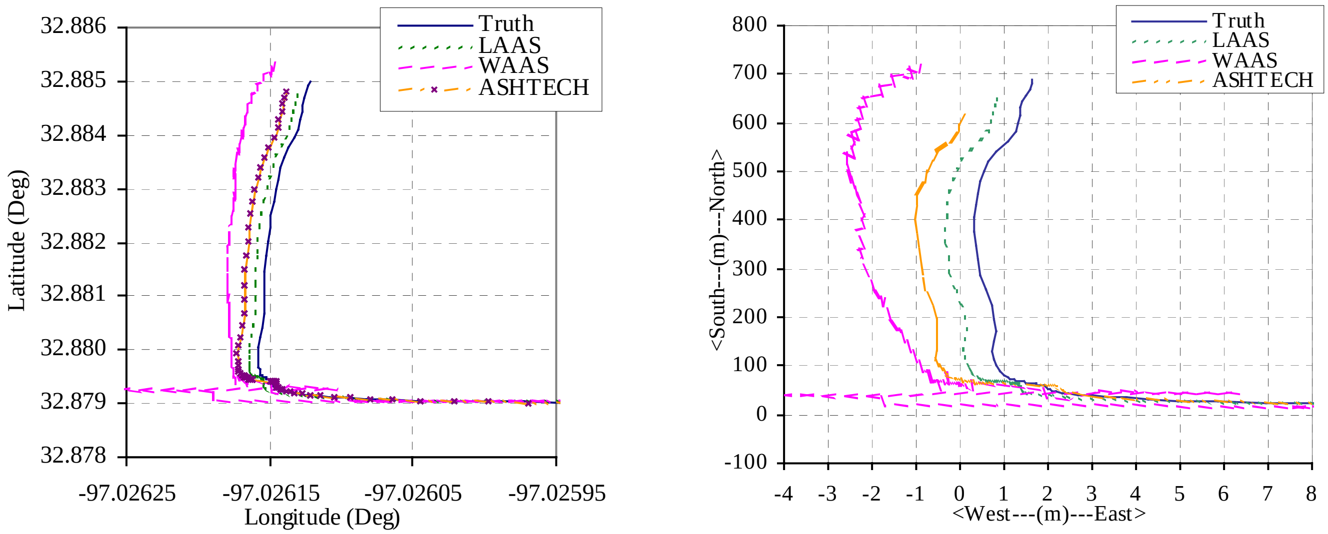


(a)Track in Lat/Lon coordinates.

(b) Small section of track in runway coordinates.

Figure 18: Ground track along taxiway P traveling south en route to runway 17C to execute Profile 2. The east/west scale in (a) and (b) has been greatly exaggerated to show track error.

For the majority of the test runs, all systems performed well. When airborne (Figure 15-17), the Ashtech tracked the Truth data best. It was followed by the LAAS system. The WAAS was the least accurate of the three systems. Similarly on the surface (Figure 18), the Ashtech system was most accurate followed by LAAS and finally WAAS. The WAAS system was also observed to have the most variability on the ground. There was one anomaly found for the Ashtech system at the base of runway 17C. It tended to be less accurate than the LAAS along the first 600 to 700 meters (figure 19). This was believed to be caused by a blockage of the Ashtech differential signal. When the aircraft was in the take off position at the base of 17C, the Ashtech differential antenna was on the opposite side of the aircraft from the Ashtech ground station. This could occasionally put the Ashtech out of differential mode (discussed later).



(a)Track in Lat/Lon coordinates.

(b) Small section of track in runway coordinates.

Figure 19: Ground track of a rejected take off scenario (Profile 2) on runway 17C heading north. The east/west scale in (b) is greatly exaggerated to show track error. The aircraft actually travels in a relatively straight northerly track.

Vertical Accuracy

Vertical accuracy comparisons are made based on the raw Mean Sea Level (MSL) height output from each system. The MSL height was charted with the latitude to give a spatial perspective of the altitude profiles approximately along the runway. It is also important to look at the temporal aspect. Figure 20-22 show some typical altitude profiles executed at DFW. Figure 20 shows the typical altitude profile for runs during which the aircraft performed a go-around maneuver (Profile 1). It shows the descent and subsequent climb above the runway. The arrow indicates the direction of travel.

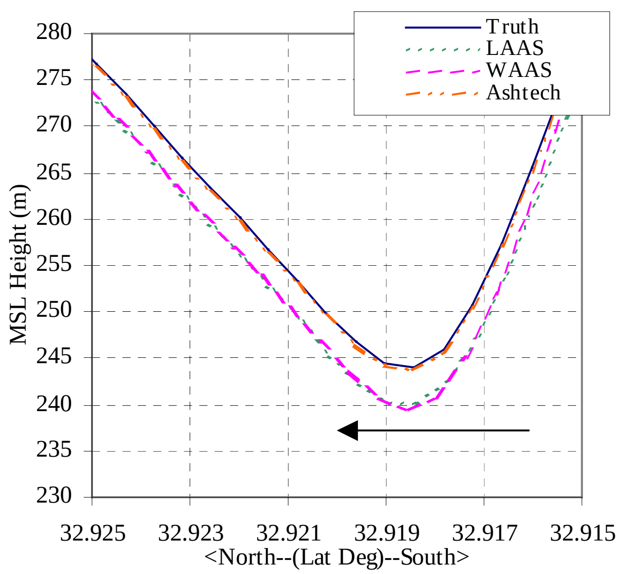


Figure 20: Altitude profile of a go-around on approach to 17C based on raw data.

Figure 21 shows the altitude profile of a landing such as performed during Profile 6 or 7. Only the final approach and landing is shown. According to the published Jeppesen map of DFW, runway 17C is at an elevation of 171.36 meters (562.2’). Recall that the GPS antenna, from where the measurement data was referenced, was mounted above the fuselage at a height of about 6.25 meters (20.5’). Hence the rollout portion of the height profile should be at about 177.61 meters (582.7’) MSL. This was in very good agreement with the height given by the Truth track in the figure. On the final stretch rollout, the data indicates that the Ashtech was about 8cm high while the LAAS and WAAS systems were about 5 meters, and 4 meters low respectively.

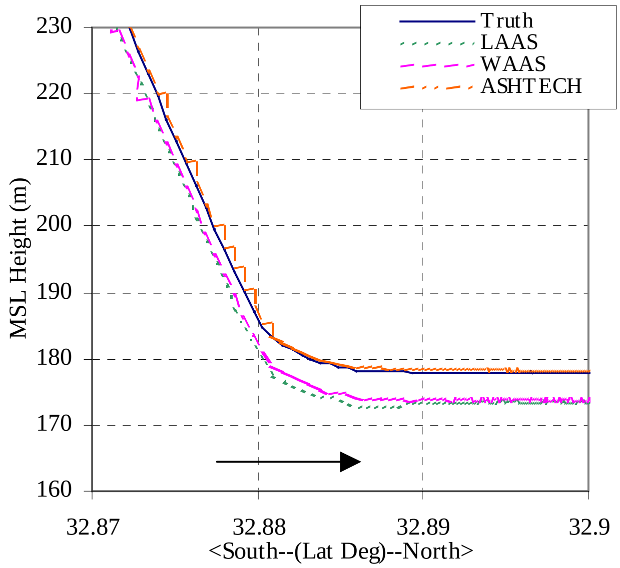


Figure 21: Altitude profile of landing on 35C. Based on raw data.

Figure 22 shows the profile for a flight north of DFW. The westerly transit was in preparation for a test run execution. This track passed the Ashtech ground beacon to the north. For the most part, the plots show that the Ashtech system gave the most accurate altitude reports followed by the LAAS and WAAS. This is consistently true except for cases on the airport surface when the Ashtech lost the differential signal. An example of this is plotted in Appendix C Figure 2G.

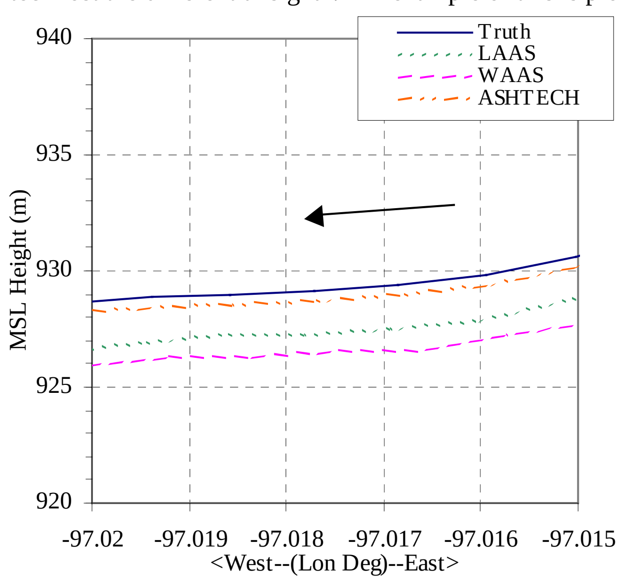


Figure 22: Altitude profile of westerly transit. Based on raw data.

Ashtech, LAAS, and WAAS Averages

The preceding sections assessed the accuracy of the position data based on several representative samples. The tables below give the average accuracy for all the tracks from runs during the test week. Some runs from the technology demonstration are also included. The average reported in the tables below is a root-mean-square (RMS) average and not a variance. Errors above 500 meters were excluded from the average because these points were rare anomalies. However, their magnitudes were large enough to distort the average. This point is discussed later. The data for each system is partitioned by profile as described in above sections. This organization of the data groups similar activities in each average.

The RMS errors are given in runway coordinates where the origin is at the surveyed center point of the threshold of runway 17C. The X-axis runs approximately east/west and the Y-axis runs along the center of the runway. The X and

Y distances are the delta from the Truth point to the subject point. This is calculated by converting the raw lat/lon positions into north/south and east/west radials from the surveyed threshold point. The runway heading is accounted for by rotating the resulting values by the runway heading (0.26degrees). More ground tracks are plotted in Appendices B-G.

Ashtech System

As seen in Table 5, the Ashtech system shows about half meter error in the horizontal. This appears to be consistent for both air and ground activities. In the vertical axis, the Ashtech contains up to 4 meters error. Note that the larger errors occur while airborne. For the three ground profiles, the vertical error is up to about one meter. Profile 6 and 7 contain some air and ground movement data and has vertical error of about one to two meters.

Table 5: Spatial correlated RMS error summaries for Ashtech.

Ashtech Spatial correlated error summaries					
Activity	**Profile**	**Points**	**X (m)**	**Y (m)**	**Height (m)**
Air	P1	21350	0.580	0.535	4.377
Air	P4	13715	0.595	0.581	3.019
Air/Ground	P7	10804	0.486	0.451	1.640
Air/Ground	P6	20392	0.533	0.447	1.897
Ground	P5	4734	0.231	0.182	0.690
Ground	P2	8419	0.231	0.199	0.984
Ground	P3	11951	0.235	0.350	0.730

Another factor that can cause the Ashtech system to be less accurate is the loss of differential correction signal from the ground station. Recall that the Ashtech beacon was installed at the top of the Harvey Hotel. There were five test runs in which the ground tracks did not contain differentiated Ashtech data. These are listed in Table 6. It appears that the aircraft was on the ground during each of the five runs. Unfortunately, the Ashtech GPS receivers can only be setup to output either non-differentially corrected positions or differentially corrected positions and not both. Therefore only a small data sample is available as indicated in the table.

Table 6: Runs where non-corrected Ashtech data exists.

Run	**Profile**	**Seconds of Data**
R170_08	P2	153
R170_09	P3	23
R170_13	P2	250
R171_25	P3	6
R171_31	P2	93

Figure 23 and 24 plot the locations where the Ashtech system lost the differential signal from the ground beacon. All the data available indicates that the signal was lost after turning onto 17C. It is very peculiar that reception was lost only on the runway and not on taxiway ER. It was not believed to be a range problem. As previously noted, there was a high probability of line of sight blockage from the body of the aircraft in the take off orientation. The beacon antenna was mounted on top of the hotel at 210.5m (690.8 ft) high. The aircraft antenna was about 6.3m (20.5') above the ground at the south end of the runway, over three miles away from the beacon. There was a Federal Express Hanger at the north end of the runway and a large Delta Hanger that was about 870m (2850ft) north east of the location where differential correction signal was lost. It was possible that these structures caused some scatter or blockage at near ground levels. Table 7 gives the average error experienced in the absence of the differential signal. The vertical error is about 10 meters while the horizontal error ranges 2 to 12 meters.

Table 7: RMS errors for non-differential Ashtech data.

RMS errors for non-differential Ashtech data				
Profile	**Points**	**X (m)**	**Y (m)**	**Height (m)**
P2	496	1.129	12.337	10.897
P3	29	3.037	2.403	9.672

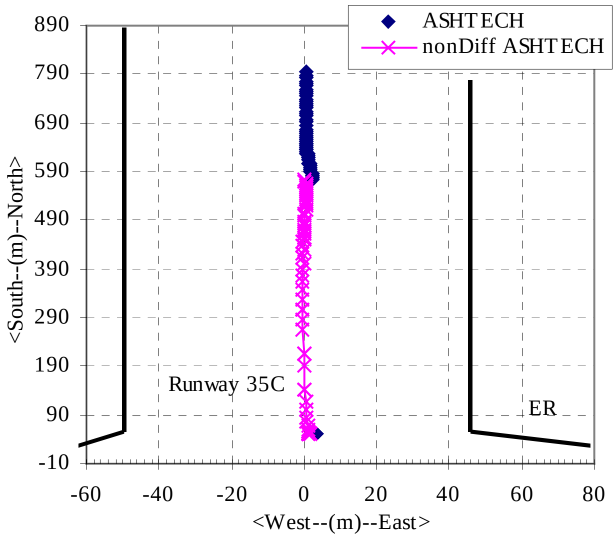


Figure 23: Location where Ashtech lost differential corrections. (Run R170_13)

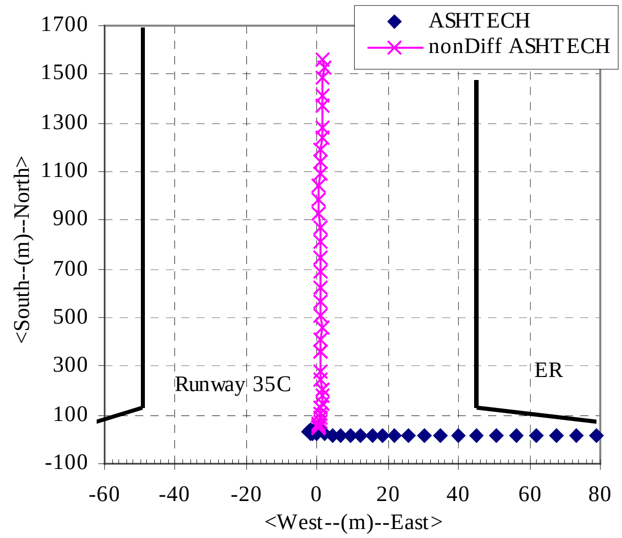


Figure 24: Location where Ashtech lost differential corrections. (Run R171_31)

LAAS System

The LAAS system operated in differential mode for a majority of the test days. However, data indicating non-differential operations were available during the third day (flight R172) because the LAAS ground station was not powered on. For that day, LAAS operated entirely in non-differential mode. Two runs on the forth day (flight R173) also indicated non-differential LAAS operations. The RMS error summaries are shown in Table 8 for LAAS data and Table 9 for non-differentially corrected LAAS data. There does not seem to be a significant difference between LAAS operating in differential or non-differential mode. Horizontal error ranges from .5 to 1.2 meter for both. It is not theoretically possible for non-differential GPS to be as accurate as differential GPS, but the data recorded at DFW indicates that the performance is comparable with Selective Availability (SA) turned off. However, operating in differential mode tends to increase integrity and reliability of the GPS reception. Vertical error for differential LAAS ranges from 4 to 7 meters while non-differential LAAS can error up to 8 meters. There appears to be about a 5 meter bias in the vertical axis for both LAAS and WAAS. It is not clear what this bias is attributable to, but this bias is also observed in the raw tracks in Figures 20-22 for both systems.

Table 8: Spatial correlated RMS error summaries for LAAS.

LAAS Spatial Correlated error summaries					
Activity	**Profile**	**Points**	**X (m)**	**Y (m)**	**Height (m)**
Air	P1	16620	1.199	1.159	6.917
Air	P4	9190	0.830	0.862	5.272
Air/Ground	P7	9179	0.880	0.971	4.706
Air/Ground	P6	17115	1.001	0.841	4.470
Ground	P5	4734	0.603	0.563	5.072
Ground	P2	7269	0.549	0.532	4.543
Ground	P3	10553	0.799	0.813	5.246

Table 9: Spatial correlated RMS error summaries for LAAS without differential corrections.

Non-differentiated LAAS Spatial Correlated error summaries					
Activity	**Profile**	**Points**	**X (m)**	**Y (m)**	**Height (m)**
Air	P1	4705	0.548	0.560	2.867
Air	P4	4525	0.921	0.996	5.020
Air/Ground	P7	1625	0.837	0.150	5.786
Air/Ground	P6	3277	1.368	0.482	5.569
Ground	S2	2185	0.990	0.655	5.635
Ground	S3	1457	0.635	0.548	8.034

WAAS System

Table 10 shows the RMS error summaries for the WAAS data. This system had a horizontal error ranging from .7 to 2.2 meters. The vertical error ranges 4 to 5.8 meters. The error was consistent for air and ground activities. One run was found where the WAAS system did not function normally (R173_49). During this run, position updates were not available for the first 142 seconds of the run, then became available for 45 seconds, and again failed for the remaining 258 seconds. During the failure periods, the position did not changed. The data for this run was not included in the averages in Table 8.

Table 10: Spatial correlated RMS error summaries for WAAS.

WAAS spatial correlated error summaries					
Activity	**Profile**	**Points**	**X (m)**	**Y (m)**	**Height (m)**
Air	P1	20744	2.162	1.151	4.216
Air	P4	13715	1.567	0.997	4.578
Air/Ground	P7	9590	1.425	1.070	4.429
Air/Ground	P6	20392	1.740	1.102	5.251
Ground	P5	4734	1.489	0.775	4.774
Ground	P2	9454	1.313	1.071	5.758
Ground	P3	12010	1.071	1.703	4.063

Blended Position Accuracies

Recall that data from the IRU in the Inertial Navigation System (INS) was blended with the Ashtech and LAAS to create two additional position reports. In general, the blending of Ashtech and INS yielded less accurate position reports than the Ashtech alone. This is true for the horizontal axis where the Ashtech alone ranges about .2 to .6 meter while the blended Ashtech had an error range of 1 to 3.7 meters. This is apparent in Table 11, which compares the horizontal accuracy of the two data channels. The vertical axis error averages, given in Table 12, showed that the Ashtech/INS channel is more accurate than the Ashtech while the aircraft was airborne. However, Ashtech/INS was less accurate on the ground.

Table 11: Ashtech/INS horizontal versus Ashtech

Activity	**Profile**	**Ashtech/INS**			**Ashtech**		
		Points	**X (m)**	**Y (m)**	**Points**	**X (m)**	**Y (m)**
Air	P1	21351	1.355	1.321	21350	0.58	0.535
Air	P4	12987	1.628	1.544	13715	0.595	0.581
Air/Ground	P7	9833	1.572	1.522	10804	0.486	0.451
Air/Ground	P6	20392	1.299	1.12	20392	0.533	0.447
Ground	P5	4734	3.38	2.697	4734	0.231	0.182
Ground	P2	9454	2.38	2.855	8419	0.231	0.199
Ground	P3	11646	3.652	2.561	11951	0.235	0.35

Table 12: **Ashtech**/INS vertical error compared to Ashtech

Activity	**Profile**	**Ashtech/INS Height (m)**	**Ashtech Height (m)**
Air	P1	2.308	4.377
Air	P4	2.295	3.019
Air/Ground	P7	1.916	1.64
Air/Ground	P6	1.82	1.897
Ground	P5	2.278	0.69
Ground	P2	3.168	0.984
Ground	P3	2.457	0.73

Although the RMS averages indicated that the Ashtech/INS was generally less accurate, there were some tracks found where it was more accurate than the Ashtech track. Figure 25 shows a case where the blended Ashtech/INS was better than the Ashtech. Figure 26 shows the typical case where the Ashtech is more accurate.

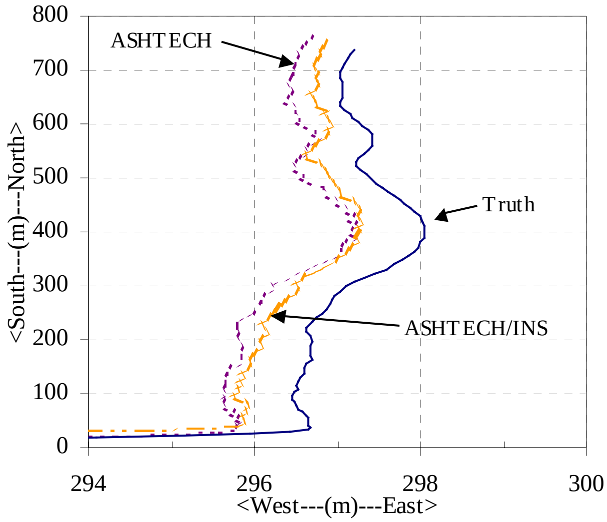


Figure 25: Ground track on taxiway Papa heading south.

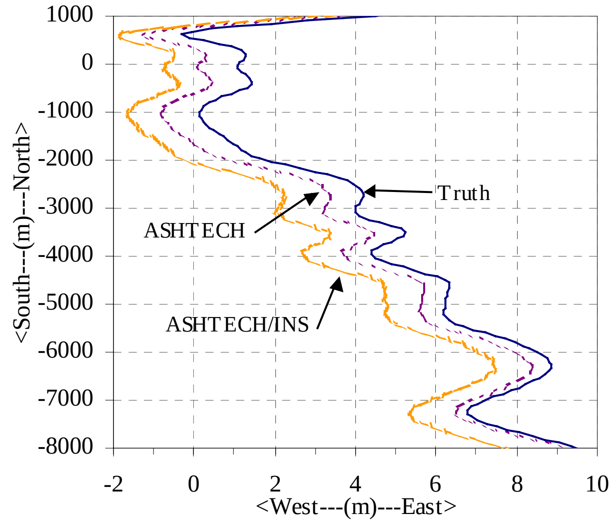
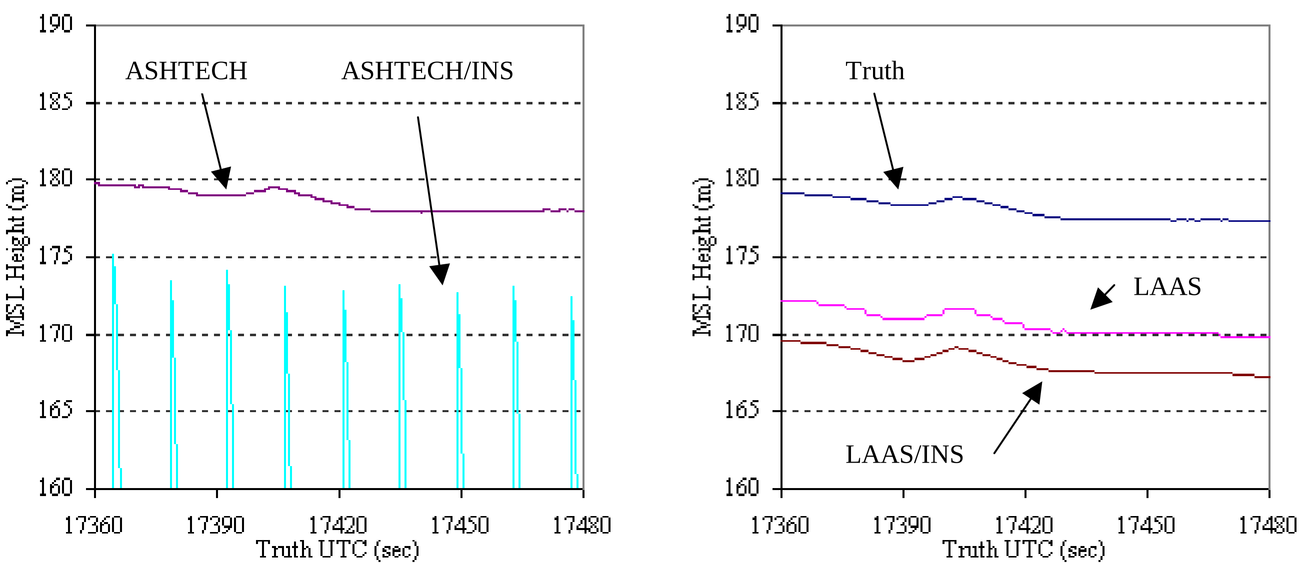


Figure 26: Final approach and landing onto 35C heading North

There was an anomaly found in the height comparison. During a Profile 3 run R174_58, the Ashtech/INS height consistently spiked four times every minute for the entire run. The reported peak-to-peak value for the MSL height was 360 meters. This is improbable given that the ARIES was on the ground during the run. This does not appear to be from the INS since the LAAS/INS blended height reports are consistent with the LAAS primary system.



(a): Ashtech/INS versus Ashtech height report. (b) LAAS/INS versus LAAS height report

Figure 27: Ashtech/INS height report anomaly during ground taxi. (b) gives the LAAS and LAAS/INS report during the same period. Both (a) and (b) show the same time period.

A significant amount of data was also available to compare the LAAS and its blended version. Table 13 compares the horizontal errors for LAAS/INS with LAAS. Like the Ashtech, LAAS updated with INS data, appears to produce a slightly less accurate track. LAAS/INS horizontal errors range from 1.0 to 2.8 meters while LAAS errors range from .4 to 1.2 meters. The vertical axis errors are very similar between the two data channels. LAAS is slightly more accurate with error ranges from 5 to 7 meters verses LAAS/INS with a range of 6 to 8 meters. Some tracks of the LAAS/INS blend with LAAS are given in Figures 28 and 29. The data for LAAS working in differential mode was used in Table 13 and 14.

Table 13: LAAS/INS horizontal error compared to LAAS

Activity	Profile	LAAS/INS			LAAS		
		Points	X (m)	Y (m)	Points	X (m)	Y (m)
Air	P1	21331	1.173	1.246	16620	1.199	1.159
Air	P4	13715	1.196	1.207	9190	0.83	0.862
Air/Ground	P7	10804	1.893	1.391	9179	0.88	0.971
Air/Ground	P6	20392	1.226	1.087	17115	1.001	0.841
Ground	P5	4734	2.738	2.322	4734	0.603	0.563
Ground	P2	9454	1.867	2.306	7269	0.549	0.532
Ground	P3	12010	2.783	2.063	10553	0.799	0.813

Table 14: LAAS/INS vertical error compared to LAAS

Activity	Profile	LAAS/INS Height (m)	LAAS Height (m)
Air	P1	7.041	6.917
Air	P4	6.577	5.272
Air/Ground	P7	7.761	4.706
Air/Ground	P6	6.28	4.47
Ground	P5	7.552	5.072
Ground	P2	7.3	4.543
Ground	P3	8.01	5.246

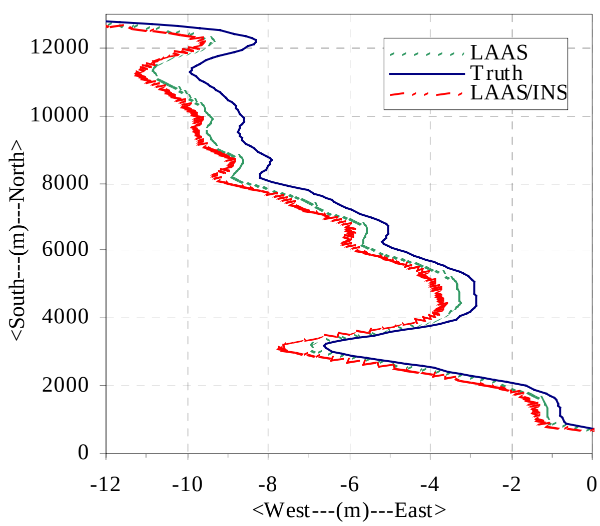


Figure 28: Go around executed above 17C heading South.

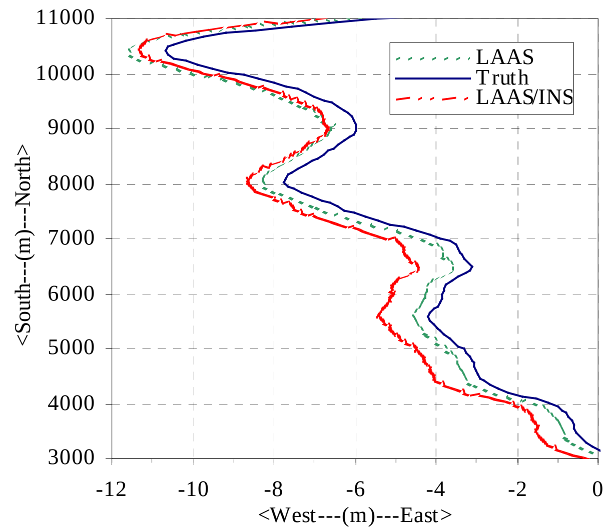
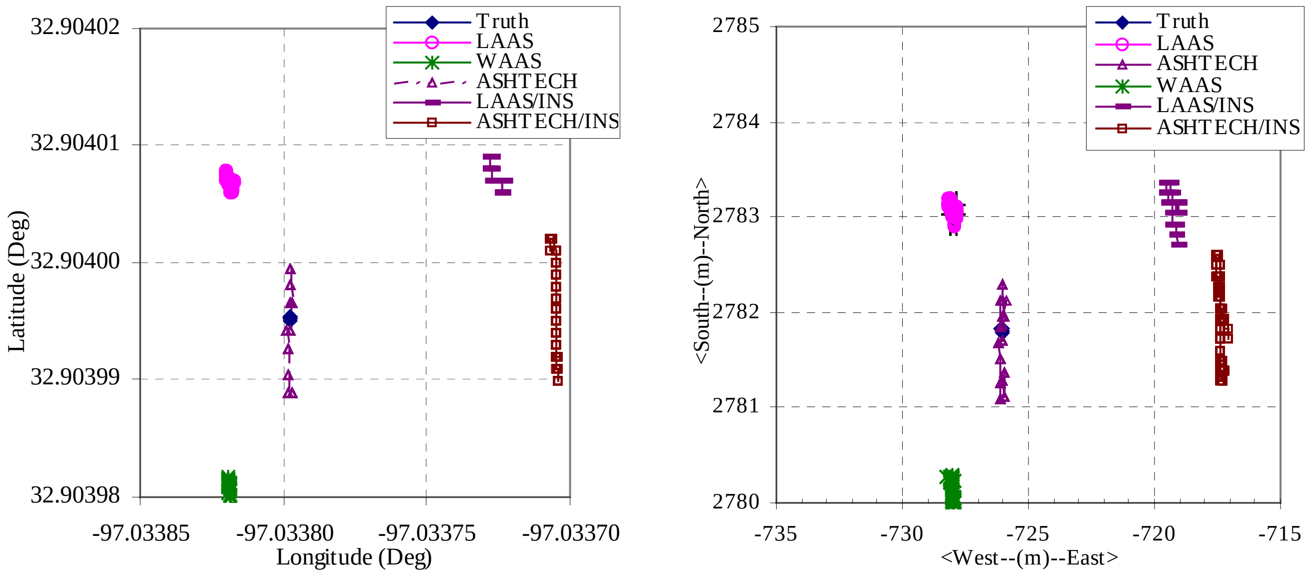


Figure 29: Go around executed above 17C heading South.

Stationary Periods

An independent way to assess system accuracies that avoid latency and other timing anomalies is to examine the systems during periods that the aircraft was essentially stationary. During these periods, timing errors have no impact on the result since there is no motion. Three segments of data were identified where there was significant period of no movement. The first was a taxi to the ramp (Profile 5) that contained about 150 seconds of data. Another period was found during a Profile 2 run which contained about 300 seconds of inactivity. The third segment occurred when the ARIES was holding short of 35C preparing to execute Profile 3. All three cases showed that the Ashtech was the most accurate of the three GPS systems.

Figure 30(a) gives the raw positions of all five systems for a stationary segment of a Profile 5 run (R171). Part (b) of the figure puts the locations in runway coordinates. Table 15 shows that LAAS and WAAS errors, respectively, to the (0.9 meter) north and (1.7 meters) south of the Truth. The LAAS was about 1.5 meters off while WAAS was about 1.7 meters off to the west of the Truth. Note in Figure 30b that the blended channels were off to the east. This was because the blended data was referenced to the IRU while all other data was referenced to the GPS antenna. Figure 31 shows the accuracy of the Ashtech/INS and LAAS/INS after adjusting their references to the GPS antenna. The Ashtech system was operating in differential mode during this period.



(a) Position profile from raw data.

(b) Position in Runway Coordinates. Note that the scale on the X and Y axis is not the same.

Figure 30: Position reports of GPS systems while ARIES was stationary. Data from Profile 5 run R171_19.

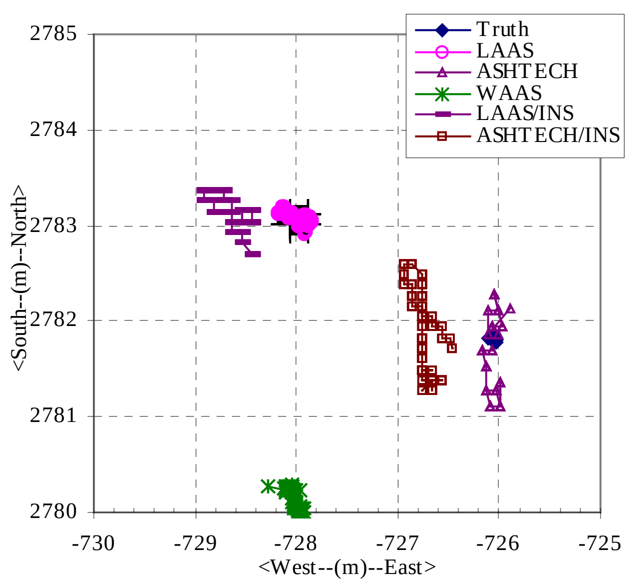
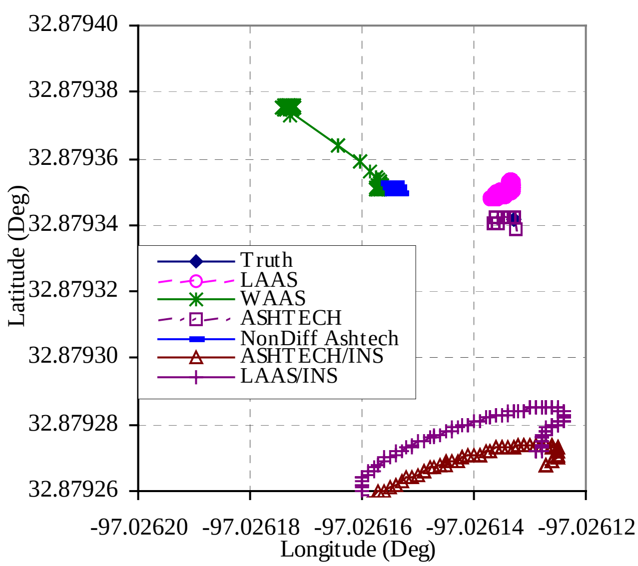


Figure 31 LAAS/INS and Ashtech/INS references adjusted to GPS antenna location.

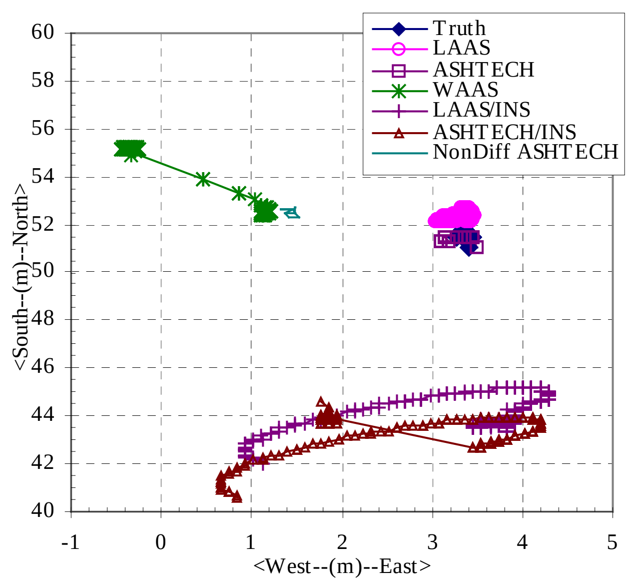
Table 15: RMS errors for stationary segment of Profile 5 run.

RMS errors for stationary segment of R171_19				
System	**Points**	**X(m)**	**Y(m)**	**Height (m)**
Ashtech	309	0.147	0.279	0.940
Ashtech/INS	309	6.724	2.522	1.676
LAAS	309	1.494	0.815	5.887
LAAS/INS	309	5.310	2.151	8.288
WAAS	309	1.663	1.145	2.345

Figure 32 shows another segment of data where the aircraft was stationary. This segment occurred at the beginning of a Profile 2 run (R170_13) where the aircraft was waiting at the base of runway 35C. The aircraft was apparently waiting to start the take-off roll, which ended in a rejected takeoff (RTO). This data is about 300 seconds in length and includes a segment when the Ashtech was not in differential mode. When on the ground, this location was one of the farthest places that the aircraft could be from the Ashtech differential beacon. Note in Figure 32b that the non-differential Ashtech position was at the same place as the LAAS position. The Differential Ashtech data was again the most accurate of all the systems. During this data segment, the WASS, Ashtech/INS as well as the LAAS/INS data had a large variation. Like Figure 30b, Figure 32b also shows that the two channels with INS blending were the worst of the systems. It is not known why there was more variability during this data segment compared to the previously discussed data segment. The RMS summaries are given in Table 16. Note that the Ashtech data is split between a 96 second period with differential mode, and a 195 second period without differential corrections. Figure 33 re-plots the blended channels referenced to the GPS antenna. Due to the greater variability of the data in this case, vertical/horizontal bars are used to note the range of the data for each channel to avoid cluttering all the points in one area of the graph.



(a) Position profile from raw data.



(b) Position in Runway Coordinates. Note that the X and Y scales are not similar.

Figure 32: ARIES at base of runway 35C. Based on raw data from run R170_13.

Table 16: RMS errors for stationary segment of Profile 2 run.

RMS errors for stationary segment of R170_13				
System	**Points**	**X(m)**	**Y(m)**	**Height(m)**
Ashtech	202	0.130	0.063	0.311
Ashtech/INS	606	2.952	5.155	7.095
LAAS	606	0.319	0.607	3.605
LAAS/INS	606	2.558	4.931	6.088
Non-diff. Ashtech	404	1.174	0.846	11.177
WAAS	606	2.143	1.984	3.712

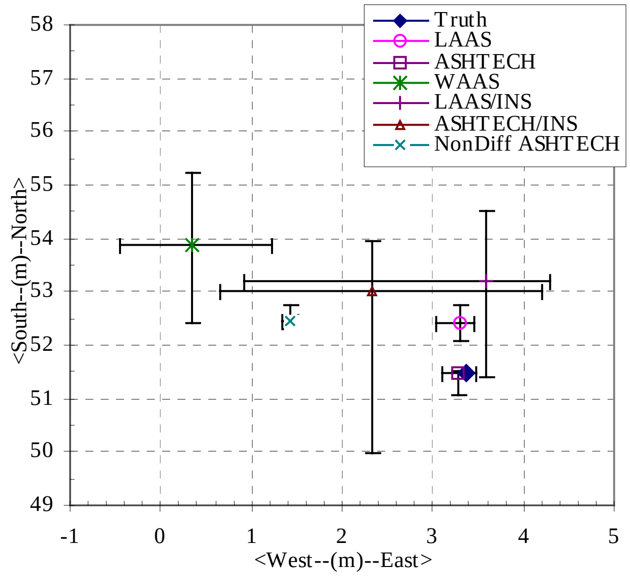
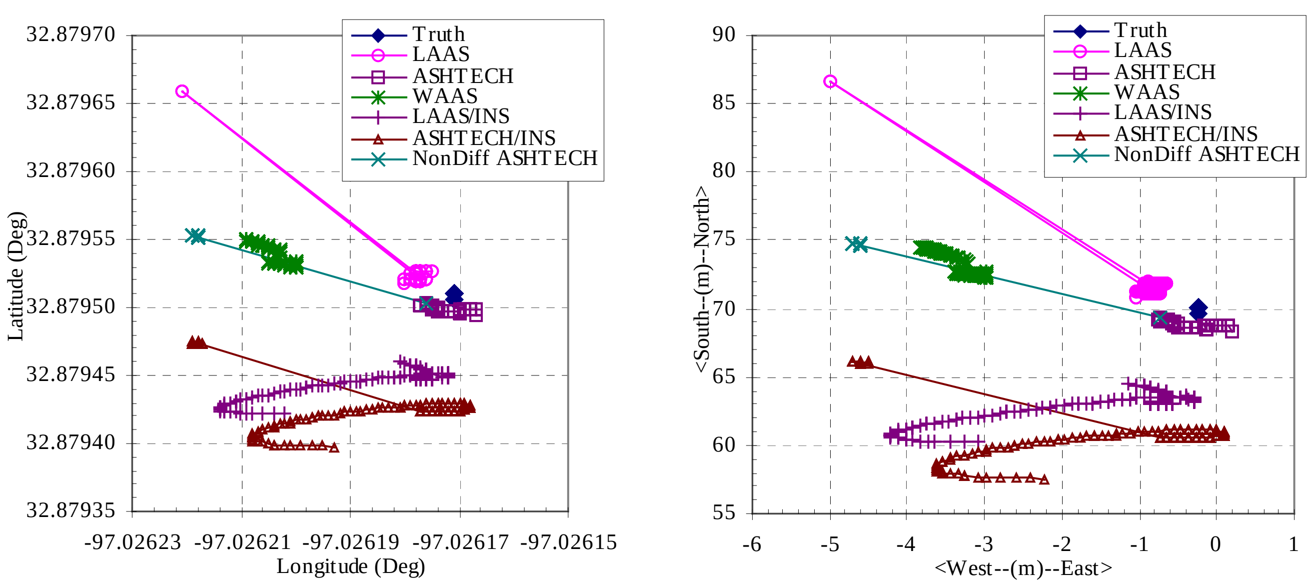


Figure 33: ARIES at base of runway 35C. Based on raw data from run R170_13. Position in Runway Coordinates with blended data referenced to GPS receiver antenna.

Figure 34 shows the accuracy of the systems during a stationary period of a Profile 3 run. There is a great amount of variability in the LAAS and the non-differential Ashtech data. Part (b) of the figure plots the position in runway coordinates where the origin is the threshold of runway 35C. As can be seen in the figure, there was a LAAS point reported over 4 meters from the cluster of other points. Table 17 gives the RMS errors for this period. The Ashtech system seems to be slightly less accurate during this period. The increased variability in the LAAS position reports affected its X-axis RMS average as compared to Table 16. The WAAS average horizontal error is similar to that of Table 16 but the vertical error is almost doubled. Figure 35 again re-plots the data with the Ashtech/INS and LAAS/INS referenced to the GPS antenna. Note that in order to avoid clutter, bars are used to show the range of the data instead of plotting the full data set.



(a) Position profile from raw data. (b) Position in Runway Coordinates..

Figure 34: ARIES in position for a Profile 3 execution

Table 17: RMS error for stationary segment of run R170_09

RMS error for stationary segment of run S3/R170_09				
System	**Points**	**X(m)**	**Y(m)**	**Height(m)**
Ashtech	214	0.479	0.700	1.305
Ashtech/INS	261	3.483	5.047	4.289
LAAS	261	1.020	0.873	5.457
LAAS/INS	261	2.707	3.940	7.734
Non-diff. Ashtech	47	2.888	2.523	8.396
WAAS	261	2.341	1.885	6.866

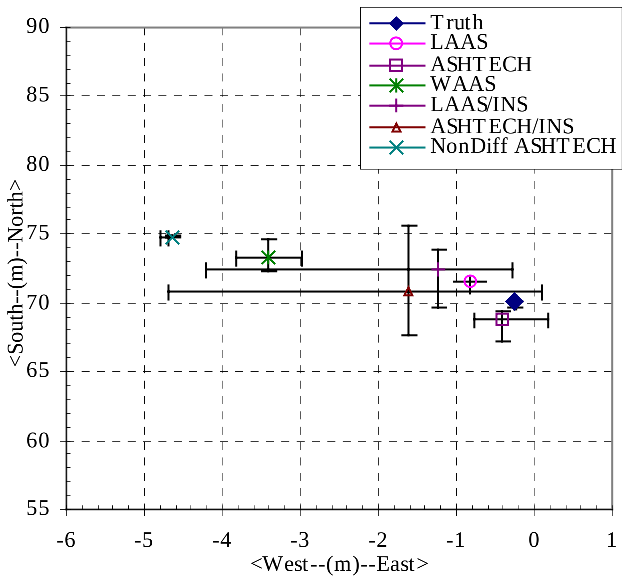


Figure 35: Position report in Runway Coordinates with Ashtech/INS and LAAS/INS points adjusted to GPS antenna reference

System Parameter Comparisons

All GPS receiver systems trilaterate their position based on signals received from multiple satellites in the GPS constellation. GPS receivers have intrinsic parameters that report the quality of the position, as well as the number of satellites tracked. The Dilution of Position (DOP) parameters give a qualitative measure of the satellite geometry as well as the accuracy of the position determination. These values range from 1 indicating ideal condition to 6 indicating the poorest condition. They are affected by the number of satellites visible as well as the orientation of the satellites relative to the GPS receiver. All GPS receivers in the ARIES reported Vertical DOP (VDOP), and Horizontal DOP (HDOP). The Ashtech system, in addition, reported Time DOP (TDOP) and Geometric DOP (GDOP). TDOP indicates the accuracy of the time calculation and GDOP is an aggregate combination of HDOP, VDOP and TDOP ($GDOP^2 = HDOP^2 + VDOP^2 + TDOP^2$). The tables below averaged the DOP reported by each system for each day of flight. The tables are grouped by flight since these parameters are more time dependent (one flight per day). The data was also matched to the first ATIS whether report for the day to determine if there were any correlations. No detailed analysis was performed for this correlation because the weather data was recorded manually and spotty at best. The DOP values were consistently very low throughout the test. No difference was seen in the DOP data from altitude variations.

Table 18: Ashtech DOPS summaries.

Ashtech DOP averages					
Flight	**HDOP**	**VDOP**	**TDOP**	**Clouds**	**Dew point**
R170	1.111	1.986	1.325	Few at 3600	17
R171	1.178	2.078	1.467	14000BKN/25000OVC	16
R172	1.310	2.103	1.695	Few at 16000	14
R173	1.043	1.992	1.321	Few at 3000	14
R174	1.118	2.037	1.329	4100SCT/6000BKN/9000BKN/25000OVC	17
R175	1.333	2.333	1.667	Few at 5000/30000OVC	15
R176	1.333	2.333	1.684	Few at 5000/10000SCT/150000BKN	17
R177	2.072	3.464	2.440	Few at 10000/Thunderstorms	20

Table 19: LAAS DOPS summaries

LAAS DOP averages				
Flight	**HDOP**	**VDOP**	**Clouds**	**Dew point**
R170	1.129	1.741	Few at 3600	17
R171	1.163	1.813	14000BKN/25000OVC	16
R173	1.136	1.786	Few at 3000	14
R174	1.236	2.016	4100SCT/6000BKN/9000BKN/25000OVC	17
R175	1.670	2.653	Few at 5000/30000OVC	15
R176	1.929	2.822	Few at 5000/10000SCT/150000BKN	17
R177	2.310	3.374	Few at 10000/Thunderstorms	20

Table 20: WAAS DOPS summaries

WAAS DOP averages				
Flight	**HDOP**	**VDOP**	**Clouds**	**Dew point**
R170	1.492	2.312	Few at 3600	17
R171	1.123	1.756	14000BKN/25000OVC	16
R172	1.234	1.697	Few at 16000	14
R173	1.024	1.634	Few at 3000	14
R174	1.277	2.131	4100SCT/6000BKN/9000BKN/25000OVC	17
R175	1.221	1.778	Few at 5000/30000OVC	15
R176	1.234	1.803	Few at 5000/10000SCT/150000BKN	17
R177	1.732	2.779	Few at 10000/Thunderstorms	20

There are 28 satellites in the GPS constellation. A GPS receiver may simultaneously have line of sight to as many as 12 satellites in any given instance. In general, only satellites visible 10 degrees above the horizon are used in position determination. In industry jargon, the number of satellites tracked is the number of satellites whose signal is being used in the position calculation. In general, 4 or more satellites are required to give good position estimates in the vertical axis. The tables below report the satellite counts for the primary systems. As indicated in Tables 21 to 23, satellite coverage from the GPS constellation during the DFW test was very good. This is perhaps attributable to the flat terrain.

Table 21: Ashtech satellite visibility

Ashtech satellites visibilities						
Flight	Satellites Visible		Satellites Used		Clouds	Dew point
	Min	Max	Min	Max		
R170	5	8	5	8	Few at 3600	17
R171	6	8	6	8	14000BKN/25000OVC	16
R172	5	7	5	7	Few at 16000	14
R173	6	8	6	8	Few at 3000	14
R174	6	8	6	8	4100SCT/6000BKN/9000BKN/25000OVC	17
R175	6	7	6	7	Few at 5000/30000OVC	15
R176	6	7	6	7	Few at 5000/10000SCT/150000BKN	17
R177	5	6	5	6	Few at 10000/Thunderstorms	20

Table 22: LAAS satellite visibility.

LAAS satellites visibilities						
Flight	Satellites Visible		Satellites Used		Clouds	Dew point
	Min	Max	Min	Max		
R170	7	10	5	8	Few at 3600	17
R171	7	10	6	8	14000BKN/25000OVC	16
R173	7	9	4	8	Few at 3000	14
R174	7	9	4	8	4100SCT/6000BKN/9000BKN/25000OVC	17
R175	7	10	4	8	Few at 5000/30000OVC	15
R176	7	10	4	6	Few at 5000/10000SCT/150000BKN	17
R177	7	9	4	7	Few at 10000/Thunderstorms	20

Table 23: WAAS satellite visibility.

WAAS satellites visibilities						
Flight	Satellites Visible		Satellites Used		Clouds	Dew point
	Min	Max	Min	Max		
R170	5	11	5	8	Few at 3600	17
R171	9	11	6	8	14000BKN/25000OVC	16
R172	9	11	5	8	Few at 16000	14
R173	10	11	6	8	Few at 3000	14
R174	9	11	4	7	4100SCT/6000BKN/9000BKN/25000OVC	17
R175	9	11	6	8	Few at 5000/30000OVC	15
R176	9	12	5	8	Few at 5000/10000SCT/150000BKN	17
R177	9	12	4	7	Few at 10000/Thunderstorms	20

Histogram of Errors for Full Dataset

Tables 24 to 29 give the distribution of position errors for the primary GPS systems. There is one horizontal and one vertical error distribution per system. As with the averages, this distribution data is partitioned by the run profile and sorted by activity (Air, Air/Ground, Ground). Unlike the RMS tables, where errors above 500 meters are excluded from the average, no exclusions are made for this distribution data. Also, in contrast to the RMS tables, this set gives the horizontal data as the radius ($\sqrt{X^2 + Y^2}$) error instead of in the X, Y components. This allows for categorization of the data points into concentric rings with the maximum error radius expanding in each bracket.

As seen in Table 24, over 77% of the Ashtech horizontal position reports are within 0.5 meter, and a total of almost 96% within 1 meter of the Truth position. About 4.5% of the position reports had greater than 1 meter error. Note that the profiles that include ground activities (P5, P2, P3) tend to have many fewer points in the higher error brackets (> 2 meters). This is consistent with Table 5, which showed lower RMS errors for ground profiles. One can readily see that very few points were excluded from the averages in Table 5 since there are very few points are in the >50 meters bracket (1 out of 91366 points).

Table 24: Ashtech horizontal error distribution.

Ashtech, Horizontal Axis -- Position Error Distributions.										
Profile	**Total Pts**	**<=0.5m**	**.5 to 1.0m**	**1.0 to 1.5m**	**1.5 to 2.0m**	**2.0 to 3.0m**	**3.0 to 5.0m**	**5.0 to 10.0m**	**10.0 to 50.0m**	**>50.0m**
P1	21351	16219	4129	263	140	168	276	155	0	1
P4	13715	9922	2997	321	71	91	189	124	0	0
P7	10804	8855	1500	207	42	63	83	54	0	0
P6	20392	15093	4109	599	129	122	245	95	0	0
P5	4734	4237	489	8	0	0	0	0	0	0
P2	8419	7261	1108	48	2	0	0	0	0	0
P3	11951	9283	2268	290	93	17	0	0	0	0
Total	**91366**	**70870**	**16600**	**1736**	**477**	**461**	**793**	**428**	**0**	**1**
Percentage		**77.6%**	**18.2%**	**1.9%**	**0.5%**	**0.5%**	**0.9%**	**0.5%**	**0.0%**	**0.0%**

The vertical distribution for the Ashtech, in Table 25, shows a smaller 35.6% of position reports within the 0.5 meter radius. 36% of the height position reports contained greater than 1 meter error. This is consistent with the higher height error averages reported in Table 5.

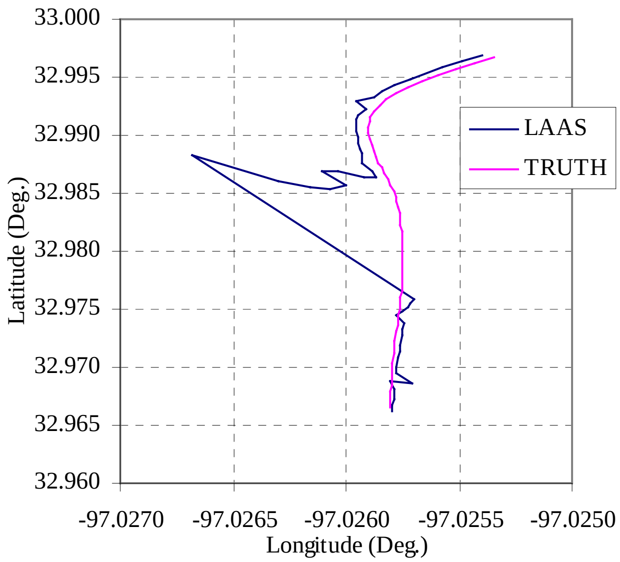
Table 25: Ashtech vertical error distribution.

Ashtech, Vertical Axis -- Position Error Distributions										
Profile	**Total Pts**	**<=0.5m**	**.5 to 1.0m**	**1.0 to 1.5m**	**1.5 to 2.0m**	**2.0 to 3.0m**	**3.0 to 5.0m**	**5.0 to 10.0m**	**10.0 to 50.0m**	**>50.0m**
P1	21351	5381	5929	2874	1277	1637	2319	960	834	140
P4	13715	4304	3942	2103	467	901	1113	426	459	0
P7	10804	4236	3100	1034	259	891	1154	130	0	0
P6	20392	6742	5578	2403	1630	1916	1682	350	91	0
P5	4734	2208	1966	504	56	0	0	0	0	0
P2	8419	3742	1915	1156	904	393	293	15	1	0
P3	11951	5957	3596	1490	539	369	0	0	0	0
Total	**91366**	**32570**	**26026**	**11564**	**5132**	**6107**	**6561**	**1881**	**1385**	**140**
Percentage		**35.6%**	**28.5%**	**12.7%**	**5.6%**	**6.7%**	**7.2%**	**2.1%**	**1.5%**	**0.2%**

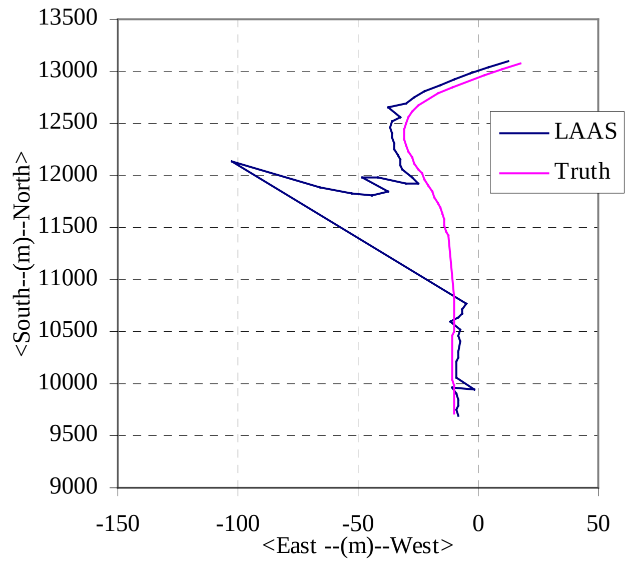
From Table 8, it was shown that the LAAS horizontal error averaged 1 to 2 meters. For the most part, this is reflected in the error distribution (Table 26) with 80% of the data points in the three bins below 1.5 meters. The data is slightly more distributed than the Ashtech system. Anomalies occurred during a test run (R171_15) and a demonstration flight (R177_92) contributing to the greater number of points in the higher (greater than 50 meters) error brackets for the Profile 1 activity in Table 26. One instance during R177_92 where this occurred is plotted in Figure 36 below. Table 27 gives the vertical error distribution for the LAAS system. Eight-six percent of the data is concentrated in the 3 to 10 meter range. This concurs with Table 8 showing that there is about five meters vertical bias in the LAAS system. Note that Profile 4 and 5 show all points have greater than 2 and 3 meters error respectively. This is particular interesting since the horizontal distribution does not show this same behavior for Profile 4 and 5.

Table 26: LAAS horizontal error distribution.

LAAS, Horizontal Axis -- Position Error Distributions.										
Profile	**Total Pts**	**<=0.5m**	**.5 to 1.0m**	**1.0 to 1.5m**	**1.5 to 2.0m**	**2.0 to 3.0m**	**3.0 to 5.0m**	**5.0 to 10.0m**	**10.0 to 50.0m**	**>50.0m**
P1	16625	4238	4305	3376	1775	1634	1141	135	18	3
P4	9190	2529	3007	1534	1094	964	60	2	0	0
P7	9179	2634	2529	1667	872	1187	290	0	0	0
P6	17115	3721	5851	3305	1994	1457	782	2	3	0
P5	4734	2593	929	808	219	185	0	0	0	0
P2	7269	2998	2964	827	312	166	2	0	0	0
P3	10553	4481	2133	1434	1304	584	560	55	2	0
Total	**74665**	**23194**	**21718**	**12951**	**7570**	**6177**	**2835**	**194**	**23**	**3**
Percentage		**31.1%**	**29.1%**	**17.3%**	**10.1%**	**8.3%**	**3.8%**	**0.3%**	**0.0%**	**0.0%**



(a) Ground track in raw Lat/Lon coordinates.



(b) Ground track in runway coordinates.

Figure 36: LAAS track segment showing large deviation. Based on raw data. (Source file S1/r177_92)

Table 27: LAAS vertical error distribution.

LAAS, Vertical Axis -- Position Error Distributions.										
Profile	**Total Pts**	**<=0.5m**	**.5 to 1.0m**	**1.0 to 1.5m**	**1.5 to 2.0m**	**2.0 to 3.0m**	**3.0 to 5.0m**	**5.0 to 10.0m**	**10.0 to 50.0m**	**>50.0m**
P1	16625	293	355	415	567	1214	9946	3438	345	52
P4	9190	0	0	0	0	213	5198	3775	4	0
P7	9179	0	195	647	199	771	2257	5110	0	0
P6	17115	187	147	217	737	1451	9865	4484	27	0
P5	4734	0	0	0	0	0	1948	2786	0	0
P2	7269	148	132	327	245	861	1085	4471	0	0
P3	10553	0	0	0	230	198	4356	5763	6	0
Total	**74665**	**628**	**829**	**1606**	**1978**	**4708**	**34655**	**29827**	**382**	**52**
Percentage		**0.8%**	**1.1%**	**2.2%**	**2.6%**	**6.3%**	**46.4%**	**39.9%**	**0.5%**	**0.1%**

The WAAS error distribution is given in Table 28 for the horizontal axis and Table 29 for the vertical axis. Over ninety-six percent of the data are distributed in the 0 to 5 meter range. About forty-three percent of the data is concentration in the 1 meter or less brackets and 34% of the data is in the 2 to 5 meter brackets. The WAAS data had a large number of points with errors greater than 50 meters. This was from several periods during which the WAAS system did not appear to be functioning. It was not known whether the source of the error was a malfunction in the receiver system or a systemic problem on the aircraft or elsewhere. The WAAS system did not function normally for test run R173_49 (Profile 1). During this run, position updates were not available for the first 142 seconds of the run, then became available for 45 seconds and again failed for the remaining 258 seconds. During the failure periods, the position did not changed. This accounts for a total of 607 data points with horizontal error over 50 meters. The 1215 points also with horizontal errors greater than 50 meters occurred during test run R173_50 (Profile 7). In this instance the WAAS UTC remains "05:06:43.493156 " for the entire run. The source of error was also not known.

Table 28: WAAS horizontal error distribution.

WAAS, Horizontal Axis -- Position Error Distributions.										
Profile	**Total Pts**	**<=0.5m**	**.5 to 1.0m**	**1.0 to 1.5m**	**1.5 to 2.0m**	**2.0 to 3.0m**	**3.0 to 5.0m**	**5.0 to 10.0m**	**10.0 to 50.0m**	**>50.0m**
P1	21351	5145	4015	2775	2036	3198	3270	176	104	632
P4	13715	2273	3999	1591	1301	3473	989	47	42	0
P7	10804	2741	2167	417	727	2574	908	29	26	1215
P6	20392	4214	5061	1723	2006	3430	3295	573	88	2
P5	4734	1348	515	331	744	1528	263	2	3	0
P2	9454	1683	2060	1216	1149	2520	663	109	54	0
P3	12010	3078	1505	1203	621	2737	2783	81	2	0
Total	**92460**	**20482**	**19322**	**9256**	**8584**	**19460**	**12171**	**1017**	**319**	**1849**
Percentage		**22.2%**	**20.9%**	**10.0%**	**9.3%**	**21.0%**	**13.2%**	**1.1%**	**0.3%**	**2.0%**

The vertical error distribution for the WAAS system was very similar to LAAS. There appears also to be about a five meters bias in the data. This is apparent in Table 29 as 69.3% of the data fell in the error range of 3 to 5 meters. Note that Profile 5 in the table also contains no points in the 0 to 1 meter brackets but that the horizontal axis Profile 5 had a distribution typical of other profiles.

Table 29: WAAS vertical error distribution.

WAAS, Vertical Axis -- Position Error Distributions.										
Profile	**Total Pts**	**<=0.5m**	**.5 to 1.0m**	**1.0 to 1.5m**	**1.5 to 2.0m**	**2.0 to 3.0m**	**3.0 to 5.0m**	**5.0 to 10.0m**	**10.0 to 50.0m**	**>50.0m**
P1	21351	58	209	621	1153	4458	8335	5837	73	607
P4	13715	14	104	601	78	1556	6464	4822	76	0
P7	10804	459	933	831	39	496	1237	5475	120	1214
P6	20392	188	634	553	221	2605	6859	9171	161	0
P5	4734	0	0	88	269	2188	611	1578	0	0
P2	9454	577	30	0	4	1758	1120	5457	508	0
P3	12010	1872	1788	217	382	610	1371	5770	0	0
Total	**92460**	**3168**	**3698**	**2911**	**2146**	**13671**	**25997**	**38110**	**938**	**1821**
Percentage		**3.4%**	**4.0%**	**3.1%**	**2.3%**	**14.8%**	**28.1%**	**41.2%**	**1.0%**	**2.0%**

Conclusions

The objective of this report was to present an accuracy comparison of the GPS positioning systems used for the RIPS flight test conducted at DFW. Examining the performance of the LAAS and WAAS is relevant since these systems are being phased into the NAS. The performance data presented in this report is especially significant in light of the fact that the FAA intends to use the WAAS to support up to CAT I operations. The LAAS is slated to support CAT I/II/III operations at high traffic airports.

The ground tracks of each system are charted against the Truth data. This yielded a visual estimate of the accuracies of the systems in a spatial sense. The tracks are also put in runway coordinates so that a visual approximation can be obtained for the accuracy of the individual systems. The ground track plots for selected runs from this evaluation are in

Appendix B to H. Distance errors calculated using a geometric technique are used to correlate to the ground track plots. Finally, statistical distributions are produced to substantiate the geometric averages.

Each system has its weaknesses and strengths. Every system has some clocking variations. All systems are observed to have VDOP and HDOP readings of about two during the flight test. The Ashtech indicates 6 to 8 satellites visible throughout the flight test. The LAAS system saw up to 10 satellites and the WAAS saw up to 12 GPS satellites. The good visibility is a testament to how flat the terrain is around DFW.

A numerical assessment of the performance of the systems is attempted by computing the error of the test system based on matched points in UTC time. Several timing anomalies in the data acquisition system were discovered in this effort and a comparison technique was developed to minimize the effect of the timing problems on the numerical assessment. The original interpolation technique used to derive the Truth position yielded average errors that were not consistent with visual inspection of the ground tracks due to the difficulty of matching UTCs. The spatial technique of computing distance error generally yielded smaller position errors than interpolation because timing irregularities are eliminated. As a result, the averages computed using the geometric technique are more consistent with visual inspection of the plots.

The Ashtech system appears to be the most accurate of the systems when compared with the Truth data ground track. The RMS averages yielded less than 1 meter error on the horizontal and 1 to 4 meters on the vertical (Table 5). In the horizontal axis (Table 24) over 90% of the points are less than 1.5 meters from the Truth data. This shows that it is highly precise in the horizontal. In the vertical axis (Table 5) the errors are more disbursed indicating less precision. The differential Ashtech position is more accurate than the LAAS positioning. When the differential signal is not received, the Ashtech performs much worse than LAAS. However, this is not conclusive because there is not much non-differentiated Ashtech data available. With the INS blending, the error ranges from 1.120 to 3.652 meters in the horizontal and 1.820 to 3.168 vertical (Table 11).

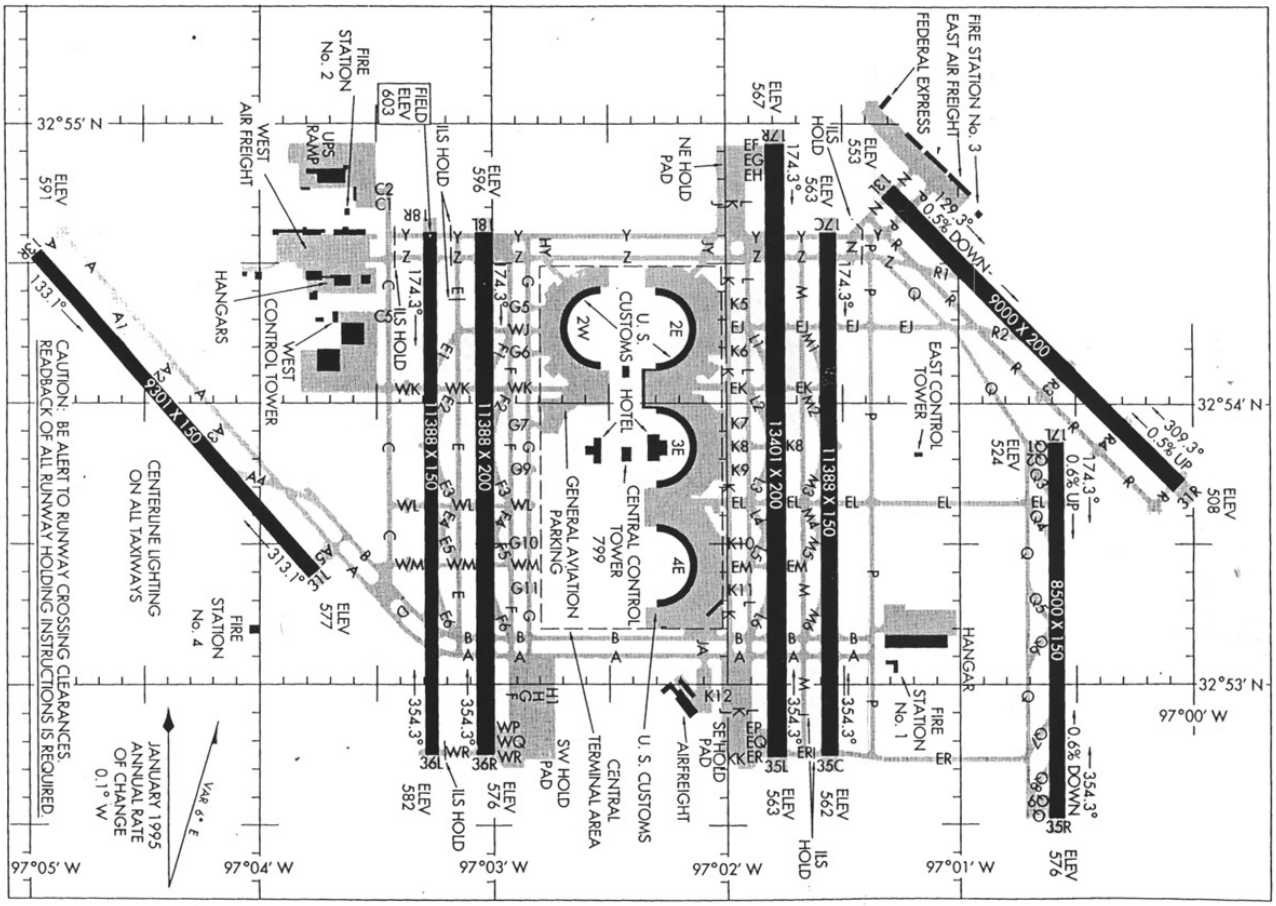
As expected, LAAS is generally more accurate than WAAS. The horizontal error for the LAAS system, in differential mode, ranges from .532 to 1.199 meters while the vertical ranges 4.4 to 6.9 meters (Table 8). In non-differential mode, the average degrades only very slightly to range from .54 to 1.368 meters horizontal and 2.867 to 8.034 meters vertical (Table 9). This insignificant difference between the LAAS versus non-differentiated LAAS is a bit surprising but is substantiated by visual inspection of the ground tracks. The LAAS/INS blending yielded the average accuracy ranging from 1.087 to 2.783 meters in horizontal and 6.280 to 8.010 meters in vertical (Table 13). LAAS is less accurate than the Ashtech system but it should be noted that the LAAS receiver used on the aircraft was an uncertified prototype.

The WAAS receiver performed a respectable third. The WAAS ground tracks are often very close to the LAAS with spatial averages ranging from 0.775 to 2.162 meters horizontal and 4.063 to 5.758 meters vertical (Table 10). There is believed to be a 5 meters bias in both the LAAS and the WAAS. The source of this error is not known. The WAAS as with the LAAS almost always produces lower MSL altitude readings than the Ashtech and the Truth data.

This accuracy assessment of LAAS and WAAS systems is a benchmark for both the user and developer community. It gives the user community an inkling of what to expect as the WAAS and then the LAAS infrastructure is phased into the NAS. Both systems range about 1 to 2 meters in accuracy during this test. To add some perspective to this, consider that the research aircraft, a Boeing 757 commercial transport, is 47.3 meters long and has a wingspan of 38 meters. Its body width is 3.7 meters. Bear in mind that this data came from prototype systems. The accuracy of the operational systems will presumably be improved.

Appendix A: Dallas Ft. Worth Airport Map

This is a map of the DFW that is used by pilots when flying into DFW. It is published by Jeperson who publishes airport navigation maps.



Appendix B: Profile 1 Ground Tracks.

This appendix gives the horizontal and vertical tracks for four Profile 1 test runs. This scenario is executed completely in the air. It involves a go-around near 61 meters (200 ft.). The tracks generally include a loop around the east side of the airport and a final approach on to runway 35C/17C. The plots are generated based on the raw latitude, longitude, and height reports that are converted into runway coordinates. The local coordinate system used is based at the center of the threshold for the south end of runway 35C/17C with positive X to the east and positive Y to the north. In order to show small track variations in the horizontal plots, some cases require exaggerating the latitude and/or longitude grid. Additionally, it should be noted that most plots only show a small segment of the entire run. The data for this profile as well as Profile 4 include travel over a large area because these two profiles were executed completely in the air. It was not possible to show the minute differences between the tracks over the entire movement area. Although the positioning data is equally relevant through out the movement area, the segments chosen are mostly around the runway where the testing was targeted.

Each test run, in Appendix B to G, is presented identically with seven plots and a table. The first plot (Figure A) gives the Truth data and shows all the data included in the run. The truth data is given in lat/lon coordinates to provide a check for other plots. The plot frequently covers a large area and does not show system differences well. The plots that compare the positioning systems (Figure B through F) show smaller travel areas to illustrate the differences between the systems. Figure B gives the movement in lat/lon coordinates while the others are converted to a local coordinate system based at the center of the runway threshold of 35C. For each run, Figure G compares the height data recorded for each system. The Height is plotted on a time axis.

Flight 170 run R170_01

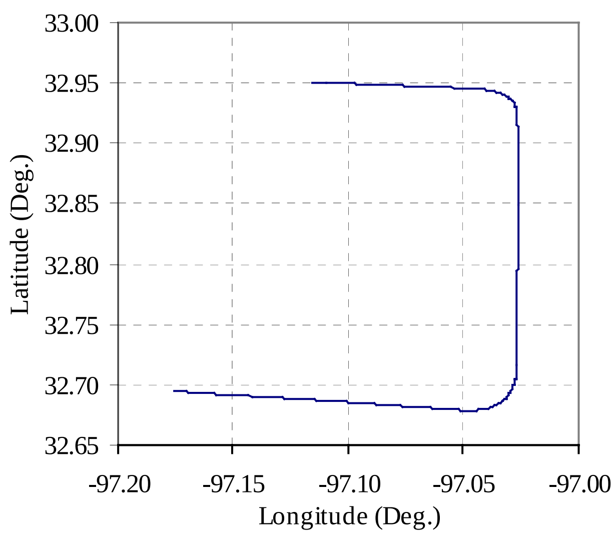


Figure B1A: Truth data for entire ground track.

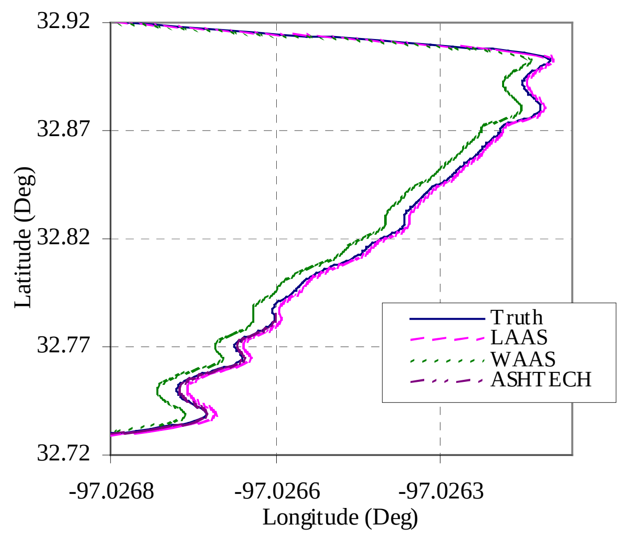


Figure B1B: Raw horizontal position of all systems.

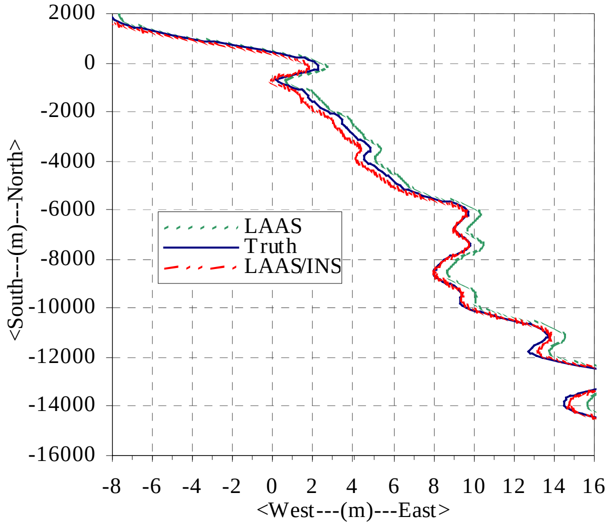


Figure B1C: LAAS versus Truth track

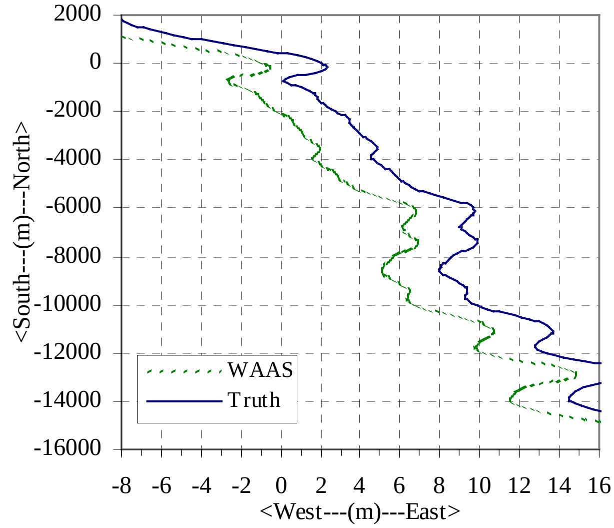


Figure B1D: WAAS versus Truth track..

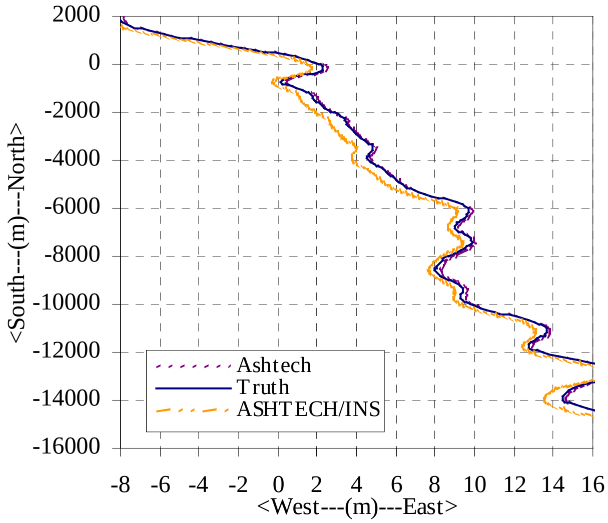


Figure B1E: Ashtech versus Truth track.

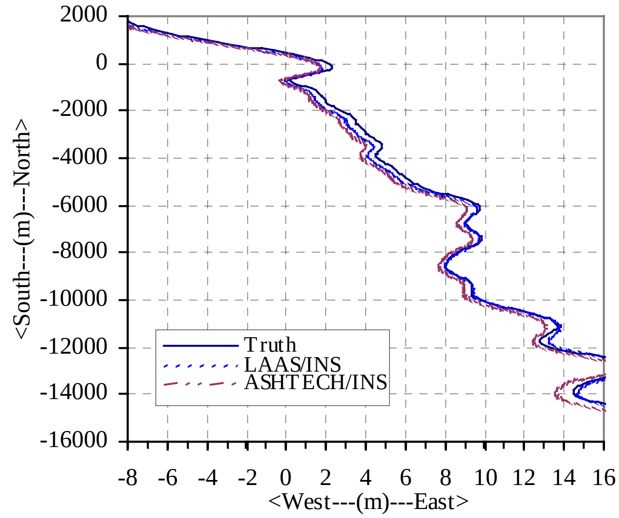


Figure B1F: Blended versus Truth track.

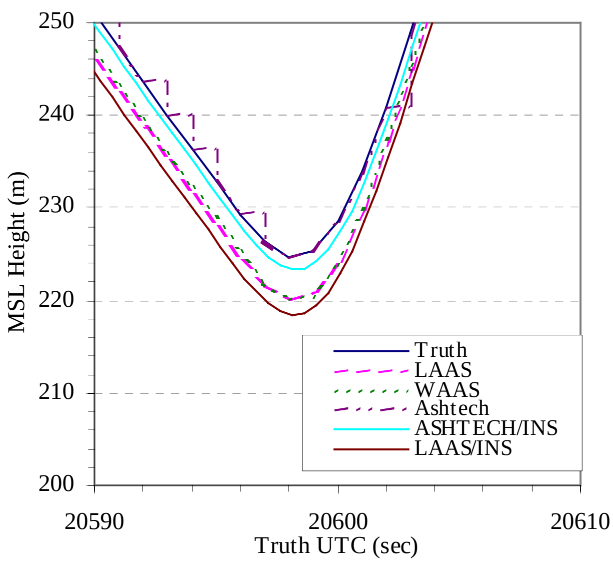


Figure B1G: MSL height comparison.

Flight 171 run R171_15

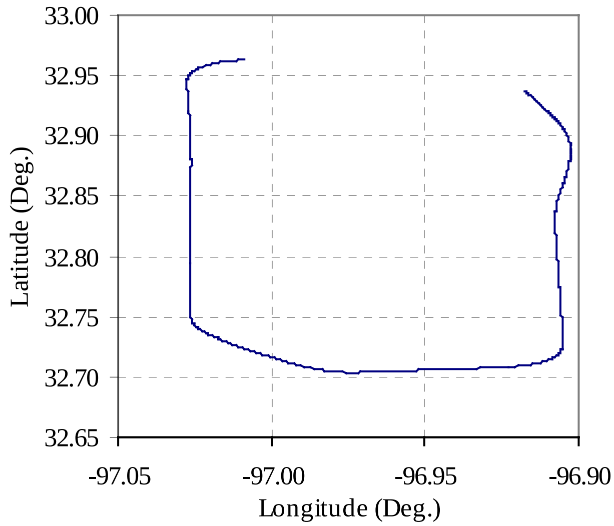


Figure B2A: Truth data for entire ground track

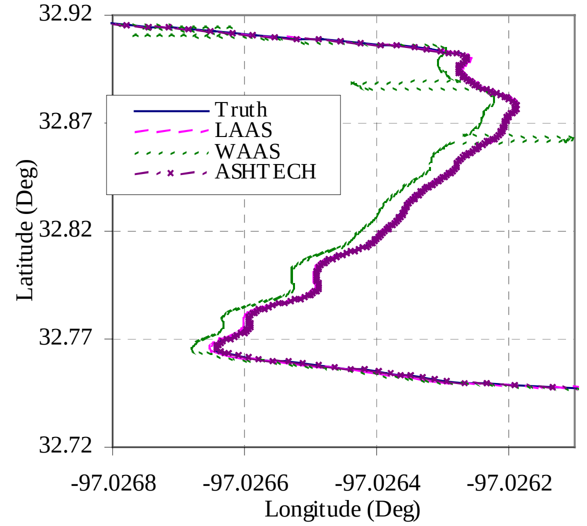


Figure B2B: Raw horizontal position of all systems.

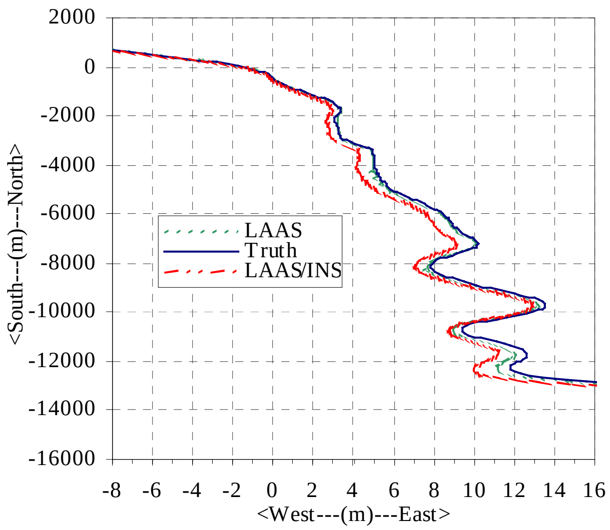


Figure B2C: LAAS versus Truth track.

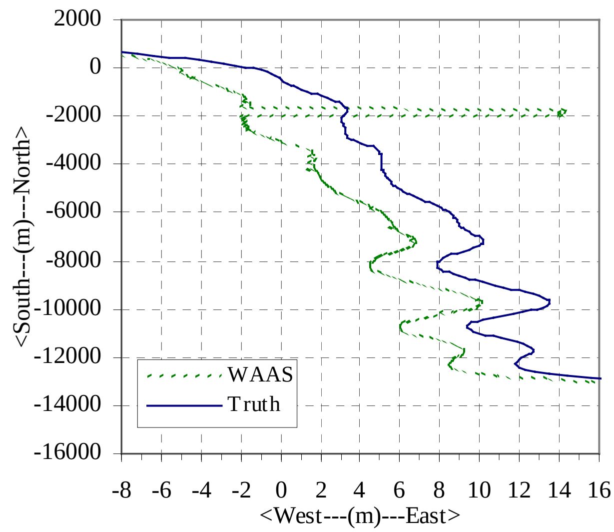


Figure B2D: WAAS versus Truth track.

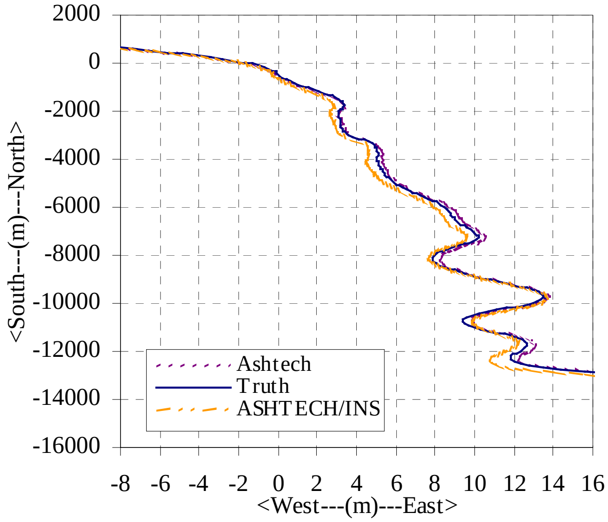


Figure B2E: Ashtech versus Truth track.

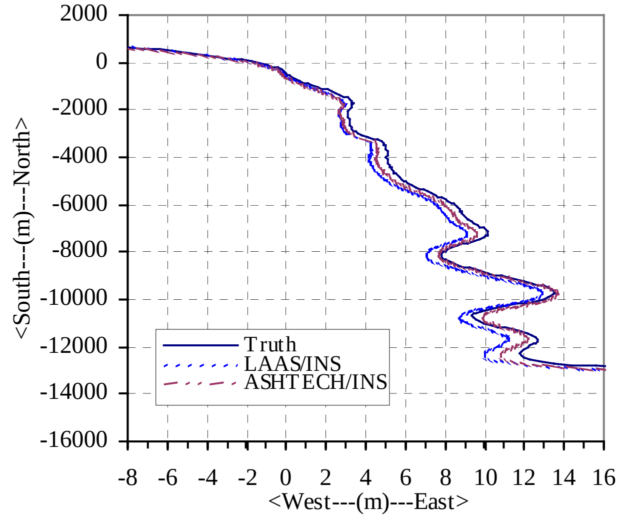


Figure B2F: Blended versus Truth track.

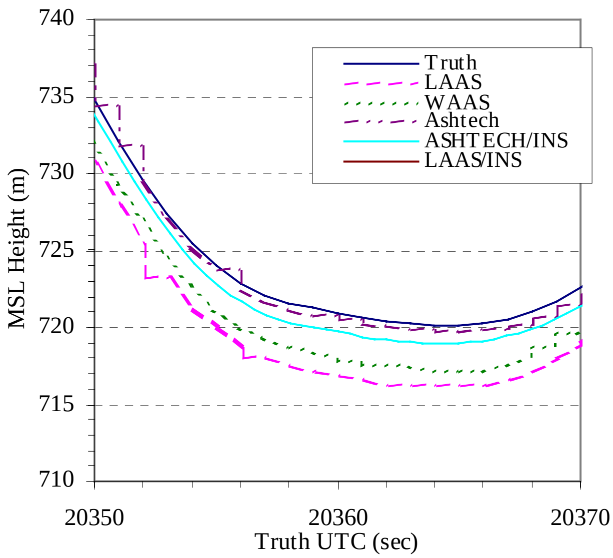


Figure B2G: MSL height comparison.

Flight 172 run R172_45

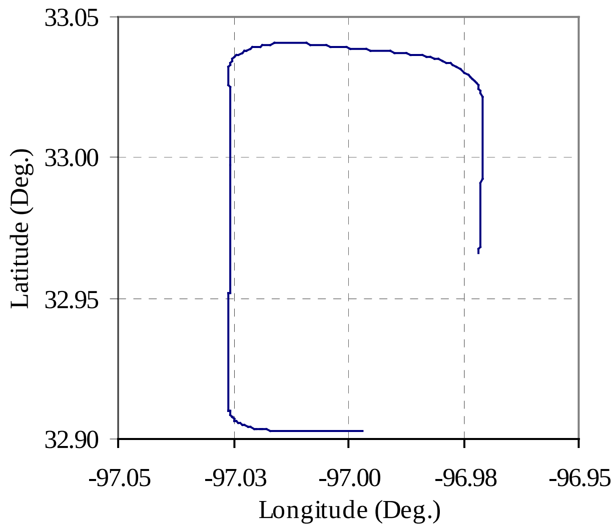


Figure B3A: Truth data for ground track.

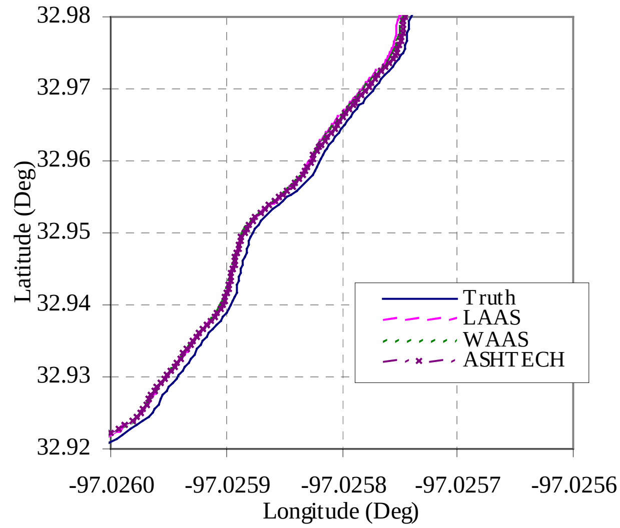


Figure B3B: Raw horizontal position of all systems.

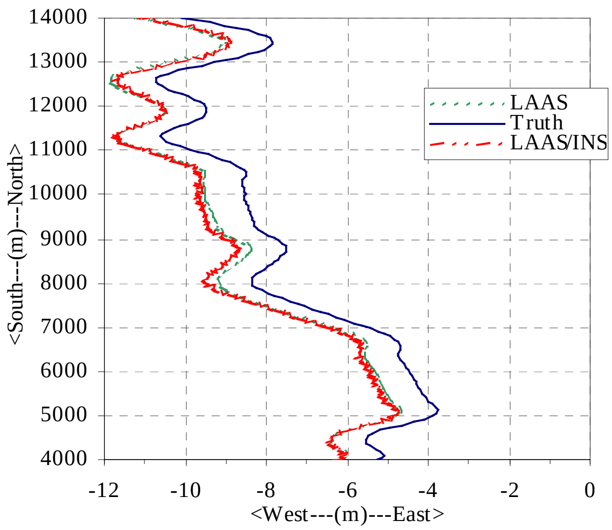


Figure B3C: LAAS versus Truth track.

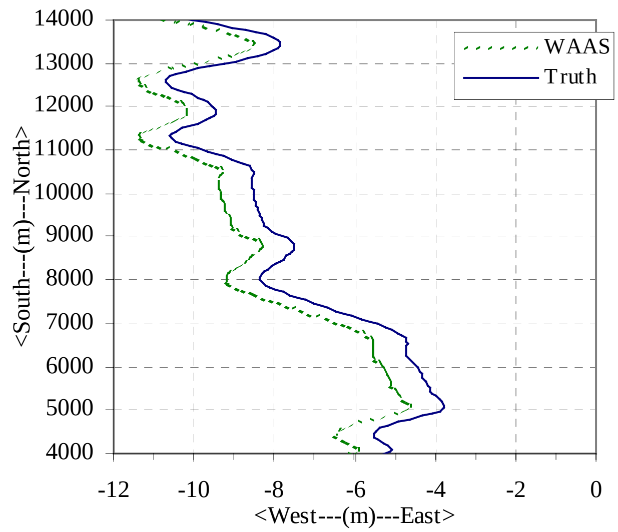


Figure B3D: WAAS versus Truth track.

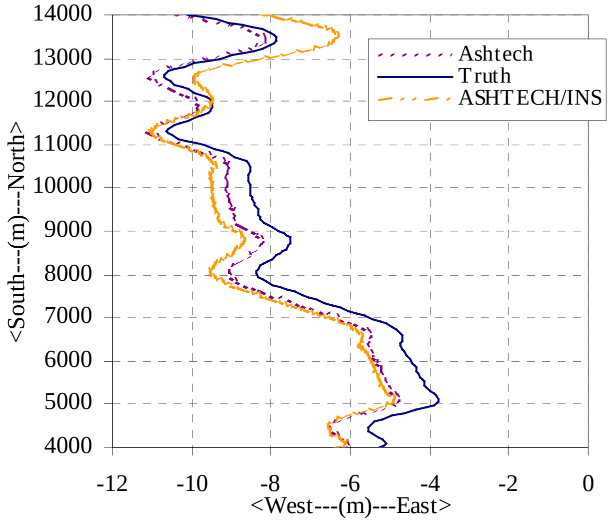


Figure B3E: Ashtech versus Truth track.

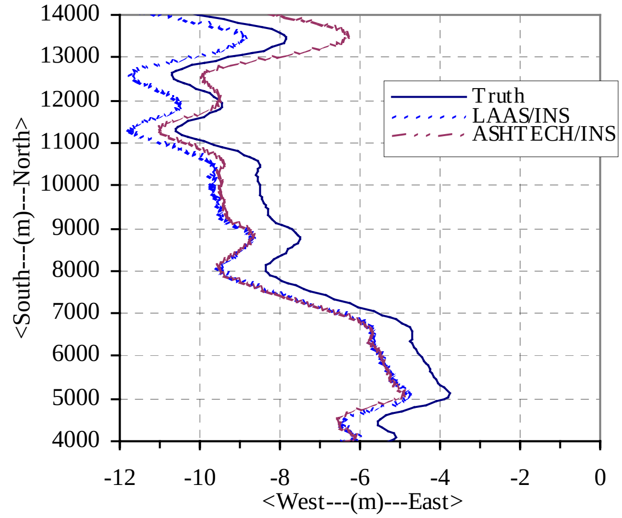


Figure B3F: Blended versus Truth track.

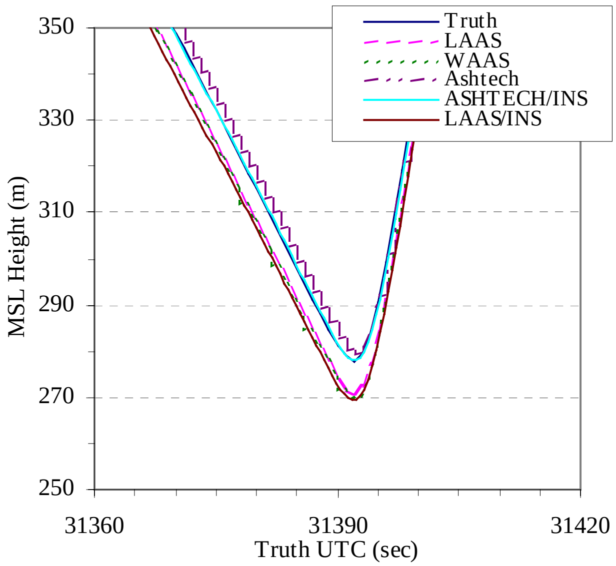


Figure B3G: MSL height comparison.

Note:

1) The LAAS ground station was not operating during this run.
2) The Ashtech height plot shows the time skew problem.

Flight 174 run R174_72

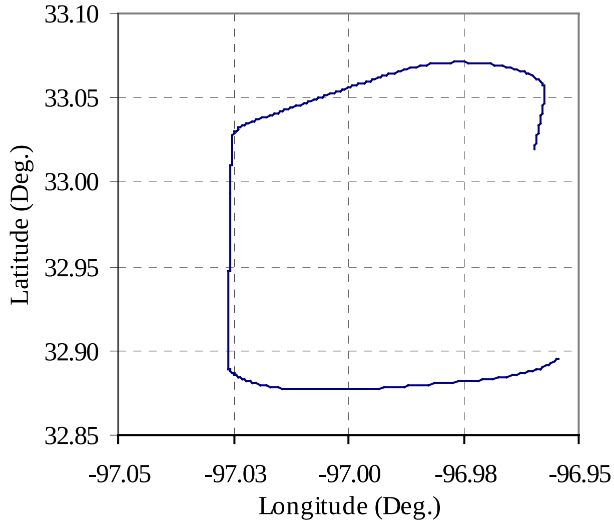


Figure B4A: Truth data for ground track.

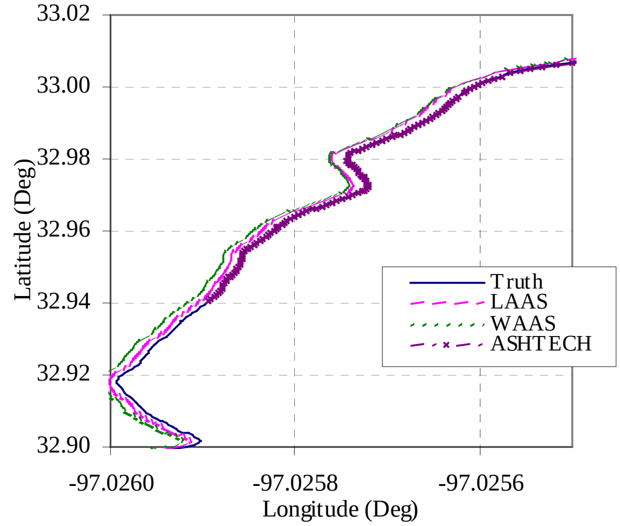


Figure B4B: Raw horizontal position of all systems.

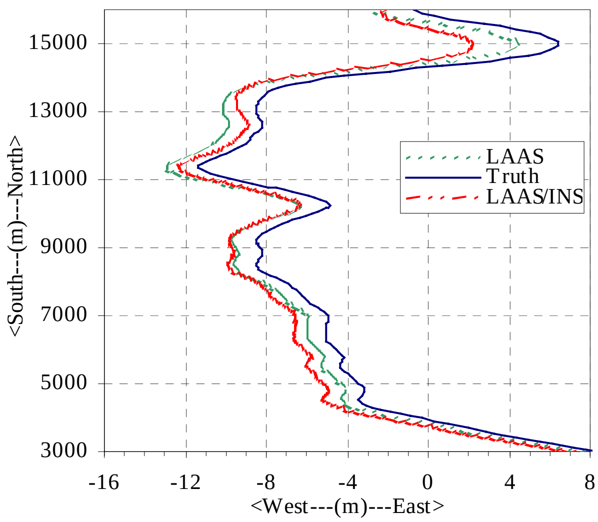


Figure B4C: LAAS versus Truth track.

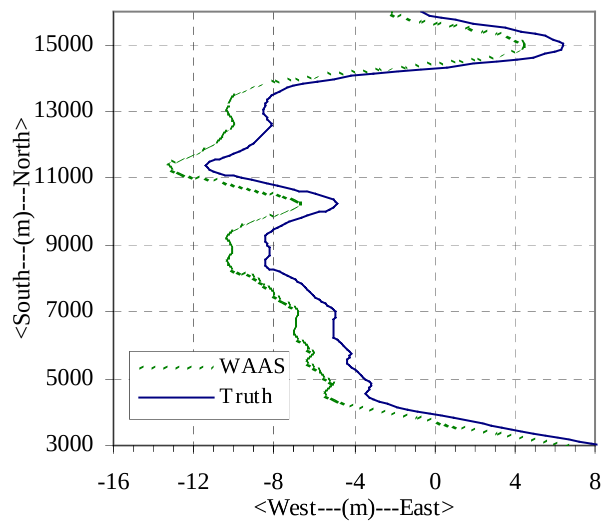


Figure B4D: WAAS versus Truth track.

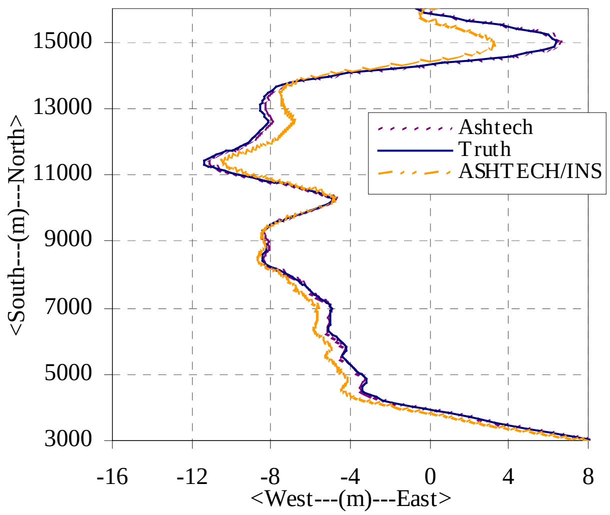


Figure B4E: Ashtech versus Truth track.

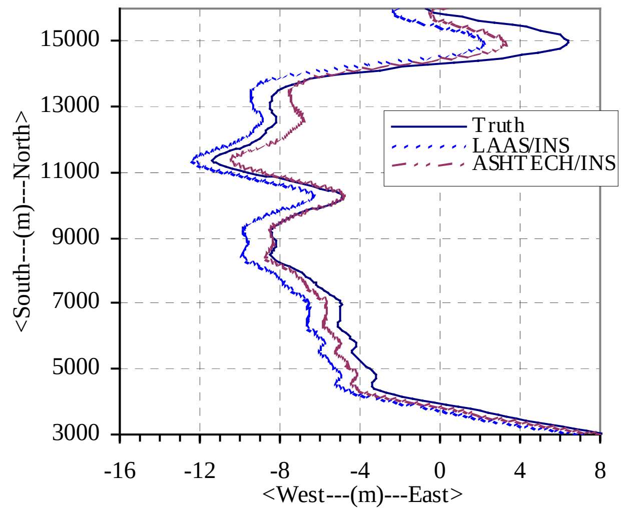


Figure B4F: Blended versus Truth track.

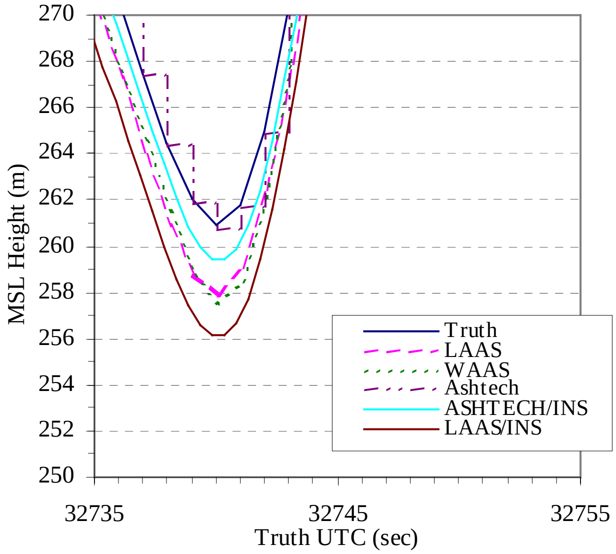


Figure B4G: MSL height comparison.

Appendix C: Profile 2 Ground Tracks.

Profile 2 is a rejected take off scenario where the aircraft begins a standard take-off roll but aborts generally before 120 knots. Data recorded for this profile generally include some movement on the adjacent taxiways.

Flight 170 run R170_08

The data for this run encompasses a turn off the runway onto taxiways and back onto 35C. The Ashtech data was used in the blending algorithm.

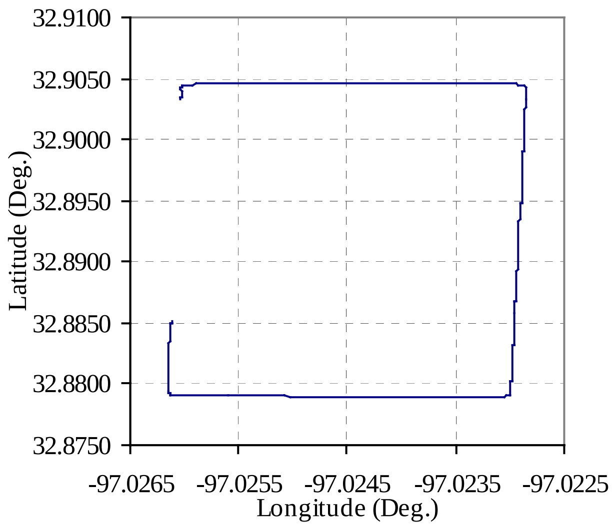


Figure C1A: Truth data for ground track.

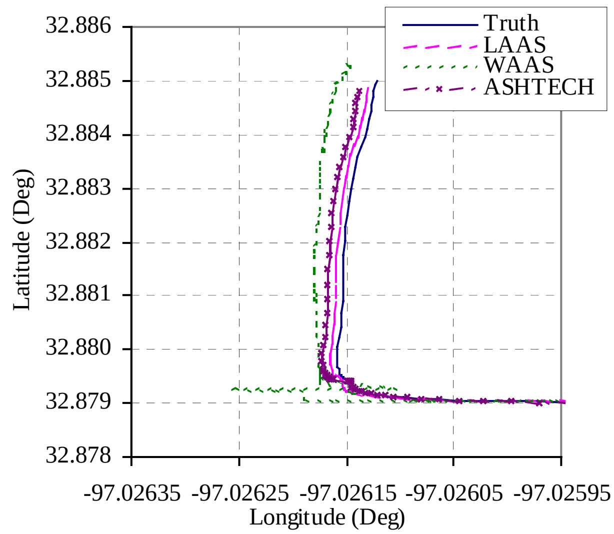


Figure C1B: Raw horizontal position of all systems

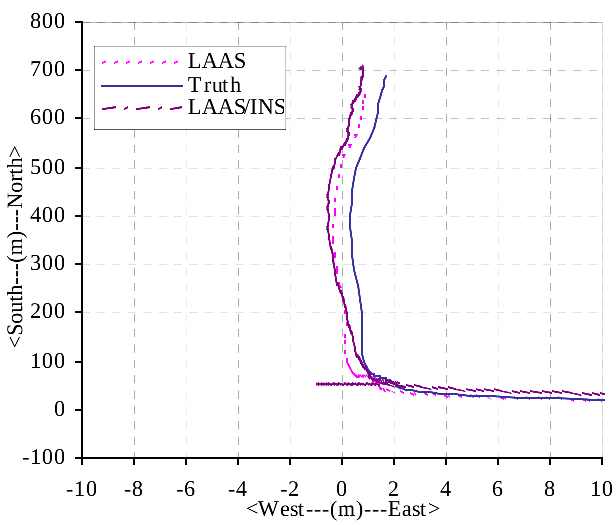


Figure C1C: LAAS versus Truth track.

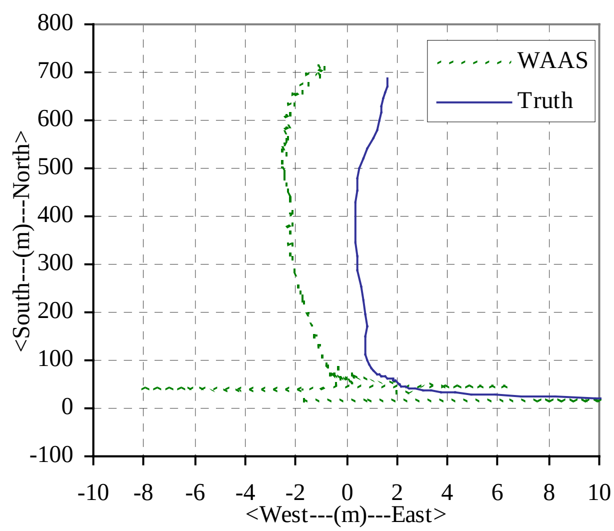


Figure C1D: WAAS versus Truth track.

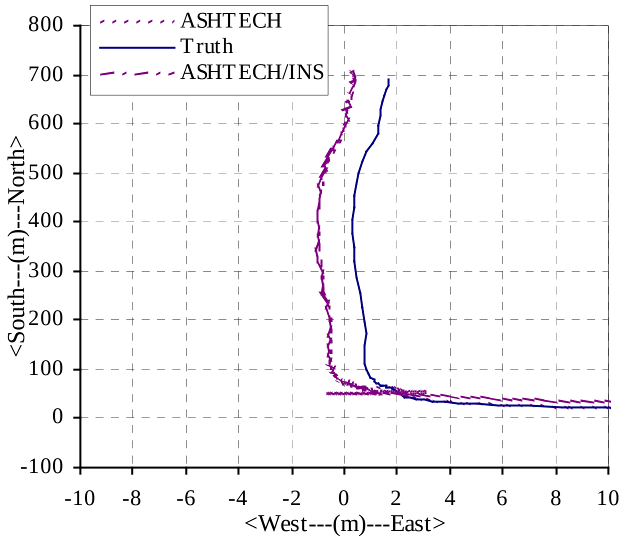


Figure C1E: Ashtech versus Truth track.

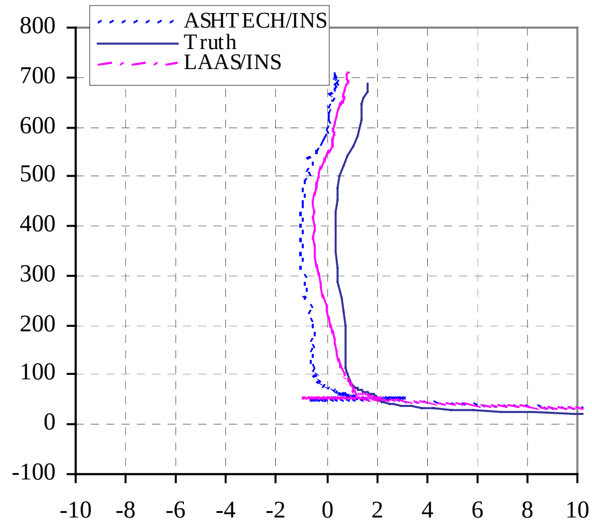


Figure C1F: Blended versus Truth track

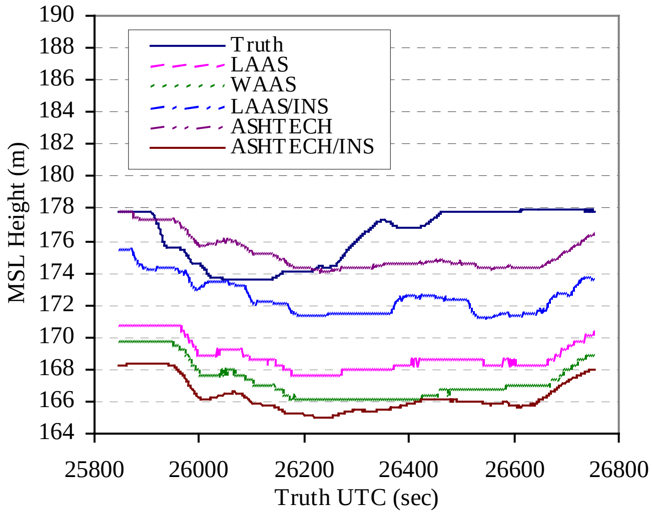


Figure C1G: MSL height comparison.

Flight 170 run R170_13

The Ashtech/INS blend was used for this test. Figure C2F showed that LAAS/INS blend was more accurate than the Ashtech/INS blend during this run. This is because the Ashtech receiver did not receive the differential correction signal for part of the run. This is most evident in Figure C2B, which shows the Ashtech system switching to a more accurate ground track between 32.884 and 32.885 degree Latitude. This is presumed to be when the Ashtech system reacquired the corrections signal.

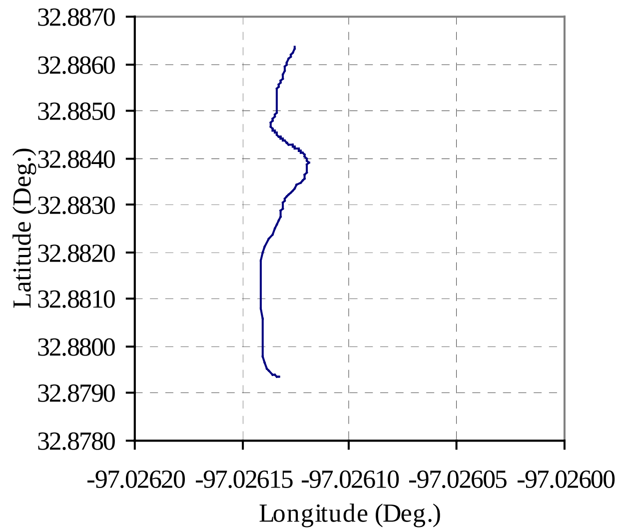


Figure C2A: Truth data for ground track.

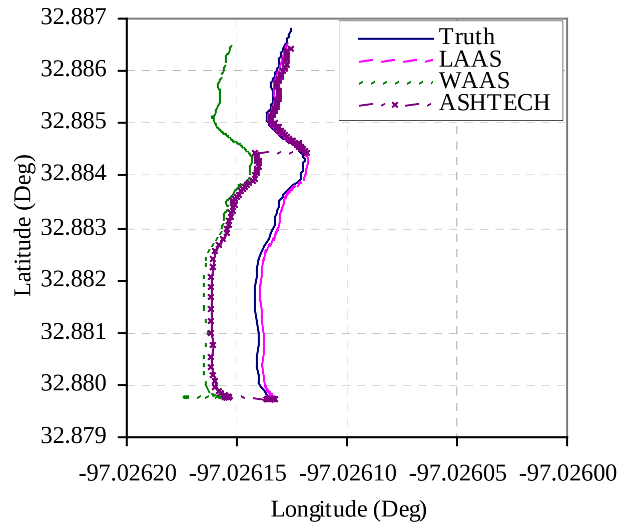


Figure C2B: Raw horizontal position of all systems

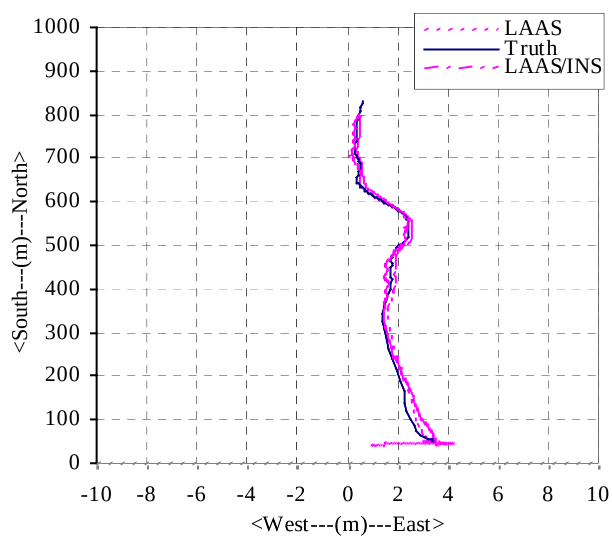


Figure C2C: LAAS versus Truth track.

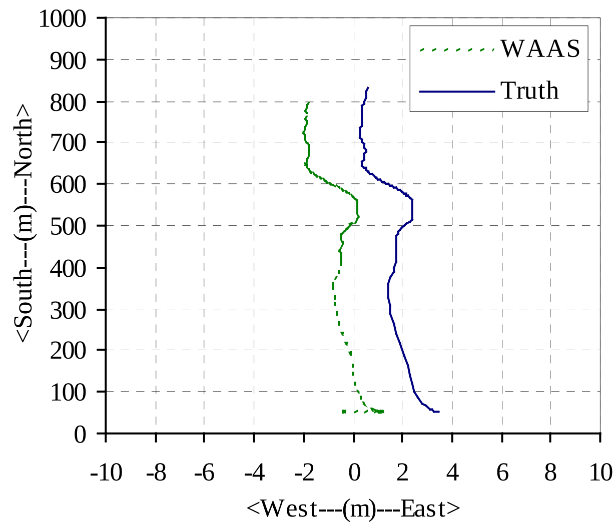


Figure C2D: WAAS versus Truth track.

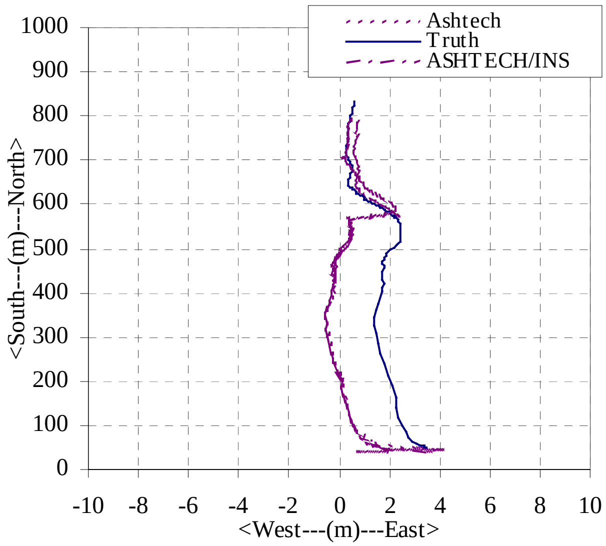


Figure C2E: Ashtech versus Truth track.

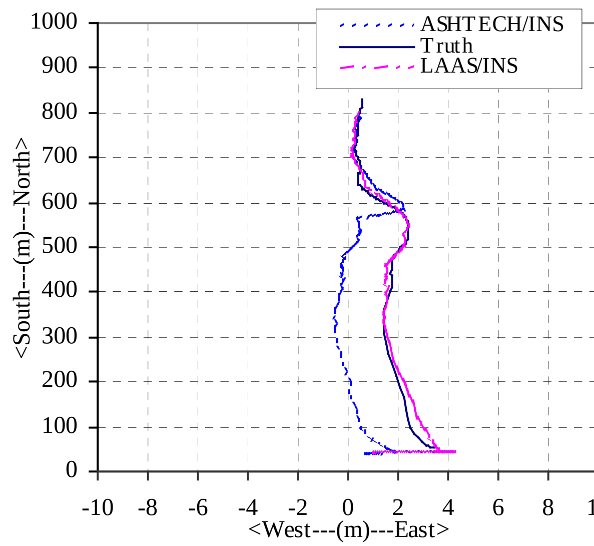


Figure C2F: Blended versus Truth track

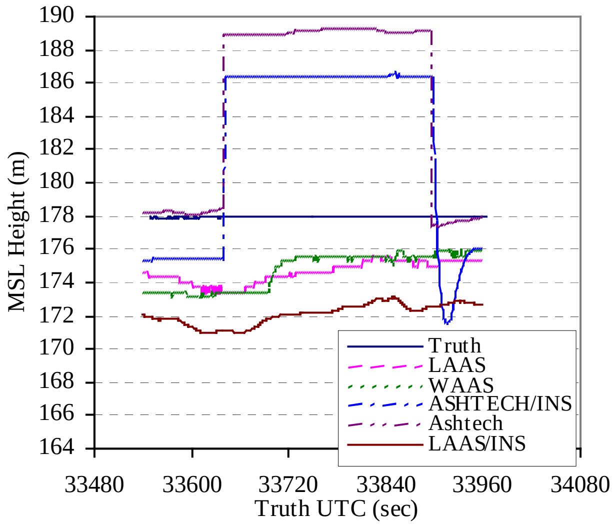


Figure C2G: MSL height comparison.

Note:

1) The Ashtech system was not in differential mode but later reacquired the differential signal. (Figure C2B, C2E, C2F)
2) The Ashtech and its blended channel had a 10 meters jump in height during the period when the Ashtech differential signal was not received.

Flight 172 run R172_38

The Ashtech/INS blend was used for this run even though LAAS/INS blend was also available.

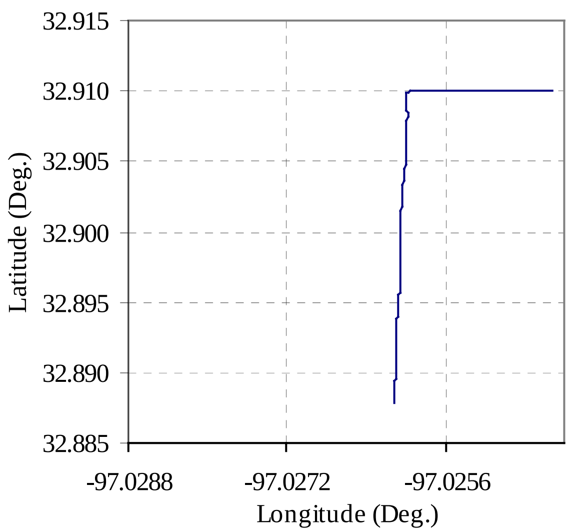


Figure C3A: Truth data for ground track.

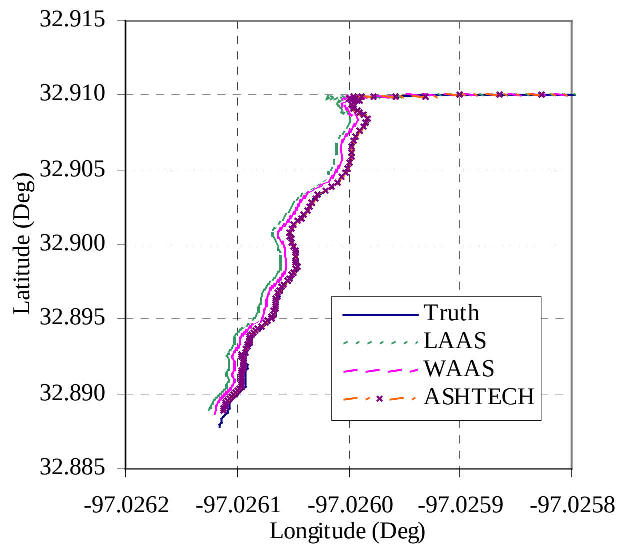


Figure C3B: Raw horizontal track of all systems.

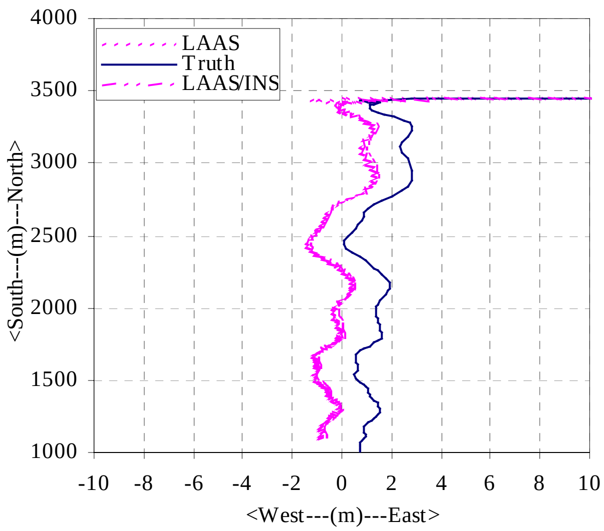


Figure C3C: LAAS versus Truth track.

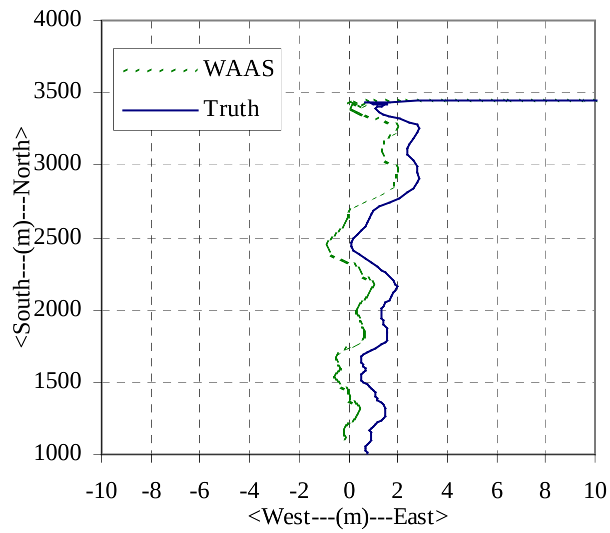


Figure C3D: WAAS versus Truth track.

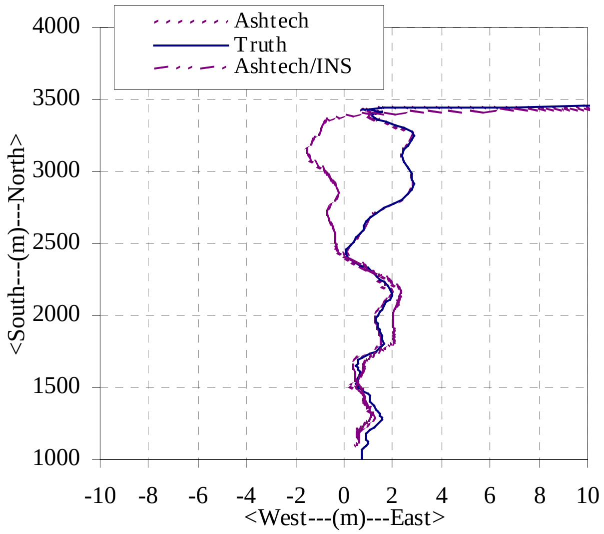


Figure C3E: Ashtech versus Truth track.

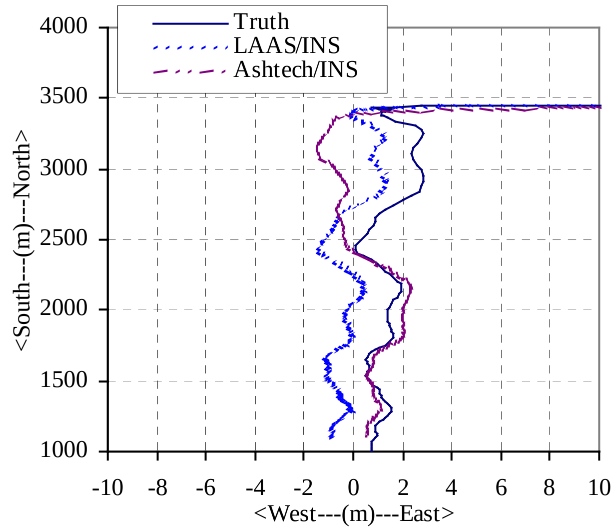


Figure C3F: Blended versus Truth track

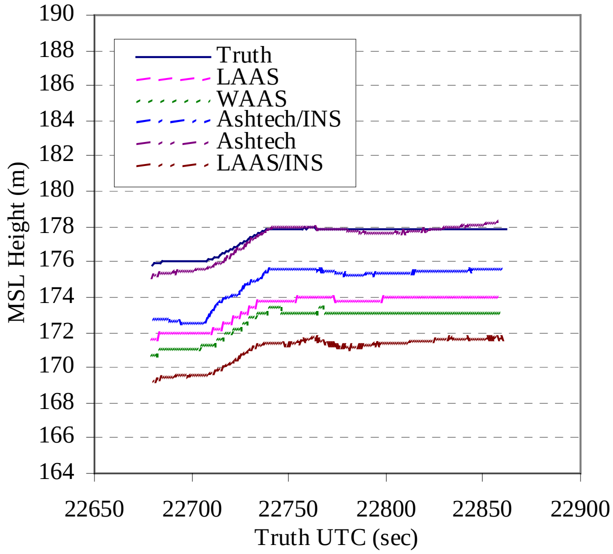


Figure C3G: MSL height comparison.

Flight 173 run R173_56

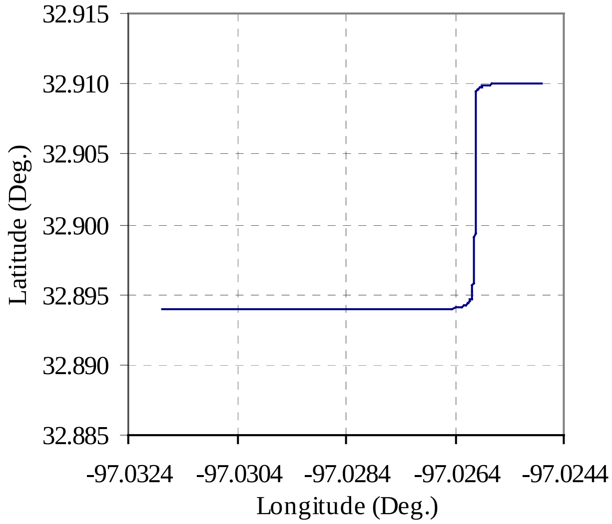


Figure C4A: Truth data for ground track.

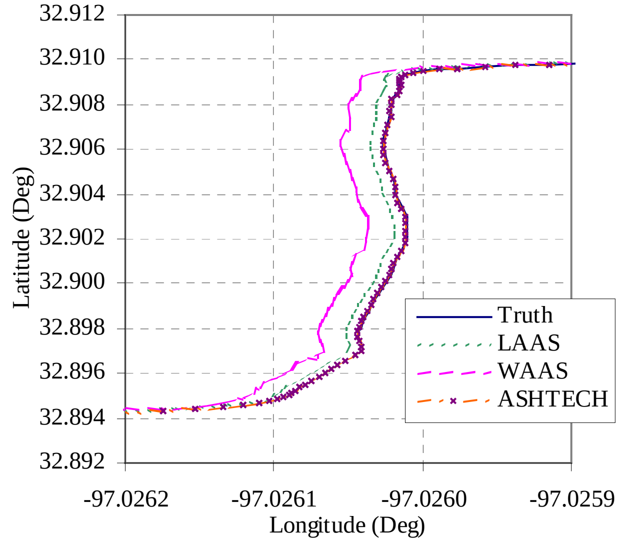


Figure C4B: Raw horizontal position of all systems.

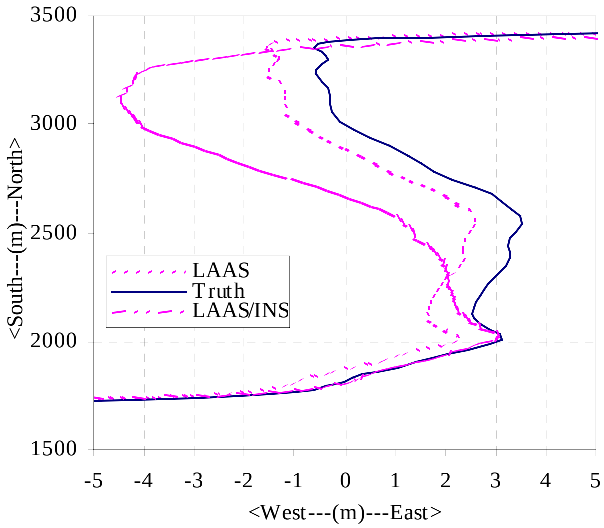


Figure C4C: LAAS versus Truth track.

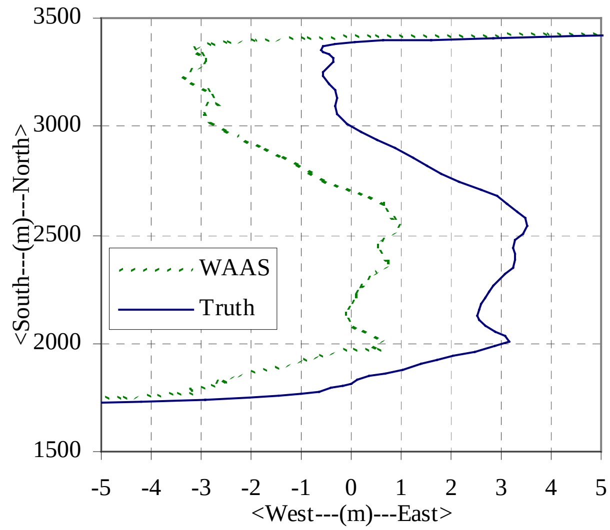


Figure C4D: WAAS versus Truth track.

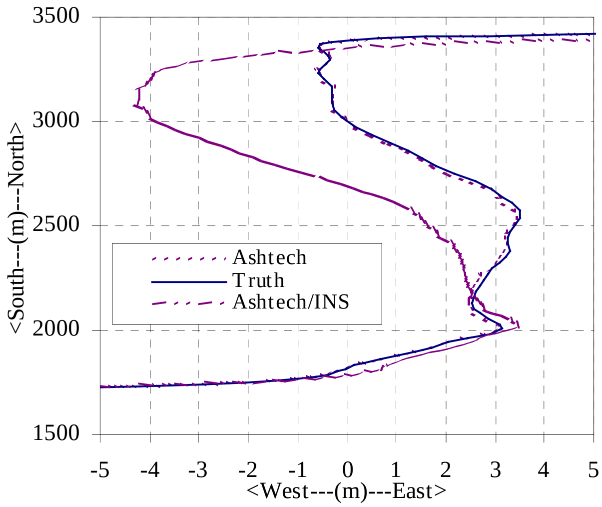


Figure C4E: Ashtech versus Truth track.

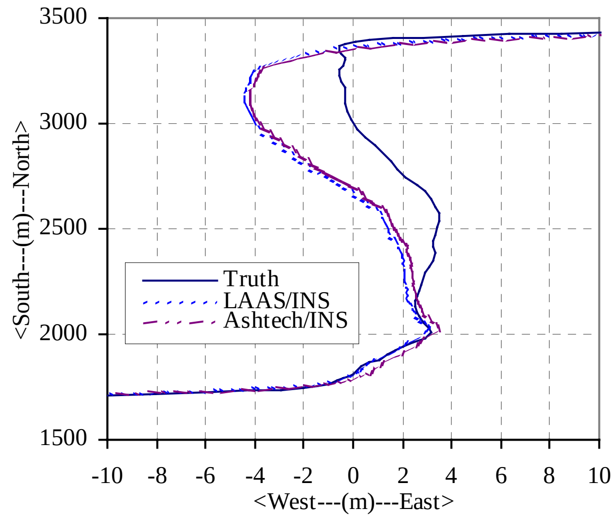


Figure C4F: Blended versus Truth track

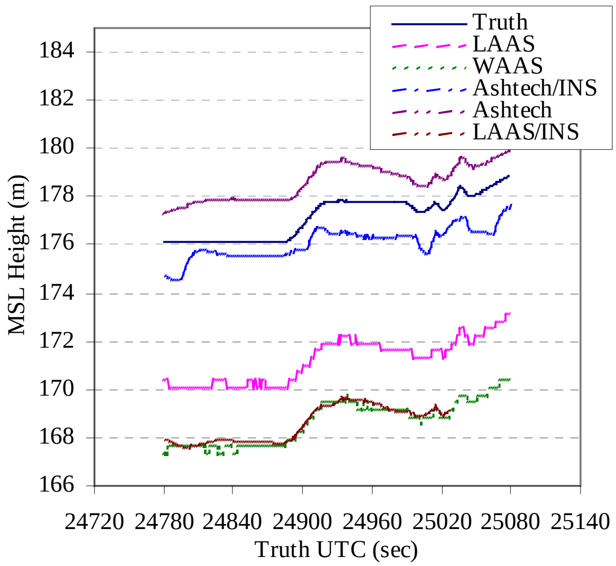


Figure C4G: MSL height comparison.

Appendix D: Profile 3 Ground Tracks.

These runs were typically very short and consist of mostly movement on taxiways.

Flight 170 run R170_04

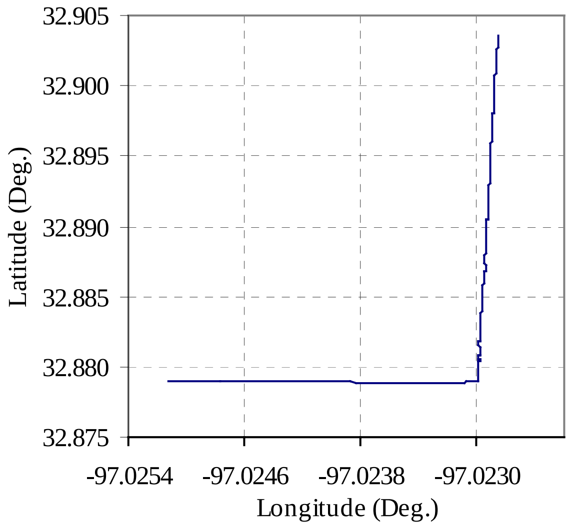


Figure D1A: Truth data for ground track.

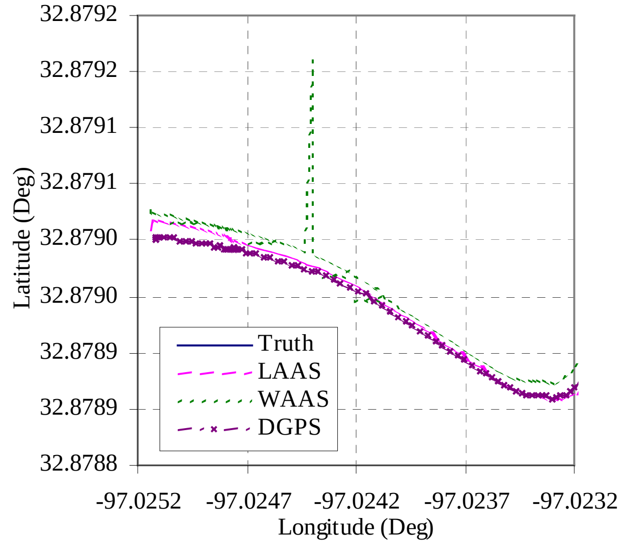


Figure D1B: Raw horizontal position of primary systems.

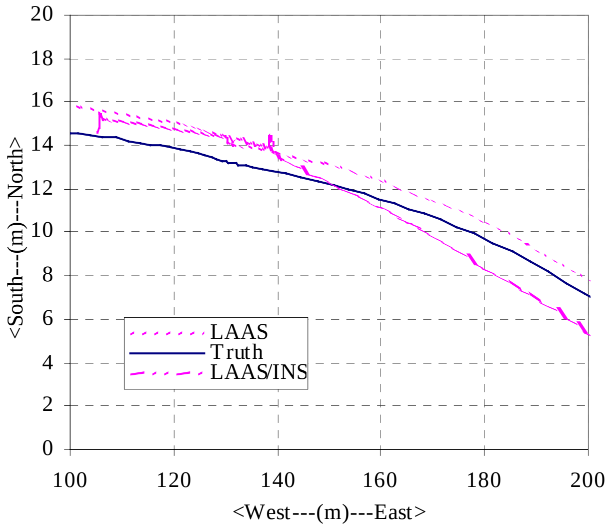


Figure D1C: LAAS versus Truth track.

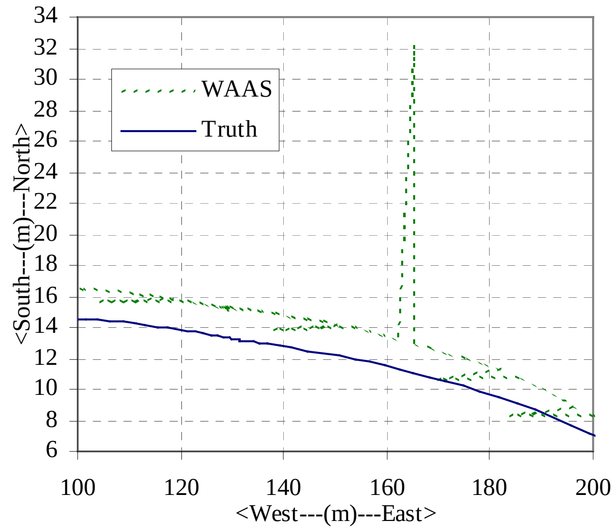


Figure D1D: WAAS versus Truth track.

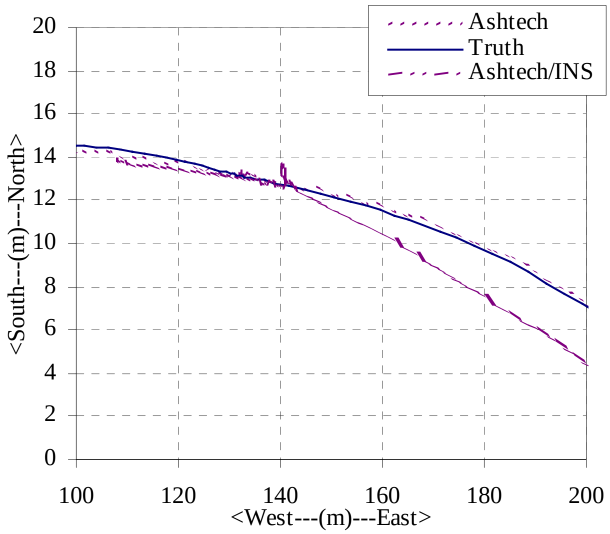


Figure D1E: Ashtech versus Truth track.

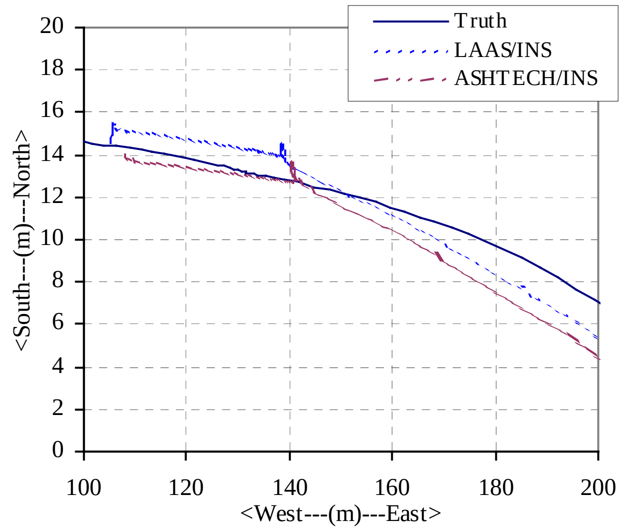


Figure D1F: Blended versus Truth track

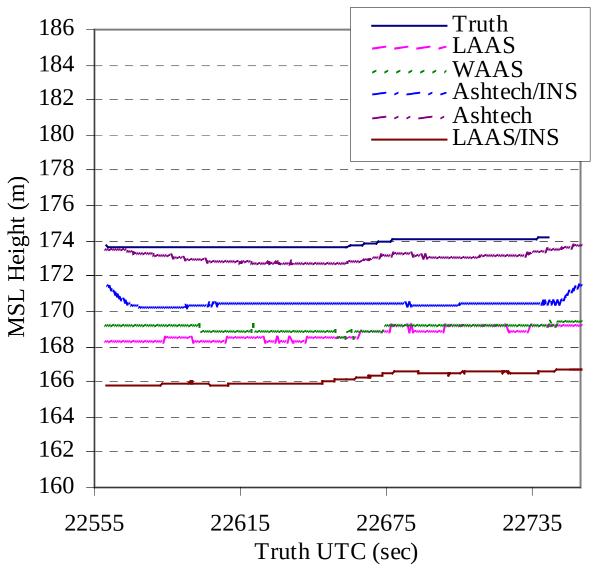


Figure D1G: MSL height comparison.

Note:

1) The WAAS system had a relatively large error in Figure D1D.
2) Blended channels in Figure D1F show mixed results. Both systems reported a similar track.

Flight 170 run R170_09

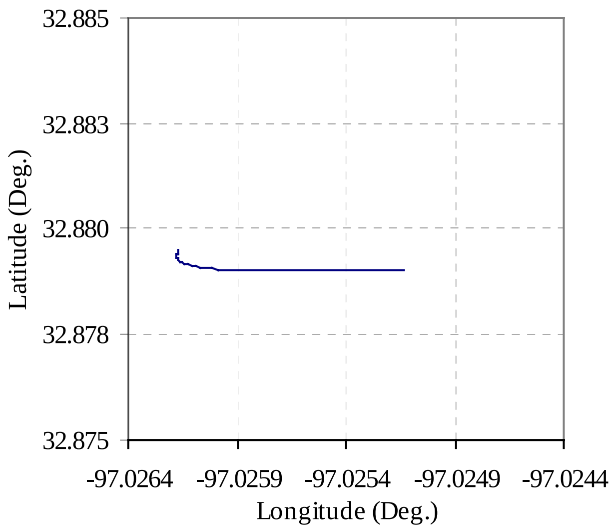


Figure D2A: Truth data for ground track.

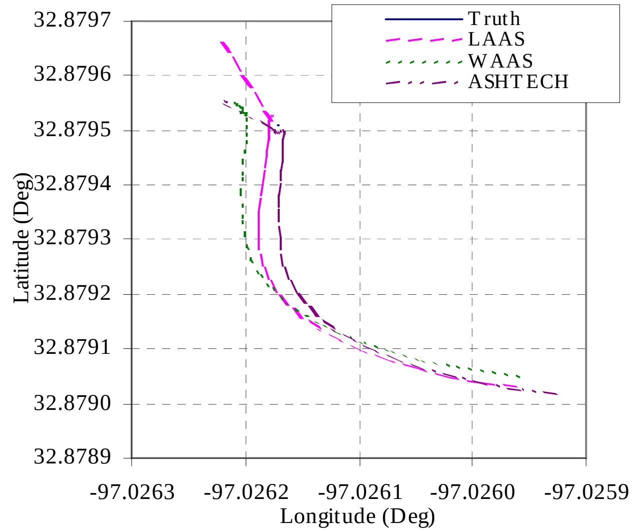


Figure D2B: Raw horizontal track of all systems.

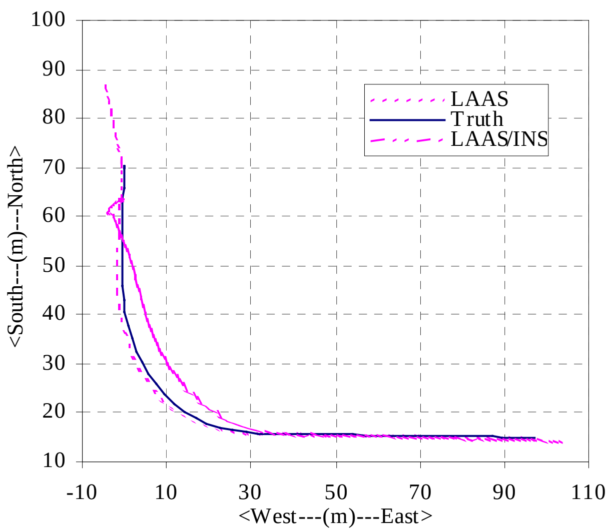


Figure D2C: LAAS versus Truth track.

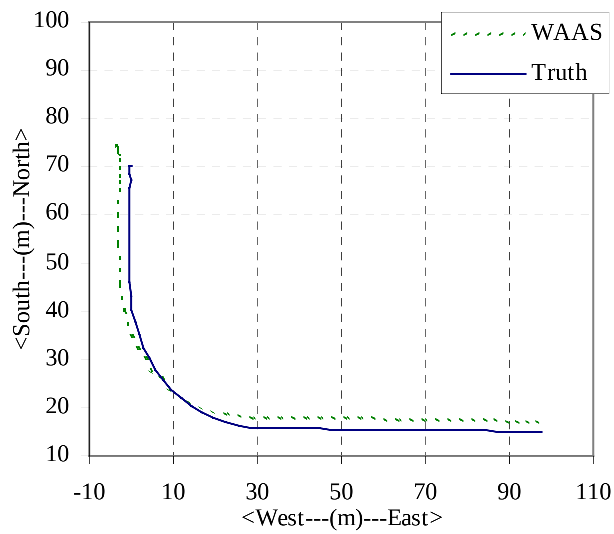


Figure D2D: WAAS versus Truth track.

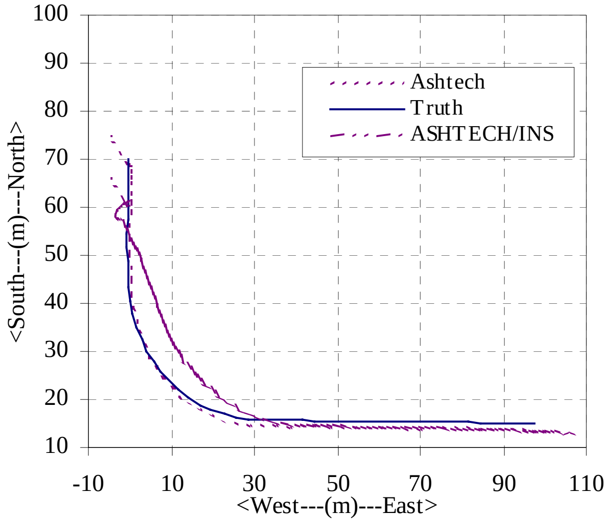


Figure D2E: Ashtech versus Truth track.

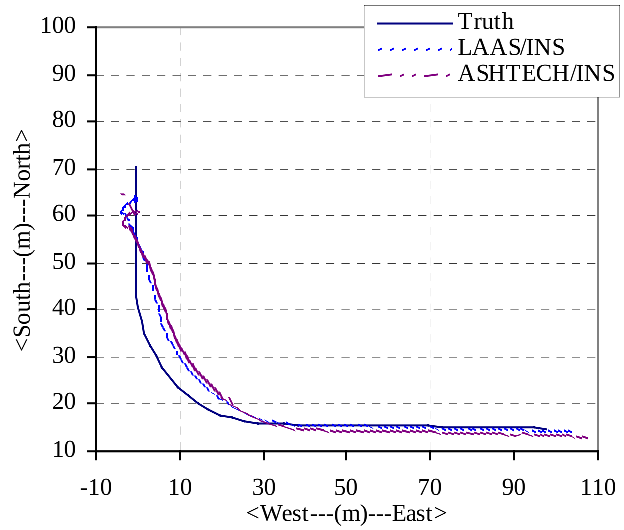


Figure D2F: Blended versus Truth track

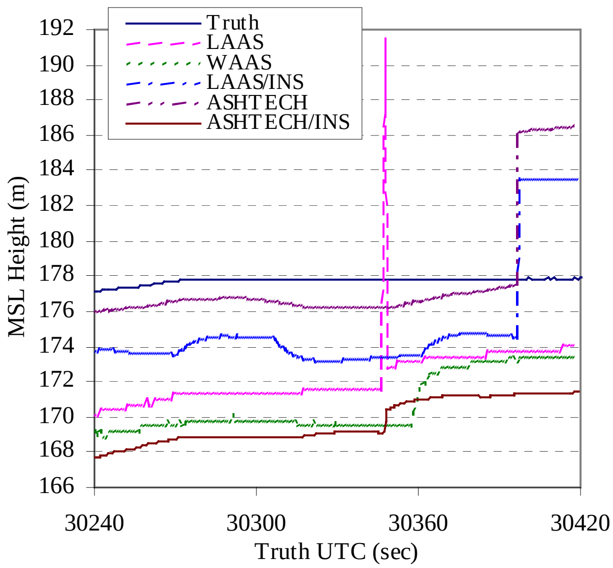


Figure D2G: MSL height comparison.

Note:

1) Figure D2G shows some peculiar behavior with several systems. The LAAS system has an 18 meters spike.
2) Figure D2G, the LAAS/INS as well as the Ashtech both jumped about 8 meters at the same place.

Flight 171 run R171_25

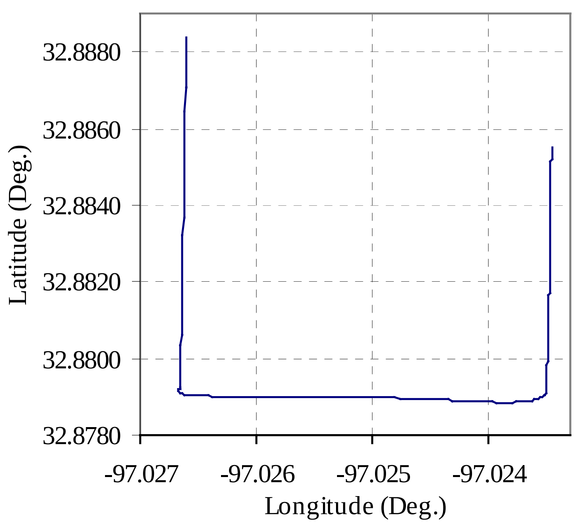


Figure D3A: Truth data for ground track.

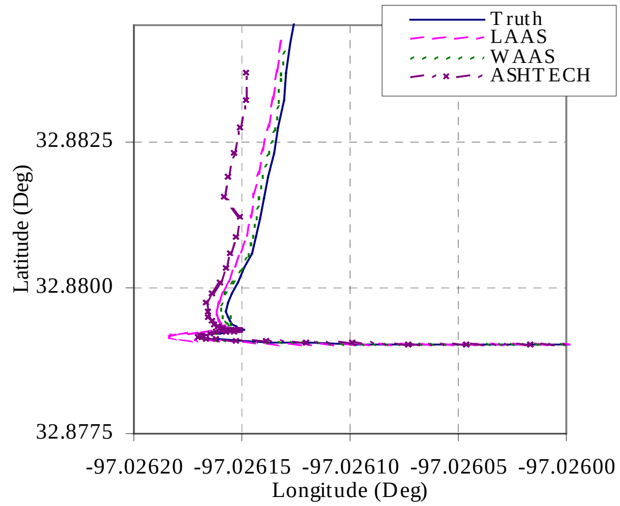


Figure D3B: Raw horizontal position for all systems.

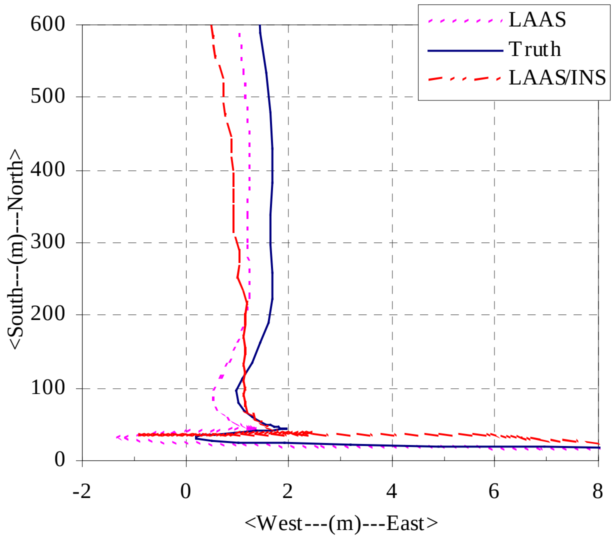


Figure D3C: LAAS versus Truth track.

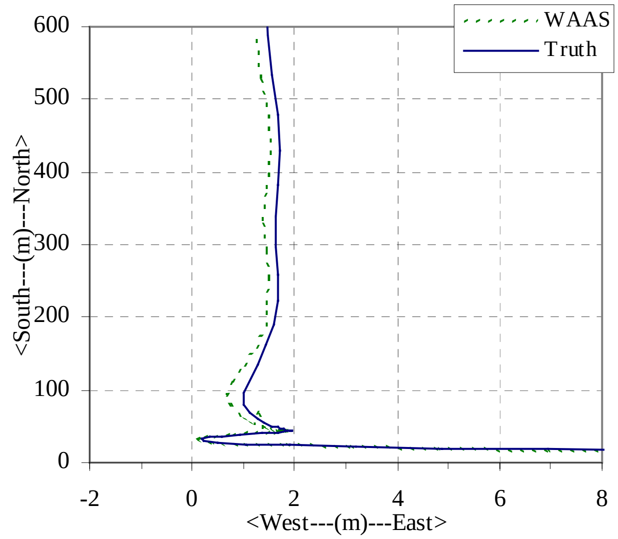


Figure D3D: WAAS versus Truth track.

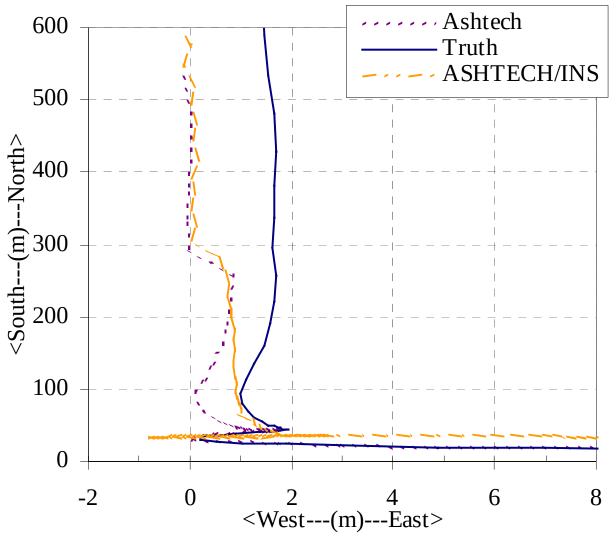


Figure D3E: Ashtech versus Truth track.

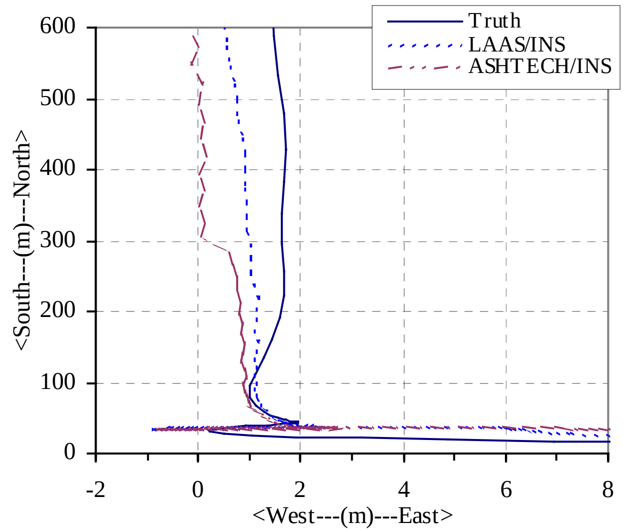


Figure D3F: Blended versus Truth track

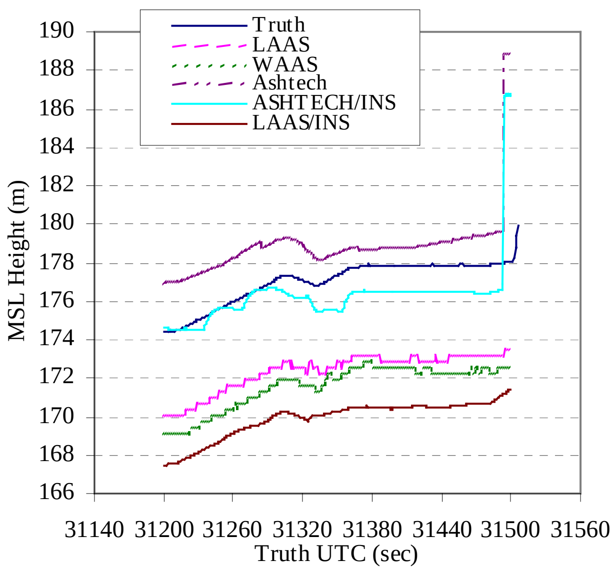


Figure D3G: MSL height comparison.

Flight 172 run R172_43

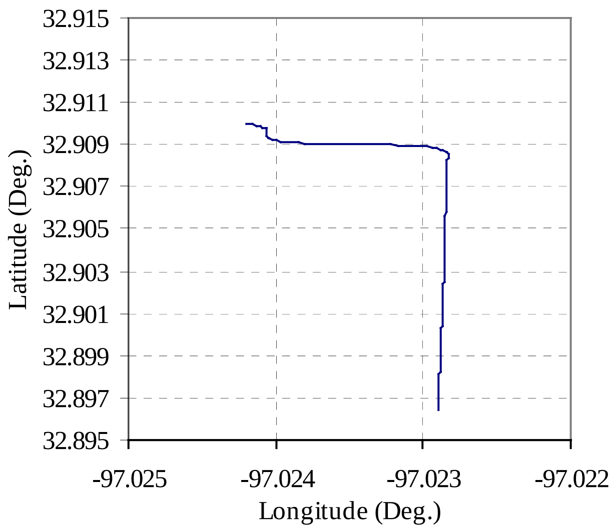


Figure D4A: Truth data for ground track.

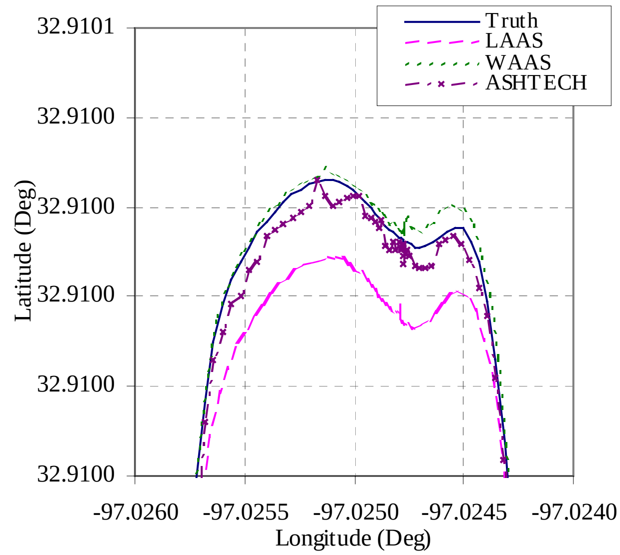


Figure D4B: Raw horizontal position of all systems.

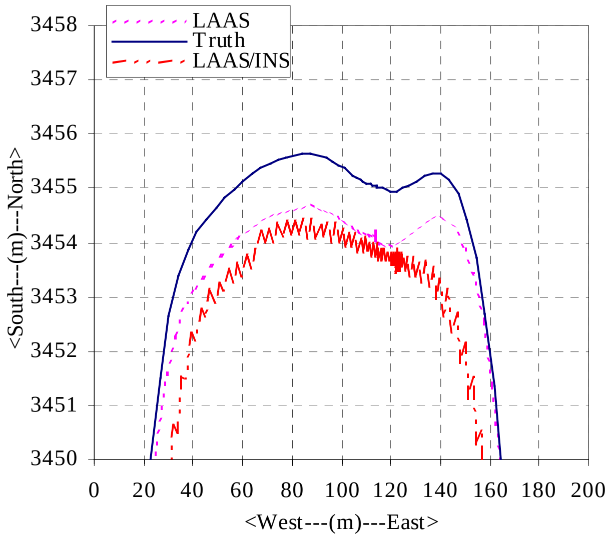


Figure D4C: LAAS versus Truth track.

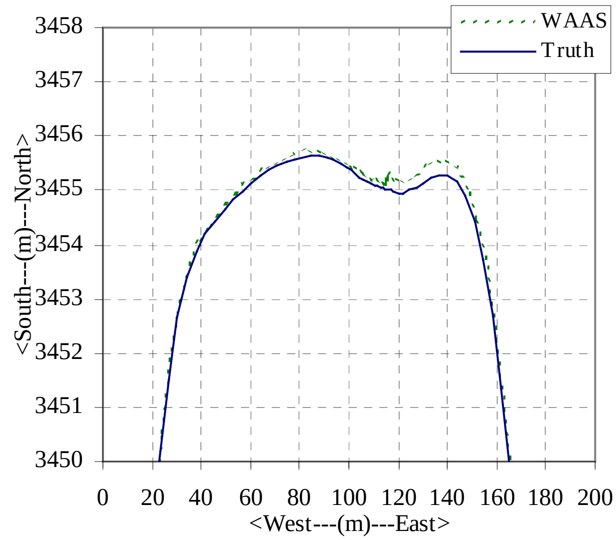


Figure D4D: WAAS versus Truth track.

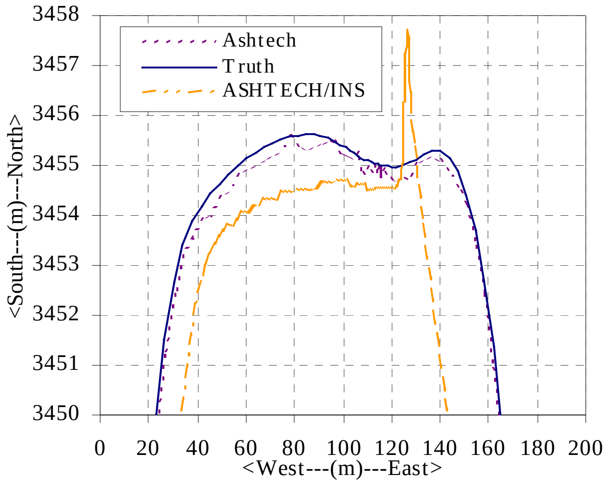


Figure D4E: Ashtech versus Truth track.

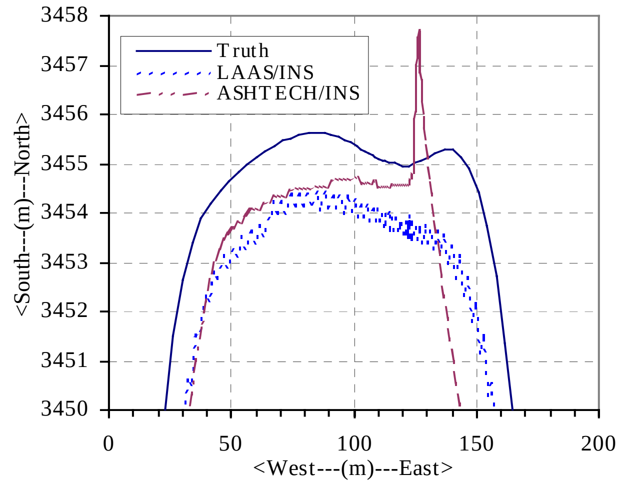


Figure D4F: Blended versus Truth track

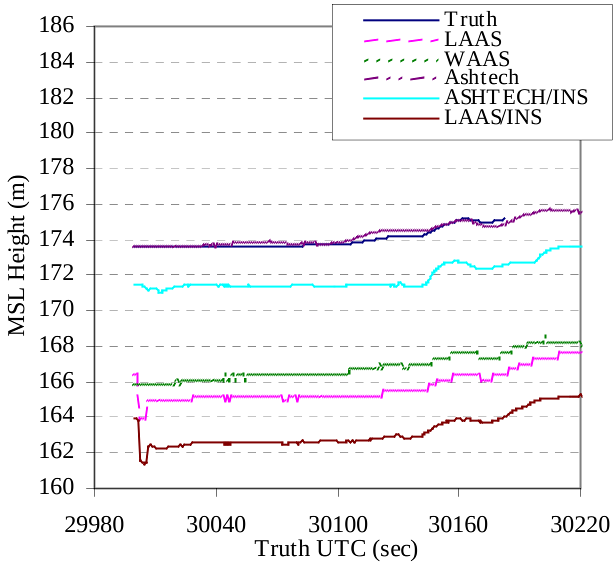


Figure D4G: MSL height comparison.

Appendix E: Profile 4 Ground Tracks.

This profile involves an aborted landing with aircraft movement profiles similar to those of Profile 1. In this profile, the data often includes a loop around the airport and an approach on the runway. For accuracy assessment purposes, these flights are identical to Profile 1 flights.

Flight 170 run R170_05

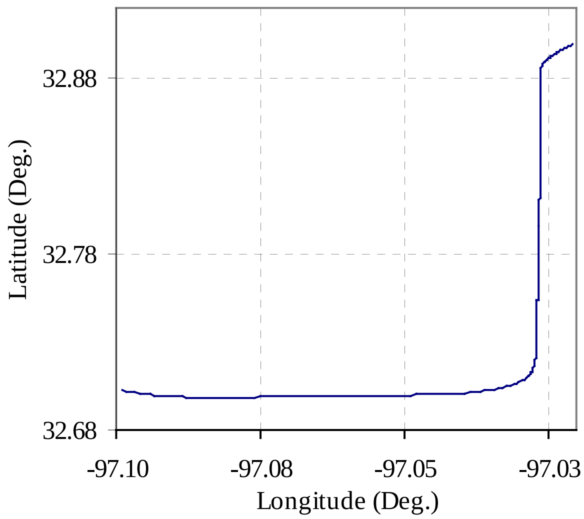


Figure E1A: Truth data for ground track.

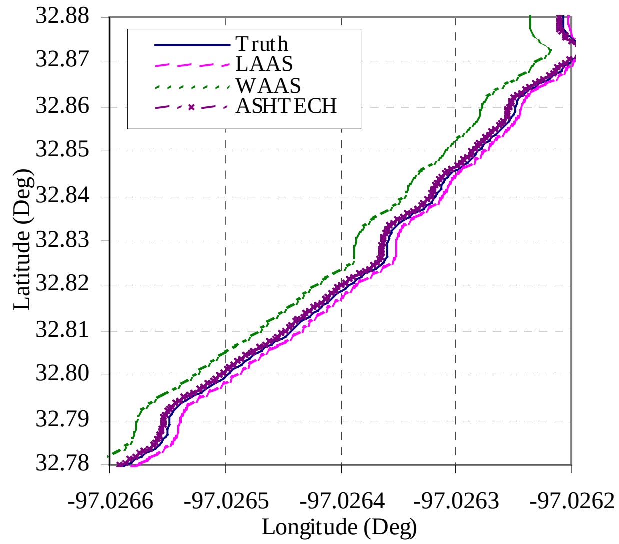


Figure E1B: Raw horizontal position of all systems.

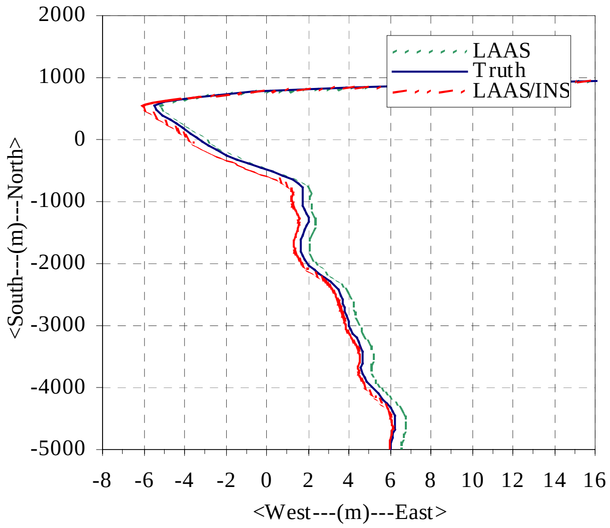


Figure E1C: LAAS versus Truth track.

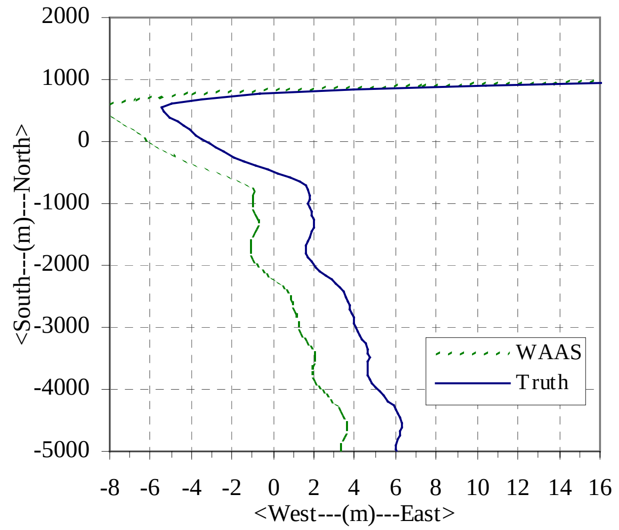


Figure E1D: WAAS versus Truth track.

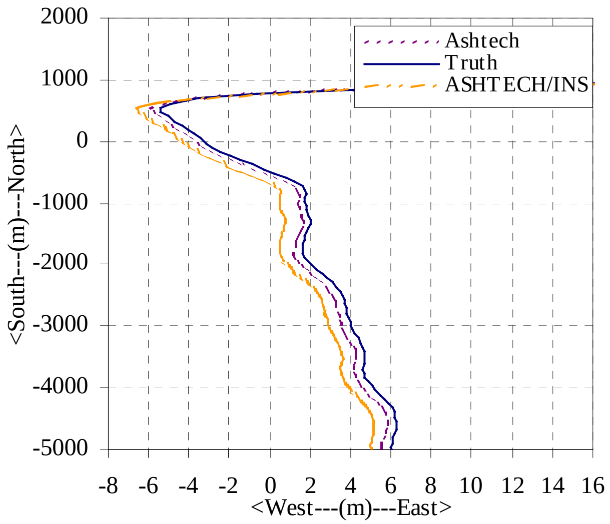


Figure E1E: Ashtech versus Truth track.

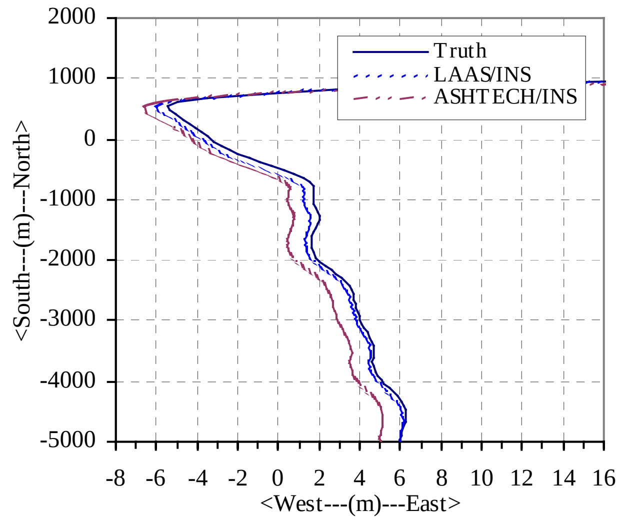


Figure E1F: Blended versus Truth track

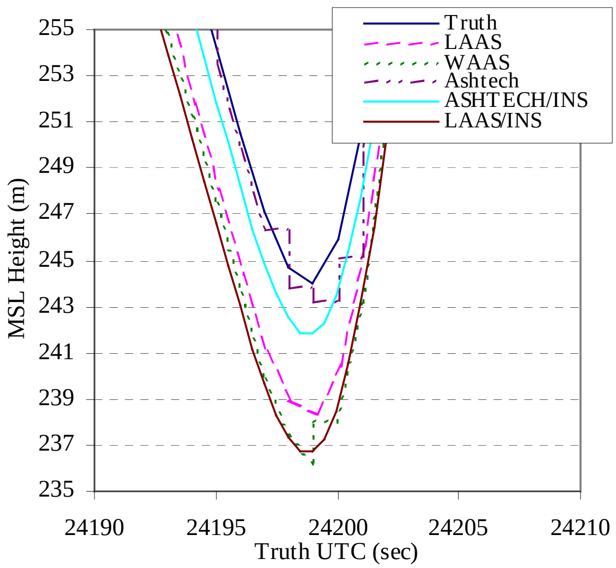


Figure E1G: MSL height comparison.

Flight 171 run R171_16

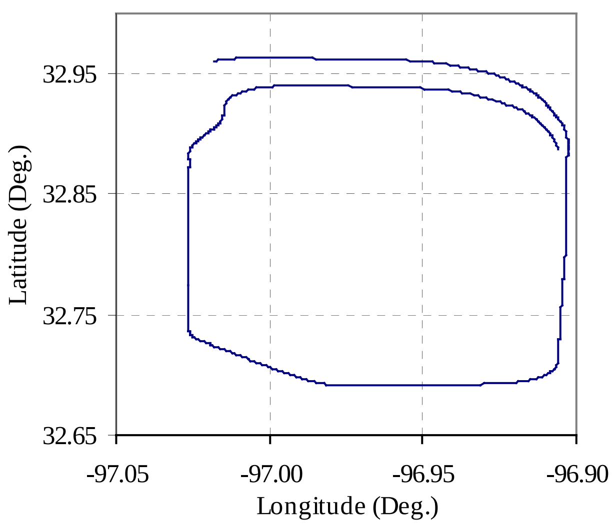


Figure E2A: Truth data for ground track.

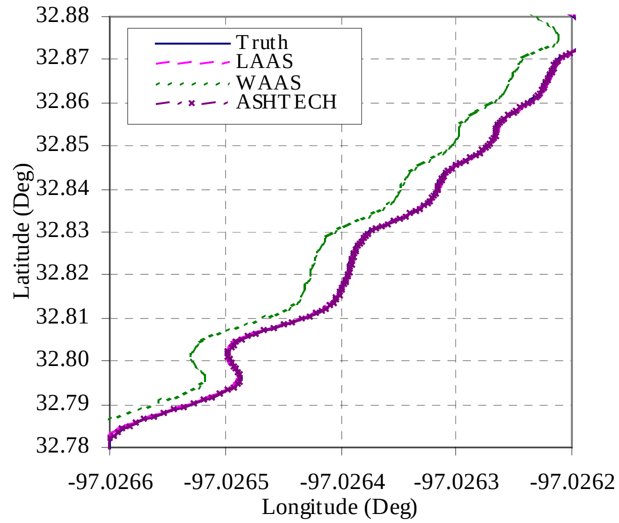


Figure E2B: Raw horizontal position of all systems.

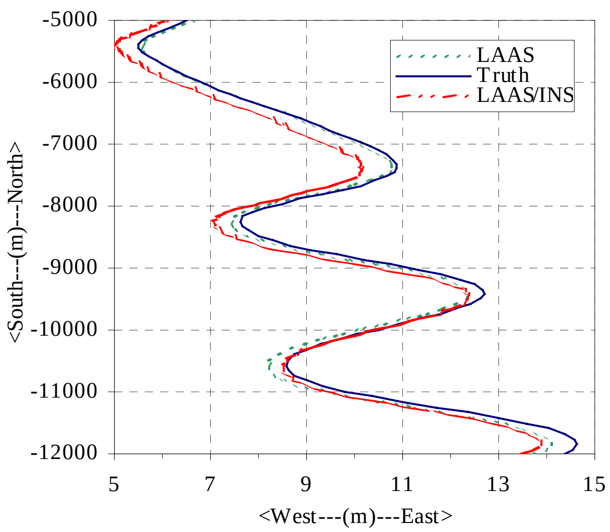


Figure E2C: LAAS versus Truth track.

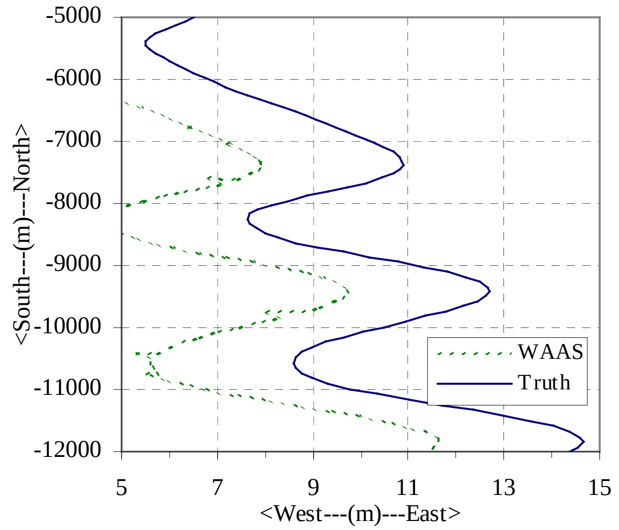


Figure E2D: WAAS versus Truth track.

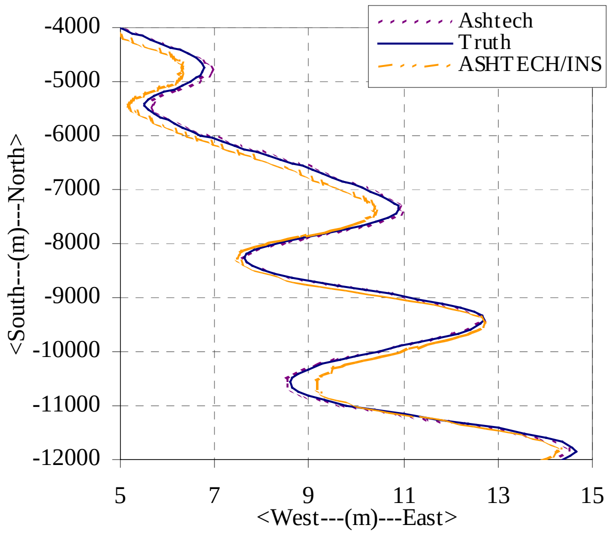


Figure E2E: Ashtech versus Truth track.

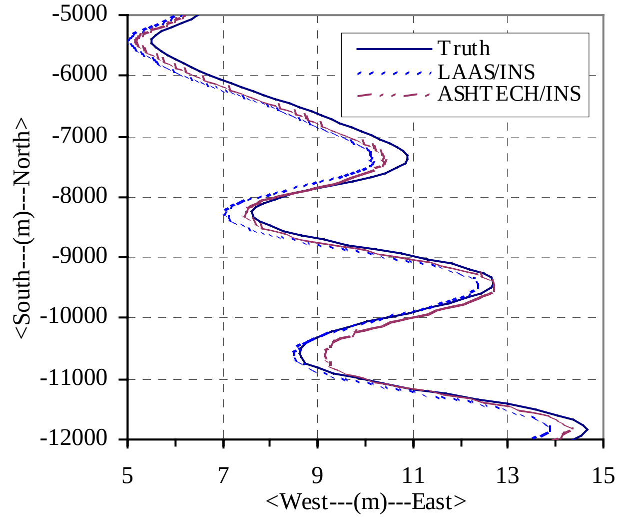


Figure E2F: Blended versus Truth track

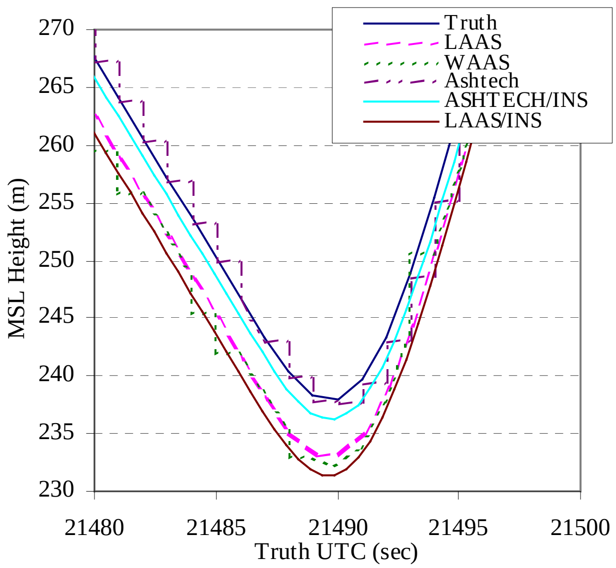


Figure E2G: MSL height comparison.

Flight 172 run R172_41

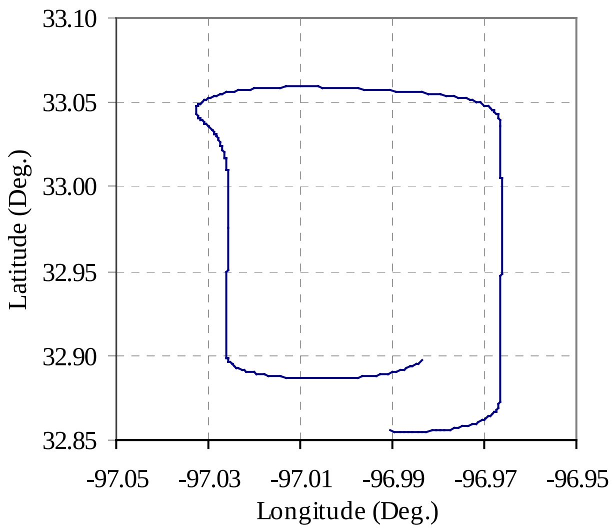


Figure E3A: Truth data for ground track.

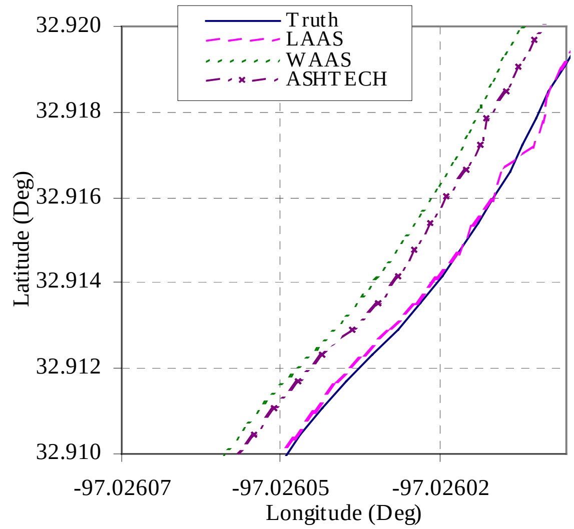


Figure E3B: Raw horizontal track of all systems.

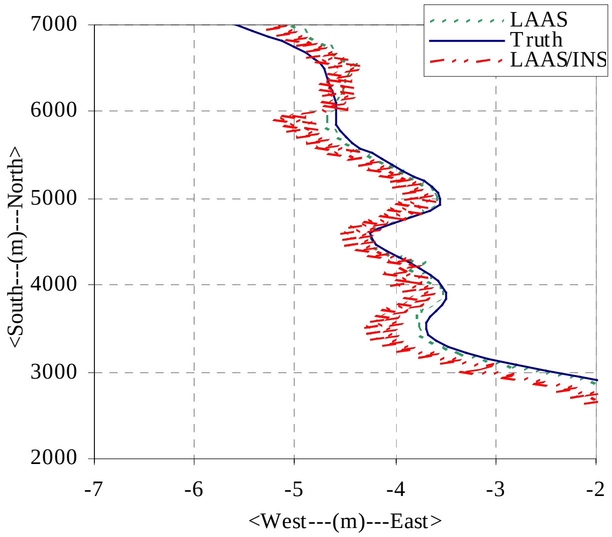


Figure E3C: LAAS versus Truth track.

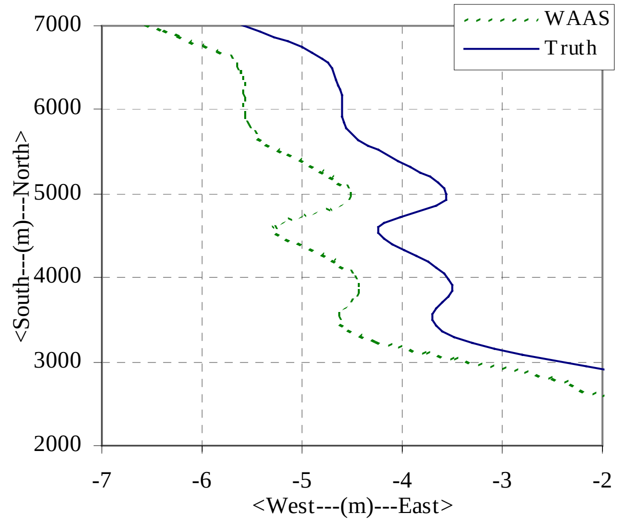


Figure E3D: WAAS versus Truth track.

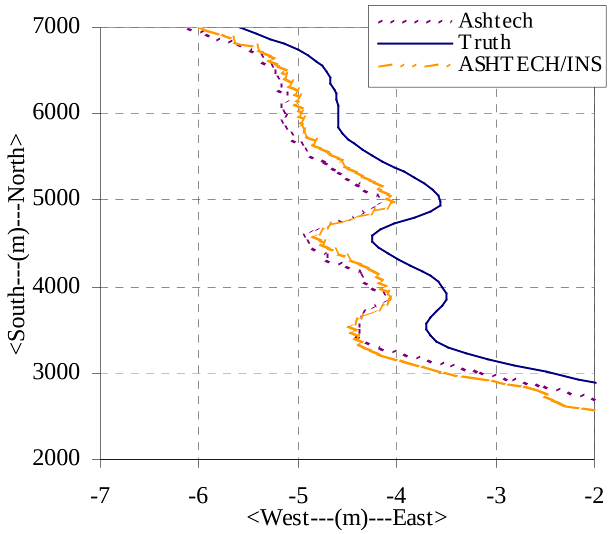


Figure E3E: Ashtech versus Truth track.

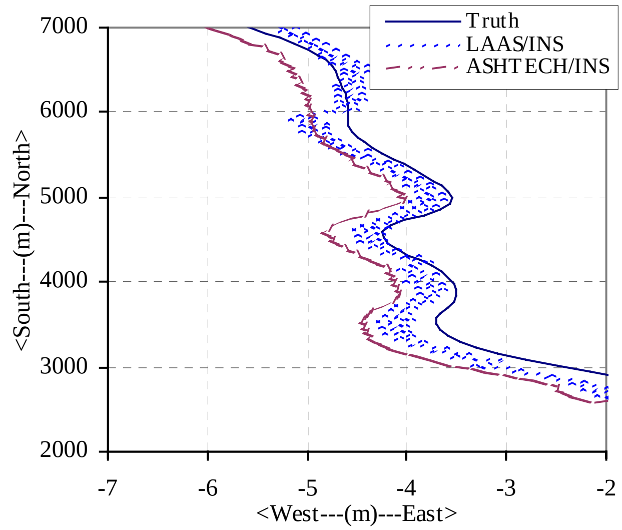


Figure E3F: Blended versus Truth track

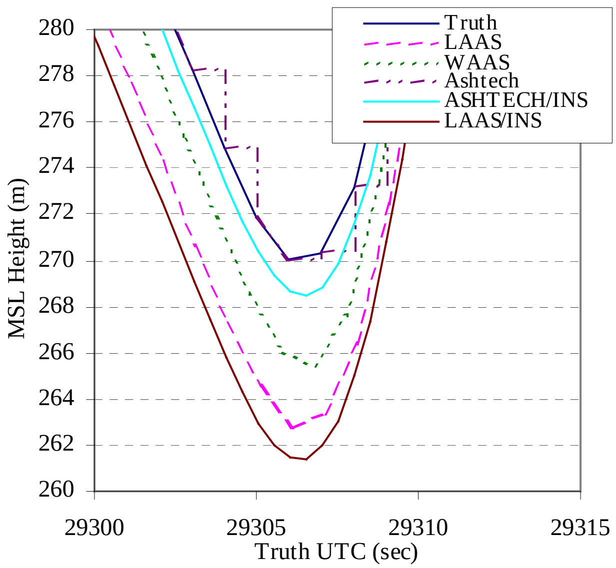


Figure E3G: MSL height comparison.

Flight 174 run R174_69

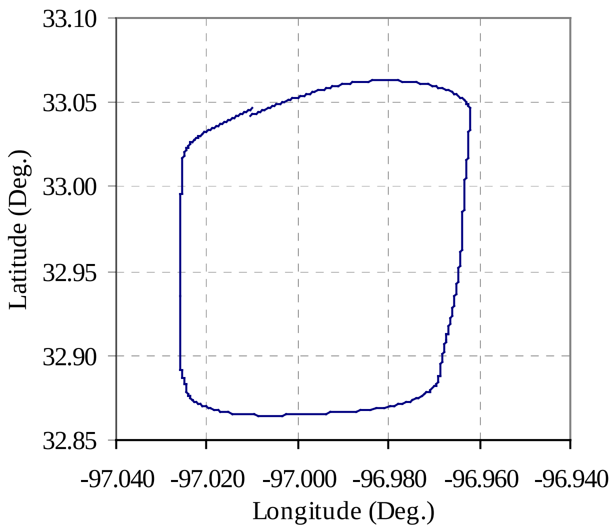


Figure E4A: Truth data for ground track.

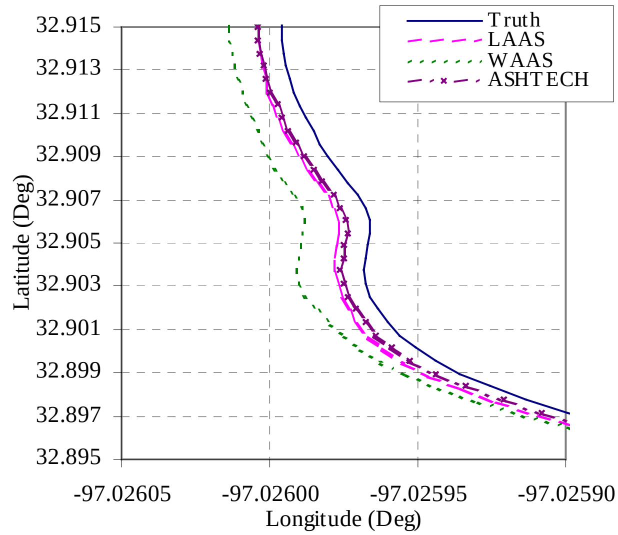


Figure E4B: Raw horizontal track of all systems.

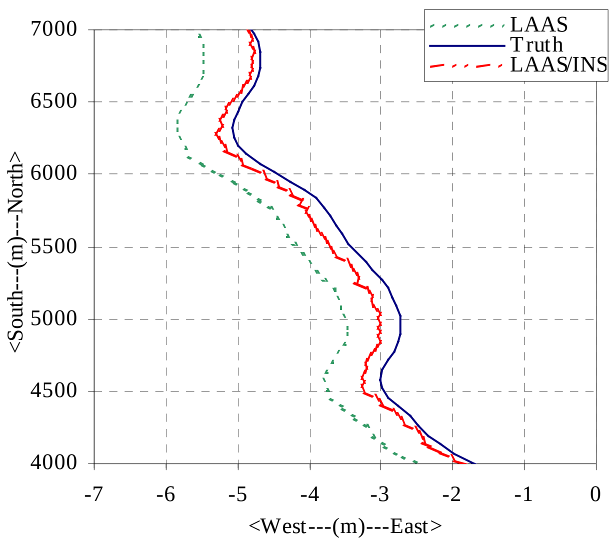


Figure E4C: LAAS versus Truth track.

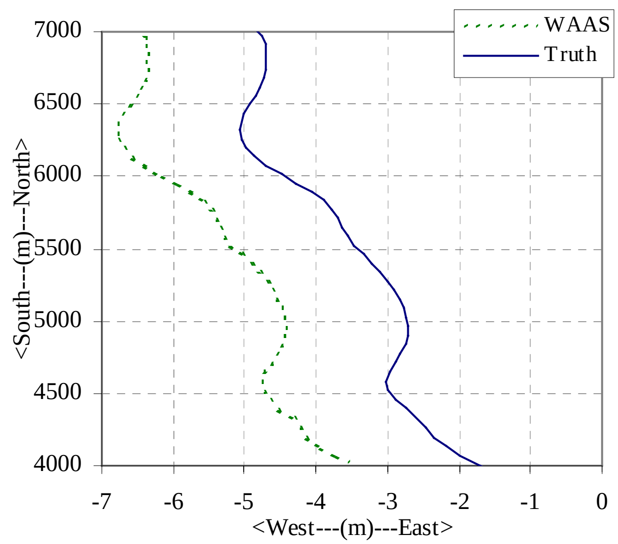


Figure E4D: WAAS versus Truth track.

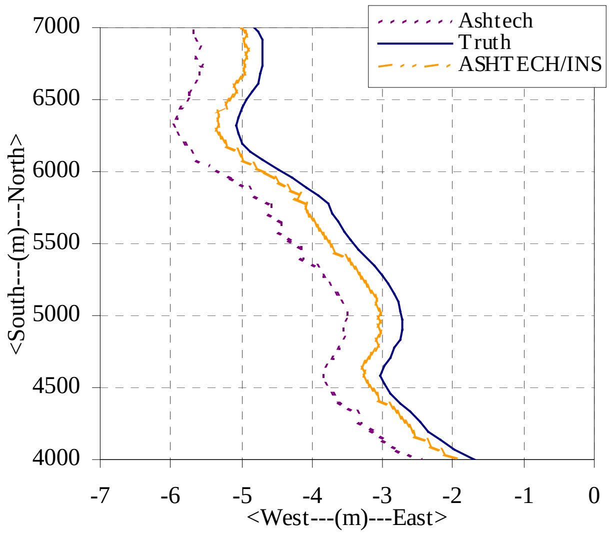


Figure E4E: Ashtech versus Truth track.

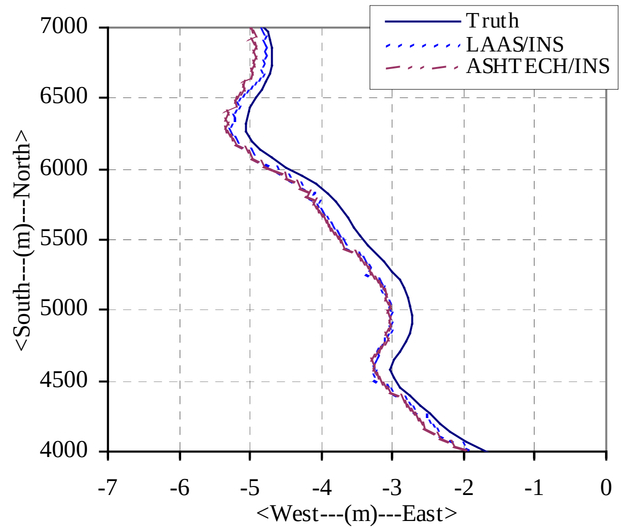


Figure E4F: Blended versus Truth track

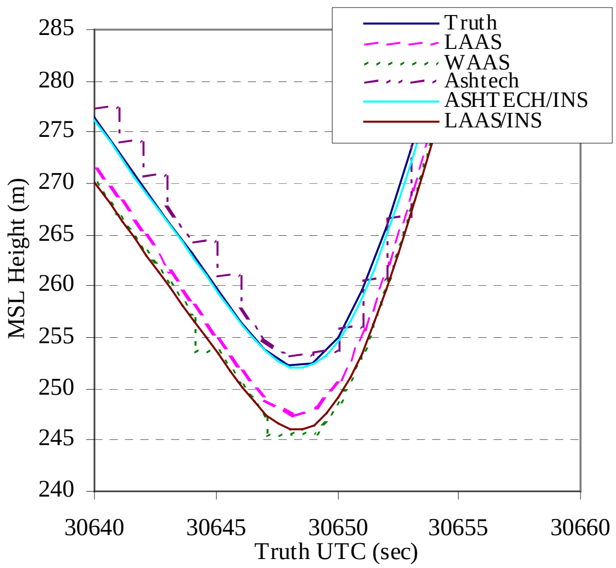


Figure E4G: MSL height comparison.

Appendix F: Profile 5 Ground Tracks.

Profile 5 consists of taxiing the aircraft from the runway area to gates in Terminal C (see DFW map in Appendix A). For logistics reasons, the aircraft actually did not park at the terminal. Instead, the aircraft approached the building as close as possible while still allowing the aircraft to move away from the terminal on its own power.

Flight 171 run R171_19

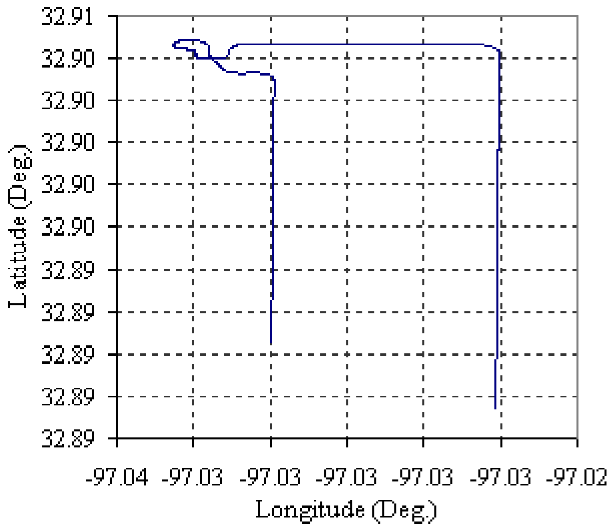


Figure F1A: Truth data for ground track.

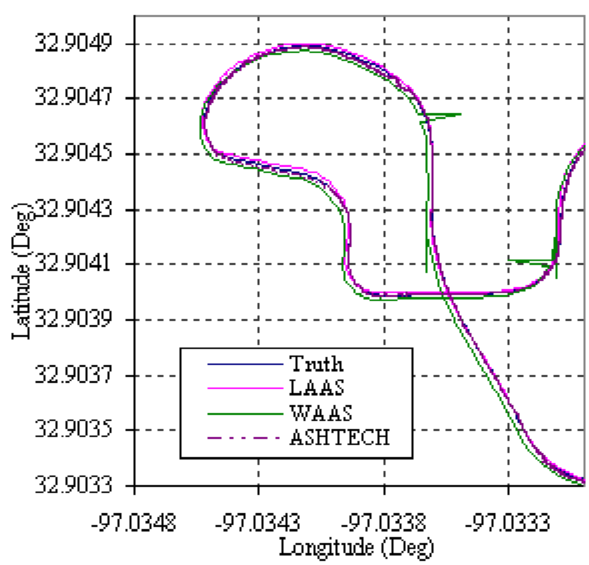


Figure F1B: Raw horizontal track of all systems.

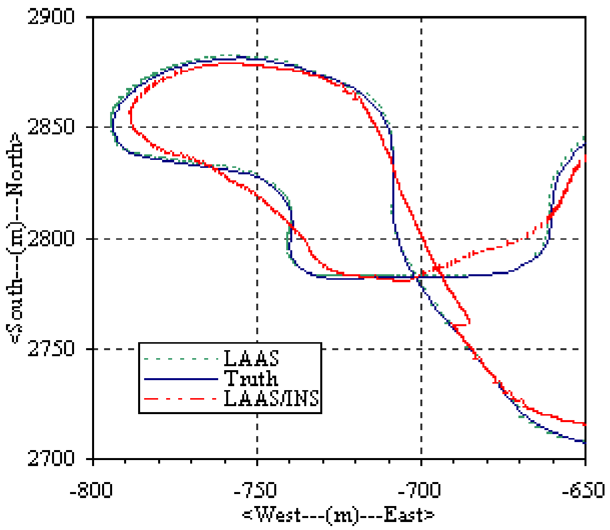


Figure F1C: LAAS versus Truth track.

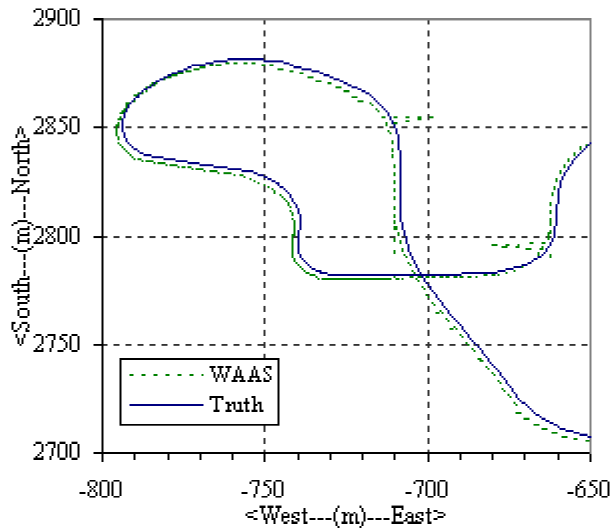


Figure F1D: WAAS versus Truth track.

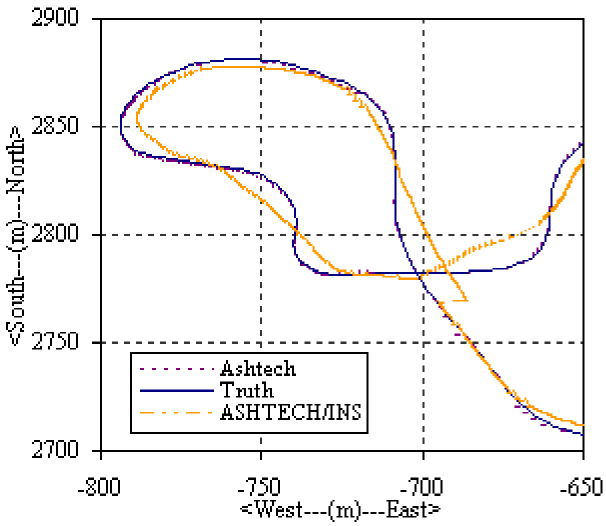


Figure F1E: Ashtech versus Truth track.

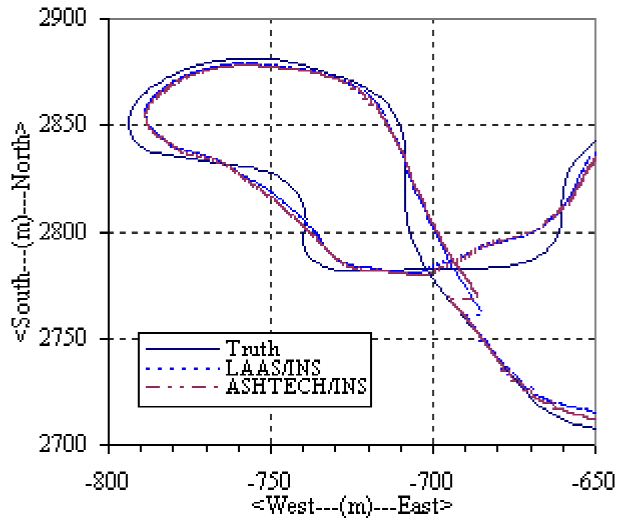


Figure F1F: Blended versus Truth track

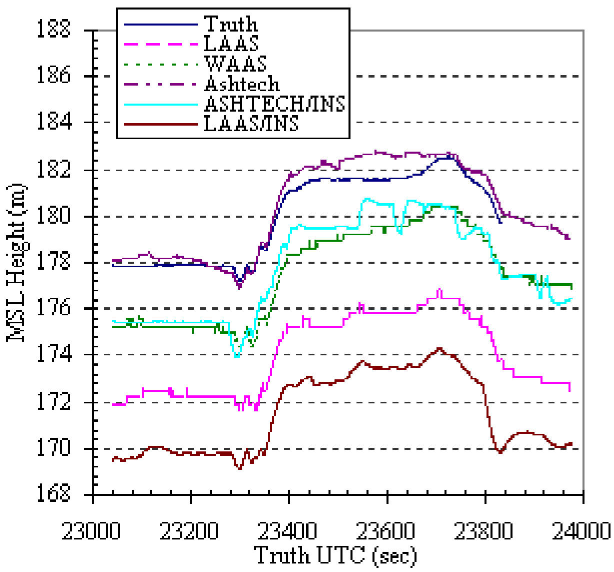


Figure F1G: MSL height comparison.

Note:

1) Figures F1B to F1F show the loop that the ARIES made at the terminal area.
2) Figure F1B shows the WAAS system had three sharp jumps in positions during this period.
3) Figure F1G the LAAS height reports were less accurate than WAAS height reports. Both blended channels faired worse than their primary systems.

Flight 173 run R173_57

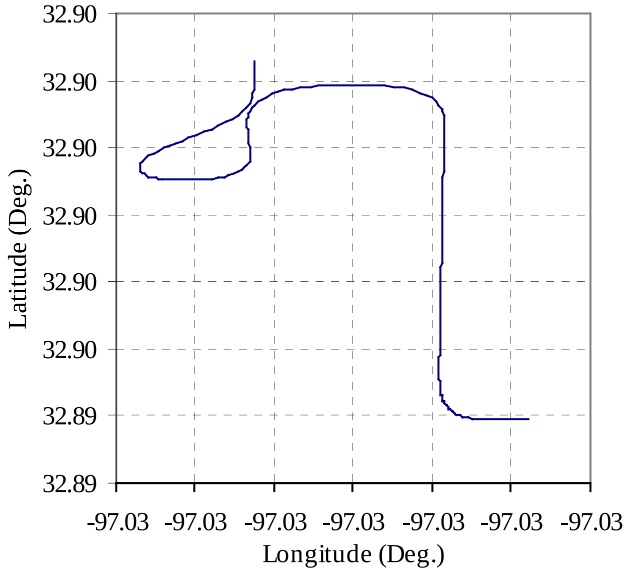


Figure F2A: Truth data for ground track.

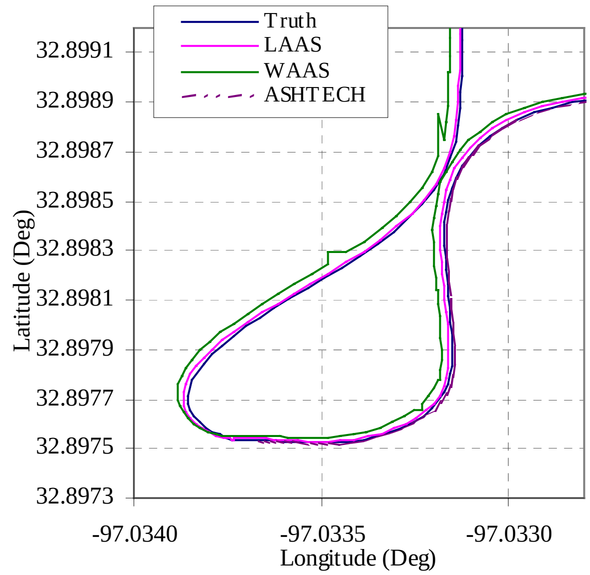


Figure F2B: Raw horizontal track of all systems.

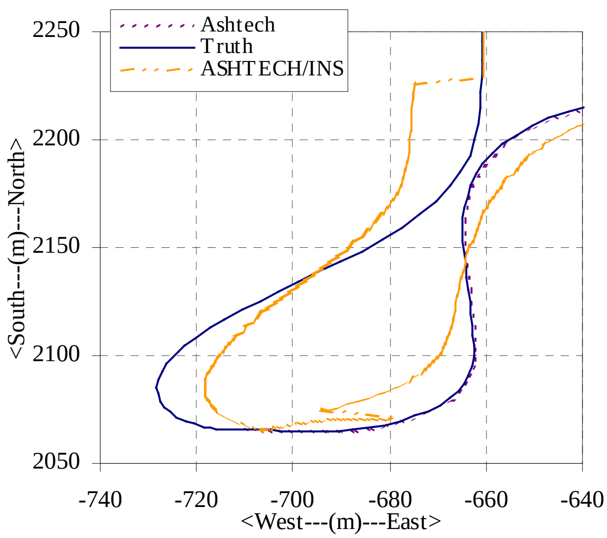


Figure F2C: LAAS versus Truth track.

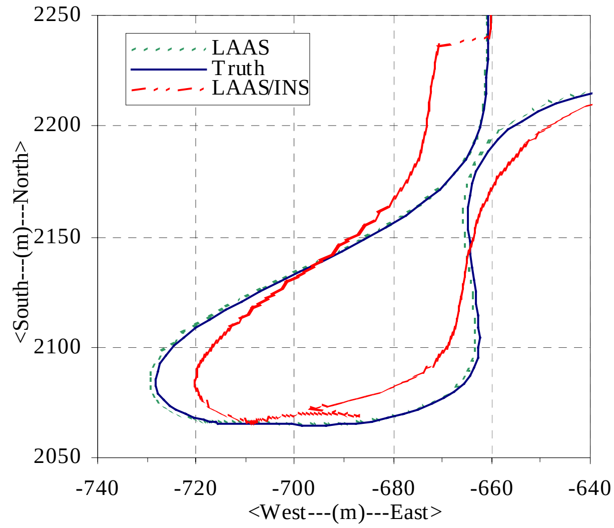


Figure F2D: WAAS versus Truth track.

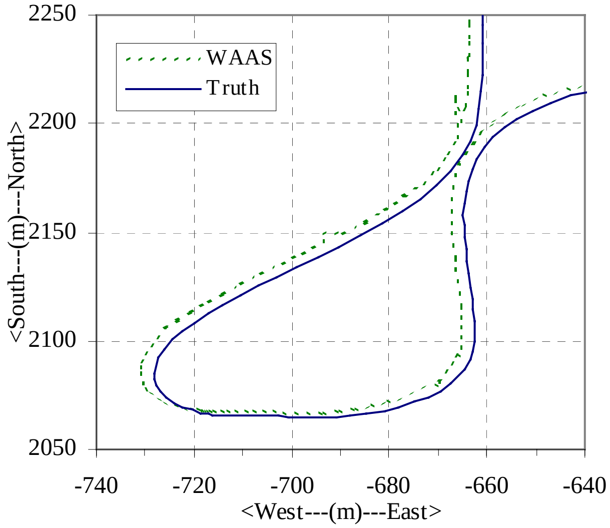


Figure F2E: Ashtech versus Truth track.

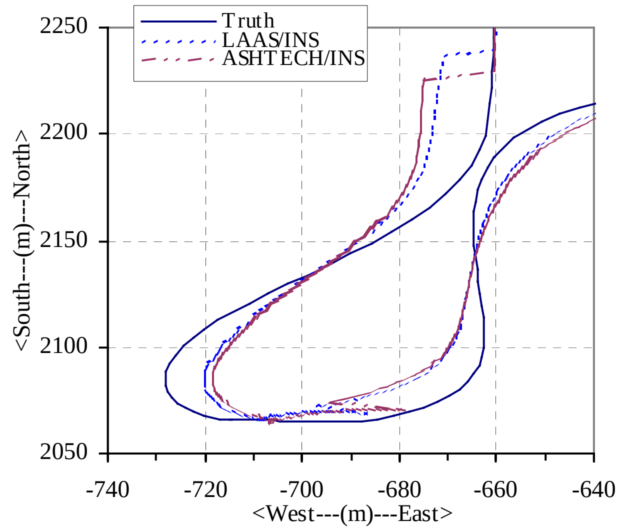


Figure F2F: Blended versus Truth track

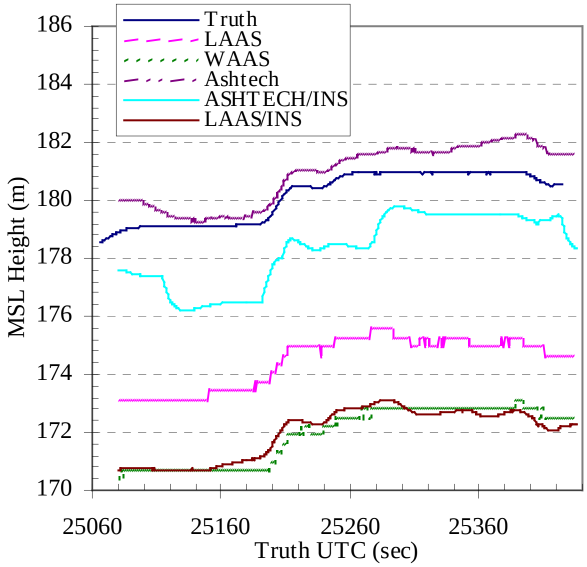


Figure F2G: MSL height comparison.

Appendix G: Profile 6 Ground Tracks.

Flight 173 run R173_54

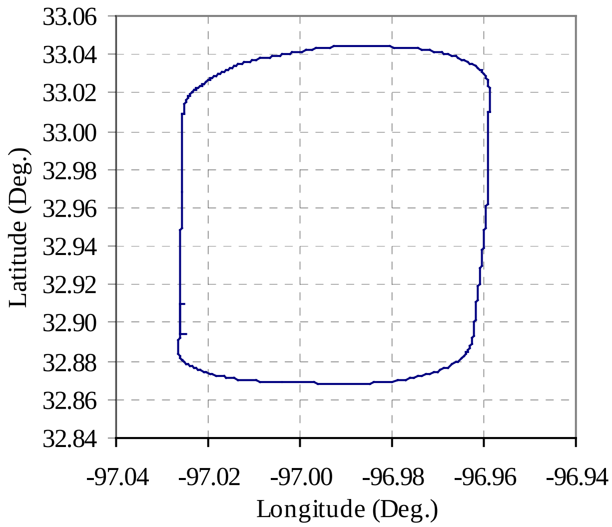


Figure G1A: Truth data for ground track.

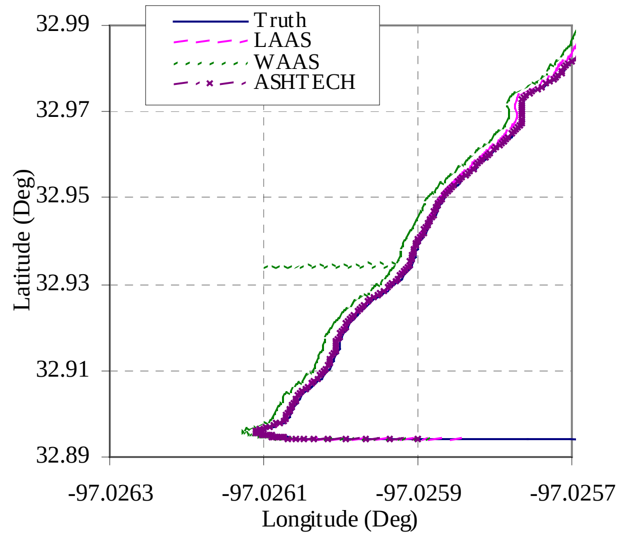


Figure G1B: Raw horizontal track of all systems.

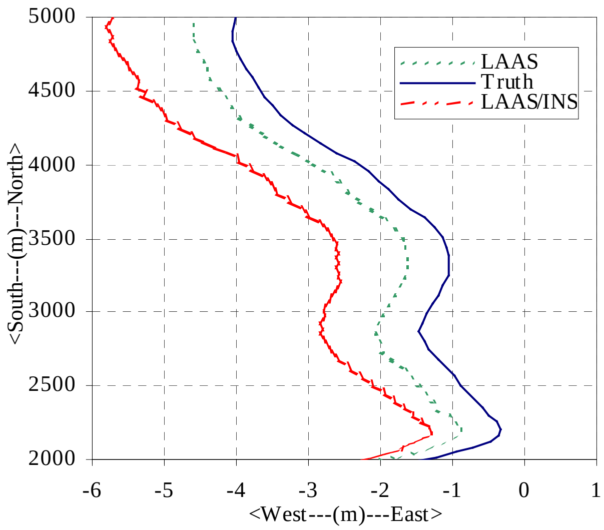


Figure G1C: LAAS versus Truth track.

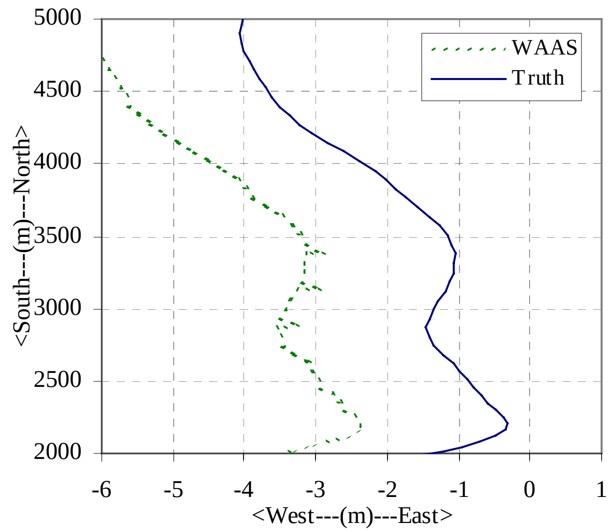


Figure G1D: WAAS versus Truth track.

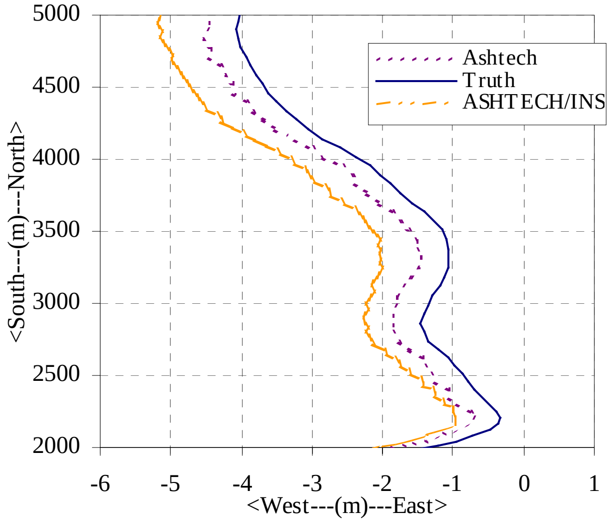


Figure G1E: Ashtech versus Truth track.

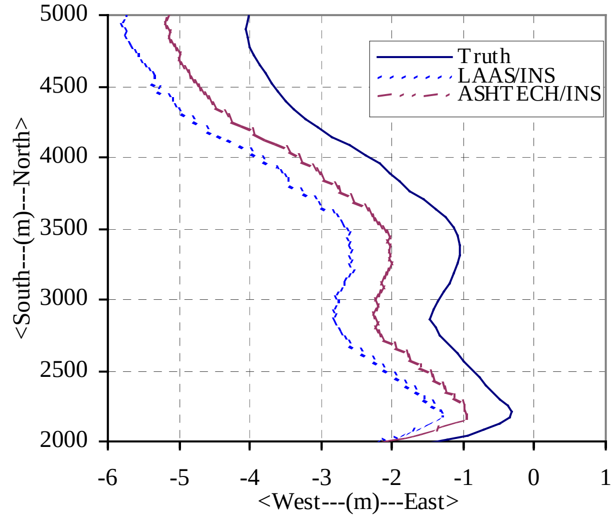


Figure G1F: Blended versus Truth track

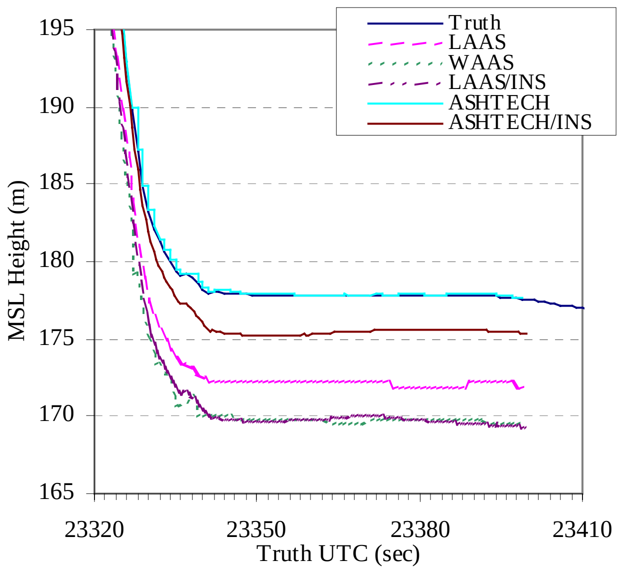


Figure G1G: MSL height comparison.

Flight 174 run R174_66

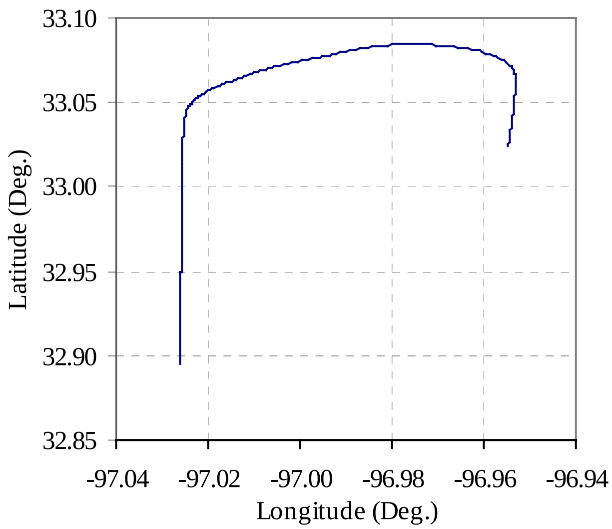


Figure G2A: Truth data for ground track.

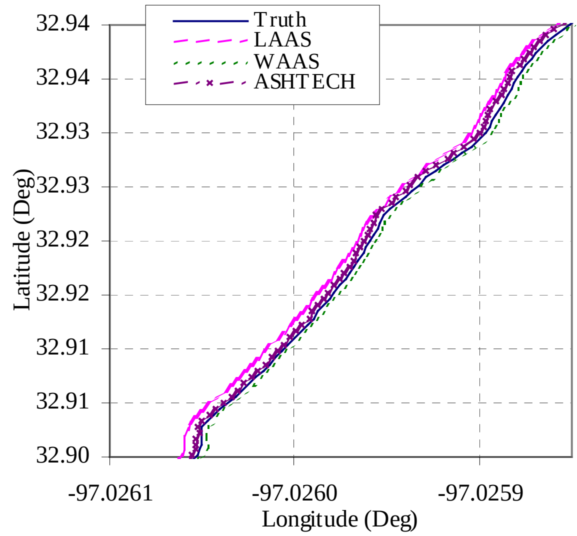


Figure G2B: Raw horizontal track of all systems.

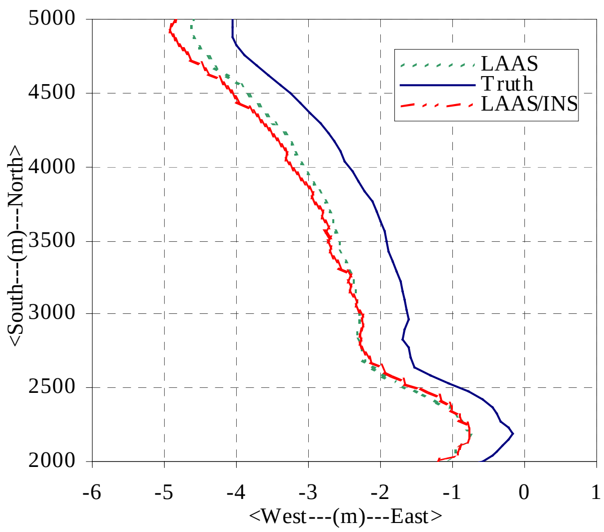


Figure G2C: LAAS versus Truth track.

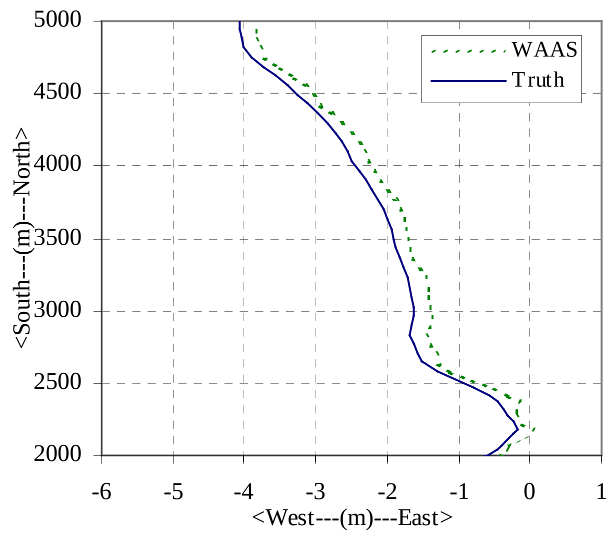


Figure G2D: WAAS versus Truth track.

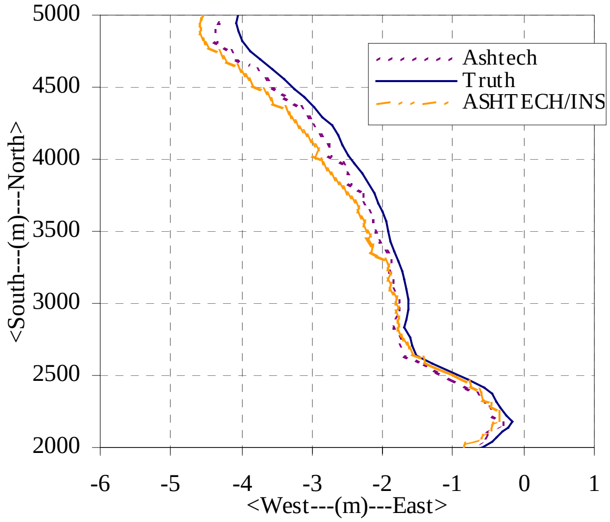


Figure G2E: Ashtech versus Truth track.

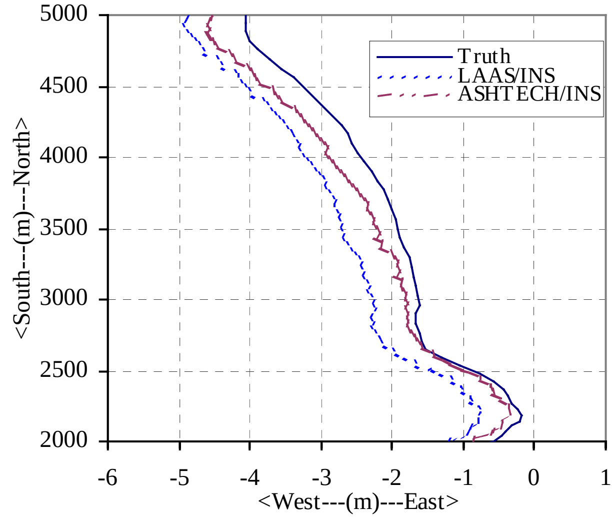


Figure G2F: Blended versus Truth track.

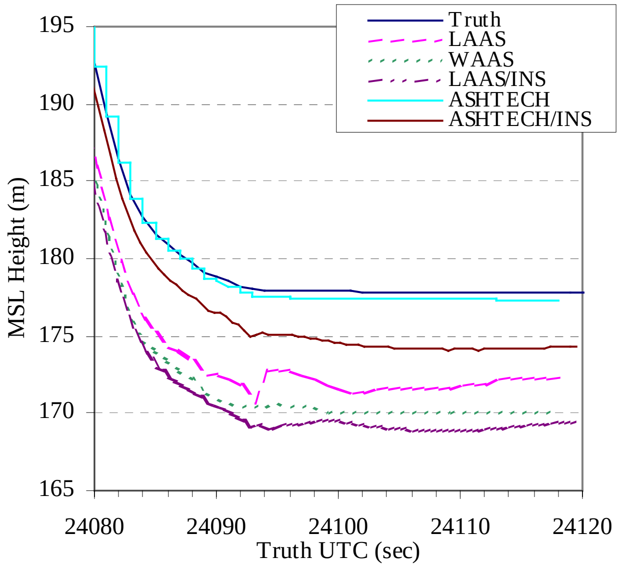


Figure G2G: MSL height comparison.

Appendix H: Profile 7 Ground Tracks.

Flight 170 run R170_07

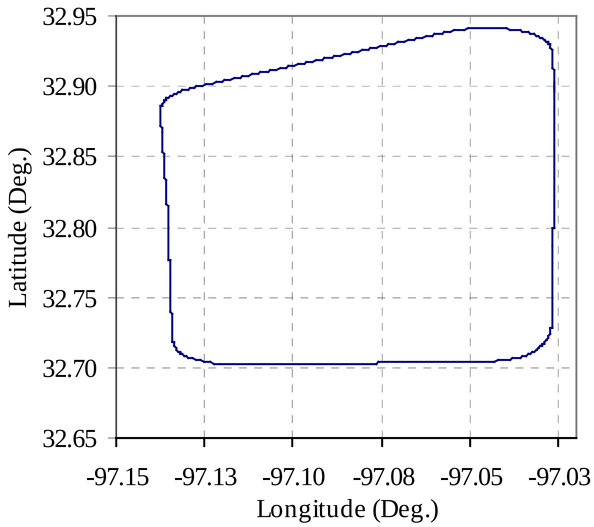


Figure H1A: Truth data for ground track.

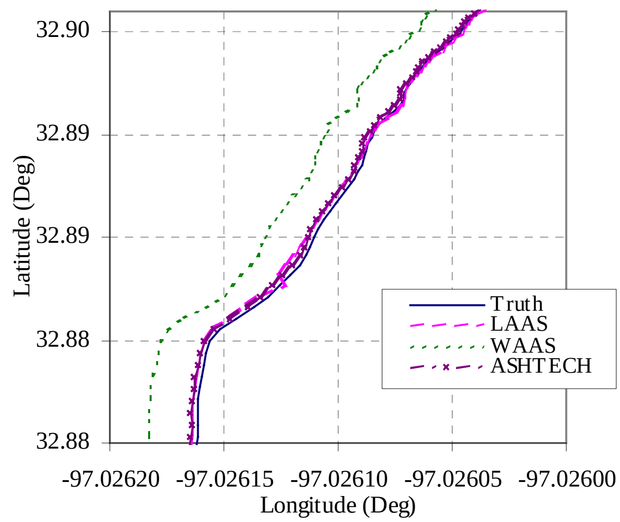


Figure H1B: Raw horizontal track of all systems.

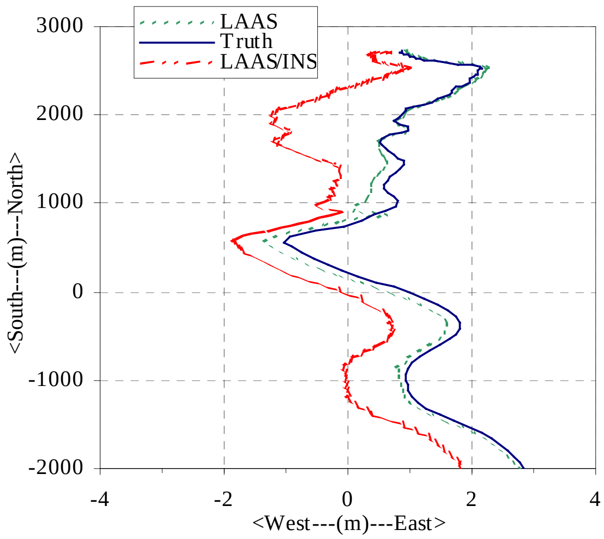


Figure H1C: LAAS versus Truth track.

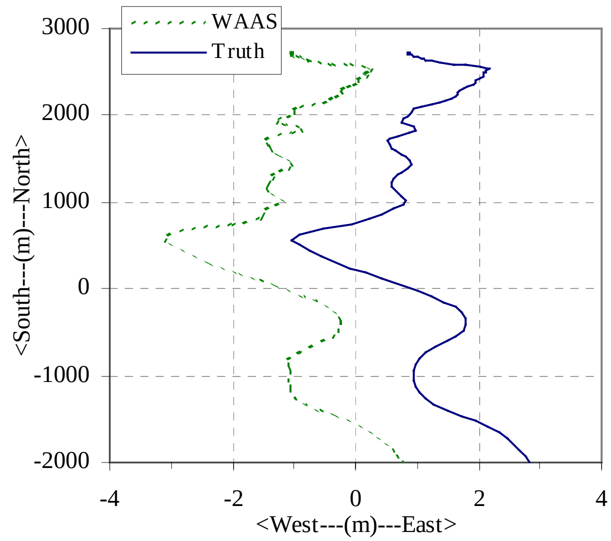


Figure H1D: WAAS versus Truth track.

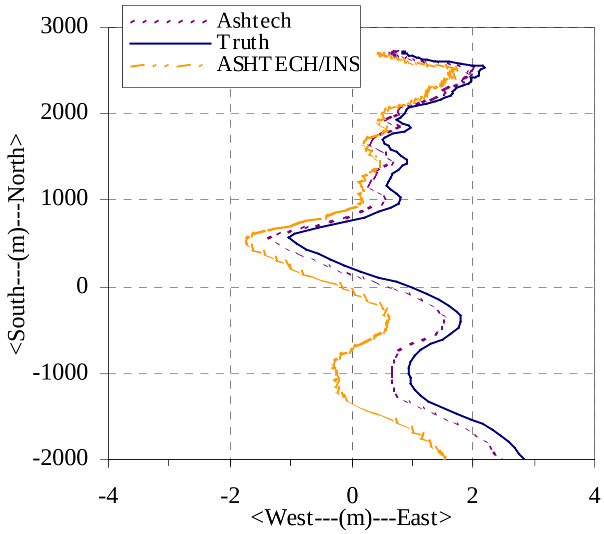


Figure H1E: Ashtech versus Truth track.

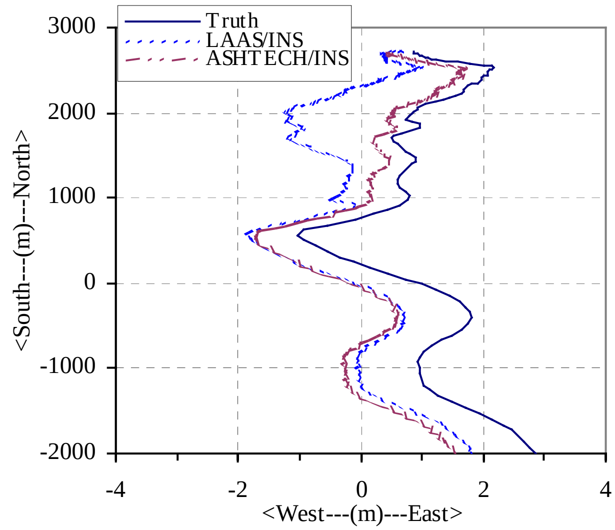


Figure H1F: Blended versus Truth track

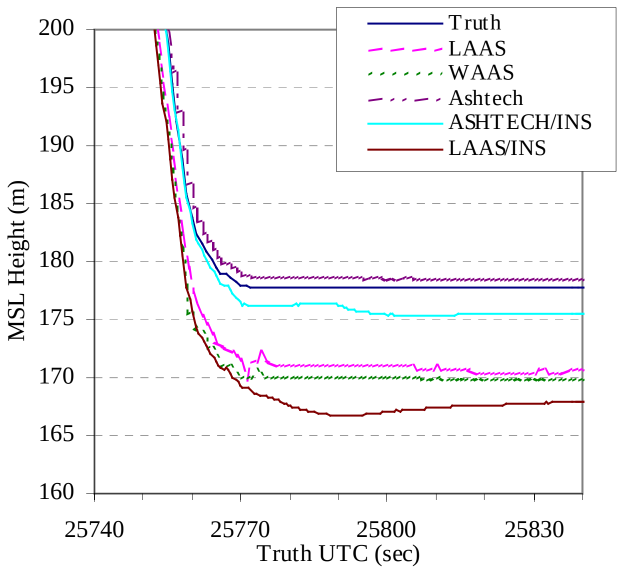


Figure H1G: MSL height comparison.

Flight 171 run R171_23

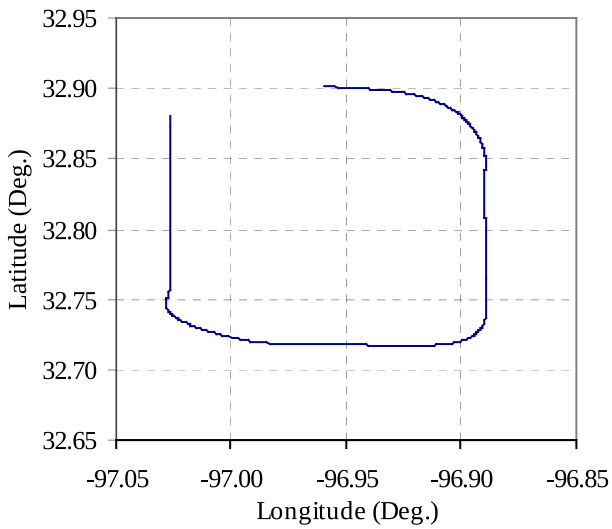


Figure H2A: Truth data for ground track.

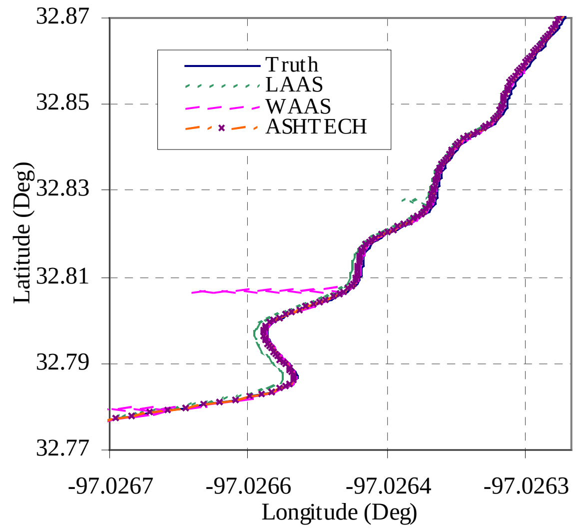


Figure H2B: Raw horizontal track of all systems.

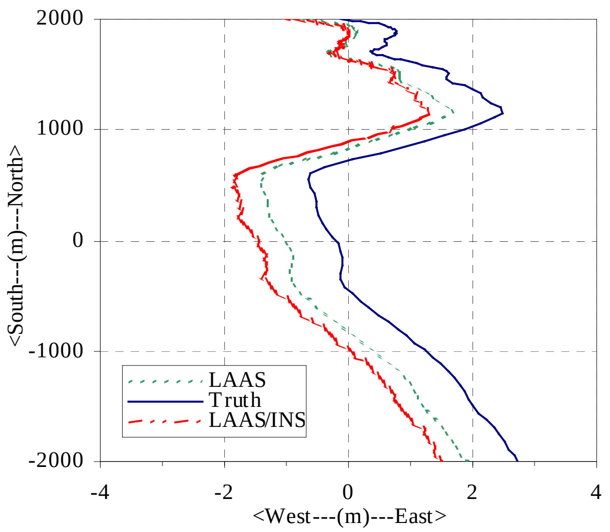


Figure H2C: LAAS versus Truth track.

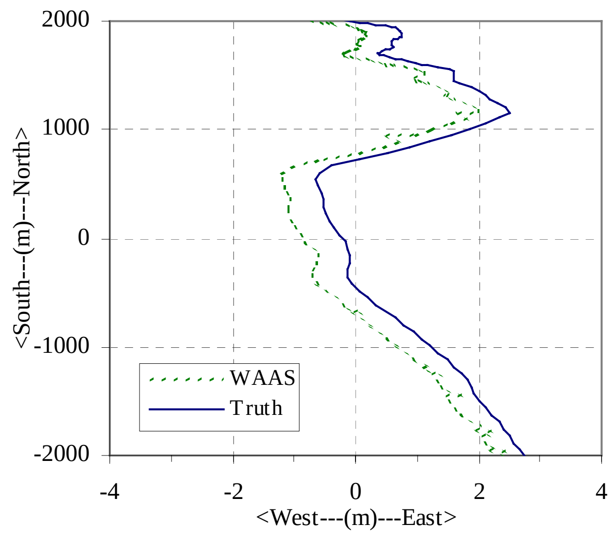


Figure H2D: WAAS versus Truth track.

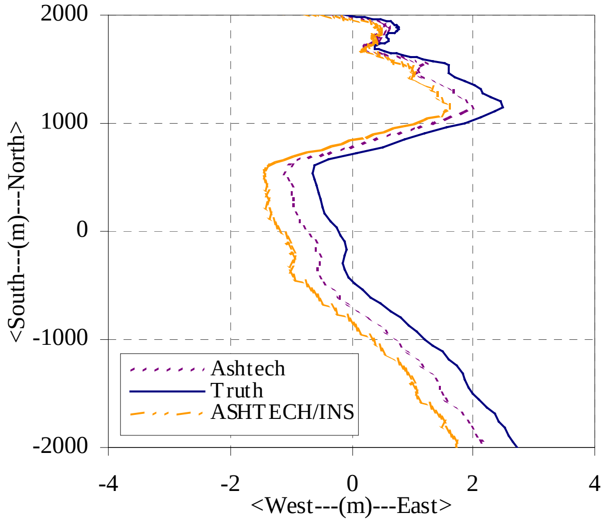


Figure H2E: Ashtech versus Truth track.

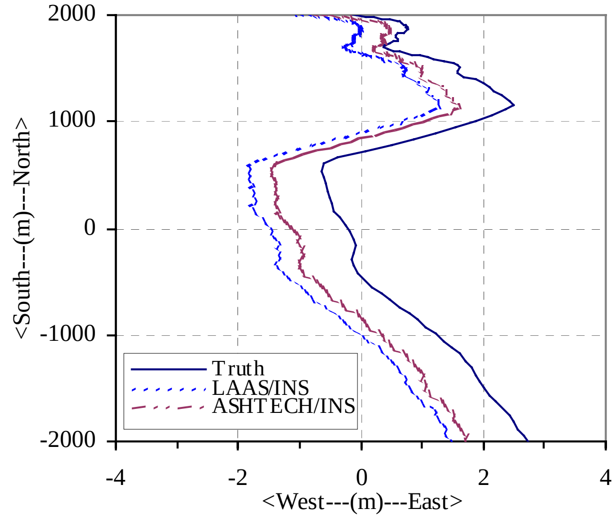


Figure H2F: Blended versus Truth track.

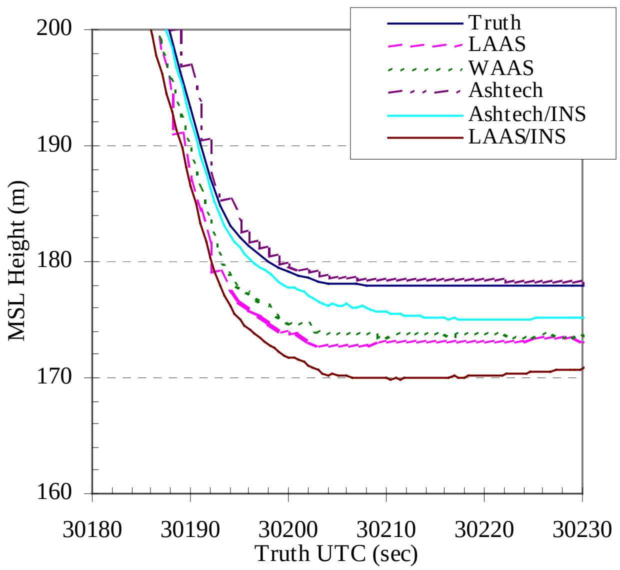


Figure H2G: MSL height comparison.

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14. ABSTRACT
NASA/Langley Research Center collaborated with the Federal Aviation Administration (FAA) to test a Runway Incursion Prevention System (RIPS) at the Dallas Fort Worth International Airport (DFW) in October 2000. The RIPS combines airborne and ground sensor data with various cockpit displays to improve pilots' awareness of traffic conditions on the airport surface. The systems tested at DFW involved surface radar and data systems that gather and send surface traffic information to a research aircraft out fitted with the RIPS software, cockpit displays, and data link transceivers. The data sent to the airborne systems contained identification and GPS location of traffic. This information was compared with the own-ship location from airborne GPS receivers to generate incursion alerts. A total of 93 test tracks were flown while operating RIPS. This report compares the accuracy of the airborne GPS systems that gave the own-ship position of the research aircraft for the 93 test tracks.

15. SUBJECT TERMS
Dallas-Ft. Worth RIPS Testing; GPS; LAAS; RIPS; Runway Incursions; WAAS

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