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Deployment and Evaluation of the Helicopter In-Flight Tracking System (HITS)

Final Report

Anastasios Daskalakis and Patrick Martone
U.S. Department of Transportation Volpe Center, Cambridge, Massachusetts

Sponsored by
Advanced Air Transportation Technologies Project
Ames Research Center, Moffett Field, California

December 2004

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1. Introduction

1.1 Rationale for Helicopter In-Flight Tracking System (HITS)

Figure 1-1 depicts the Gulf of Mexico region airspace, including existing radar coverage at 18,000 ft. Two distinct regions (and corresponding user groups) of Gulf airspace are of interest to this effort—high-altitude Oceanic Sectors and low-altitude Offshore Sectors. Oceanic Flight Information Regions (FIRs) are assigned to the U.S. by international agreements. They begin approximately 75 nmi south of the U.S. coastline, and extend southward to boundaries with FIRs assigned to Mexico and Cuba, 300–350 nmi from the U.S. coast. High-altitude Oceanic Sectors extend upward from Flight Level 180 (FL180) to Flight Level 600 (FL600). Large fixed-wing aircraft, including scheduled/chartered air carriers, are the predominant users.

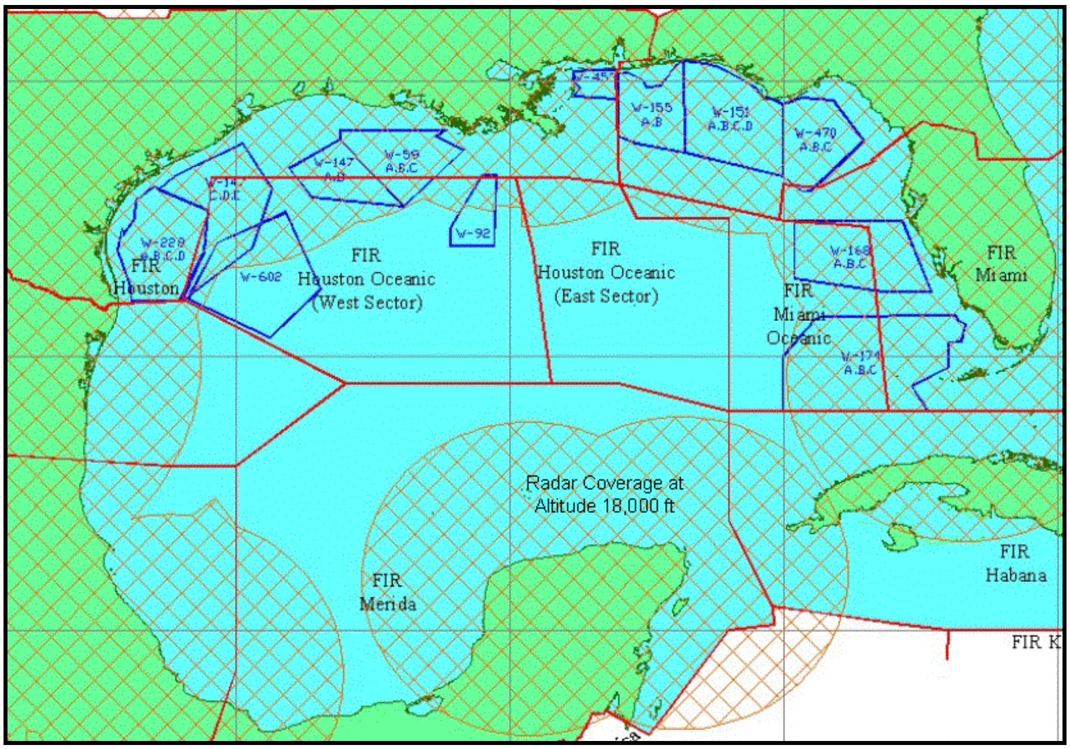

Figure 1-1 Gulf of Mexico Airspace.

In contrast, Offshore Sectors (not explicitly indicated in figure 1-1) lie within 100 nmi of the coast, and between 1500 and 7000 ft in altitude. Helicopters and small fixed-wing aircraft are the predominant users, with helicopters servicing petroleum platforms being an important component. The regions contiguous to these two are of less interest to this effort, because (1) airspace above the Offshore Sector is well-covered by radar, and (2) low-altitude Oceanic Sectors have little instrument flight rules (IFR) traffic.

Surveillance coverage of the two airspace regions of interest herein is limited, because of (a) the low-altitude nature of the Offshore Sectors, and (b) the remoteness of the Oceanic Sectors. Much of the Oceanic Sectors lies beyond the line of sight of shore-based radars. In effect, this airspace is "physically unreachable," because placement of radars on platforms is considered to be economically infeasible. Moreover, an unavoidable consequence of the spherical shape of the Earth is that coverage of low-altitude airspace requires a relatively large number of line-of-sight sensors—e.g., approximately 24 are needed to cover the Offshore Sectors at 2000 ft. Thus continuous radar surveillance of Gulf airspace, as is done throughout the National Airspace System (NAS), has not been achievable because of a combination of economic and physical factors.

The lack of continuous surveillance significantly restricts the capacity of both types of Gulf airspace of interest herein when IFR are in effect. Aircraft in the Offshore Sectors operate primarily, and satisfactorily, under visual flight rules (VFR). The Houston Air Route Traffic Control Center (Houston ARTCC, the cognizant air traffic control facility) does not provide traffic advisories to the VFR traffic. When conditions require IFR operations in the Offshore Sector, responsibility for aircraft-to-aircraft separation shifts from the aircraft to the Houston ARTCC, which must employ inefficient, nonradar procedures to ensure safe separations. An example is the "one-in, one-out" rule governing actual instrument approaches and departures to many airports/heliports lacking a radar: If an aircraft is executing an approach under IFR, then all other IFR aircraft are separated from that traffic, by being either held on the ground, or provided with appropriate lateral and vertical separation in the air, until the first aircraft has landed and informed air traffic control of that fact. In contrast, the high-altitude Oceanic Sectors operate under IFR at all times. Aircraft separation standards are time-based, but are equivalent to approximately 50 to 100 nmi—much greater than the 5-nmi standard for domestic airspace.

1.2 Objectives of the HITS Deployment and Evaluation

The FY01 National Aeronautics and Space Administration (NASA) budget included funds "for deployment of multilateration and Mode-S-based Automatic Dependent Surveillance-Broadcast sensors for the Helicopter In-Flight Tracking System" (ref. 1). The FY02 budget legislation included language directing that funding from the NASA budget be expended for additional HITS deployment (ref. 2).

Multilateration and automatic dependent surveillance – broadcast (ADS-B) are new technologies that appear to have the potential to provide surveillance performance at least equivalent to that for secondary[*] radar, without some of the latter's limitations such as relatively high cost and large size/weight ground equipment. However, both require that aircraft be transponder-equipped, and thus are not alternatives to primary radar[†]. The HITS deployment directed by the FY01 and FY02 legislation provided the opportunity to evaluate these new technologies in the Gulf environment. Moreover, the Federal Aviation Administration (FAA) requested that NASA conduct such an assessment. *Thus the objectives of this effort were to (1) deploy the HITS, and (2) conduct a technical and (to a lesser extent) operational evaluation of the capabilities of multilateration and ADS-B relative to those of secondary radar.*

1.3 Related Efforts

During the 1999–2003 period, the FAA Safe Flight 21 (SF-21) Integrated Product Team conducted tests of ADS-B capabilities for both air-to-air and air-to-ground applications at Wilmington, Ohio; Louisville, Kentucky; and Memphis, Tennessee. Additionally, in 1999, the FAA implemented an ADS-B ground network based on a different air-ground data link—the Universal Access Transceiver (UAT)—in southwestern Alaska.

Multilateration has been tested extensively for airport surface applications—e.g., NASA tests in Atlanta, Georgia (1996), and subsequent FAA tests at Dallas-Fort Worth, Texas; Memphis, and Louisville. Based on

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* A *secondary* (also called *beacon*) radar detects a target aircraft based on energy transmitted from the onboard transponder of the aircraft after being interrogated by the radar transmitter.

† A *primary* (also called *skin track*) radar detects a target based on the small fraction of the energy transmitted from the radar that is reflected by the target and received back at the radar site.

results of these tests, a multilateration subsystem was selected to form part of the Airport Surface Detection Equipment, Model X (ASDE-X) currently being deployed by the FAA at 25 medium-to-large airports.

Prior to the HITS effort, there was no U.S. experience with multilateration for surveillance of in-flight aircraft. This application is termed wide-area multilateration (WAM), to distinguish it from multilateration on the airport surface. After HITS initiation, the U.S. Navy installed a small experimental system at Patuxent River Naval Air Station, the FAA installed/tested WAM at Memphis in 2003, and Austrocontrol installed a system at the Innsbruck, Austria, airport.

1.4 Deployment Overview

The HITS effort was sponsored by the Advanced Air Transportation Technologies (AATT) Project at NASA Ames Research Center. The U.S. Department of Transportation (DOT) Volpe National Transportation Systems Center (Volpe Center) supported the AATT Project by managing HITS installation and operation, and assessing its effectiveness. Sensis Corporation (Sensis) was responsible for the design, installation, operation, and maintenance of the HITS ground infrastructure. At NASA's invitation, the FAA actively monitored deployment and evaluation activities, and contributed aircraft for flight tests.

The HITS deployment and evaluation (figure 1-2) comprised three phases (Ø).

- Phase I involved the deployment and testing of a WAM/ADS-B system in the offshore area immediately south of Intracoastal City, Louisiana. A 21-sensor array provided WAM coverage extending upward from approximately 100 ft above sea level (ASL) over a 7000-nmi^2 footprint, and upward from 1000 ft over 8725-nmi^2 footprint—a region 50-percent larger than the coverage area for an airport surveillance radar. The first WAM test in the U.S., this phase involved some product development/improvement by Sensis.

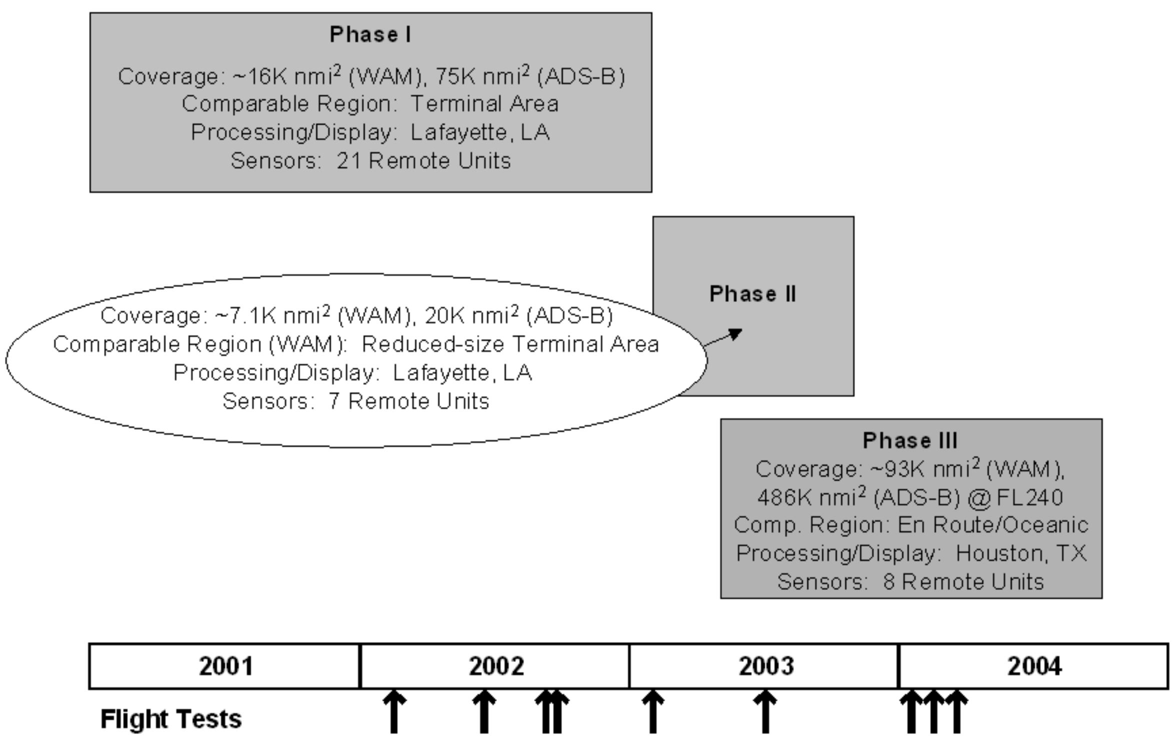


Figure 1-2 HITS Deployment and Evaluation Phases.

- Phase II constituted redeployment of a subset of the Phase I sensors around the high-intensity helicopter operating area at Intracoastal City. This phase evaluated the effectiveness of HITS WAM capability to provide surveillance services to a small airport that could benefit from them.
- Phase III shifted primary focus from offshore to oceanic airspace, and from WAM to ADS-B. This phase used a redesigned set of eight sensors that were deployed to provide ADS-B coverage of most of the U.S.-managed FIRs—a region comparable to several domestic en route sectors. A long-range WAM capability was also implemented in a smaller, sub-area of the Gulf. This was the first U.S. WAM system configured and tested for operation in en route-like or oceanic airspace—and likely the first anywhere.

The HITS ground infrastructure was a modified version of the FAA's ASDE-X subsystem that uses multilateration and ADS-B to track aircraft on the surface. ASDE-X and HITS multilateration use signals from all three types of currently deployed aircraft transponders—Air Traffic Control Radar Beacon System (ATCRBS), Mode S short squitter, and Mode S extended squitter.* Ground stations, termed remote units (RUs), measure the time of arrival (TOA) of the same transponder message at one or more locations. Aircraft horizontal position is determined by processing three or more TOA measurements at a central location. Only a single message needs to be received in an update interval for accurate position determination, because signal variability (noise) is sufficiently small that it is not necessary to average multiple measurements. Aircraft identify (Mode A code, and Mode S code when available) and barometric altitude (Mode C code) are determined from information in transponder messages.†

HITS ADS-B functionality requires signals from ADS-B Mode S extended squitter transponders that became available in this decade. When ADS-B signals are received at one or more ground sensor(s), HITS develops a target report by decoding the message, which contains aircraft identity, and position and velocity, derived from an onboard Global Positioning System (GPS) receiver. When an ADS-B message is received at three or more ground stations, a WAM target report is also generated.

1.5 Evaluation Overview

Evaluation of the HITS was based on extensive flight testing (table 1–1). Targets of opportunity (existing air traffic) were employed to address narrow objectives. The Phase I configuration was flight tested during five periods, enabling Sensis to identify and implement system improvements, and Volpe to determine ("score") HITS performance for most combinations of (i) tracking methodology (WAM or ADS-B), (ii) aircraft transponder type, and (iii) aircraft altitude regime. Tests were conducted for three altitude regimes: above 20,000 ft ("high"), approximately 10,000 ft ("medium"), and less than 7000 ft ("low").

The single Phase II test period was targeted at the low-altitude, ATCRBS transponder, WAM tracking performance of a reduced and relocated sensor matrix from Phase I. The three Phase III flight-test periods were restricted to high-altitude flights, but involved all possible combinations of tracking methodology and transponder type.

* ATCRBS (also called Mode A/C) transponders and interoperable radars were introduced in the 1950s; Mode S short squitter transponders and Mode S short and extended squitter radars were introduced in the 1980s; and Mode S extended squitter transponders and ADS-B ground equipment were introduced in the 2000s. See references 4, 5, and 8 through 11 for additional information.

† Conceptually, WAM can estimate aircraft altitude from four TOA measurements. However, the estimate has little usefulness for air traffic control purposes, because its accuracy is adequate only in very restricted locations.

Table 1-1 HITS Flight-Test Periods

Ø	Date	Purpose	Aircraft	HITS Status	Scored?
	Feb. ‘02	Checkout (low altitude)	Volpe Piper Aztec	Receiver hardware problem identified	✗
	June ‘02	Checkout (low altitude)	PHI[†] Bell 206	Array functioning but need for tuning found	✗
I	Sept. ‘02	Checkout (high altitude)	NASA Boeing 757	Needed fixes identified in WAM and ADS-B software	✗
	Sept. ‘02	WAM test (low altitude)	Volpe Piper Aztec, PHI Bell 206	Adequate for testing	✓
	Jan. ‘03	WAM and ADS-B test (high and medium altitude)	FAA Convair 580	Adequate for testing	✓
II	June ‘03	Helicopter Approach / Departure WAM test	Two PHI Bell 206s	Adequate for testing	✓
	Jan. ‘04	ADS-B checkout (high altitude)	FAA Boeing 727	Adequate for testing	✗
III	Feb. ‘04	ADS-B test and WAM Checkout (high altitude)	FAA Boeing 727	Adequate for testing	ADS-B ✓ WAM ✗
	Mar. ‘04	ADS-B and WAM test (high altitude)	NASA Gulfstream III, FAA Boeing 727	Adequate for testing	✓

[†] PHI: Petroleum Helicopters, Inc.

1.6 Document Organization

This document has seven chapters. Chapter 1 is introductory, providing the rationale for, and an overview description of, the HITS deployment and evaluation. Chapter 2 describes the HITS equipment that was deployed and tested for its capability to track aircraft using WAM and ADS-B technologies. Chapter 3 presents the evaluation methodology used to assess HITS performance relative to secondary surveillance radar (SSR) deployed in the NAS today. Chapters 4, 5, and 6 present results of instrumented flight tests for the three deployed configurations. Chapter 4 discusses testing of the Phase I configuration (designed to provide WAM coverage comparable to SSR coverage of a full-sized terminal area); Chapter 5 addresses testing of the Phase II configuration (designed to provide WAM coverage of a reduced-size terminal area); and Chapter 6 addresses testing of the Phase III configuration (designed to provide ADS-B coverage of a high-altitude en-route/oceanic region, and WAM coverage of a subset of that region). Chapter 7 provides a synopsis of HITS-related assumptions, goals, methodology, findings, and lessons learned.

Several appendices follow the body of this report. Appendix A elaborates on the evaluation criteria described in Chapter 3. Appendix B describes the Airborne Data-Collection System developed to provide a position reference (“truth” system) for evaluating HITS performance during some flights. Flight-test trajectories for “scored” test periods are depicted in appendix C (September 2002), appendix D (January 2003), appendix E (June 2003), appendix F (February 2004), and appendix G (March 2004).

2. HITS Technologies and Deployed Configurations

This chapter describes the Helicopter In-Flight Tracking System (HITS) surveillance technologies wide-area multilateration (WAM) and automatic dependent surveillance – broadcast (ADS-B). The ground equipment used to implement these technologies during the three phases of the HITS effort also are described.

2.1 Wide-Area Multilateration Technique

2.1.1 Multilateration Concept

During the HITS deployment and evaluation, a four-year time frame, WAM has moved from an untested concept to near-operational status at several locations. This progress is a result not just of the HITS team efforts, but also those of other organizations. The installation closest to operational control of civil air traffic is at Innsbruck, Austria, which is in preoperational testing. In the U.S., National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) have jointly funded a WAM system at St. Louis, Missouri. That system will be tested as a possible alternative to both secondary surveillance radar (SSR) and precision runway monitor (PRM) radar in the fall of 2004. The FAA is also installing a prototype/evaluation WAM system at Juneau, Alaska, that may later be upgraded to operational status.

SSR uses a mechanically rotating, directional, high-gain antenna to interrogate aircraft within its field of view, at ranges as far as 250 nmi, over 360 deg in azimuth (during a full scan period), and at altitudes from the radio horizon to approximately 100,000 ft above ground level. The directional interrogation of a radar (at 1030 MHz) elicits a response from an aircraft transponder (at 1090 MHz) that allows determination of the aircraft azimuth and slant range. Decoding transponder messages also provides the aircraft Mode A code assigned by air traffic control (referred to as the beacon code), Mode C code containing barometric altimeter information, and the Mode S identification code permanently assigned to the aircraft (for those aircraft equipped with a Mode S transponder).

Like SSR, multilateration (figure 2-1) uses aircraft transponder responses to determine aircraft position. Position determination is accomplished by processing the times of arrival (TOAs) of the same transponder reply when received at multiple, physically separated ground stations, termed remote units (RUs). The difference of any pair of TOAs defines a hyperbola that includes the aircraft position. If the aircraft is on the surface, or if its altitude is known, receipt of a message at three RUs (defining two hyperbolas) is sufficient to determine its horizontal position.[*] Similar to SSR, decoding of transponder messages provides the aircraft beacon code, altimeter code, and Mode S code (when included).

[*] A third hyperbola can be formed from three measurements, but does not provide new information. For example, assume that the measurements are TOA_1, TOA_2, and TOA_3, and that the differences used for computing aircraft position are $TOA_1 - TOA_2$ and $TOA_2 - TOA_3$. Then the difference $TOA_1 - TOA_3$ is the sum of the two differences that are used, and the equation for the associated hyperbola is given by the sum of the equations for the two hyperbolas that are used. This third hyperbola passes through the intersection of the first two.

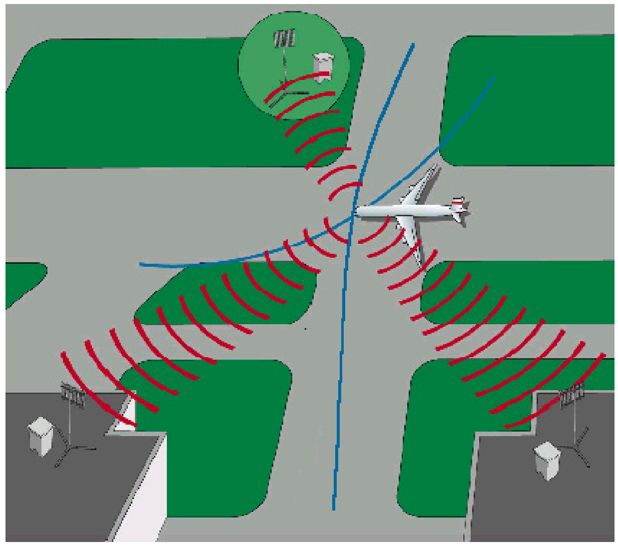


Figure 2-1 Multilateration Geometry on the Airport Surface.

2.1.2 RU Geometry and WAM Coverage

The major factors affecting coverage of a WAM system are: (1) detectability of a transponder signal received at an RU (and, similarly, the detectability of an interrogation signal received at an aircraft); and (2) the geometric relationship among the aircraft and multiple receiving RUs. WAM signal detectability is governed by the same elements that govern secondary radar and ADS-B signal detectability. These are: power of the transmitter, gains of the transmit/receive antennas, propagation loss along the path between the two antennas, cable/connector losses between the transmitter/receiver and their associated antennas, and signal blockage by the Earth (curvature and local terrain) and structures (including those on the airframe).

The geometric aspect of WAM coverage is significantly more complex than the distinction between radar range and azimuth axes, and is the major concern in selecting RU sites. For best WAM coverage, the RUs are generally sited so that:

- The footprint of the primary area under surveillance (i.e., where best performance is desired) lies within the polygon drawn through the perimeter ground stations, and
- Within the perimeter polygon, the RU sites are arranged to form a set of (approximately) equilateral triangles with common sides.

Figure 2-2 is a plan view of an idealized arrangement of seven RUs, with attention focused on the interior of the RU perimeter polygon. (Dimensions of the figure axes are distance units. However, axes labels are intentionally not displayed, because most WAM performance parameters depend only on the relative geometry of the aircraft and RUs rather than the spacing between RUs.) Because at least three RUs must be visible to an aircraft in order to derive a multilateration solution, when designing a WAM system, the common distance between adjacent RUs, termed a baseline, is chosen to be as large as possible while still ensuring coverage above each RU from the adjacent RUs for an aircraft at the minimum surveillance altitude. Thus, for figure 2-2, which was calculated for the minimum surveillance altitude, an aircraft in triangle RU0-RU1-RU2 can be seen only by those three RUs. At higher altitudes, an aircraft would be visible to more RUs.

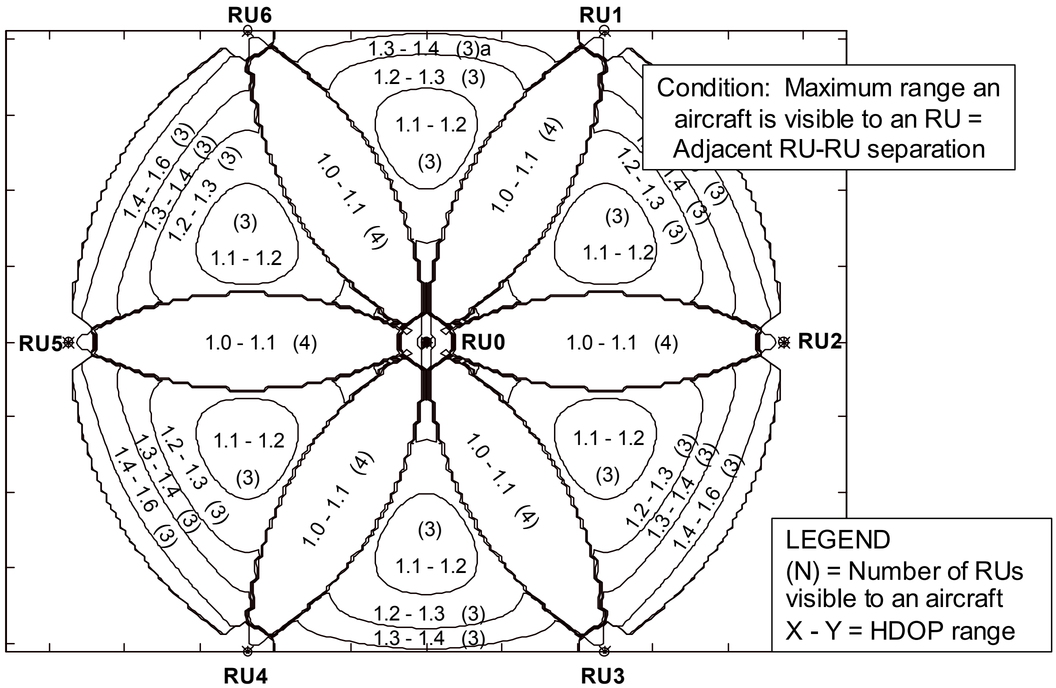


Figure 2-2 Ideal WAM Configuration with Seven RUs (Aircraft at Minimum Altitude).

Two parameters indicative of the WAM system coverage quality are shown in figure 2-2. The number of visible RUs at a possible aircraft location is shown in parentheses. This number must be at least three; when it is larger, there is some redundancy and an RU outage could be tolerated while still providing surveillance for that particular area. Horizontal dilution of precision (HDOP), also shown, is a more refined measure of the quality of the aircraft-RU geometry. In estimating the accuracy of a WAM system, HDOP acts like an amplification factor on the TOA measurement error according to the equation

RMS Horizontal Position Error = HDOP x (RMS TOA Measurement Error) **(Eq. 2-1)**

Equation 2-1 describes the statistical behavior of the WAM horizontal position error in one location, as a function of the statistical nature of the TOA measurement errors. The underlying assumptions are that (a) the RU TOA errors are independent but are statistically identical, and (b) other error sources (in particular, altimetry errors and multipath corruption of the TOA measurements) are negligible. Clearly, smaller HDOP values are better. However, by its very nature, HDOP is almost always greater than one—values less than one are indicative of significant redundancy in measurements.

For Phases I and II, the TOA measurement error was approximately 5 ft rms, primarily because of the RU clock resolution of 10 nsec. Thus, if equation 2-1 properly describes HITS WAM behavior, position errors on the order of 7.5 ft rms (or 15 ft 95 percent) would be expected in the primary coverage region. In fact, the typical errors for the FAA’s Airport Surface Detection Equipment, Model X (ASDE-X) surface multilateration system are 10 to 20 ft.

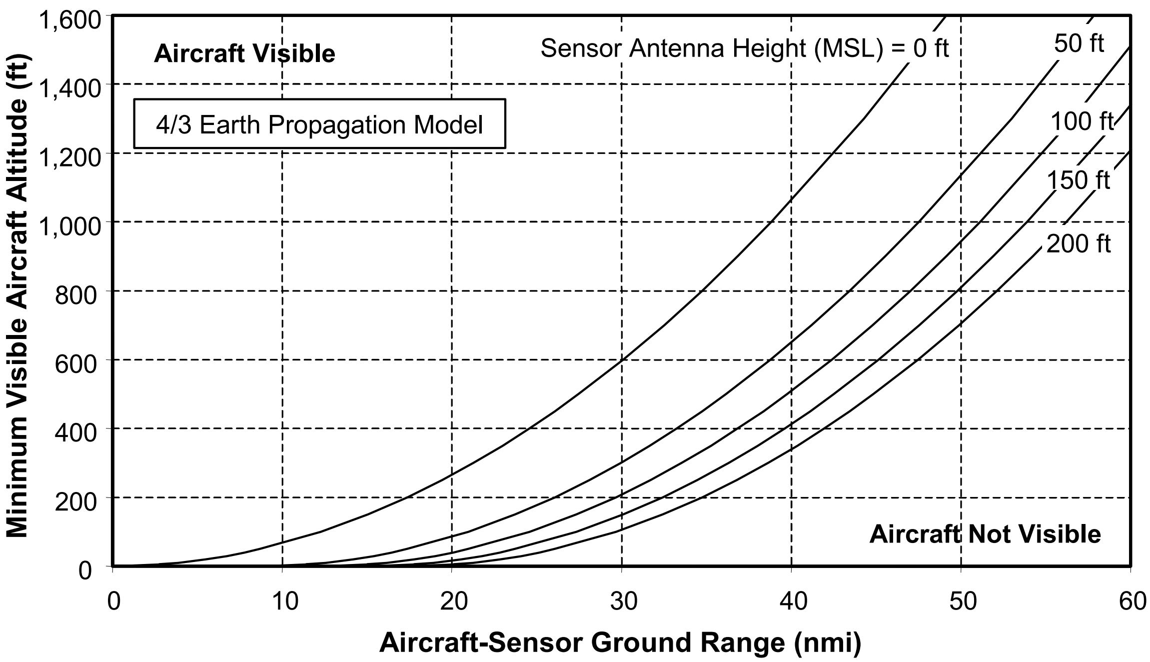
There is no accepted rule as to what constitutes a good HDOP. This document uses two thresholds:

- HDOPs up to 1.5 are desired in the inner or primary coverage area (within the perimeter polygon), the same goal as the ASDE-X multilateration system; and

- HDOPs up to 4 are desired in the outer or extended coverage area (outside the perimeter polygon), the same goal that many Global Positioning System (GPS) analyses use.

Figure 2-2 shows that, within the perimeter of the RUs, HDOPs of 1.5 or less are readily attained, even at the minimum coverage altitude. For the minimum coverage altitude, WAM is unusable outside the perimeter polygon at the minimum altitude, because a maximum of only two stations are visible.* The small HDOP circles around each RU reflect the loss of coverage from that sensor due to a "cone of silence" directly above its antenna. As altitude is increased, the effect of the cone of silence is mitigated by coverage from nonadjacent stations.

Figure 2-3 is a plot of the minimum altitude at which an aircraft is visible by a ground sensor, as a function of the ground range between the sensor and the aircraft, when line-of-sight propagation prevails (as is the case for 1030 and 1090 MHz).† The curves apply equally to multilateration RUs and radar sites. For future reference, for the Phase I/II deployments, RUs were placed 20 to 25 nmi apart, a setup that—with sensor antenna heights of 150 to 200 ft—was predicted to provide coverage down to helidecks at 100 ft above mean sea level (MSL). For the Phase III deployment, with a minimum coverage altitude of 24,000 ft, the preferred RU separation was 200 nmi.



(a) Terminal Area Distances

Figure 2-3 Minimum Visible Aircraft Altitude vs. Aircraft-Sensor Range.

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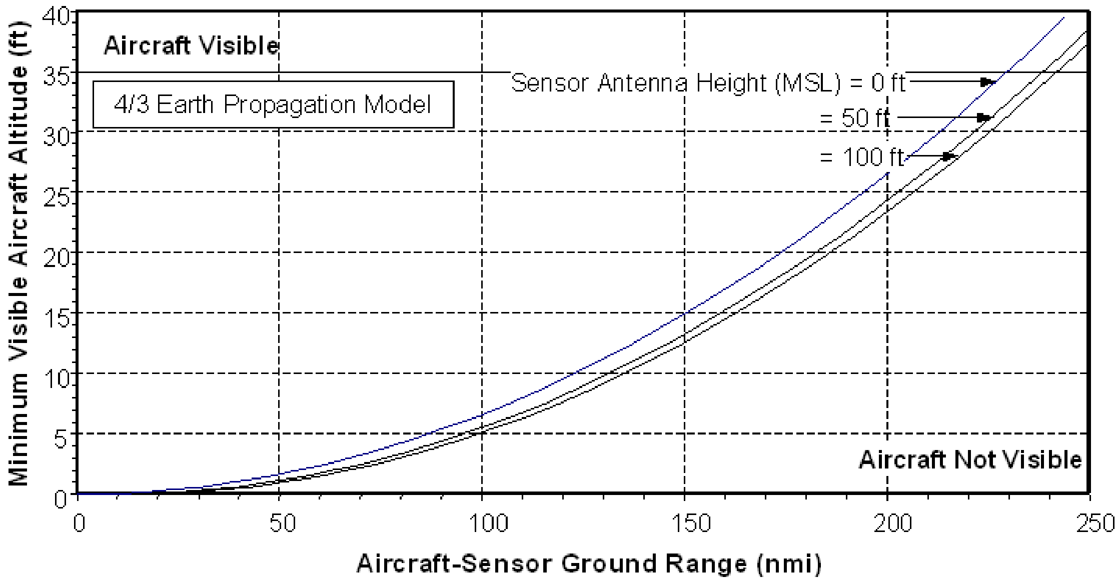
* Actually, WAM is unavailable outside the circle centered on RU0 with radius equal to the adjacent-RU-RU spacing. The small bulge of the "good HDOP region" beyond the polygon connecting the perimeter RUs is characteristic of multilateration. For simplicity, this small area is neglected in the descriptions herein, but is included in calculations and diagrams.

† Figure 2-3 is actually based on a "4/3-Earth model," which assumes that radiated signals follow a geometric straight line with respect to an Earth that is 1/3 larger than actual size. In this way, the model accounts for refraction of signals as the atmospheric density decreases with height (the signals bend slightly toward the surface). Results presented in Section 6.2 indicate that the 4/3-Earth model is a good predictor of the maximum ground range at which an aircraft is visible to an RU.



(b) En Route/Oceanic Distances

Figure 2-3 Concluded.

When an aircraft is not within the perimeter of the RU array, then the rule that “three visible RUs provide a good position measurement” does not apply. However, if the aircraft is high enough that it is visible to four or more RUs, then accurate position determination can be achieved for aircraft external to the array perimeter (i.e., in the extended-coverage region). Figure 2-4, involving five RUs, is an example. For this calculation, it was assumed that the aircraft altitude was sufficient for it to “see” RUs at distances up to twice the spacing between adjacent RUs. Within the perimeter polygon, HDOP is slightly improved by having five RUs visible (rather than three or four, as in figure 2-2). The effect of the antenna “cone of silence” is reduced, and the HDOP goal of 1.5 maximum is satisfied throughout the polygon interior.

External to the RU array perimeter, HDOP is dramatically better in figure 2-4 than it is in figure 2-2. Two conclusions can be drawn from figure 2-4. First, the best external HDOP geometry is adjacent to an array side having three or more RUs in a line (e.g., “below” RU2 in the figure). In such an area, HDOPs less than four can occur out to a distance at least equal to the RU-RU baseline. Second, the worst external HDOP geometry occurs in a wedge-shaped region that is “opposite” an acute-angle corner formed by the RUs (e.g., “below and to the left” of RU1 in the figure). In such a wedge, WAM is unusable.

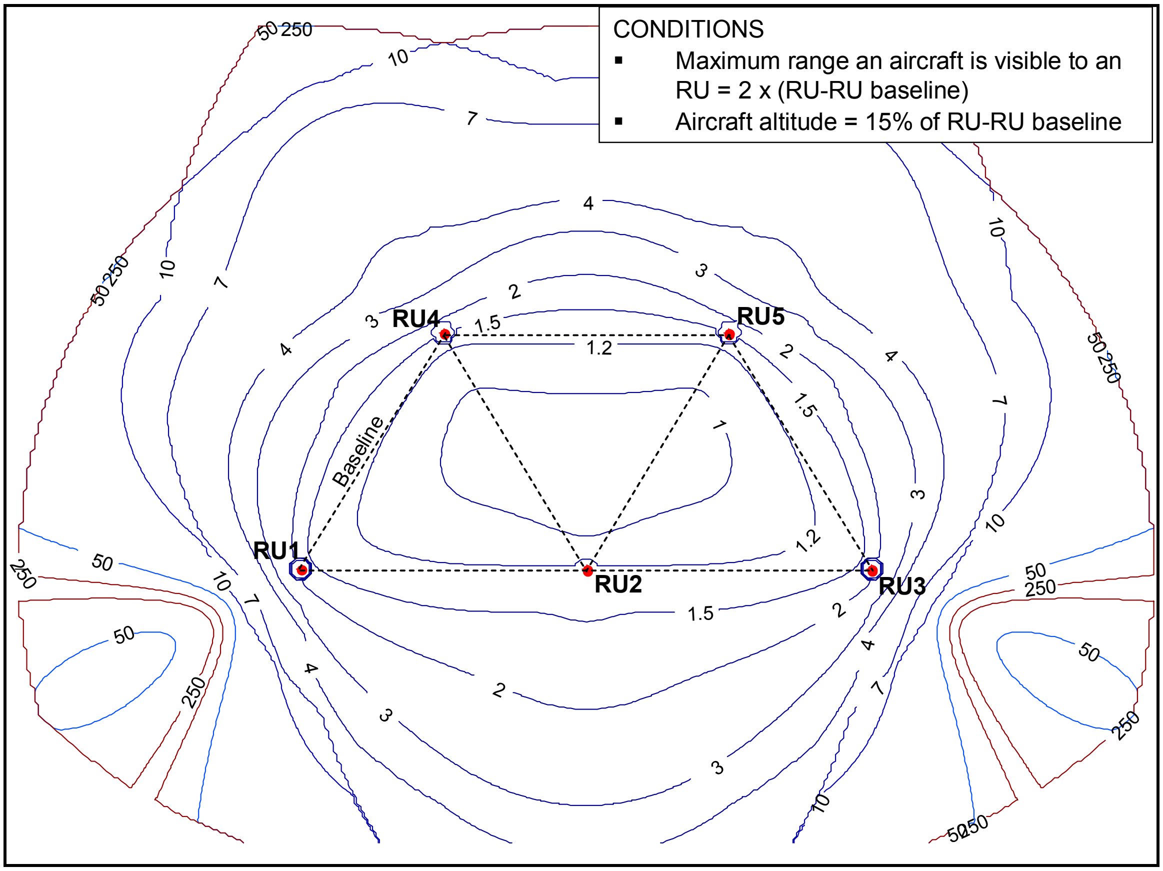


Figure 2-4 WAM HDOPs for 5 RUs (Aircraft Higher than Minimum Coverage Altitude).

2.1.3 Effect of Aircraft Altitude

Multilateration aircraft surveillance began on the airport surface, where the measurement geometry—RUs are in (essentially) the same plane as the aircraft targets—is ideally suited to the technology. In effect, the region containing the sensors and targets can be treated as two-dimensional. However, for surveillance of in-flight aircraft, the vertical dimension must be explicitly accounted for. This can be done in three ways, which are summarized in this subsection.

Two-Dimensional Multilateration with Assumed Perfect Altimetry—The simplest way to extend multilateration to three dimensions is to use the barometric altimeter as an assumed error-free measurement of aircraft height above the system horizontal reference surface.* This is essentially the same approach taken in SSR processing when applying the "slant range correction" to compute the aircraft ground range. An advantage of this approach is that the two-dimensional multilateration processing techniques/software used on the airport surface can be employed with only slight modification. A second important advantage is that it does not require deployment of additional RUs to accommodate the vertical dimension. Use of assumed-error-free barometric information is the approach followed during HITS.

* The reference surface is either (a) a horizontal plane, tangent to the Earth's surface at a location approximately in the center of the coverage area (suitable approach for a small terminal area), or (b) a spherical model for the Earth (suitable model for en route/oceanic domains).

A disadvantage of treating barometric-altimeter information as perfect is that, in fact, barometric altitude is not the quantity sought for multilateration calculations. Instead, it is the aircraft geometric height above the reference surface that is needed. The conversion from measured barometric pressure to indicated altitude is based upon a “standard-day” model of the atmosphere. Deviations of the actual atmosphere from the standard-day model can lead to geometric-barometric altitude differences of 1000 to 2000 ft for aircraft altitudes above 20,000 ft. In general, altimetry errors couple into WAM horizontal position errors according to the equation

$$\textbf{Horizontal Position Error = AECCF x Altimetry Error} \qquad \textbf{(Eq. 2-2)}$$

In equation 2-2, AECCF stands for altimetry error cross-coupling factor.

Figure 2-5 illustrates AECCF values involving an RU array comprising an equilateral triangle and seven hypothetical aircraft locations along an angle bisector (shaded insert in figure). In this figure, the independent variable, aircraft altitude relative to the length of a baseline separating the RUs, is plotted vertically. During HITS testing, aircraft altitudes ranged from a low of 1 percent to 3 percent of an RU baseline (for low-altitude helicopter flights) to approximately 20 percent of a baseline (for high-altitude tests during Phase I).

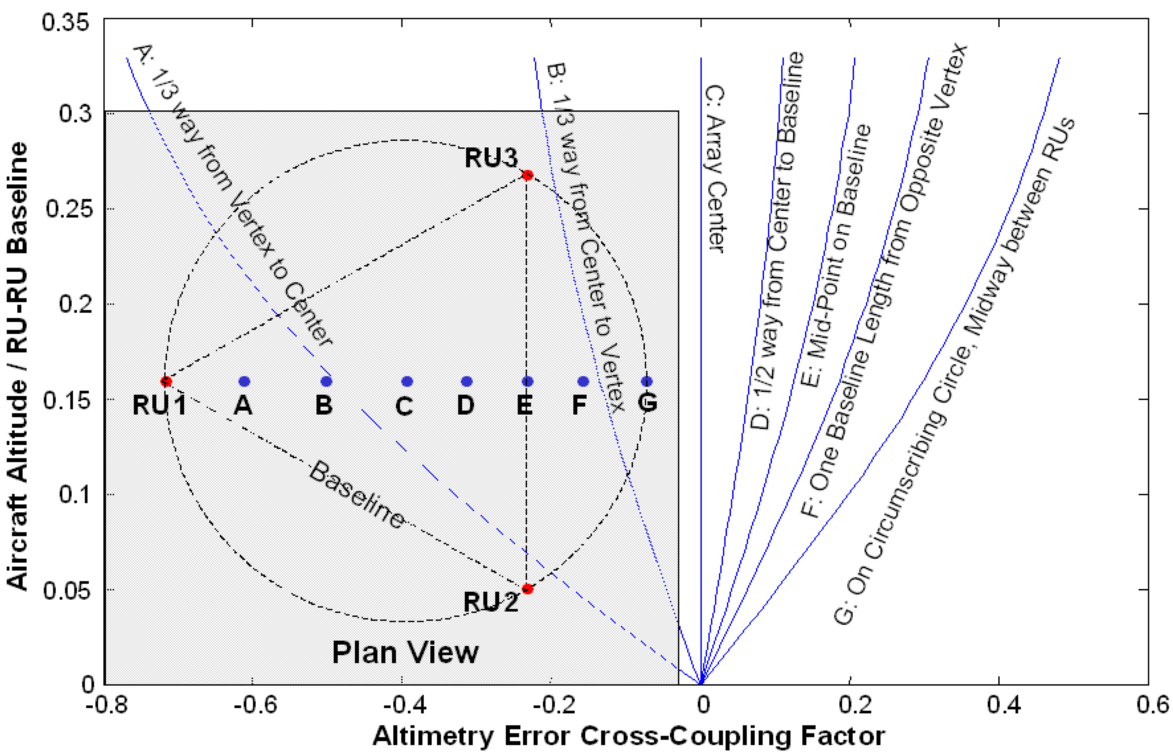


Figure 2-5 Example of Altimetry Error Cross-Coupling Factor.

The figure[*] shows that when the aircraft altitude is zero (i.e., aircraft is in the same plane as the RU array), altitude errors have no effect on WAM horizontal-position determination, regardless of the horizontal location of the aircraft with respect to the array. This is a mathematical confirmation of the earlier statement that the airport surface is the ideal multilateration application when the RUs are essentially co-planar. Also, when the aircraft is at the center of the array (location C), the AECCF is zero for all altitudes. Physically, this occurs because transponder messages generated directly above the array center are received at the three RUs simultaneously, independent of aircraft altitude. Thus, altimetry errors do not affect the computed horizontal position.

For locations other than the array center, the AECCF increases with altitude, starting from zero at the surface. In fact, the AECCF varies as the sine of aircraft altitude divided by the horizontal distance between the aircraft and the nearest RU—i.e., the sine of the elevation angle of the aircraft, in radians, as seen from the RU. The farther the hypothetical aircraft horizontal position is displaced from the array center (i.e., the closer it is to an RU), the more rapid the growth rate of AECCF with respect to altitude. Similarly, displacements in the direction of a vertex cause more rapid AECCF growth than displacements in the direction of a baseline.

Although the example in figure 2-5 is useful for demonstrating the full range of AECCF behavior, judgment must be exercised in interpreting these curves in terms of the deployed HITS arrays. This example has no measurement redundancy, whereas Phase I (see Subsection 2.3.2) involved significant redundancy, Phase II (Subsection 2.3.3) had some redundancy, and Phase III (Subsection 2.3.4) had none. With redundant measurements, the highest sensitivities (curves labeled A and G) do not occur, and, for planning purposes, the AECCF can be approximated as having unity slope:

AECCF ≈ Aircraft Altitude / RU-RU Baseline (for "good geometry") **(Eq. 2-3)**

Thus, for an altitude of 10 percent of the RU-RU baseline (e.g., 24,000 ft for an array with 20-nmi baselines, as in Phase I), AECCF values of 0.10 can readily occur. An altimetry error of 1000 ft, would result in 100 ft of WAM horizontal-position error. Without measurement redundancy, altitude-induced horizontal-position errors of two or three times this magnitude can occur near RUs.

Three-Dimensional Multilateration—When four or more TOAs for an aircraft are available, then (at least conceptually) the three-dimensional position of the aircraft can be calculated without using altimeter information. However, for altitudes that are a few percent of the RU-RU baseline, accuracy of the calculated vertical component is generally poor except in small regions close to the RUs. This behavior is fundamental to the WAM technique, and not due to equipment limitations. The standard metric used to quantify vertical performance of an array is its vertical dilution of precision (VDOP).[†] At altitudes of 1 or 2 percent of an RU-RU baseline, VDOPs over 100 are frequent. For HITS, these imply vertical errors on the order of 1000 ft (95 percent), whereas barometric-altimeter information (corrected for surface pressure) is accurate to less than 100 ft at such low altitudes.

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[*] Significance of negative AECCF values: For aircraft locations along the angle bisector, altimetry errors cause computed horizontal positions that are also along the bisector. Assuming that the barometric-indicated altitude is higher than the geometric altitude, then the computed aircraft position will be farther from the array center than the actual position. For locations A and B, the computed positions will be "to the left" of (closer to RU1 than) the actual positions; for locations D, E, F, and G, the computed positions will be "to the right" of the actual positions.

[†] WAM vertical performance can also be inferred from figure 2-5. The AECCF is small at low altitudes because, in that regime, altitude changes have little effect on the TOA differences that are used to compute horizontal position. However, TOA differences that are insensitive to altitude are not useful in computing vertical position.

As aircraft altitude is increased, altitude determination from TOA measurements becomes a possibility. For example, figure 2-6 shows VDOP contours for aircraft altitude equal to 15 percent of the RU-RU baseline (the assumed RU array and other conditions are similar to those for figure 2-4). In the figure, VDOPs of 10 to 20 prevail throughout most of the region with favorable HDOPs. If the TOA measurement error is equivalent to 10 ft (95 percent), these VDOPs imply vertical-position determination errors of 100 to 200 ft (95 percent)—much better than approximately 1000 ft of error expected with barometric altimetry. However, the fact that three-dimensional multilateration cannot be used for low-altitude aircraft makes it less useful overall than employing the aircraft-reported barometric altitude as an error-free measurement. Thus, although HITS equipment implemented both capabilities, during testing barometric-altimeter data were used for altitude determination.

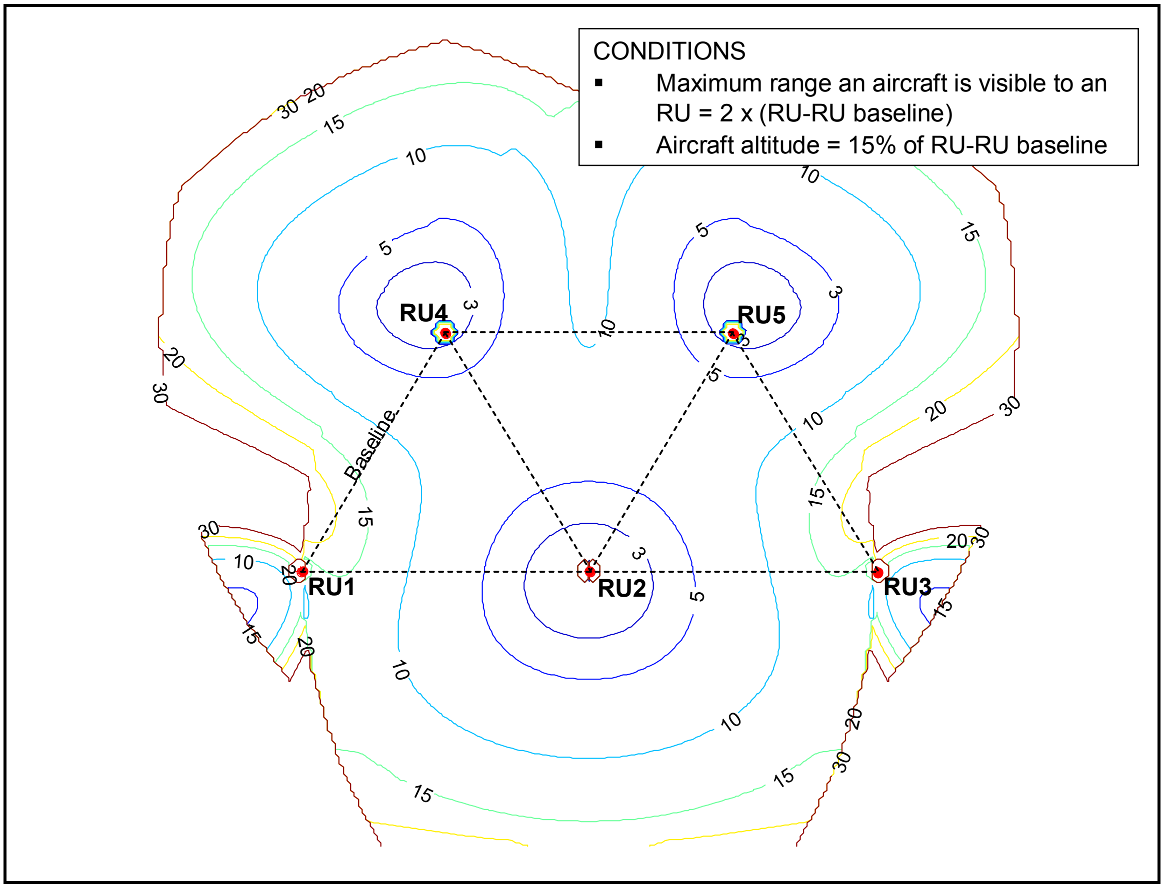

Figure 2-6 WAM VDOPs for Five RUs (Aircraft Higher than Minimum Coverage Altitude).

Three-Dimensional Multilateration Combined with Barometric-Altimeter Data—A third method of determining aircraft altitude (not included in the HITS equipment) is to use both TOA measurements and barometric-altimeter data. The error statistics for both data types can be accounted for in a processing algorithm that, in effect, blends the two types of altitude information based on their relative accuracies. Such an algorithm would be more effective if it also included a tracking capability—i.e., capability to combine current measurements with previous measurements. This would enable use of TOAs to accurately determine geometric altitude when VDOP is low, followed by use of barometric data to determine altitude changes when the aircraft is in a region of poor VDOP.

2.1.4 Summary of Expected Accuracy

For HITS WAM, the major sources of horizontal-position error were expected to be (1) "normal" TOA measurement errors, amplified by HDOP; (2) barometric-altimetry errors (deviations from geometric altitude), amplified by AECCF; and (3) multipath effects on TOA measurements. "Normal" TOA errors are due to the resolution of the RU clocks (10 nsec, equivalent to 10 ft) and measurement jitter due to detecting transponder messages in the presence of noise, particularly at the edge of the array coverage region. Normal TOA errors are assumed to be independent but statistically similar at all RUs. Both normal TOA errors and altimetry errors are assumed to be stationary (i.e., have the same statistical distribution) over substantial portions of a flight. Multipath errors are different from the other two in that they are not stationary and not statistically consistent across RUs.

For an ensemble of measurements, the combined effect of normal TOA and altimetry errors has the form

$$\textbf{RMS Horizontal Position Error} = \{ [\, \text{HDOP} \times (\text{RMS TOA Error}) \,]^2 + [\, \text{AECCF} \times \text{RMS Altimetry Error} \,]^2 \}^{1/2} \qquad \text{(Eq. 2-4)}$$

That is, the squares of the RMS normal TOA and altimetry errors add, because the error sources are independent. When transitioning from the surface to an altitude of one-third the separation between RUs, HDOP generally begins at values between one and four and increases slowly, whereas AECCF begins at zero approximately linearly (see eq. 2-3).

2.1.5 Interrogation and Reply Issues

HITS RUs were configured to receive/decode messages from the three types of transponders in use by civil aviation (table 2-1):

Table 2-1 Transponder Messages Decoded/Used by HITS

Mode/Format	Primary Information	How Obtained?
ATCRBS Transponder (12 bits)		
Mode A	Beacon code	Elicited by HITS
Mode C	Barometric altitude	Elicited by HITS
Mode S "Short Squitter" Transponder* (56 bits)		
DF04	Barometric alt. code & Mode S ID	Elicited by HITS and SSRs
DF05	Beacon code & Mode S ID	Elicited by HITS and SSRs
DF11	Mode S ID (24 bit)	Squittered (unelicited)
Mode S "Long Squitter" (ADS-B) Transponder† (112 bits)		
DF17, Types 9–18	Lat/lon, baro. alt., Mode S ID	Squittered (unelicited)
DF17, Types 20–22	Lat/lon, GPS alt., Mode S ID	Squittered (unelicited)
DF17, Type 19	Velocity, Mode S ID	Squittered (unelicited)

* Also emits Air Traffic Control Radar Beacon System (ATCRBS) messages in response to appropriate interrogations.

† Also emits ATCRBS and 56-bit Mode S messages in response to appropriate interrogations.

The HITS Target Processor (TP) computed multilateration solutions and generated target reports for each of these transponder message types. However, the WAM target reports did not always contain the full set of data present in a radar target report.

An SSR target report contains four data items (table 2-2) describing the aircraft involved—specifically its: (a) slant range, (b) azimuth angle from North, (c) Mode A (12-bit “beacon”) code, and (d) Mode C (12-bit barometric altitude) code. The latitude/longitude information provided by WAM (and ADS-B) is functionally equivalent to the range/azimuth information provided by an SSR, and was always present in a WAM target report. However, beacon and altitude code information may or may not have been present. This subsection addresses the topic of incomplete target reports and others related to the HITS interrogation and reply processing.

Table 2-2 Surveillance System Target Report Data Items

Surv. System / Data Item	SSR	WAM with Transponder	
		ATCRBS	Mode S Short
Horizontal position (two data items)	Always	Always	Always
Beacon (‘Mode A’) code	Almost[*] always	Always	Sometimes[‡]
Barometric-altitude (‘Mode C’) code	Almost[*] always	Sometimes[†]	Sometimes[#]
Report complete?	Almost always	Sometimes	Sometimes

[*] For the worst-case combination of an ATCRBS radar and transponder, the fraction of SSR target reports lacking an altitude code is estimated to be less than 3 in 100; the fraction of reports lacking a beacon code is estimated to be less than 1 in 1000.

[†] For ATCRBS aircraft, doublet interrogations, intended to elicit beacon and altitude codes, are used; a target report is formed when a beacon code is detected, regardless of the barometric code-detection result.

[‡] For Mode S aircraft, beacon code is contained only in a DF05 response elicited by a UF05 interrogation; beacon code is not present in a DF11 Traffic Alert and Collision Avoidance System (TCAS) squitter or DF04 altitude response.

[#] For Mode S aircraft, barometric-altitude code is contained only in a DF04 in response elicited by a UF04 interrogation; altitude code is not present in a DF11 TCAS squitter or DF05 beacon-code response.

ATCRBS Transponder TP Messages—Because ATCRBS transponders do not broadcast unelicited messages, HITS had to interrogate them to obtain both Mode A and Mode C information. Latitude and longitude values were obtained by processing the TOAs of Mode A replies, whereas altitude information was obtained simply by decoding Mode C replies. For ATCRBS aircraft, the practice was to employ a series of interrogation “doublets”—a Mode A interrogation followed, a short (milliseconds) well-controlled time later, by a Mode C interrogation. When received transponder replies were similarly spaced, they were assigned to the same aircraft. Aircraft latitude/longitude were determined based on successful reception of the same Mode A code at three or more RUs. A target report was then formed within the TP, with the altitude field unpopulated.

When the beacon code was validated (and only when this occurred), Mode C data altitude information was decoded from the RUs that received the Mode A code, and the Mode C data were compared. If the Mode C comparison test also passed, altitude data were included in the All-Purpose Structured EUROCONTROL Radar Information Exchange (ASTERIX) Category 10[*] target report output by the TP. Otherwise, the

[*] ASTERIX (All-Purpose Structured EUROCONTROL Radar Information Exchange) is a family of surveillance system data formats developed over the past 10 years. WAM and ADS-B data provided by the HITS TP were in ASTERIX Category 10 format. Of the current FAA radars, only the ASR-11 outputs data in ASTERIX format.

altitude field in the target report was not populated. (It does not "make sense" to form ATCRBS aircraft target reports with latitude, longitude, and altitude information without the Mode A code to identify the aircraft. Thus, the HITS implementation did not permit this possibility.) The fraction of ATCRBS aircraft reports lacking altitude information, roughly 15 percent, is a possible issue when considering WAM as an alternative to SSR. Automation systems that now process SSR reports expect all four data fields to be populated, but can "coast" the aircraft altitude if the information is not present in a report.

Mode S Transponder TP Messages—Unlike ATCRBS transponder messages, all Mode S messages broadcast by a Mode S transponder contain the unique aircraft 24-bit Mode S identification. (Also unlike an ATCRBS transponder, a Mode S transponder emits a DF11 message once per second without being interrogated.) Similarly, all Mode S interrogations broadcast by a Mode S radar contain the Mode S ID of the intended aircraft. The Mode S ID:

- Enables a Mode S radar to interrogate Mode S aircraft individually (unlike an ATCRBS radar, which interrogates every aircraft within its beam). Individual interrogations reduce the total amount of replies in the air at any time, decreasing the likelihood that replies from different aircraft will "collide" at the radar antenna and thus be difficult to decode.[*]
- Enables every transponder reply received by a radar (or HITS RU) to be associated with a specific aircraft (regardless of what other information is contained in the message). Thus the likelihood of a radar associating an altitude reply with the wrong aircraft ("altitude swap") is greatly reduced.

Perhaps surprisingly, use/dissemination of the Mode S ID is limited to ground radars and aircraft transponders. Current FAA interfaces do not enable radars to provide a Mode S ID to air traffic control automation computer/software, nor could such software use the Mode S ID if it were supplied. Instead, as shown in table 2-2, the 12-bit aircraft beacon code—first developed as the ATCRBS Mode A code and later embedded in Mode DF05 messages—remains the mechanism by which secondary radars "tell" the automation software which aircraft is the subject of a target report.

For HITS, the most prevalent Mode S short squitter transponder message used for WAM processing was the DF11 squitter (table 2-1), which is broadcast once each second. A latitude/longitude solution was calculated from the TOAs of message, and HITS generated a corresponding ASTERIX Category 10 target report with both the Mode A and Mode C fields unpopulated. Less frequently (e.g., once each 5 sec or 10 sec) UF04 (altitude) and UF05 (beacon code) interrogations were scheduled sufficiently closely that their corresponding DF04 and DF05 replies could be combined in forming an ASTERIX Category 10 target report. In these cases, the report would contain latitude/longitude and (a) the beacon code, or (b) the barometric altitude, or (c) both.

In addition to being able to coast altitude when barometric information is not present in a target report, current FAA automation software can use SSR reports without a Mode A aircraft identifier. In such cases, the report is treated like a report from a primary radar. Scan-to-scan correlation is based on horizontal position only, with some resulting degradation in tracking performance. The FAA and the Standard TRACON Automation Replacement System (STARS) contractor are evaluating the resources needed to incorporate WAM messages into the STARS. This could involve changing the STARS interface to accept the Mode S aircraft identifier.

Interrogation Issues—When selecting Mode S UF04 and UF05 interrogation rates, the primary factors were: (1) the update rate needed for FAA Automation systems (e.g., once per 5 sec in the terminal area) and (2) the probability of receiving a reply to an interrogation (termed the "round reliability"). For radars, Mode S round reliabilities are much higher than those for ATCRBS, because of the Mode S use of error-detection/-correction techniques (an error in one or two received bits may be correctable using the

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[*] This phenomenon, called synchronous garble when the replies are the result of the same interrogation, was a primary argument for the development of Mode S.

checksum bits at the end of a message). Another consideration is that, because HITS Mode S interrogations are made only to obtain the beacon code and altitude information, which generally change much more slowly than aircraft horizontal position (which may be available once per second from DF11 messages), an argument can be made than even a 5-sec update period for these quantities may not be necessary if the Mode S code is used for aircraft identification. Thus significantly lower interrogation rates were used for Mode S aircraft than were used for ATCRBS aircraft, and different Mode S interrogation schemes were used during different test periods to determine the best balance between HITS surveillance performance (which improves with higher interrogation rates) and protection of nearby SSRs from interference (which increases with higher HITS interrogation rates).

The HITS interrogators (receive-transmit units (RTs)) used omnidirectional antennas—unlike SSRs, which use narrow-beam antennas. To avoid interrogating every ATCRBS-equipped aircraft in view and suffering the interference that results from a large number of overlapping replies, HITS used a variation of the whisper-shout technique that was developed for the TCAS. The number of interrogation power levels and the inter-level power differential were varied from test period to test period. Although the whisper-shout technique does limit transponder replies, it has another mechanism by which it degrades the performance of nearby SSRs. A transponder within range of a HITS RT that is not replying to an interrogation (individual level within the whisper-shout sequence) is "suppressed," preventing it from replying to other interrogators as well. Because SSRs are the principal air traffic control surveillance mechanism, limits were placed on HITS interrogations.

The FAA Office of Spectrum Policy and Management is the governmental body responsibile for managing the 1030- and 1090-MHz SSR frequencies. For this effort, the primary concern of the FAA "Spectrum Office" was ensuring that HITS did not cause degradation in the surveillance services provided by existing SSRs. Thus, the FAA Spectrum Office included, in the license to radiate on 1030 MHz in the Gulf of Mexico, the requirement that HITS not elicit more than 10 replies per second from any aircraft transponder. The FAA Spectrum Office also expressed (verbally) a strong desire that the HITS system be implemented in such a way that WAM interrogations would "occupy" a transponder for a maximum of 0.25 percent of the time (sometimes expressed as 2500 μsec/sec). A transponder is occupied by HITS if it is either replying to a HITS interrogation or is being suppressed by HITS. Generally suppression time was much greater than reply time.

The HITS informal requirement of 0.25-percent maximum occupancy time is stringent. In contrast, TCAS has a formal requirement of 1-percent maximum transponder occupancy time. It would be appropriate to revisit this issue, using simulation or another analysis tool, to directly compare the impact of the TCAS requirement in a busy terminal area (where several different TCAS aircraft might each suppress a given victim transponder) with the HITS goal. It might also be appropriate to have separate WAM occupancy standards for regions that are within and outside of SSR coverage.

2.1.6 Advantages and Disadvantages

SSR and WAM systems both have inherent advantages and disadvantages (table 2-3). Although radar position update intervals (ranging from 5 to 12 sec) are governed by the rotation period of the mechanically scanned-in-azimuth directional antenna, multilateration's use of fixed, omnidirectional-in-azimuth antennas enables update rates as high as several times per second. Radar azimuth error, measured in linear distance units, increases as aircraft range increases, because of spreading of the antenna beam. In contrast, WAM accuracy is essentially constant throughout the coverage area when the sensors are properly distributed. Low-altitude coverage of an SSR is constrained by the radio line of sight from one location, limiting the ability of a radar to "see" low-flying aircraft at large ranges. Although the same principles govern reception by individual RUs, their low cost/smaller size permit optimization of the number/distribution of ground receivers for a specific coverage region—e.g., RUs placed near the outer edge of the coverage region. Also, WAM can be installed at terrain-constrained locations where radar cannot. Innsbruck and Juneau are examples of locations where airport approach/departure are between mountains and are not straight enough for a radar to have line-of-sight visibility over the entire route.

Table 2-3 WAM Advantages and Disadvantages vs. SSR

Advantages	Disadvantages
▪ Ground-station equipment is simple – Small/lightweight, low cost, low power – Fixed antenna, many sites passive ▪ Uses current aircraft transponders ▪ Potentially good performance – High accuracy – High update rate — e.g., 1 Hz ▪ Low-altitude coverage potentially better than radar away from airport (dependent on RU siting) ▪ Can be installed at terrain-constrained locations where radar cannot ▪ Can be configured to tolerate failure of some RUs/communications links ▪ Ground stations also receive ADS-B messages	▪ Large number of ground stations (vs. radar or ADS-B) – Increased site-acquisition costs – Increased maintenance costs ▪ Significant communications requirement – Cost concern – Potential reliability issue ▪ Less-robust air-ground RF link than radar—possible issue for – Detection range – Low-altitude aircraft – Low-end transponders – Partially obstructed aircraft antennas

A significant disadvantage for WAM is that it requires multiple, geographically distributed transmit/receive sensors, whereas SSR requires only a single transmit/receive sensor for the same surveillance volume. Additionally, the high-gain antenna of a SSR (approximately 20 dB) provides significant RF uplink and downlink margin advantages, thus more link reliability, relative to the multilateration systems discussed here. To achieve such high gains, SSR antennas have narrow azimuthal beams, and thus must be scanned (rotated) to "cover" the area under surveillance. As a result, connectivity between a transponder and radar can occur less than 1 percent of the time. In contrast, WAM systems, by virtue of their omnidirectional-in-azimuth antennas, can receive transponder signals at any time. Thus WAM systems partially compensate for their lower probability of detecting a single transponder message by having more opportunities for detection.

2.2 ADS-B Technique

ADS-B (figure 2-7), unlike radar and multilateration, does not involve measurement of the location of the aircraft from one or more ground sites. Instead, an airborne GPS receiver determines the aircraft position (latitude/longitude) and, for some receivers, velocity. This information is provided to a Mode S extended squitter transponder, which broadcasts the GPS information—together with aircraft identity and barometric-altitude data—twice each second. The transponder also responds to radar interrogations in the same way that a Mode S short squitter transponder does.

When an ADS-B message is received by a HITS RU, it decodes and forwards the message content to the TP, which develops an ADS-B target report from the message. If the same ADS-B message is received at three or more RUs, a WAM target report is also generated.

The factors to be considered in ADS-B coverage predictions are similar to those for a radar, with the most important being (a) line-of-sight visibility from the RU site, and (b) detectability of the transponder message by an RU receiver at large ranges. Line-of-sight visibility from an RU can be predicted from figure 2-3.

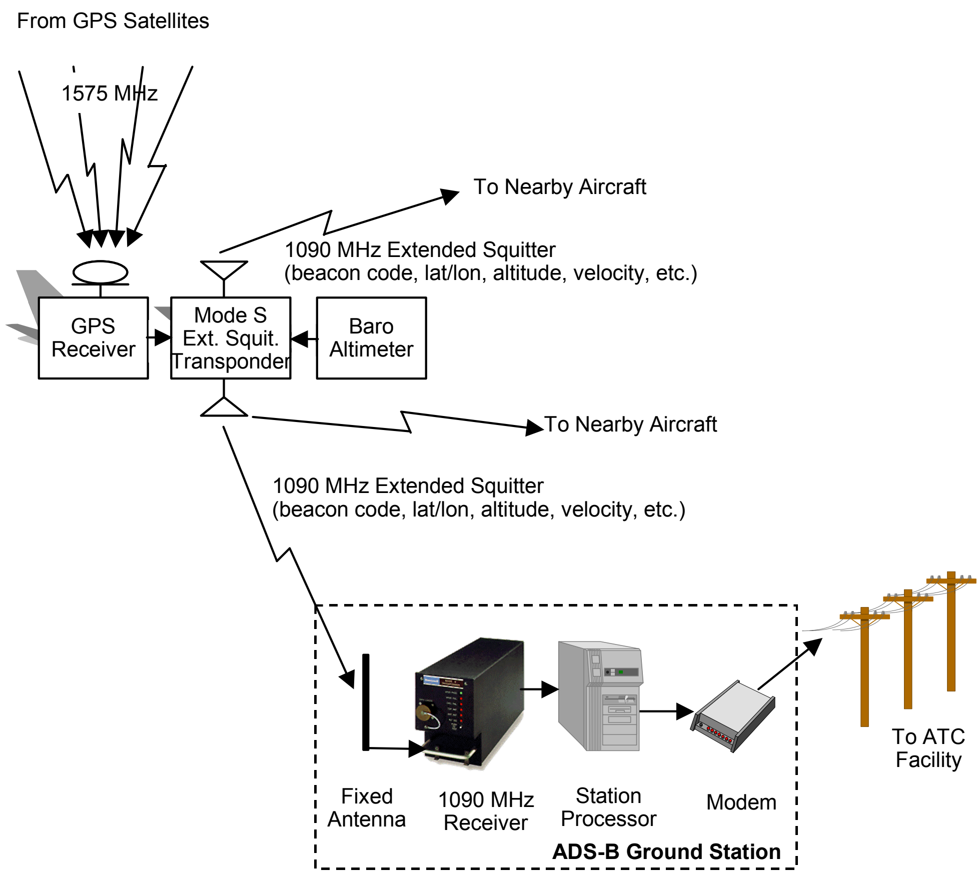

Figure 2-7 ADS-B Concept.

A "link budget" is the standard method for predicting radio/radar signal detectability over significant distances. Table 2-4 is a link budget applicable to the Phase I/II HITS equipment (and similar to one in ref. 3). It predicts that ADS-B messages broadcast by an aircraft with a high-end transponder can be reliably received 100 nmi away by a Phase I/II RU with a standard FAA DME antenna. Although useful, such calculations involve assumptions and approximations—particularly with regard to cable losses and antenna gains—and must be confirmed by flight testing.

Table 2-4 ADS-B Air-to-Ground Link Budget (Phase I/II, without Multipath)

Link Element	Value		Comment
Transmitter power, 500 W	57.0	dBm	FAA Tech Center aircraft
Aircraft antenna gain	0.0	dB	Standard assumption
Path loss, 100 nmi	–138.5	dB	Standard calculation
Antenna gain, on platform	8.0	dB	DME antenna†
Cable losses	–3.0	dB	Reasonable assumption
Received signal level	–76.5	dBm	Numerical sum of previous five link elements
Receiver MTL*	–80.0	dBm	Sensis provided value (Phase I/II)
Link margin	3.5	dB	Ref. 3 recommends 4 dB

* Minimum trigger level
† Distance measuring equipment

GPS and WAM share some basic characteristics, because both are based on the principle of multilateration using TOA measurements. However, ADS-B can be expected to perform better than WAM, at significantly lower cost to the surveillance service provider (table 2-5). The performance advantage of ADS-B over WAM is due to several factors: (1) greater maturity of GPS technology, (2) better GPS measurement geometry, and (3) superior multipath-error resistance of the GPS signal.

Table 2-5 ADS-B Advantages and Disadvantages vs. WAM

Advantages	Disadvantages
▪ Fewer (approx. one-third) ground stations – Lower equipment-acquisition costs – Lower installation/maintenance costs – Lower communications costs ▪ Typically better performance – Higher accuracy – Higher update rate	▪ Requires new aircraft equipage ▪ Failure/jamming of GPS satellite signals causes loss of both GPS navigation and ADS-B ▪ Equipment implementing the basic concept would be easy to spoof

A mature system is one whose performance is limited by the technology and physics pertinent to the basic system concept—i.e., all significant errors of omission and commission have been detected and corrected. When mature, the accuracy of a navigation or surveillance system based on TOA measurements should be limited by the following mechanisms:

(a) Error in knowledge of the off-aircraft transmitter/receiver locations,

(b) Uncertainty in knowledge of propagation delays between transmitters and receivers,

(c) Ability of receiver to detect the signal in the presence of background noise, and

(d) Multipath and other interference.

As a result of 30 years of government-funded development (at a cost of several billions dollars) and a large receiver market, GPS performance has been refined to the limits imposed by these mechanisms. Indeed, the FAA Wide Area Augmentation System (WAAS) and Local Area Augmentation System (LAAS) have extended the basic GPS concept and significantly reduced errors due to mechanisms (a) and (b). WAAS-aided GPS position errors are expected to be less than 20 ft, and LAAS-aided GPS errors less than 10 ft.

In the fall of 2000, at the inception of the HITS deployment, WAM technology was immature. HITS became the first and largest effort to date with a concentration on WAM. Although directed primarily at deployment and testing, significant technical maturation did occur. However, there is room for additional development. It is not reasonable to presume that resources comparable to those devoted to GPS will be available.

In terms of measurement geometry, WAM is somewhat limited by the necessity of locating all its RUs in essentially the same plane (Subsection 2.1.3). In contrast, GPS satellites can be both overhead and on the horizon. For most times/locations, GPS is a true three-dimensional position-determination system with HDOP less than 1.5 and VDOP less than 2. Lastly, GPS uses a continuous waveform that was designed to be resistant (although not immune) to multipath effects, whereas SSR signals were not designed to be multipath-resistant.

Weighted against the performance and cost advantages of ADS-B are the need for new aircraft equipage, its susceptibility to spoofing,[*] and dependence on the GPS satellite signals. With ADS-B, the same source of aircraft position information is used for navigation and surveillance, increasing the impact of a failure in that source.

2.3 HITS Ground Equipment

2.3.1 RU and CPS Components

The basic HITS equipment architecture involves:

- A set of RUs (figure 2-8), sited to receive transponder emissions from aircraft in the region under surveillance; some RUs are receive-only (RO) units, and some are RT units that elicit messages from aircraft transponders; and
- A central processing site (CPS) where data provided by the RUs are processed to derive aircraft positions; the CPS also displays aircraft positions and monitors the status of the system.

Remotely located reference transponders (RXs, housed in separate electronics cabinets having the same size/shape as RU cabinets) were used in Phases I and II to synchronize the RU clocks. RU clock synchronization was necessary to ensure consistency of the TOA measurements used in multilateration calculations. Commercial telecommunications linked the RUs and CPS.

(a) RU Electronics Cabinet (24 x 18 x 42 in.) **(b) AS-177B Omnidirectional Antenna (6.5 x 20 in.)**

Figure 2-8 Remote-Site Equipment.

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[*] In this context, spoofing means deceiving ADS-B ground equipment (and users of outputs from that equipment) into believing in the presence of aircraft that do not exist. For example, the combination of a computer on the ground and a Mode S extended squitter transmitter could generate/broadcast ADS-B messages for fictitious aircraft on collision courses or headed toward public buildings.

RU antennas were either a Navy AS-177B (omnidirectional azimuthal coverage with 2.9 dBi of mainbeam gain) or an FAA DME Model 5100A (omnidirectional azimuthal coverage with 8 dBi of mainbeam gain). Each RU also had an uninterruptible power supply and a router that provided the interface to the microwave communications system linking the RU with the CPS.

The CPS for each phase included the TP computer, maintenance and display terminal (MDT), and communications equipment (figure 2-9). The TP received decoded aircraft transponder messages and associated TOA timestamps over the commercial communications network. Functionally, the TP "clustered" transponder messages from different RUs—i.e., determined whether all received messages in a candidate set were due to the same aircraft transmission. The TP also performed multilateration calculations on a set of TOAs associated with cluster messages to determine the aircraft horizontal position. These calculations required the geographical coordinates of the RUs, which were obtained from a survey during installation, and the aircraft altitude, which was determined by decoding transponder messages.

Figure 2-9 Target Processor and Maintenance and Display Terminal.

The output of the TP was interfaced with a MDT within the CPS via a local-area network. The MDT had a graphical user interface for interacting with the RUs and TP. It monitored the status of the RUs and TP, could reconfigure the RUs if needed, and provided a graphical display of the aircraft being tracked by HITS. Separate T1 lines linked the CPS with the Volpe Center in Cambridge, Massachusetts, and Sensis Corporation in DeWitt, New York. Remote MDTs were located at each of these sites, enabling remote operation and maintenance of the HITS, as required, and continuous data recording for timely analyses.

2.3.2 Phase I Network Architecture

The HITS ground-equipment architecture for Phase I is shown in figure 2-10. This configuration comprised 21 RUs—11 ROs and 10 RTs—and 7 RXs. The CPS was located at Petroleum Helicopters, Inc. (PHI) in Lafayette, Louisiana.

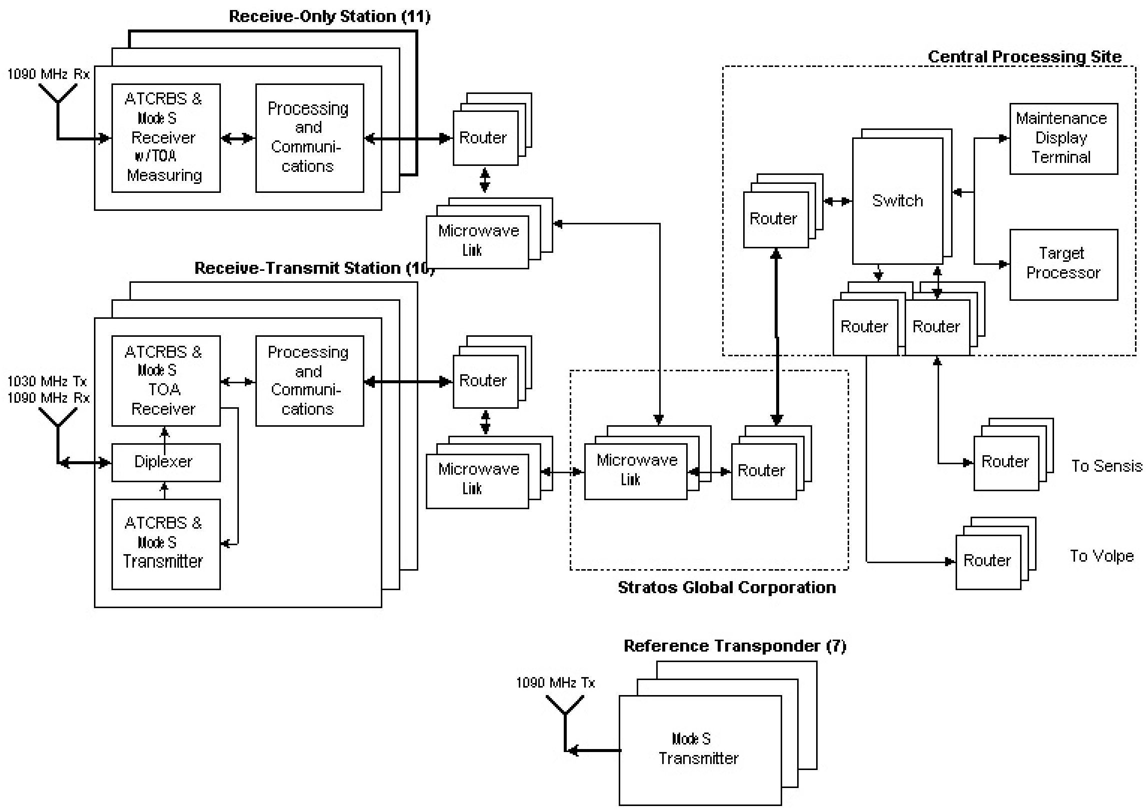

Figure 2-10 Phase I Ground-Equipment Architecture.

Figure 2-11 shows the RU locations and types. Individual sites, which were placed in the form of a grid of triangles with 20- to 25-nmi sides, were chosen to provide WAM coverage down to 100-ft altitude in the region enclosed by the polygon connecting the perimeter stations. This inner or primary coverage area had a footprint of approximately 7000 nmi^2. The strip approximately 20-nmi wide (the nominal spacing between RUs) surrounding inner coverage area was the outer or extended coverage region. WAM coverage in the outer region extended upward from 1000 ft over a footprint of approximately 8750 nmi^2.

In terms of coverage footprint and altitude regime, the region under WAM surveillance was approximately 50-percent larger than the terminal area served by an airport surveillance radar. Thus, Phase I provided an initial assessment of the suitability of WAM as a terminal-area SSR replacement. Phase I ADS-B coverage was expected to extend at least 100 nmi from the perimeter of the ground stations, provided aircraft had sufficient altitude to have a line of sight with at least one ground site.

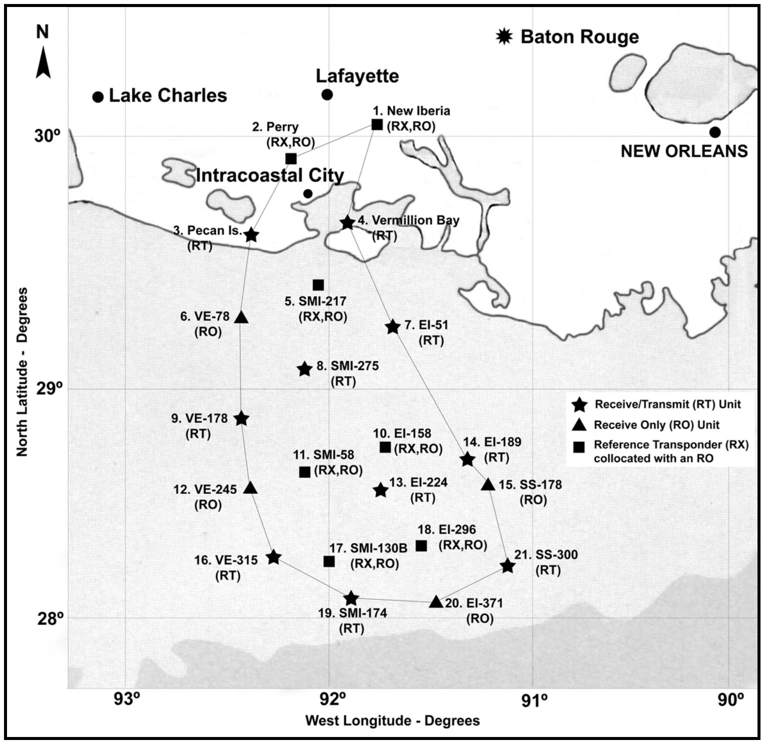

Figure 2-11 Phase I RU Locations.

2.3.3 Phase II Network Architecture

The Phase II configuration involved a reduction in the number of the Phase I RUs (sites numbered 2 through 8 were retained) and relocation of some equipment. This configuration employed 7 RUs—3 ROs and 4 RTs—and 2 RXs. The ROs used AS-177B omnidirectional antennas, and the RTs had DME 5100A antennas. The CPS remained at the PHI facility in Lafayette, Louisiana.

The Phase II sites were selected to provide WAM coverage of the area surrounding Intracoastal City (INCY, figure 2-12). The inner coverage area, depicted by the polygon connecting the perimeter ground sites, had a footprint of 1600 nmi^2 and corresponded to WAM coverage down to 100 ft of altitude. The strip approximately 20 nmi wide surrounding inner coverage area constituted the outer coverage region. WAM coverage in the outer region extended upward from 1000 over a footprint of approximately 5500 nmi^2. WAM coverage was designed for the surveillance of helicopter launch and recovery operations at Intracoastal City, and included all the offshore IFR arrival/departure navigation fixes. ADS-B coverage extended approximately 100 nmi from the inner coverage area in all directions—an area with a footprint of approximately 20,000 nmi^2.

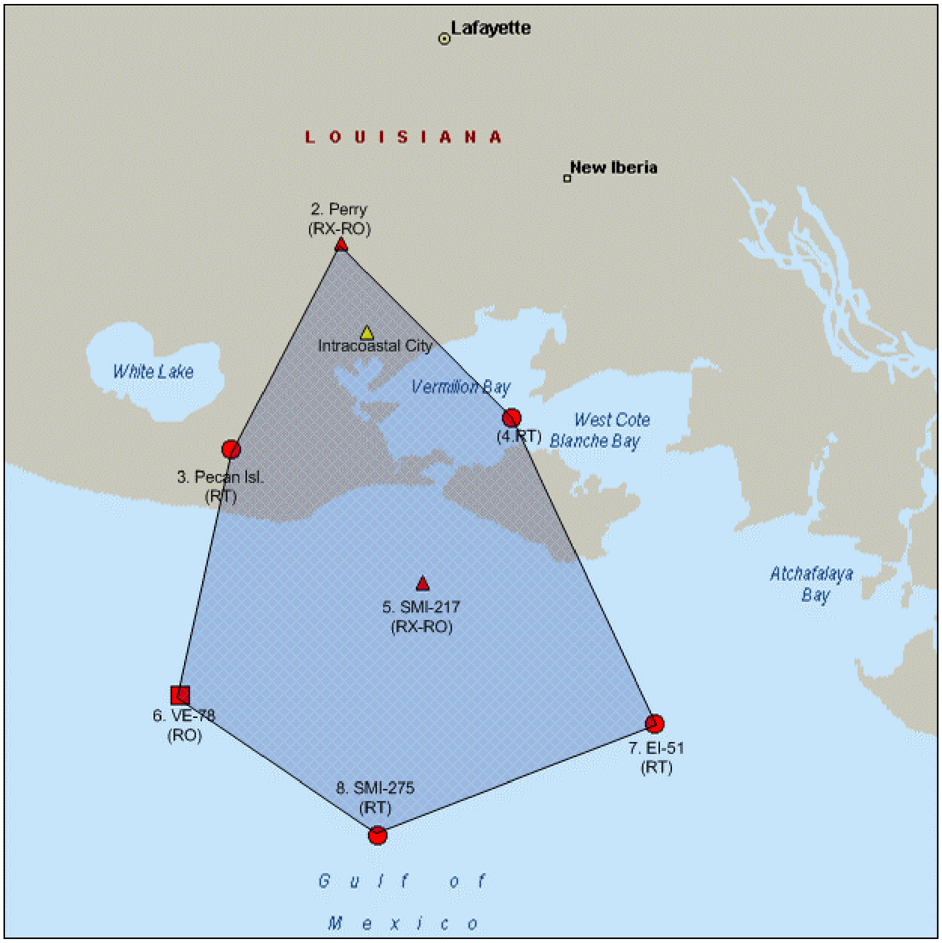

Figure 2-12 Phase II RU Locations.

For Phase II, several modifications were made to the HITS WAM adaptation parameters within the TP. First, to reduce the amount of false target reports, the TP maintained an internal tracker that predicted the position for each plot report. When the horizontal distance between the actual report and the predicted position of the tracker exceeded 1000 ft, the TP did not output the report. The predicted report position also assisted the TP in scheduling interrogations of the aircraft by the RT ground units.*

2.3.4 Phase III Network Architecture

Whereas Phases I and II were directed at WAM surveillance of terminal-area-like airspace regions, the first objective of the Phase III configuration was providing ADS-B coverage of en route/oceanic airspace. Specifically, the Phase III system was designed to provide ADS-B surveillance coverage across most of the U.S. flight information regions (FIRs) in the Gulf at 24,000 ft above sea level (ASL) and higher (figure 2-13). To accomplish this goal, 8 RUs were sited in and around the Gulf of Mexico—5 on shore and 3 on deep-water platforms 100 to 120 nmi from the U.S. southern coast (table 2-6). The sites selected were located on the backbone of the network installed by Stratos Global Corporation, a commercial telecommunications service provider, to minimize communications installation costs and improve reliability. Accordingly, these sites were not optimally located for multilateration performance. The CPS for Phase III was located in the Dynamic Simulator (DySim) room within the FAA's Houston Air Route Traffic Control Center (ARTCC).

* Similarly, a Mode S radar contains a tracker that is used to schedule interrogations of individual targets.

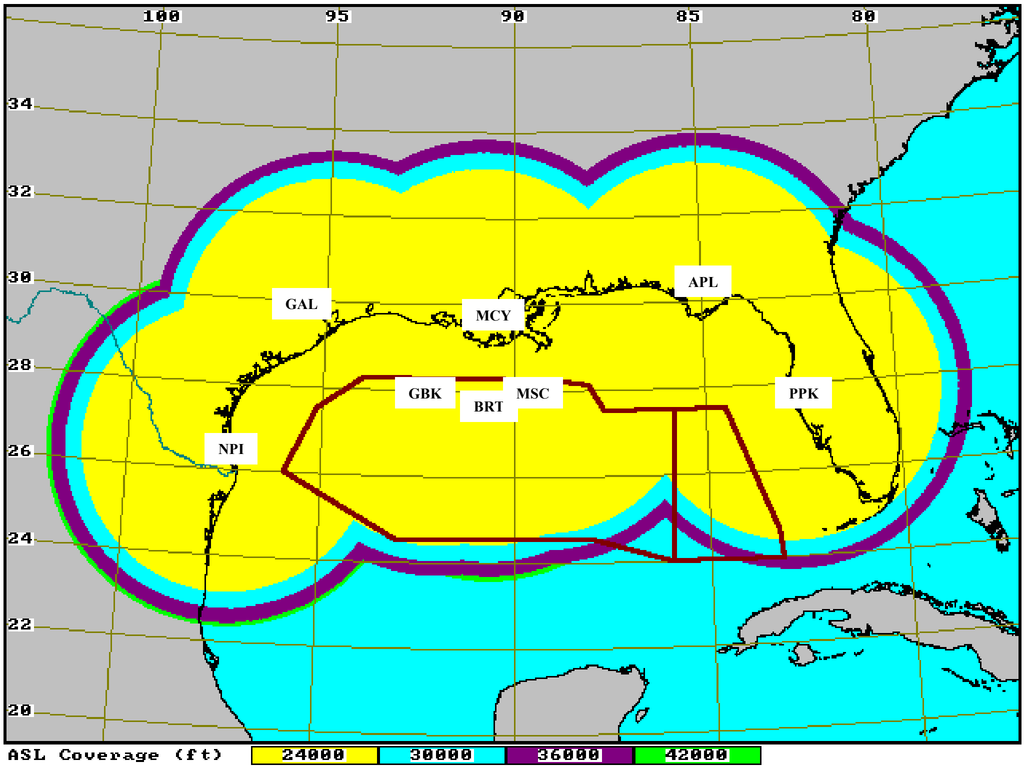

Figure 2-13 Phase III RU Locations and Predicted ADS-B Surveillance Coverage.

Table 2-6 Phase III RU Locations

Symbol	Location	Symbol	Location
NPI	North Padre Island, Texas	PPK	Pinellas Park, Florida
GAL	Galveston, Texas	GBK	Garden Banks (platform)
MCY	Morgan City, Louisiana	BRT	Brutus (platform)
APL	Appalachicola, Florida	MSC	Mississippi Canyon (platform)

Coverage of such a large area (approximately 486,000 nmi^2) necessitated several significant equipment/ deployment changes from Phases I/II: (a) wider spacing of RUs (approximately 200 nmi vs. 20–25 nmi for Phases I/II); (b) exclusive use of the higher-gain FAA DME Model 5100A antennas at the RUs (for reception over greater distances); (c) a newly developed high-power interrogator (for transmitting over greater distances); and (d) a GPS receiver within each RU to synchronize the clocks (eliminating the use of reference transponders, which required line-of-site visibility to multiple RUs.

Two high-power interrogators were purchased from DRS Signal Solutions West (formerly Zeta Corporation) and integrated with the Sensis RT equipment. One unit was installed at Morgan City, Louisiana (MCY), to elicit information from ATCRBS and Mode S transponders. The remaining high-power interrogator was retained as a laboratory test specimen and spare. As in earlier phases, each site had an uninterruptible power supply and a router that provided the interface to the communications system linking the RU with the CPS.

3. Test and Evaluation Methodology

Section 3.1 summarizes the roles and responsibilities of the organizations involved in the Helicopter In-Flight Tracking System (HITS) deployment and evaluation effort. Section 3.2 summarizes the features of the secondary surveillance radar (SSR) systems now deployed in the U.S. Section 3.3 describes the rationale for evaluation criteria established during this effort for HITS wide-area multilateration (WAM) and automatic dependent surveillance – broadcast (ADS-B) capabilities. (Appendix A provides more detailed information regarding these criteria.) The evaluation criteria themselves are presented in Section 3.4. Section 3.5 identifies the method used in evaluating individual criteria, and provides results for those criteria that were evaluated by factory acceptance or site-acceptance test, rather than flight test.

3.1 Organizational Roles and Responsibilities

The organizations involved in the HITS Test and Evaluation (T&E) effort, and their roles/responsibilities, can be summarized as follows:

1. The National Aeronautics and Space Administration (NASA) funded the deployment and evaluation, and had overall HITS management responsibility.
2. NASA engaged the U.S. Department of Transportation (DOT) Volpe National Transportation Systems Center (Volpe Center) to conduct the evaluation and serve as contracting agent.
3. The Volpe Center contracted for dual-technology aircraft-tracking equipment—WAM and ADS-B—and engineering expertise from Sensis Corporation (Sensis).
4. At NASA's invitation, the Federal Aviation Administration (FAA) was involved in the deployment and evaluation from the outset—during FY01 and FY02 on a consultative basis, recommending objectives and monitoring progress, and as an active collaborator during FY03 and FY04.
5. For each project phase, the U.S. Government and Sensis mutually agreed on the operational objectives, the desired surveillance system functionality, and the locations of onshore/offshore remote-unit (RU) sensor sites and central processing site (CPS).
6. Prior to testing, Sensis (a) designed the ground infrastructure and presented the design to the U.S. Government in a Design Review, (b) prepared a Site Installation Plan, (c) validated equipment operation in the Sensis facility in a Factory Acceptance Test, (d) arranged for real-time communications between each site and the shore, (e) installed and optimized the RUs and CPS, and (f) validated operation of the deployed system in a Site Acceptance Test.
7. Prior to testing, the Volpe Center: (a) developed the Data Collection and Analysis System (DC&AS) that interfaced with the target processor (TP) computer at the CPS; (b) formulated WAM and ADS-B evaluation criteria based on documented requirements for existing functionally analogous SSR systems (see Section 3.2 and appendix A); and (c) formulated laboratory and flight-test procedures.
8. For each dedicated flight-test period, the Volpe Center: (a) developed flight profiles that were coordinated with the NASA task manager and aircraft flight crew; (b) arranged for flight-test aircraft (table 3-1); and (c) managed the flight tests, including: conducting preflight briefings, communicating with the instrumented aircraft, and performing postflight assessments.
9. During testing, Sensis supported the equipment infrastructure and was responsible for its calibration and operation.
10. Following each test, the Volpe Center analyzed data collected by the DC&AS and the instrumented/controlled aircraft. Sensis conducted separate analyses, and the organizations coordinated their findings. Both organizations presented their findings to NASA.

3.2 Deployed SSR Systems

Several generations of SSR systems are either deployed or being deployed in the National Airspace System (NAS). The oldest are the Air Traffic Control Radar Beacon Interrogator (ATCBI) Models 4 and 5 (ATCBI-4 and -5), fielded in the 1970s. These are based on the Air Traffic Control Radar Beacon System (ATCRBS) standard (ref. 4). ATCRBS radars simultaneously interrogate all aircraft in their antenna coverage region (i.e., they cannot address aircraft individually). ATCRBS radars can interrogate for and receive only Mode A (12-bit beacon code) and Mode C (12-bit barometric altitude code) transponder messages. ATCBI-4 and -5 radars are typically installed at en route sites or at airports that qualify for a radar, but are not among the busiest 130 or so airports. All the SSRs covering the HITS deployment region during the evaluation period—the long-range installations at both Lake Charles and Slidell, Louisiana, and the terminal installation at Lafayette, Louisiana, airport—were ATCBI-5 systems.

Table 3-1 Flight-Test Aircraft

Ø	Date	Aircraft	Organizational Arrangement
I	Feb. ‘02	Volpe Piper Aztec	Provided/operated by the Volpe Center
	June ‘02	Bell 206 Long Ranger	Leased from/operated by PHI*
	Sept. ‘02	Boeing 757	Provided/operated by NASA Langley Research Center
	Sept. ‘02	Piper Aztec Bell 206 Long Ranger	Provided/operated by the Volpe Center Leased from/operated by PHI
	Jan. ‘03	Convair 580	Provided/operated by the FAA
II	June ‘03	Two Bell 206 Long Rangers	Leased from/operated by PHI
III	Jan. ‘04	Boeing 727	Provided/operated by the FAA
	Feb. ‘04	Boeing 727	Provided/operated by the FAA
	Mar. ‘04	Gulfstream III Boeing 727	Provided/operated by NASA Ames Provided/operated by the FAA

*PHI: Petroleum Helicopters, Incorporated

The Mode S radar system, fielded in the late 1980s and 1990s, follows the Mode S standard (ref. 5) developed in the 1970s and 1980s as a significant improvement on ATCRBS.[*] Relative to ATCRBS, the Mode S SSR: (a) broadcasts a different set of signals in space (messages can be 56 or 112 bits long and have different waveforms) with more information content; (b) can address interrogations to individual aircraft; (c) have improved azimuth measurement accuracy based on the monopulse technique[†]; and (d) have reduced message-error rate because of the use of error-check bits embedded in transmitted and received messages. Monopulse measurement accuracy combined with the ability to address individual aircraft significantly reduces the number of transponder messages needed to derive a position fix—from 10–15 for ATCRBS to 3–4 for Mode S.[‡] Approximately 130 Mode Ss are installed in the NAS, almost all at large/busy airports.

[*] Note that the term *Mode S* is used for both a radar system and the concept/capability that the radar implements. In this document, the context should make clear which of these two entities is being discussed.

[†] The monopulse capability itself is so important that secondary radars implementing it are often referred to as MSSRs.

[‡] Additionally, Mode S radars have the capability, using extended-length (112-bit) messages, to interrogate for and receive information such as aircraft flight number, position, and velocity. This capability is only beginning to be used by Mode S radars, and only in Europe. However, the Mode S extended-length message standard is also used for ADS-B.

The FAA developed the ATCBI-6 specification (ref. 6) upon which the HITS evaluation is based during the 1990s. The ATCBI-6 SSR implements most of the Mode S standard, but cannot interrogate for or receive 112-bit messages. The FAA is currently deploying ATCBI-6s, primarily at long-range radar sites, where they are replacing ATCBI-4 and -5 units that have been in service for more than 30 years. This category includes the Lake Charles and Slidell, Louisiana, sites. A total of 123 operational ATCBI-6 installations are planned—101 colocated with a primary radar and 22 as beacon-only sites. At the date of this report, 58 ATCBI-6 units had been received from the manufacturer (Raytheon). Of these, 22 had been fully installed/tested and placed into operational service.

3.3 Rationale for Selecting HITS Evaluation Criteria

In developing the HITS evaluation criteria, the underlying premise was that: (a) if a HITS-like WAM/ ADS-B system were deployed in the NAS, its function would be surveillance of transponder-equipped aircraft, the role currently filled by SSR systems; and (b) the ATCBI-6 is the most recent SSR system procured for the NAS. Thus the evaluation criteria—both capabilities and numerical parameter values—were chosen based on the rationale that *HITS WAM and ADS-B capabilities should be equivalent in function and performance to those of the ATCBI-6 SSR*.

The criteria presented herein were developed expressly for this evaluation. They were not Sensis contractual requirements, nor are they necessarily those that would be chosen in acquiring an operational WAM and/or ADS-B system. They are incomplete with respect to those traditionally used for operational air traffic control equipment—nonperformance topics are omitted, as are some detailed performance-related topics contained in the ATCBI-6 specification. Conversely, some criteria found herein are not in the ATCBI-6 specification.

During this effort, the ATCBI-6 specification (ref. 6) was analyzed and corresponding criteria developed for the HITS WAM and ADS-B (figure 3-1). In many instances, SSR parameters were transformed to account for differences among the three technologies. In brief:

- SSR measures aircraft range and azimuth relative to a single ground location; a ground-interrogation/aircraft-transponder-response methodology is employed; and ground sites have mechanically scanned high-gain directional antennas.
- WAM measures the times of arrival (TOAs) at three or more ground stations of both unelicited (squittered) and elicited transponder signals; aircraft location is computed in rectangular coordinates with respect to the geographic reference system used to define the ground-station locations; and ground sites have omnidirectional low-gain stationary antennas.
- ADS-B avionics obtain aircraft position and velocity from an onboard Global Positioning System (GPS) receiver, and squitter this information to one or more ground stations over a digital data link; and ground sites have omnidirectional low-gain stationary antennas.

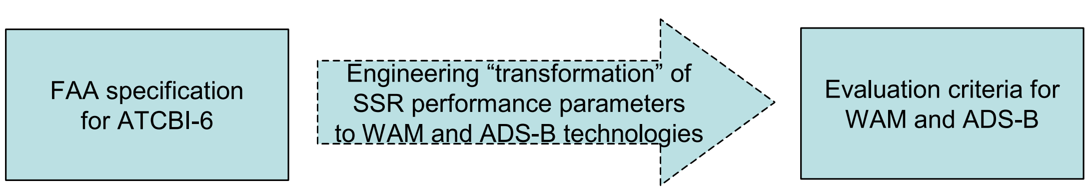

Figure 3-1 Approach to Deriving Evaluation Criteria.

Fundamentally, radar is a station-referenced* surveillance system; WAM is an area surveillance system; and ADS-B is the combination of an area navigation system and a digital data link.

In addition to the ATCBI-6 specification (ref. 6), several documents were consulted to develop the HITS criteria. The Airport Surface Detection Equipment, Model X (ASDE-X) specification (ref. 7) is the standard for multilateration/ADS-B systems designed for airport surface surveillance. The primary standards that all FAA beacon radars are required to satisfy are: FAA Order 1010.51.A (ref. 4, developed for the identification friend or foe (IFF) Mark X system); FAA Order 6365.1A (ref. 5, developed for Mode S); and International Civil Aviation Organization (ICAO) Annex 10 (ref. 8). ICAO Annex 10 has precedence over FAA Order 6365.1A when conflicts arise.

It is emphasized that, for most parameters (see Section 3.5) the *deployed HITS* was evaluated against criteria derived from the *specification for the ATCBI-6*. This approach was selected partly for expediency (a published specification was available) and partly to fulfill an FAA request that this be done. However, this is generally not the approach taken by the FAA in evaluating a new radar system. Instead, a two-step process is followed. First, as part of the procurement process, the radar is evaluated against its specification at a test facility (e.g., FAA Technical Center). During this evaluation, a strong effort is made to remove external sources that can degrade radar performance. Most importantly, (a) the test region is, to the extent possible, cleared of structures/objects that cause signal refraction† and diffraction,‡ and (b) high-quality transponders are employed that fully meet their applicable specifications and are installed with unobstructed antennas.

In the second step, at each operational site the radar is flight checked using an FAA aircraft specifically equipped for that function. During the flight-check process, one or more measured parameters may be out of specification (e.g., azimuth error in one direction is larger than permitted). When this occurs, the flight-check team must make a determination as to whether or not the installation will be certified. If it can be reasonably concluded that out-of-specification measurements are due to environmental factors rather than the radar (e.g., excessive azimuth error occurs at the same angle as the location of a large smokestack), then the installation may be accepted for operational use.

Stated simply, the performance of an operational radar may not satisfy the specification for that radar for all locations/targets within its coverage volume. Other factors—e.g., environmental and the transponder—must be considered when making such a determination.

3.4 HITS WAM and ADS-B Evaluation Criteria

Table 3-2 presents the ATCBI-6 requirements and evaluation criteria developed for the HITS WAM and ADS-B capabilities. Italicized numbers in the headings for entries in the first column refer to sections in the ATCBI-6 specification. Italicized numbers in the headings for entries in the second/third columns refer to subsections in appendix A, where additional information can be found.

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* The terms *station-referenced* and *area* surveillance systems are adopted from the navigation field, where similar terms were introduced approximately 10 years ago to emphasize the differences between traditional systems (e.g., very high frequency omnidirectional radio range (VOR), distance measuring equipment (DME), and instrument landing system (ILS)) that provide information relative to a single ground site and then emerging area navigation systems (e.g., GPS, long-range navigation system-C (LORAN-C) and DME/DME) that provide information relative to a latitude/longitude grid.

† Radio-wave speed and direction change due to change in the index of refraction—e.g., due to moisture in the air over a lake or a temperature inversion.

‡ Radio-wave direction change (bending) around the edge of an obstruction such as a building.

Table 3-2 ATCBI-6 Specifications and HITS WAM/ADS-B Evaluation Criteria

ATCBI-6 ***(Heading Number = Ref. 6 Section)***	**HITS** ***(Heading Number = This doc. Appendix A Section)***	
	WAM	**ADS-B**
3.1.1 Coverage Volume Altitude: 0 to 100,000 ft above ground level (AGL) Elevation angle: Horizon to 40 deg Slant range: 125 and 250 nmi Azimuth angle: 360 deg	*A.1 Coverage Volume* Each RU: • Altitude: 0 to 100,000 ft AGL • Elevation angle: Horizon to 40 deg • Slant range: 50 nmi (terminal) or 200 nmi (en route) • Azimuth angle: 360 deg HITS coverage area: • Horizontal dilution of precision (HDOP) max 1.5 (primary area) or 4 (secondary area) • Coverage by at least 1 RT	Same as WAM subcriterion for each RU
3.1.2 Probability of Target Detection and Probability of False Target Detection 99% detection of all targets; ATCRBS false target detected 0.1%; No false Mode S targets Processing for a minimum of 64 nonfixed and 64 fixed reflectors	*A.2 Probability of Target Detection (Update Interval) and Probability of False Target Detection* 99% detection of targets in 5 sec (terminal) or 10 sec (en route); Each detection includes Mode 3/A and Mode C data; ATCRBS false target detected 0.1%; No false Mode S/ADS-B targets	99% detection in 5 sec (terminal) or 10 sec (en route); No false targets
3.1.3 Horizontal Position Accuracy (Error) Range bias: ±30 ft; Range jitter: 25 ft rms; Azimuth bias: ±0.033 deg; Azimuth jitter: 0.066 deg rms;	*A.3 Target Plot Report Position Accuracy (Error)* Terminal: 416 ft (95%) En route: 4375 (95%)	Not applicable
3.1.4 Target Resolution 2 ATCRBS targets with slant-range separation <1.7 nmi: 1.2 deg < Az < 2.4 deg, detected 98%; Az < 1.2 deg, detected 90% Correct codes available 90% Closely spaced Mode S targets resolvable 100%	*A.4 Target Resolution* Two ATCRBS targets with <1.7-nmi slant-range separation: • Detected 98% • Correct codes available 90% • All other target combinations resolvable 100%	Two closely spaced targets resolvable 100%
3.1.5 Interrogation Modes Interrogate and process replies from ATCRBS and Mode S targets	*A.5 Interrogation Modes* Same requirement	Not applicable
3.1.6 Multiple ATCRBS Reply Processing Decode at least four replies simultaneously	*A.6 Multiple ATCRBS Reply Processing* Same requirement	Not applicable
3.1.7 Identity Code Reliability and Validity Modes 3/A codes correct 99%; Correct Mode 3/A codes validated 99%; Incorrect Mode 3/A codes validated 1%; Mode S ID correct 99.9%	*A.7 Identity Code Reliability and Validation* Modes 3/A codes correct 99%; Correct 3/A codes validated 99%; Incorrect 3/A codes validated 1%; Mode S ID correct 99.9%	ADS-B ID correct 99.9%

Table 3-2 Continued

ATCBI-6 *(Heading Number = Ref. 6 Section)*	**HITS** *(Heading Number = This doc. Appendix A Section)*	
	WAM	**ADS-B**
3.1.8 Altitude Report Reliability & Validation Mode C code correct 99%; Correct Mode C code validated 95%; Incorrect Mode C code validated 1%	*A.8 Altitude Report Reliability and Validation* Mode C code correct 99%; Correct code validated 95%; Incorrect code validated 1%	ADS-B altitude correct 99.9%
Not applicable	*A.9 ADS-B Navigation Data Reliability* Not applicable	Navigation data correct 99.9%
3.1.9 Spectrum/Pulse Repetition Frequency (PRF) Max PRF 300 Hz (3 mode interlace); ATCRBS waveform and spectrum per FAA Order 1010.51A Section 2.4; Mode S waveform and spectrum per FAA Order 6365.1A, Section 2.4.1	*A.10 Spectrum/PRF* Receive-transmit units (RTs) elicit no more than 10 replies/sec from any transponder Goal of 0.25% (maximum) fraction of time during which a transponder can be “occupied” by WAM interrogations	Not applicable
3.1.10 Target Capacity/Overload Processing Process returns for 1400 beacon targets/360-deg scan; Peak 32 beacon targets/2.4-deg wedge; Primary radar reports (standards are not relevant to HITS)	*A.11 Target Capacity* Each RU must process messages from 1400 transponders (all types) in 5 sec (terminal) or 10 sec (en route) Full HITS must process: Average 1 target per 35 nmi^2 in entire coverage area Peak 1 target per 10 nmi^2 in 1% of coverage area	
3.1.10 Target Capacity/Overload Processing Detect overload condition and report to remote system control terminal and NIMS; targets discriminately and dynamically reduced for optimum operational capability	*A.12 Overload Processing* Detect overload condition and report via TP; targets discriminately and dynamically reduced for optimum operational capability	
3.1.11 Data Timeliness For terminal use, detect, process, and display transponder replies between min. 5/64 and max. 3/32 of a scan period (approx. 0.375 sec, min., and 0.5 sec, max.)	*A. 13 Data Latency* Detect, process, and output transponder replies within 0.5 sec of the transmission time of each transponder	
3.2.10.7 Beacon Parrot System shall include a beacon parrot transponder capability to be located at two fixed locations	*A.14 RU Clock Calibration* WAM subsystem shall include a means to synchronize the time of arrival clocks of the RUs	Not applicable
3.2.12 System Calibration Shall have beacon transponders within coverage volume for automatic North mark alignment (true or magnetic) Calibration of range and azimuth measurements	*A.15 Continuous Certification* Continuously certify that the WAM subsystem is operating properly	Similar criterion

Table 3-2 Concluded

ATCBI-6 *(Heading Number = Ref. 6 Section)*	HITS *(Heading Number = This doc. Appendix A Section)*	
	WAM	ADS-B
3.2.17 Processing/Display of Special Position Identification (SPI) Responding Targets Process and specifically display transponder responses that are accompanied by an SPI pulse	*A.16 Processing /Display of SPI Responding Targets* Process and uniquely display targets responding with the SPI pulse	Not applicable

3.5 Test Methods and Nonflight Test Results

The parameters in table 3-2 were evaluated in the factory (at Sensis Corp, DeWitt, New York) and in the field (Gulf of Mexico area during the flight-test periods), as appropriate.

3.5.1 Parameters Evaluated by Flight Tests

The following parameters were evaluated by analyzing flight-test data. The performance achieved is presented in Chapters 4 through 6.

- Coverage Volume (ref. 6, Section 3.1.1),
- Probability of Target Detection/Update Interval (ref. 6, Section 3.1.2)
- Probability of False Target Detection (ref. 6, Section 3.1.2),
- Horizontal Position Accuracy (ref. 6, Section 3.1.3),
- Target Resolution (ref. 6, Section 3.1.4),
- Interrogation Modes (ref. 6, Section 3.1.5),
- Identity Code Reliability and Validity (ref. 6, Section 3.1.7),
- Altitude Report Reliability and Validity (ref. 6, Section 3.1.8),
- Spectrum/PRF (ref. 6, Section 3.1.9),
- Data Timeliness (ref. 6, Section 3.1.11), and
- Processing/Display of SPI Responding Targets (ref. 6, Section 3.1.17).

3.5.2 Parameters Evaluated by Factory and Site-Acceptance Tests

The remaining parameters in table 3-2 (i.e., those not addressed by flight test and listed in Section 3.5.1) were evaluated during factory acceptance tests conducted in November 2001 in DeWitt, New York, and during the site-acceptance test conducted in July 2002, in the Gulf of Mexico region. Results of those tests are summarized as follows:

Multiple ATCRBS Reply Processing (ref. 6, Section 3.1.6)—A test was conducted to determine if four interleaved ATCRBS replies (i.e., the F1 pulse of the fourth reply preceded the SPI pulse position of the first reply) could successfully be decoded by individual RUs and outputted by the TP. The HITS test equipment was configured for six RUs and two Reference Transponders (RefTrans). The ATCRBS and Mode S generator injected overlapping ATCRBS replies to all four RUs. Four ATCRBS replies (Mode A codes (octal): 1111, 2222, 3333, and 4444) were interleaved and injected by the ATCRBS radio frequency (RF) generator. The portable display terminal (PDT) was interfaced with each of the six RUs to verify correct decoding of the interleaved replies. Each ATCRBS target was displayed on the HITS test laboratory maintenance display terminal (MDT) to validate the output of the injected targets. HITS successfully demonstrated the capability to decode four interleaved ATRCBS replies and display the targets.

Target Capacity/Overload Processing (ref. 6, Section 3.1.10)—The Target Capacity test case verified the capability of an RU to acquire and process 1400 transponder messages within a 5-sec interval. Subsequently, HITS was tested to verify that an overload condition was detected when more than 1400 targets were injected. The HITS Test Laboratory was configured for six RUs and two RefTrans. The Mode S RF generator was configured to emit 225 target replies per sec and the ATCRBS RF generator to emit 75 replies per sec. The PDT was connected to each RU to validate at least 300 replies/sec were detected. The Mode S RF generator and ATCRBS RF generator target replies subsequently were increased until the HITS central processing site (CPS) ceased operation. The MDT appropriately notified the operator of the cessation of operation for HITS. HITS successfully demonstrated the capability to acquire and process 1400 transponder messages in a 5-sec interval.

Data Timeliness (ref. 6, Section 3.1.11)—Data timeliness was evaluated during the site acceptance to measure the time to detect, process, and output any transponder reply from an RU to the output of the TP. The maximum time allowed by the evaluation criteria was 500 msec. Data latency was measured by recording both the TP workstation central processing unit (CPU) time at which the transponder reply was received at the RU and the time at which the reply was placed in the Ethernet buffer for transmission to an external interface. Each RU time is referenced to the TP clock to provide a common reference. The difference between the two times represents the processing latency (including RU communication delay). The transponder emission time was considered negligible in the computation of the HITS data-latency time.

Two initial tests were conducted. During the first test, 12,964 target reports were collected and assessed; of these, 32 replies were computed to have a latency greater than 500 msec. During the second test, 16,408 target reports were collected; of these, 5 replies were determined to have latency greater than 500 msec. Subsequently, a third test was conducted wherein 24,879 target reports were collected; the maximum data latency was 449 msec. However, changes were adapted to the TP during the third test to reduce the data latency of the transponder emissions. These changes were found to cause degradation in system performance and the results were discarded. Based on the first and second tests, HITS did not meet (albeit by a small amount), the specific data-latency requirement.

Beacon Parrot (ref. 6, Section 3.1.10.7) and System Calibration (ref. 6, Section 3.2.12)—The WAM analog to a traditional SSR beacon parrot is the RefTran, which is used to synchronize the clocks at RUs that receive its messages. Each RefTran is assigned a unique Mode S address and has its antenna position surveyed. Each RefTran emits a DF11 message once per sec, which when received by three or more RUs enables HITS to compute the position of the RefTran using multilateration algorithms. This computed position is compared to the surveyed position. If the two-dimensional difference of the two positions is greater than 200 ft, HITS signals an alarm to the MDT.

RU clock calibration capability was demonstrated by normal operation of the HITS during both factory and field testing. In the factory, the RU calibration and continuous certification test cases verified the synchronization of all the RUs, and demonstrated that HITS monitored and validated the operation of its subsystems. RU calibration and continuous certification was demonstrated by injecting a 5-min target scenario, which included a dynamic Mode S target and ATCRBS target and a stationary Mode S target, with replies being received from seven RUs and three RefTran units. Each RU was seen by at least one RefTran. Data were recorded on the MDT to validate that each time difference of arrival and RU drift rate was being recorded and corrected. The MDT-validated HITS correctly computed, tracked, and offset each RU time drift. Continuous certification of the HITS was maintained by monitoring the position computation by HITS for each individual RefTran. During field testing of HITS, normal operation was observed, indicating that system calibration was being maintained. In the few instances where RU failure occurred, whether because of a communications or router outage, the HITS system notified the operator appropriately.

4. Phase I: High-Density Helicopter Terminal/Offshore Logistical Support Configuration

This chapter addresses testing of the Phase I Helicopter In-Flight Tracking System (HITS) sensor configuration that was described in Subsection 2.3.2. Section 4.1 describes the objectives of the flight tests and summarizes the ground-equipment architecture. Section 4.2 describes the flight-test aircraft and flight patterns. Test results are detailed in Section 4.3 (WAM with ATCRBS transponder), Section 4.4 (WAM with Mode S transponder), and Section 4.5 (ADS-B).

4.1 Phase I Overview

4.1.1 Objectives

HITS Phase I (January 2001 to January 2003) was implemented for two purposes:

- Operational goal—Assess wide-area multilateration (WAM) as a flight-following technique for potential use by helicopter fleet operators servicing the offshore petroleum exploration/production industry, and
- Engineering goal—Measure WAM and automatic dependent surveillance – broadcast (ADS-B) performance as terminal-area surveillance systems, using flight tests, and compare the findings to the specification for the Air Traffic Control Radar Beacon Interrogator Model 6 (ATCBI-6) secondary surveillance radar.

Flight Following—Flight following, as practiced in the Gulf of Mexico, is a process whereby helicopter transportation service providers track the location of their fleets, based on periodic position reports provided by their pilots. A Federal Aviation Administration (FAA)-approved flight-following process is a requirement for all offshore operations conducted under Federal Aviation Regulation Part 135, but not for those conducted under Part 91. Most offshore operators have some formalized means of monitoring the location of their aircraft, required or not, to enhance the safety and efficiency of their operations. Flight following in the Gulf has traditionally been accomplished by very-high-frequency (VHF) radio reports. Recently, some helicopter fleet operators have begun investing in a satellite communications capability that provides (a) automated position updates from helicopters to their operations centers, and (b) a data channel from the operations centers to the aircraft.

The Phase I HITS system was implemented, in part, to evaluate WAM flight-following capability for the offshore service providers. Because virtually all Gulf helicopters are equipped with Air Traffic Control Radar Beacon System (ATCRBS) transponders, the intent was that WAM flight following would not require additional aircraft equipage. However, the practice in the Gulf is that, for VFR operations (which are used most of the time), each fleet operator is assigned one beacon code for its entire fleet, unique from the codes assigned to other operators. With WAM, this enables operators to distinguish their own aircraft from those in other fleets, but not to identify individual aircraft. This limitation strongly reduced fleet operators' interest in WAM flight-following technology, and none requested a feed of the HITS-derived traffic information. Mode S transponder equipage would enable WAM surveillance to identify individual aircraft, but these avionics are just beginning to be installed on Gulf rotorcraft.

Performance Measurements—Phase I provided a valuable opportunity to assess WAM and ADS-B surveillance technologies as alternatives to secondary radar, including determining the impact of the harsh Gulf environment on their performance. Although multilateration had been developed and tested as a surface-surveillance technology, WAM had not been assessed in the U.S. as a potential airborne-surveillance technology.

The Gulf of Mexico environment, for both its weather and remoteness, provided unique challenges to assessing a potential future surveillance system, not only for the offshore operations but also for potential for high-altitude sectors. Challenges included: surveillance coverage of low-altitude offshore users, signal reflections off the sea surface, reliable telecommunications between offshore oil platforms and onshore facilities, and maintenance and repair of remote ground stations.

4.1.2 Ground-System Architecture

A description of the HITS Phase I system is provided in Subsection 2.3.2. The system consisted of 21* remote units (RUs) spaced approximately 25 nmi apart to provide WAM coverage for helicopters departing and arriving on oil platforms approximately 100 ft above the water over approximately a 7000-nmi^2 area, with a central processing site (CPS) in Lafayette, Louisiana. In terms of its horizontal and altitude extents, the WAM coverage region is similar to that of a terminal-area secondary surveillance radar (SSR).

Figure 4-1 simultaneously depicts: (a) the Phase I system WAM primary ("inner") and extended ("outer") coverage regions; (b) coverage limits for terminal radars at Lake Charles, Lafayette, Baton Rouge, and New Orleans; and (c) coverage contours for several altitudes for the en route radars at Lake Charles and Slidell. The HITS coverage area is transected by domestic and oceanic high-altitude jet routes, a low-altitude Victor airway, and includes portions of Special Use Airspace, allowing collection of target-of-opportunity data from a variety of aircraft types and operations.

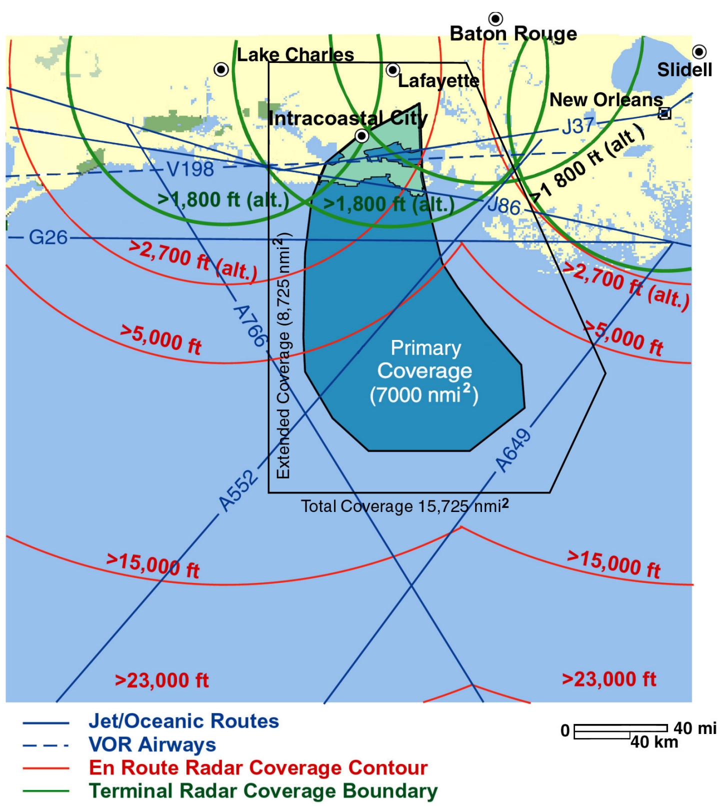

Figure 4-1 Predicted HITS Phase I WAM and FAA Radar Coverage.

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* In the interim between ground-equipment installation and the beginning of formal testing, Site 9 (Vermillion 178, on the western perimeter) became unavailable because of the cessation of oil-production activities and the subsequent shutdown of electrical power. Figure 4-1 shows predicted WAM coverage for the system as designed.

The HITS Phase I system was the subject of five flight-test periods (table 4-1). The first three periods were "shakedown" in nature. Their results are not reported herein, because they are not considered to be representative of WAM/ADS-B capabilities after improvements were identified and implemented. These tests were, however, important in bringing the system to a state where it was ready to be tested for performance. For example, the February 2002 test revealed a design flaw in the HITS receiver decoder board—the detection threshold for ATCRBS signals was set too low. As a result, all HITS ground-station receivers, as well as Airport Surface Detection Equipment, Model X (ASDE-X) receivers already deployed by the FAA, had to be replaced. The September 11, 2002, test revealed that the HITS WAM software was not adequate for aircraft at "high" altitudes (e.g., greater than 20,000 ft). Changes were made to several functions, including the slant-range correction and the "window" employed to accept/reject time-of-arrival (TOA) measurements. It also revealed an error in the ADS-B position-decoding algorithm.

Table 4-1 Phase I Flight-Test Periods

Date	Purpose	Aircraft	Altitude Regime	Transponder	Scored?
Feb. '02	Checkout	Volpe Piper Aztec	Low (<5k ft)	ATCRBS	✗
June '02	Checkout	PHI Bell 206	Low (<5k ft)	ATCRBS	✗
Sept. '02	Checkout	NASA Boeing 757	High (>20k ft)	Mode S extended squitter	✗
Sept. '02	WAM test	Volpe Piper Aztec, PHI Bell 206	Low (<3k ft)	ATCRBS	✓
Jan. '03	WAM and ADS-B tests	FAA Convair 580	Medium (10k ft) & High (>22k ft)	Mode S extended squitter	✓

A thorough characterization of HITS performance required that flight tests address two surveillance technologies (WAM and ADS-B); three transponder types (ATCRBS, Mode S short squitter, and Mode S extended squitter (ADS-B)); and three altitude regimes (below 5000 ft, approximately 10,000 ft, and above 20,000 ft). This chapter presents WAM performance for (a) aircraft equipped with ATCRBS transponders flying at low altitudes (September 2002), and (b) aircraft equipped with Mode S extended squitter transponders flying at high altitudes (January 2003). No testing was performed with Mode S short squitter transponders during Phase I.

In performing quantitative evaluations, HITS performance was compared to the specification for a terminal-area secondary radar—the rationale being that the coverage volumes (horizontal footprint and altitude regimes) for a terminal radar and HITS WAM during Phase I are similar. However, as can be seen in figure 4-1, much of the HITS coverage volume was within en route airspace. Thus, it could be argued that it was more appropriate to compare HITS WAM performance to the less-stringent standards for en route radar.* Standards for terminal surveillance were employed, because the operations addressed by the HITS I configuration involved approaches and departures from platforms.

4.2 Test Aircraft Flight Patterns

4.2.1 September 17–18, 2002 Test Description

A Bell 206 Long Ranger helicopter (leased from Petroleum Helicopters, Inc., PHI) and Piper Aztec twin-piston-engine aircraft (operated by the Volpe Center) were employed for the September 17–18, 2002, tests

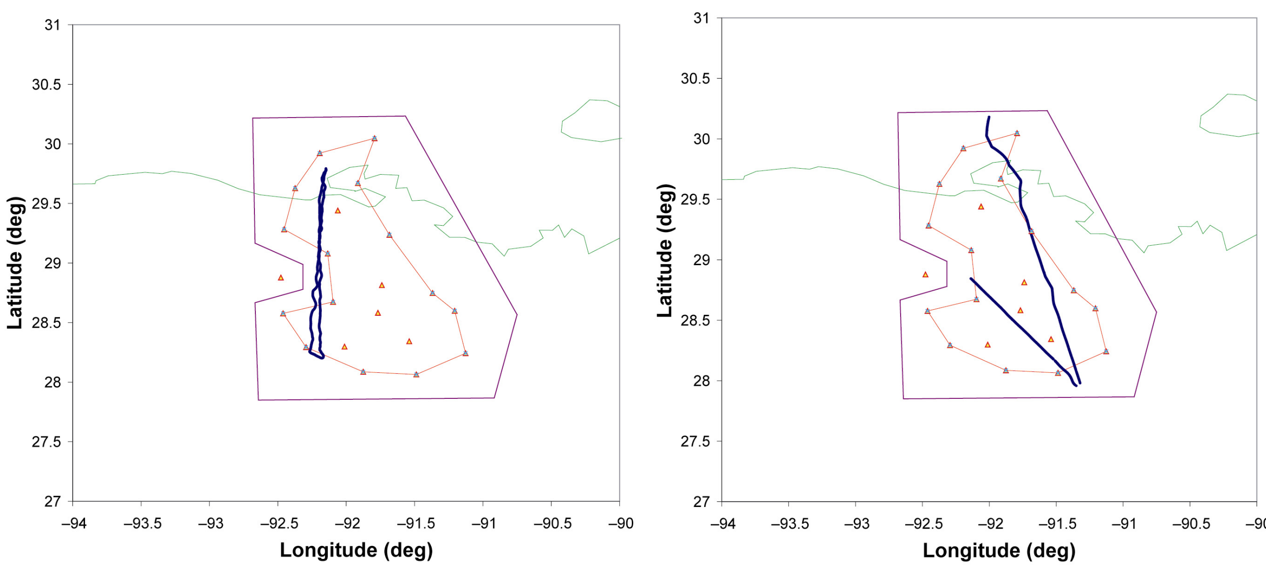
* The criteria most affected by the distinction between the terminal and en route domains are: (a) horizontal position error—the terminal standard (416 ft (95 percent)) is less than one-tenth the en route standard (4,375 ft (95 percent)), and (b) target report update interval—the terminal standard (5 sec (99 percent)) is one-half that for en route (10 sec (99 percent)).

(figure 4-2). Each was equipped with a Mode A/C ATCRBS transponder and Volpe's Airborne Data Collection System (ADCS) differential Global Positioning System (GPS) "truth" system (appendix B). Flight profiles were planned involving altitudes up to 10,000 ft. However, cloud ceilings during the test period did not permit either aircraft to fly above 3000 ft.

Prior to flight testing, the aircraft transponders were tested using a standard avionics-shop line test set to verify their proper operation and power output. HITS performance was evaluated based on a total of 7 unique flight profiles, with durations approximately 2 hr each. Figure 4-3 contains example tracks, as measured by Volpe's ADCS. These plots also show the RU locations and the WAM inner and outer coverage areas. The full set of tracks is shown in appendix C. During testing, each aircraft was assigned a separate unique Mode A code by the Houston Air Route Traffic Control Center (ARTCC) facility. VHF voice communications were maintained with the aircraft from the PHI operations center.

(a) PHI Bell 206 Long Ranger Helicopter **(b) Volpe Piper Aztec Aircraft**

Figure 4-2 September 17–18, 2002, Flight-Test Aircraft.



(a) Helo Flight 1 (WAM Reports) **(b) Piper Flight 2 (WAM Reports)**

Figure 4-3 Example Ground Tracks for September 17–18, 2002, Test Period.

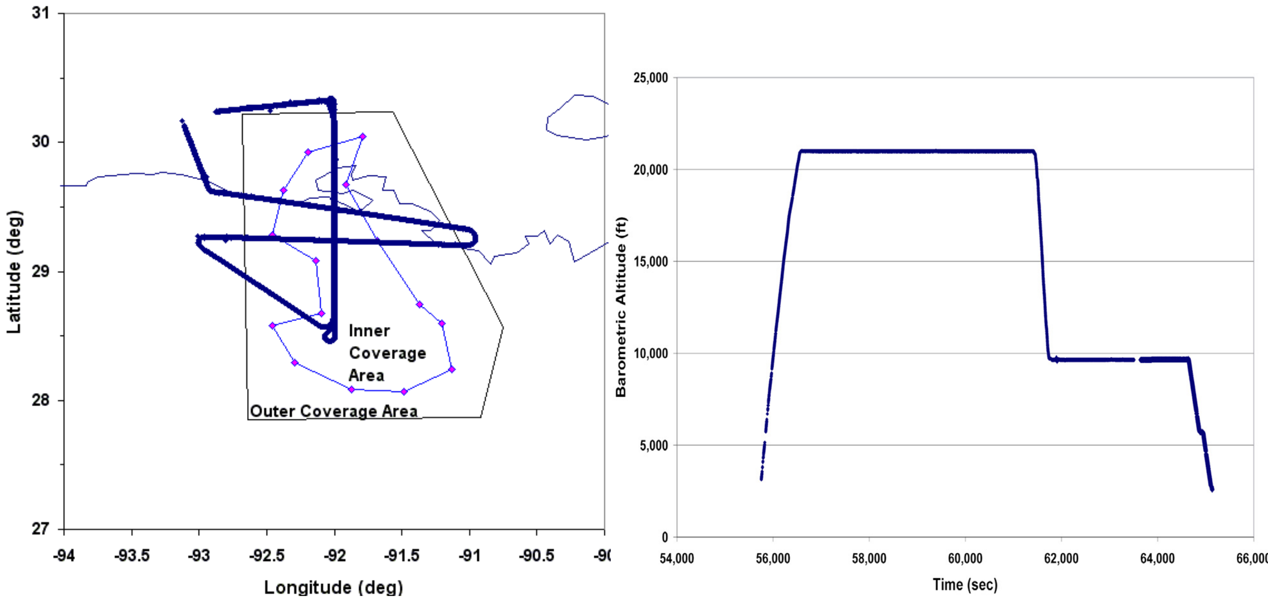
4.2.2 January 28–29, 2003 Test Description

The January 2003 flight test was conducted to address conditions not tested during the September 2002 test—specifically, the high-altitude flight regime, Mode S extended squitter transponder, and ADS-B tracking. The FAA provided a General Dynamics Convair 580 aircraft (figure 4-4) equipped with (a) a Mode S extended squitter transponder broadcasting nondifferential GPS position reports, and (b) a "truth" system comprising an onboard Honeywell GPS receiver and a second GPS receiver placed at the Lake Charles airport. Differential GPS (DGPS) accuracy was achieved by combining the recorded measurements from both receivers during postprocessing. The Convair 580 could fly to an altitude of approximately FL220 and up to approximately 100 nmi from land.

Figure 4-4 January 28–29, 2003, Flight-Test Aircraft (FAA Convair 580).

Operating from Lake Charles, Louisiana, the Convair 580 conducted flights on January 28, 2003, during both the morning and afternoon, and on the morning of January 29, 2004. Figure 4-5 depicts the full January 28 morning flight ground track and altitude profile, derived from the Target Processor (TP) All-Purpose Structural EUROCONTROL Radar Information Exchange (ASTERIX) Category 10 WAM messages. For analysis purposes, data from the January 28 flights were divided into 6 segments (4 for the morning and 2 for the afternoon), each of which was entirely within the predicted WAM outer coverage area. These segments, shown in appendix D, were used to assess HITS WAM performance for a high-altitude aircraft (22,000 ft) and a medium-altitude aircraft (approximately 10,000 ft) while equipped with a Mode S extended squitter transponder.

Upon departing the Lake Charles airport to return to its home base in New Jersey on January 29, the outbound flight was used to assess HITS ADS-B performance.



(a) Ground Track (WAM Reports) **(b) Altitude Profile (Transponder Barometric Data)**

Figure 4-5 Profiles for January 28, 2002, Morning Flight.

4.3 WAM Performance with ATCRBS Transponder (Sept. 17–18, 2002)

For this test period, aircraft equipped with ATCRBS transponders, including the two flight-test aircraft, were interrogated using 15-step whisper-shout sequences. Each sequence began at 57 dBm (500 W) and decreased in 2-dB steps, with a 4-dB difference between the interrogation and suppression pulses at each step. Each of the 9 active receive-transmit (RT) sites broadcast a sequence every 2 sec, so that an aircraft would see a minimum of 1 sequence every 2 sec and typically 1 sequence every 1 sec. Each Mode S-equipped target of opportunity was interrogated (by the nearest RT) for its beacon code (UF05) once every 5.0 sec, and for its altitude code (UF04) once every 5.1 sec.

The following parameters were used to compare the performance of the WAM performance of the HITS Phase I system against the specification for the FAA's ATCBI-6 secondary surveillance radar:

- Position accuracy
- False target probability
- Target resolution
- Update interval
  - Horizontal position / Mode A code
  - Mode C code

4.3.1 Horizontal-Position Accuracy

Horizontal-position errors were determined by comparing the HITS WAM target reports to position "truth" data recording by the onboard Volpe DGPS system. A total of 39,865 target reports were collected over

2 days of testing. The probabilistic distribution of these errors is shown in figure 4-6.* The 172 ft 95-percent position error level is smaller (better) than the standard of 416 ft, which is based on the ATCBI-6 specification with the effects of transponder jitter included. The smooth nature of the curve is indicative of random errors and a lack of abnormal system behavior. However, the pronounced "knee" in the curve (centered on approximately 75 ft and 85 percent) suggests that two separate error mechanisms were present. A reasonable conjecture is that the more frequent/smaller horizontal position errors to the left of the knee were caused primarily by random fluctuations in the TOA measurements due to receiver noise and clock quantization, whereas the less-frequent/larger position errors to the right of the knee were caused by ground-bounce multipath.†

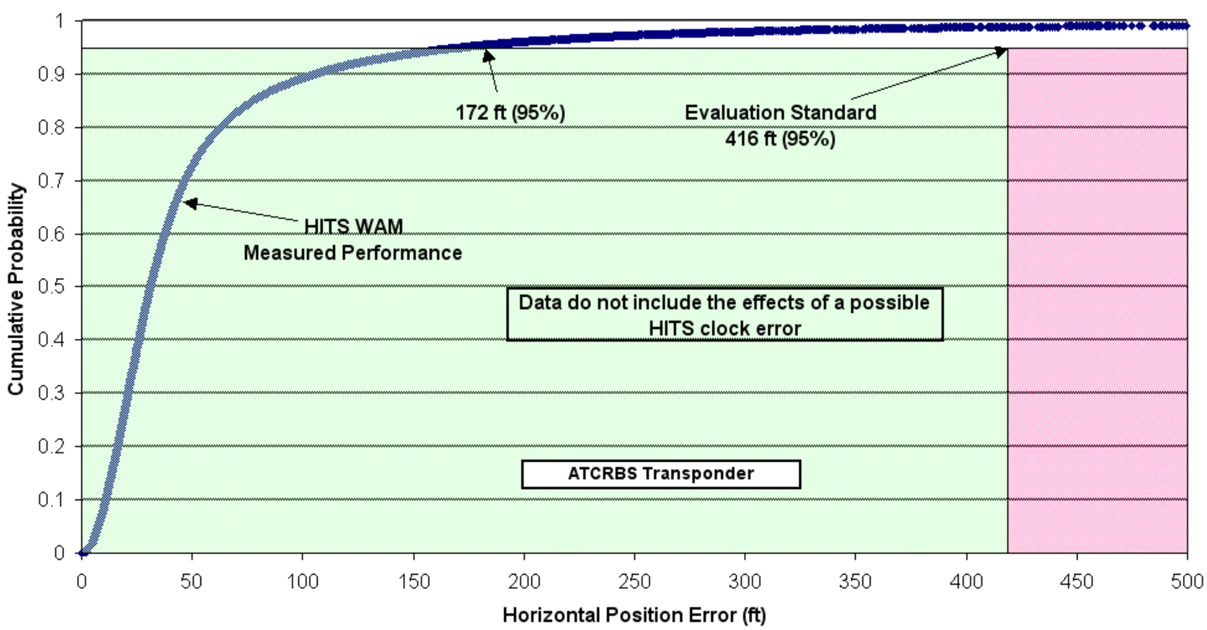


Figure 4-6 Phase I WAM Horizontal-Position Accuracy with ATCRBS Transponder.

This assessment of horizontal-position accuracy was necessarily incomplete in one regard. The WAM data-collection methodology for (only) the September 17–18, 2002, test period did not provide an absolute time tag for the measurements—only the relative time between measurements. Consequently, when the WAM data were compared with the truth data (which did have an absolute time tag), the WAM data were translated in time to best align with the truth data. The result of the alignment process was that any possible WAM clock error—which would result in a "$v\,\Delta t$" position" error, where v is the aircraft speed and Δt is the HITS clock error—was removed.

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* Plots are color-coded in the area where the evaluation criterion applies. The criterion is satisfied if the curve corresponding to measured data remains entirely within the light green area and never enters the light red area. The white area is not addressed by the criterion.

† Figure 4-6 also illustrates an important reason for selecting the 95-percent (as opposed to the 50- or 66-percent) level as the metric for position errors: for distributions resulting from two sources, the 95-percent level generally captures the effects of both sources.

4.3.2 False Target Probability

False targets were defined as horizontal position errors in excess of 1000 ft. The probability of HITS Phase I large position errors with ATCRBS transponders is shown in figure 4-7, which is a replotted version of the data in figure 4-6 with emphasis placed on large error values. The standard for this criterion is that less than 0.1 percent of ATCRBS target reports exceed 1000 ft. The measured false target probability of 0.11 percent slightly missed this standard.

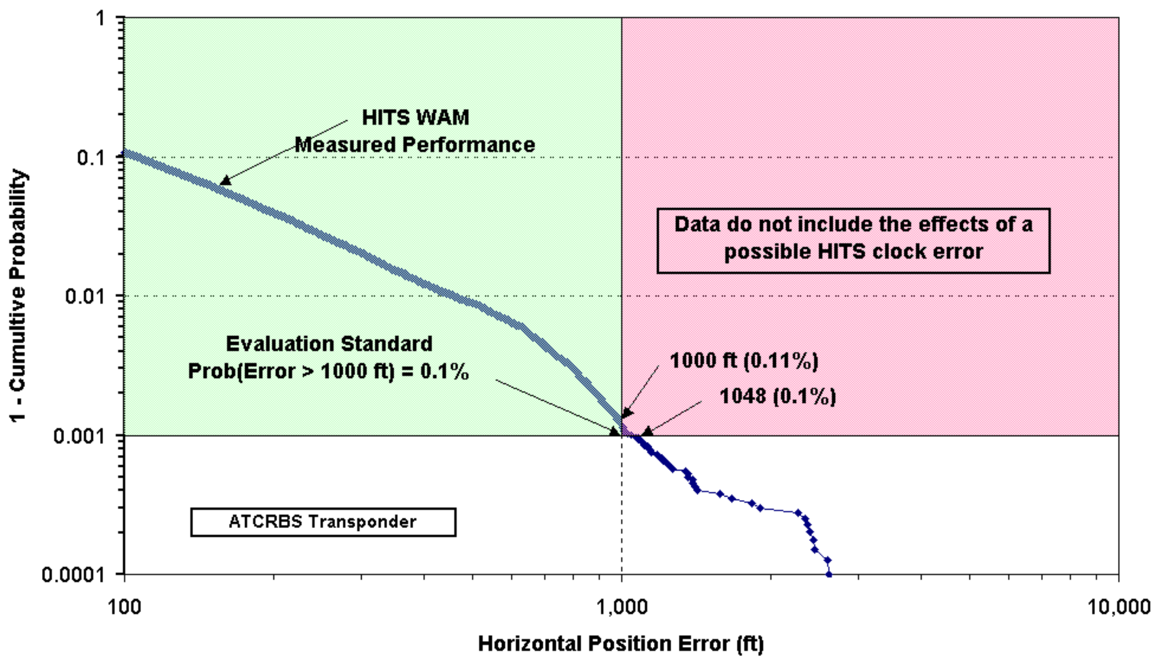

Figure 4-7 Phase I WAM False-Target Probability with ATCRBS Transponder.

4.3.3 Update Intervals: Target Position/Mode A Code and Mode C Code

For the update-interval criterion, the HITS standard for terminal applications was that there be a 99-percent probability of receiving a report for each item in an SSR target report (horizontal position, Mode A code, and Mode C code) within 5 sec of the time that a report for the same item was previously received. (In the statistical analysis, update intervals less than 0.5 sec were not considered.*) For ATCRBS transponders, WAM horizontal-position reports are derived from TOA measurements on Mode A code messages (Section 2.1.5), so update statistics for these two parameters were necessarily identical.

Figure 4-8 depicts the position/Mode A update probability distribution for the September 17–18, 2002, test. Data for the Piper Aztec and Bell Long Ranger are shown separately, and for each aircraft the distributions for both the full set of update intervals and the intervals greater than or equal to 0.5 sec are plotted. The significantly poorer performance for the helicopter is attributed to a combination of blockage of its transponder antenna by obstructions on the underside of the airframe and the lower altitudes flow by the Bell (below 1000 ft most of the time). This topic is discussed in detail in Chapter 5. Consequently, only data for the Piper are used to characterize Phase I WAM update performance. Within a 5-sec interval, the position/

* Target report data received within 0.5 sec of the previous report were ignored to avoid giving undue weight to information deemed to have no operational utility (Section A.2).

Mode A update probability was approximately 98.4 percent. Similarly, figure 4-9 depicts the Mode C update performance, and shows that the update probability was approximately 97.5 percent in a 5-sec interval. Neither parameter satisfied the standard, but the degrees of nonconformance were not great.

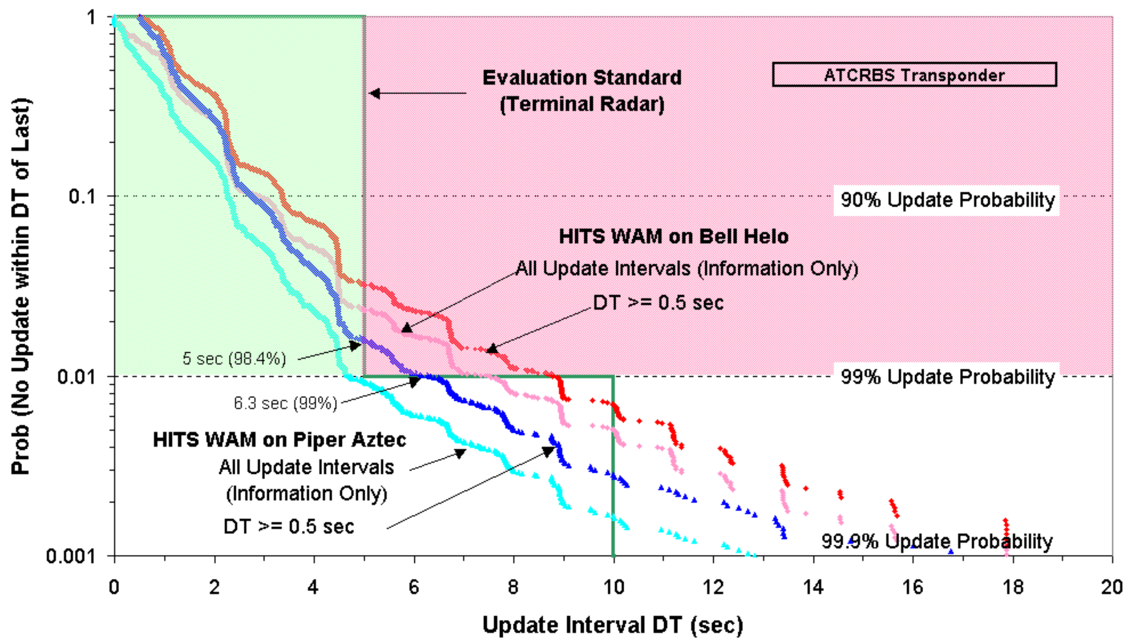

Figure 4-8 Phase I WAM Position/Mode A Update Performance for ATCRBS Transponders.

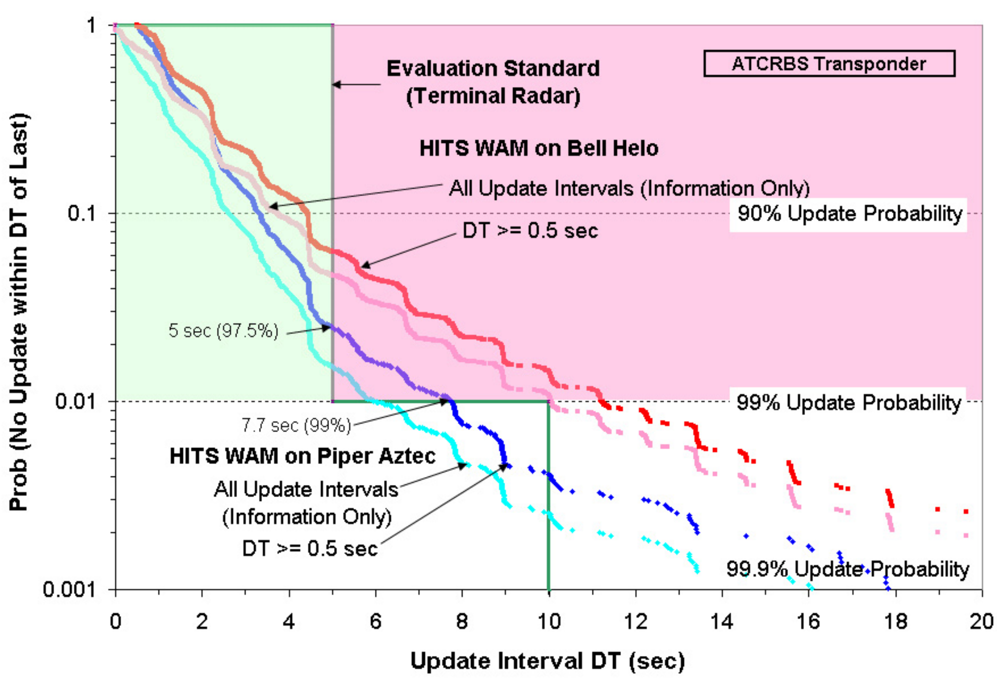

Figure 4-9 Phase I WAM Mode C Update Performance for ATCRBS Transponders.

4.3.4 Code Correctness

HITS reported altitude is derived from transponder barometric altitude (Mode C) messages. These reports can be in error as a result of incorrect decoding—a situation somewhat analogous to a horizontal-position false target report. Measured correctness is shown in table 4-2 as 99.8 percent, satisfying the standard established for this criterion of 99 percent.

Table 4-2 Phase I WAM Altitude Code Correctness for ATCRBS Transponder

Flight Segment	No. of Mode A Pos. Reports	Reports with Altitude Code			
		No. of Rpts	% Pos Rpts	No. Incorrect	% Correct
Helo_2	5045	4387	87.0%	0	100.0%
Helo_3	4680	4139	88.4%	0	100.0%
Helo_4	6496	5080	78.2%	22	99.6%
Helo_5	3451	2865	83.0%	4	99.9%
Piper_2	4969	4568	91.9%	4	99.9%
Piper_3	11,445	9426	82.4%	25	99.7%
Piper_4	7726	6826	88.4%	2	100.0%
TOTALS	**43,812**	**37,291**	**85.1%**	**57**	**99.8%**

4.3.5 Target Resolution

Resolving closely spaced ATCRBS targets—e.g., at the same horizontal position and 1000-ft altitude difference—is a difficult task for an SSR, because the reply messages received at the radar tend to overlap and interfere with each other. On September18, 2002, WAM target resolution testing for ATCRBS-equipped aircraft was performed. The standard for HITS (based on the requirement for the ATCBI-6) includes the following: "Two closely spaced ATCRBS-equipped targets, defined as having 1.7 nmi (10,336 ft) or less separation, shall be resolvable 98 percent of the time."

The Bell 206 flew straight and level profiles, and the Piper Aztec passed the Bell 206 on 6 separate occasions while maintaining an altitude separation of only 750 ft. One of the crossing profiles is illustrated in figure 4-10, where it is clear that the targets are completely resolvable even when they are at the same horizontal position. During all 6 crossing patterns, no-target resolution problems were observed. The 98-percent horizontal position/Mode A and Mode C update intervals were 4.8 sec and 5.7 sec, respectively. The former was within the standard established for this effort, but the latter was not. On the code-correctness evaluation parameter, both Mode A (100 percent) and Mode C (97.9 percent) satisfied the standard of 90 percent.

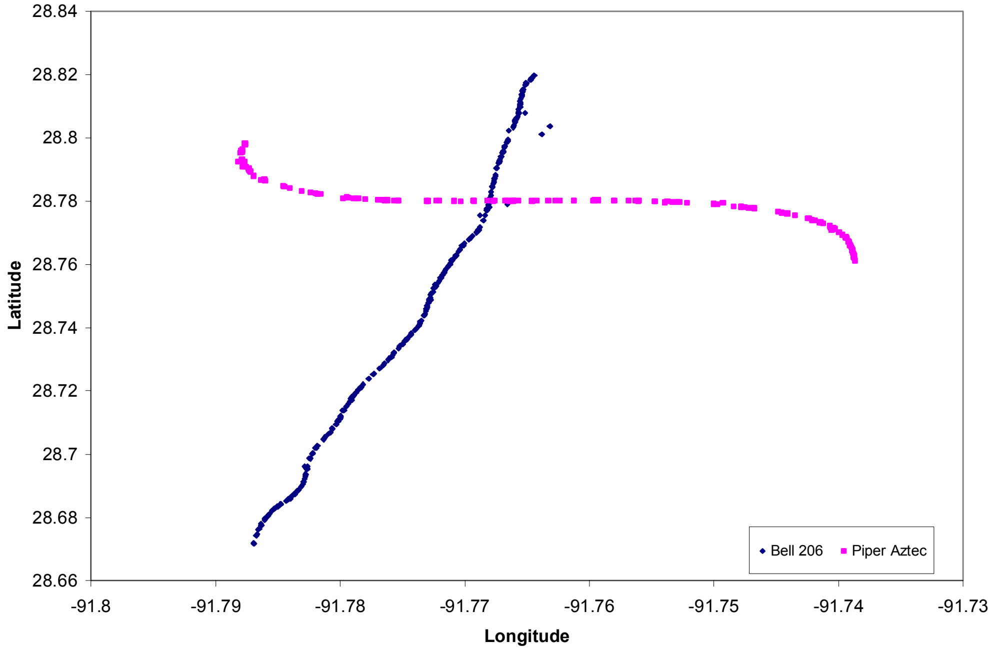

Figure 4-10 WAM Position Reports During Target-Resolution Test.

4.3.6 Summary: WAM Performance for ATCRBS Transponders

Statistics derived from analyzing measurements collected during flight testing on September 17 and 18 are presented in table 4-3, where they are contrasted with standards derived from the ATCBI-6 specification. The measured horizontal-position error, 172 ft (95 percent), easily satisfied the standard established for this evaluation. However, this value may be less than the actual error because of an instrumentation limitation during this test period. (Absolute measurement times were not available for posttest analysis, so the position data were "slid in time" to achieve best agreement with the GPS reference data.) The shape of the cumulative position error curve (with a pronounced knee) suggests that two error sources were present—possibly random TOA fluctuations and ground-bounce multipath.

The fraction of position errors in excess of 1000 ft, 0.12 percent, was slightly larger than the standard of 0.1 percent. Given that the 95-percent error was 172 ft, this indicates that "large" position errors do not follow (and occur more frequently than those for) the commonly assumed Gaussian distribution. The Gaussian distribution is most applicable when errors are due to random noise.

Target report update statistics in table 4-3 are based entirely on the Piper Aztec aircraft. (The Bell 206 update performance was poorer than the Aztec's, apparently because of the low altitudes flown and blockage of the helicopter transponder antenna.) As discussed in Subsection 2.1.5, barometric (Mode C) code update performance is poorer than position/beacon (Mode A) code performance. Update statistics for three criteria did not satisfy the standard of 5 sec (99 percent). The margins between HITS performance and the standard were not large.

Table 4-3 Phase I WAM Summary: ATCRBS Transponder (Sept. 17–18, 2002)

Criterion / Perform.	Isolated Target						Target Resolution			
	Position Error		Update Int. (99%)		Code Correct		Update Int. (98%)		Code Correct	
	95%	>1000 ft	Beacon‡	Altitude	Beacon	Alt.	Beacon‡	Altitude	Beacon	Altitude
Standard*	416 ft	0.1%	5 sec	5 sec	99%	99%	5 sec	5 sec	90%	90%
Measured	172 ft	0.12%	6.3 sec	7.7 sec	100%	99.8%	4.8 sec	5.7 sec	100%	97.9%
Difference†	95%	–20%	–54%	–1%	1%	–4.0%	–14%	–11%	9%	!L% is Not in Table

* Performance standard established for HITS evaluation—see Chapter 3 and appendix A.
† Difference is expressed as a percentage of the standard.
‡ Same statistic applies to the horizontal-position update interval.

4.4 WAM Assessment with Mode S Extended Squitter Transponder (Jan. 28, 2003)

WAM performance of the Phase I HITS system was assessed for a Mode S extended squitter transponder installed on the FAA William J. Hughes Technical Center General Dynamics Convair 580. The WAM assessment was conducted on January 28, 2003, with the aircraft departing and arriving the Lake Charles, Louisiana, airport for morning and afternoon flights. For this test, HITS RU-20 was inoperable and RU-7 was inoperable for one hour. The Volpe Center data-collection system onboard the Convair 580 recorded differential GPS "truth" data in real time.

Two altitudes were flown—approximately 10,000 ft and approximately 22,000 ft—and results are grouped accordingly. Testing on September 11, 2002, (not detailed herein) had shown significant altitude sensitivity, and data were grouped by altitude to verify that this sensitivity had been reduced/eliminated.

Lessons learned from the tests conducted on September 11 and September 17–18, 2002, were incorporated into the HITS system for this test. Interrogation rates for Mode S-equipped targets were increased to once per second for both beacon code (UF05) and altitude code (UF04). For WAM position determination of Mode S-equipped aircraft, the WAM processing used unelicited DF11 message, DF05 and DF04 responses to discrete interrogations for beacon and altitude codes, and (for ADS-B transponders) DF17 extended-length position and velocity squitters. Thus, assuming that the Convair transponder performed properly, there typically were 7 opportunities each second to obtain a WAM message with latitude/ longitude information—2 each derived from DF17 position and velocity squitters, and 1 each derived from DF11 squitters and DF04/DF05 responses. Within the TP, altitude data were incorporated in the algorithm for horizontal position, improving the accuracy of the calculated latitude/longitude. Also, wider "reasonableness" tolerances were used for accepting/rejecting TOA measurements, to avoid rejecting valid data.

4.4.1 Horizontal-Position Accuracy

Figure 4-11 shows the cumulative probability of horizontal position error within the HITS primary coverage region when the aircraft altitude was approximately 22,000 ft. A 95-percent error of 182 ft was computed from 12,011 position measurements. This error compares favorably to the standard of 416 ft. When the aircraft altitude was approximately 10,000 ft, the 95-percent error was 151 ft (computed from 20,927 position measurements). A small position-error sensitivity to altitude was thus observed, as expected based on the discussion of cross-coupling of altimetry errors into horizontal position errors in Section 2.1. Position errors for both altitude regimes are consistent with the 172 ft (95 percent) found for the September 17–18, 2002, test period.

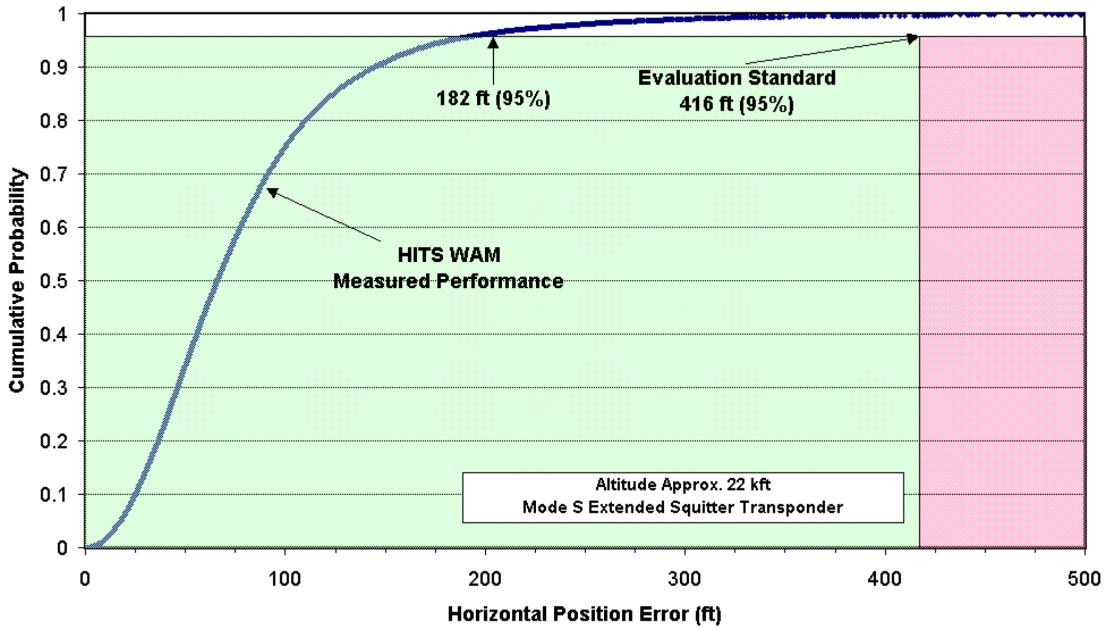

Figure 4-11 Phase I WAM Horizontal-Position Error, Mode S Extended Squitter Transponder.

4.4.2 False Target Probability

Figure 4-12 presents the tail of the accuracy distribution for those portions of the January 28 test where the Convair was flying at or above FL220 ft. The false target performance—defined as the rate of position errors exceeding 1000 ft—was 0.024 percent. The rate when the aircraft was below FL200 was 0.05 percent. The false target performance standard established for Mode S transponders of 0 percent was not satisfied for either altitude regime.

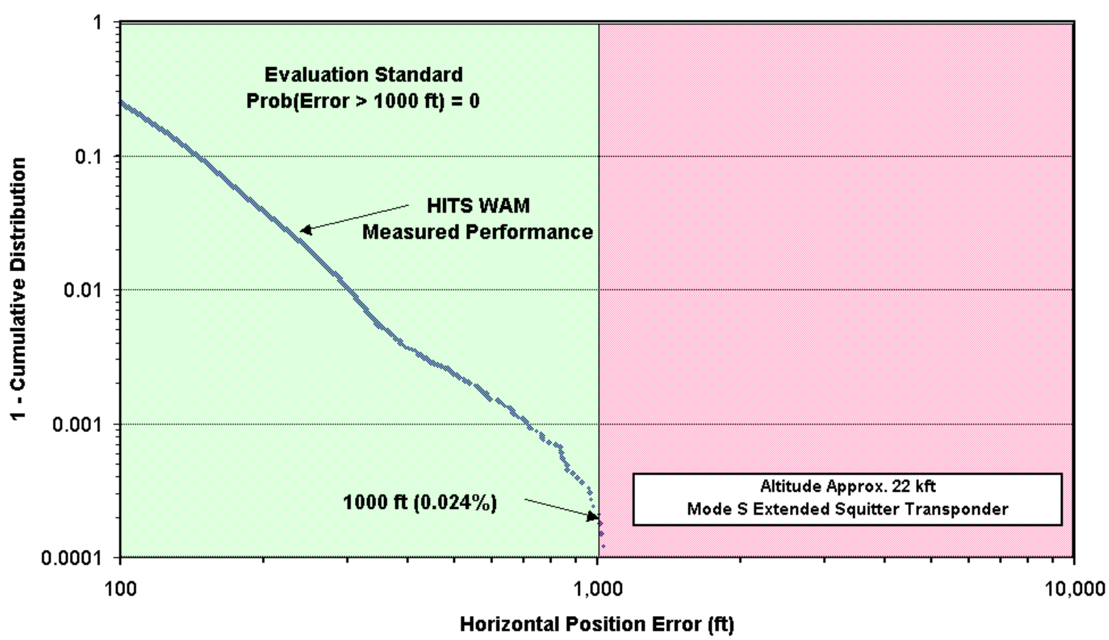

Figure 4-12 Phase I WAM False Target Probability, Mode S Extended Squitter Transponder.

4.4.3 Update Intervals: Target Position, Beacon, and Altitude Codes

WAM update intervals were determined separately for horizontal position, beacon code, and altitude code. The blue curve in figure 4-13 depicts the WAM horizontal-position update interval probability distribution for the January 28, 2003, morning and afternoon flights combined, for both altitudes. The pink curve shows the update behavior for ADS-B position squitters, which demonstrates that additional transponder message types are being used for WAM calculations. For WAM position reports during this test period, the practice of discarding update intervals less than 0.5 sec, used for almost all HITS update analysis, was not followed, because virtually all the update intervals were less than 0.5 sec.* The interval for a 99-percent probability of update is 0.44 sec, which is significantly less (better) than the standard of 5 sec.

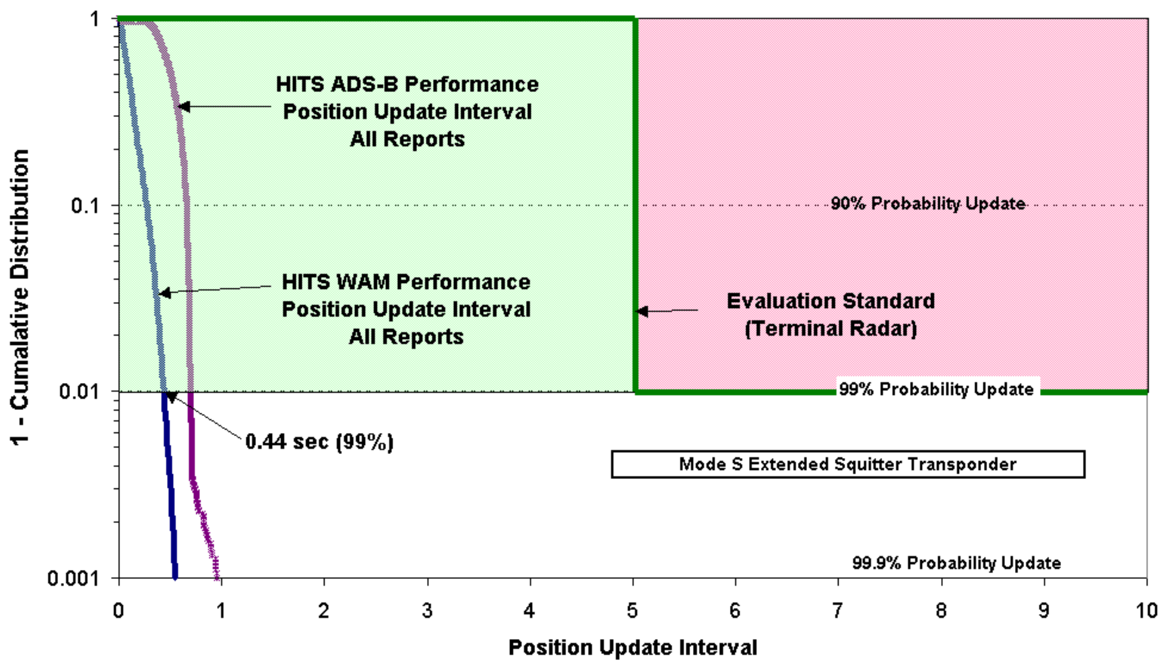

Figure 4-13 WAM Position Update Performance, Mode S Extended Squitter Transponder.

Figure 4-14 depicts the altitude update interval distribution for the two January 28, 2003, flights. The 99-percent probability update interval is 1.9 sec, significantly less (better) than the 5-sec standard. Similarly, the 99-percent probability update interval for the beacon code was 2.3 sec, also significantly better than the standard. Both the beacon code and altitude update statistics were computed after discarding update intervals less than 0.5 sec.

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* For most update analyses presented herein (involving different transponder types and target report parameters), roughly 10 to 20 percent of the update intervals were less than 0.5 sec. This fraction of data could be ignored in computing meaningful statistics, because an adequate amount of data remained. However, for the January 28, 2003, WAM position data, 99.7 percent of the update intervals were less than 0.5 sec—an amount that was too large to neglect. A possible alternative computational method for these data that accounts for the basic premise for ignoring update intervals less than 0.5 sec—that they are not operationally useful—would have been to ignore every other target report. The resulting 99-percent update interval would then have been approximately 1 sec, which also is well within the 5-sec standard established for this effort.

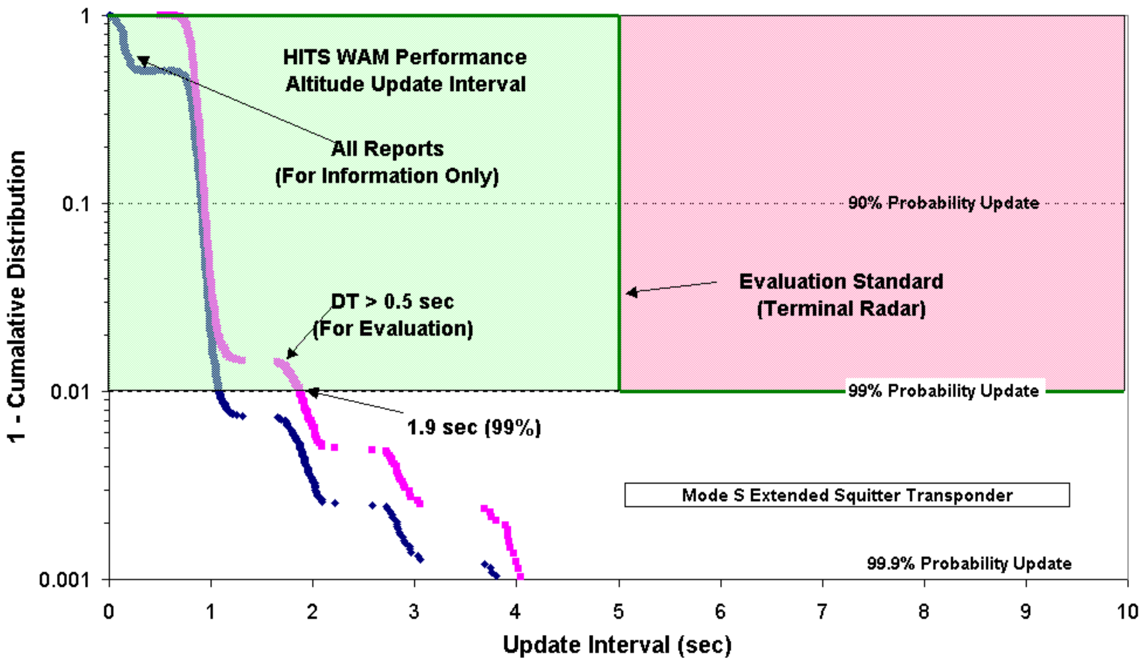


Figure 4-14 WAM Altitude Update Performance, Mode S Extended Squitter Transponder.

4.4.4 Summary: WAM Performance for Mode S Extended Squitter Transponder

Results from the January 28, 2003, flight test are summarized in table 4-4 (aircraft altitude approximately 10,000 ft) and table 4-5 (aircraft altitude approximately 22,000 ft). All performance criteria were met, with the exception of false target report rate, which was the subject of a software improvement that was implemented during Phase II. Overall, these proved to be the best WAM performance achieved during the HITS effort. The reasons are attributed to: (1) quality of the aircraft transponder and antenna installation (obstruction free); (2) relatively high aircraft altitudes permitted visibility by many RUs; and (3) relatively high RU interrogation rate. In fact, the only area of concern was the high rates of interrogating the Mode S extended squitter transponder.

Table 4-4 Phase I WAM Summary: Mode S Extended Squitter Transponder (Alt. ≈ 10K ft)

Criterion / Performance	Position Error		Update Interval (99%)			Code Correct	
	95%	>1000 ft	Position	Beacon	Altitude	Beacon	Altitude
Standard*	416 ft	0%	5 sec	5 sec	5 sec	N/A	N/A
Measured	151 ft	0.05%	0.44 sec‡	2.3 sec	1.9 sec	N/A	N/A
Difference†	64%	–0.05%	91%	54%	62%		

* Performance standard established for HITS evaluation—see Chapter 3 and appendix A.
† Difference is expressed as a percentage of the standard, except when the standard is zero.
‡ Statistic computed without deleting intervals less than 0.5 sec.

Table 4-5 Phase I WAM Summary: Mode S Extended Squitter Transponder (Alt. ≈ 22K ft)

Criterion / Performance	Position Error		Update Interval (99%)			Code Correct	
	95%	>1000 ft	Position	Beacon	Altitude	Beacon	Altitude
Standard*	416 ft	0%	5 sec	5 sec	5 sec	N/A	N/A
Measured	182 ft	0.024%	0.34 sec‡	2.3 sec	1.8 sec	N/A	N/A
Difference†	56%	–0.02%	93%	54%	64%		

* Performance standard established for HITS evaluation—see Chapter 3 and appendix A.
† Difference is expressed as a percentage of the standard, except when the standard is zero.
‡ Statistic computed without deleting intervals less than 0.5 sec.

4.5 ADS-B Flight Test Results (Jan. 29, 2003)

The January 29, 2003, flight was employed to assess the HITS Phase I system ADS-B performance relative to the ATCBI-6 specification. Two parameters were considered:

- RU detection range
- Position update interval

Additionally, this test validated the ability of the HITS Phase I system to receive and decode Mode S extended squitter ADS-B messages (DF17). The message set decoded by the RUs included the aircraft position (latitude/longitude), barometric altitude, velocity (north/east/vertical components), and flight ID. However, the ASTERIX 10 output from HITS TP to the Volpe Center's Data Collection System did not contain barometric altitude, velocity, or flight ID data items. Although it is highly desirable that all these items be available at the output interface, it should be noted that, of these, only the barometric altitude is provided by an SSR. Additionally, the FAA Tech Center Convair transponder used for this test period conformed to an older version of the RTCA standard for ADS-B messages and did not include aircraft beacon code in its DF17 squitters. The RTCA ADS-B standard has been updated to correct this oversight (ref. 11).

4.5.1 RU Detection Range

Three RUs were selected to assess the Phase I HITS ADS-B system detection range. Each had a distance-measuring-equipment (DME) antenna (8-dB gain) mounted on top of a tower stack, resulting in unobstructed omnidirectional coverage. Table 4-6 shows the measured ADS-B detection ranges of these RUs, along with their antenna heights. The aircraft for this test flew at approximately FL210. The corresponding radio line of sight is approximately 190 nmi, so Earth curvature was not considered to be a factor in limiting detection range.

Table 4-6 Selected RU ADS-B Detection Ranges (Jan. 29, 2003)

RU Site	Location	Antenna Height (ft MSL*)	Max. Detection Range (nmi)
Pecan Island	Onshore	210	149
Eugene Island 51	Offshore	115	144
South Marsh Island 275	Offshore	230	165
Average	—	—	153

* MSL= Mean sea level

The reception range for all three RUs, 144 nmi to 165 nmi, was approximately 50-percent better than the 100-nmi range that was predicted for this link (see Section 2.2). It is likely that the better-than-expected range came from a combination of factors—e.g., actual receiver sensitivity and cable losses were more favorable than was assumed.

4.5.2 Position Update Interval

The Convair transponder squittered ADS-B position messages nominally twice per second. Update intervals (99 percent) for these messages at the selected RUs are shown in table 4-7. These intervals are significantly smaller (better) than the standard of 5 sec. The table also shows the message acceptance rate* for each RU (assuming a 2-per-sec message broadcast rate), which provides another measure of how well the Mode S extended squitter messages were detected by individual RUs.

Table 4-7 ADS-B Position Update Intervals (Jan. 29, 2003)

RU Site	Message Acceptance Rate (%)	Update Interval (sec, 99%)
Pecan Island	77	2.3
Eugene Island 51	69	3.5
South Marsh Island 275	73	3.2
Average	73	3.0

4.5.3 Performance Summary

The HITS Phase I system ADS-B performance for the January 29, 2003, test is summarized in table 4-8. For those messages that were available (position squitters), detection range and update interval performance were superior to that of terminal radar. However, not all needed data were available at the interface.

Table 4-8 ADS-B Performance Summary

Criterion / Performance	Detection Range	Update Interval (sec, 99%)			False Target Prob.
		Position	Beacon Code‡	Altitude Code§	
Standard*	50 nmi	5 sec	5 sec	5 sec	0%
Measured	153 nmi	3.0 sec	N/A	N/A	0%
Difference†	206%	40%			0%

* Performance standard established for HITS evaluation—see Chapter 3 and appendix A.
† For dimensioned quantities (units of nmi or sec), the difference is expressed as a percentage of the standard.
‡ Not broadcast by aircraft transponder.
§ Broadcast by aircraft transponder but not supplied by HITS TP ASTERIX 10 interface.

* Message acceptance rate (MAR) is the fraction of transmitted messages that is received and correctly decoded. MAR is a metric commonly used to quantify the performance of communications systems.

5. Phase II Test: High-Density Helicopter Terminal Surveillance System

5.1 Rationale for Phase II

The Helicopter In-Flight Tracking System (HITS) Phase II system was configured to test wide-area multi-lateration (WAM) surveillance for a "small" terminal area—on the order of 40 nmi in diameter, as opposed to the 120-nmi diameter of a standard terminal area—at Intracoastal City, Louisiana (INCY). There is a need for less-capable/lower-cost alternatives to the "full-capability" terminal area radar surveillance systems now deployed. The Federal Aviation Administration (FAA) maintains air traffic control towers at approximately 400 airports. Of these, approximately half have terminal radars. The cost of a radar install-ation cannot be justified for the remaining half, based on insufficient traffic levels (particularly air carrier traffic) and/or insufficient frequency of instrument meteorological conditions (IMC). Some of these airports have terrain or other obstacles in/near the primary approach corridor. Additionally, there are non-FAA-towered airports with high levels of operations (albeit not air carrier) and relatively high IMC frequencies that could derive safety and capacity benefits from an alternative to conventional radar. High-density helicopter operations bases are examples of these.

For helicopters operating in the Gulf of Mexico region, instrument-flight-rules (IFR) flights over the water are conducted using nonradar procedures. The Lafayette, Louisiana, terminal radar approach control facility (TRACON) controls overland IFR traffic arriving/departing Intracoastal City, Louisiana, above a minimum altitude of 500 ft. Only one helicopter is permitted to approach/depart below 500 ft at one time ("one-in/one-out" rule). For example, a helicopter on approach to INCY necessitates that all departing aircraft hold on the ground and all arriving aircraft maintain positions outside the INCY operating area until the helicopter of interest has landed or canceled the IFR operation.

In addition to "small" terminal areas being potential beneficiaries of low-cost/reduced-capability surveil-lance service, there are several standard terminal areas in the National Airspace System (NAS) that could benefit from supplementary coverage by a second surveillance system. In some cases, there are "holes" in the airport radar coverage due to terrain or structures obstructing its line of sight, especially at lower altitudes. When these holes are over satellite airports, inhibiting radar controllers' ability to "see" aircraft arriving or departing, then one-in/one-out procedures must be implemented during IFR operations, and traffic flow is restricted.

The HITS Phase II system provided an opportunity to assess WAM as a terminal surveillance system in a high-density helicopter operations area. The assessment was conducted June 10–11, 2003, using the config-uration described in Subsection 2.3.2.

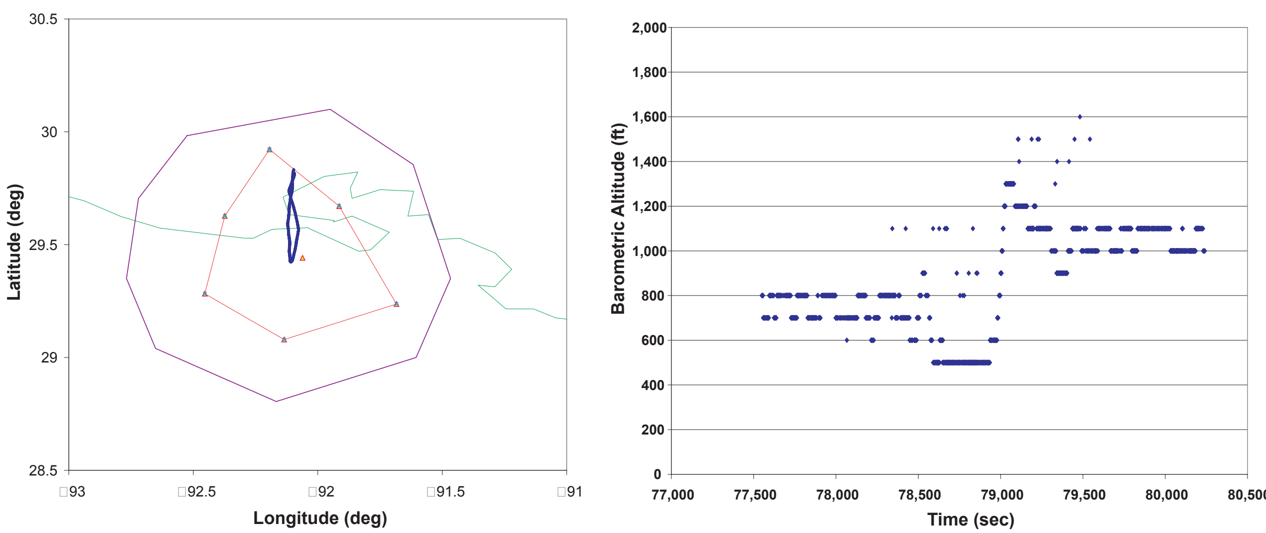
5.2 Test Aircraft and Flight Profiles

Most helicopters operating in the Gulf of Mexico region are equipped with Air Traffic Control Radar Beacon System (ATCRBS) (Mode A/C) transponders. For the Phase II test, HITS was configured to elicit ATCRBS replies at a higher rate than for the Phase I configuration. Update performance for the Phase I test conducted September 17–18, 2002, did not satisfy the criteria established for this effort. For the Phase II test, the HITS system was configured to elicit at least 2 Mode A and 2 Mode C ATCRBS replies each second, for every aircraft location in the coverage area. This was accomplished by: (a) arranging the remote units (RUs) so that each location in the coverage area was visible to 2 receive-transmit (RT) units, and (b) programming each of the 4 RTs to broadcast one 24-step whisper/shout sequence each second. Each sequence began at a power level of 57 dBm (500 W) and decreased by 1 dB in each subsequent step. Each step included both Mode A and Mode C interrogations (termed a "doublet").

Two Bell 206 Long Ranger helicopters (figure 5-1) were leased from Petroleum Helicopters, Incorporated (PHI). Each was equipped with an ATCRBS (Mode A/C) transponder and the Volpe Center Airborne Data Collection System (ADCS, appendix B). Performance characteristics of both transponders were validated prior to each day's testing. The full set of "for-the-record" flight profiles is provided in appendix E; figure 5-2 shows an example. Flights were launched from Lafayette Regional Airport and operated under visual flight rules (VFR) at less than 2000 ft of altitude, because of cloud ceilings.

(a) Tail Number N2777D **(b) Tail Number N906PH**

Figure 5-1 Bell 206 Long Ranger Helicopters Leased from PHI.



(a) Ground Track (WAM Target Reports) **(b) Altitude (Transponder Mode C Reports)**

Figure 5-2 Tail Number N2777D Flight Profile on June 10, 2003.

5.3 WAM Performance with ATCRBS Transponder (June 10–11, 2003)

The HITS Phase II system was employed to assess the following WAM performance parameters:

- Horizontal position accuracy
- False target rate
- Update intervals
  - Horizontal position/Mode A (beacon) code
  - Mode C (altitude) code
- Target resolution
- Transponder occupancy time
- Special Position Identification

Position accuracy, false target rate, and update interval parameters were tested on June 10–11.* Only target reports collected within the inner and outer coverage areas at the proper altitudes (100 ft and above for the inner coverage area and 1000 ft and above for the outer coverage area) were used. The helicopters were assigned individual/unique Mode A beacon codes, to distinguish them and simulate code assignments for IFR operation.

5.3.1 Horizontal-Position Accuracy

Figure 5-3 depicts the cumulative distribution of horizontal-position errors—defined as the difference between WAM target reports and the Global Positioning System (GPS) reference—for four flights on June 10 and 11, 2003, involving a total of 14,676 target reports. Errors for the two aircraft were comparable, as were the errors for latitude/longitude axes. Qualitatively, the appearance of figure 5-3 is quite similar to horizontal-position error distributions found during Phase I (figures 4-6 and 4-11). All three curves have distinct knees, suggesting the presence of two error mechanisms. Quantitatively, the aggregate Phase II error, 105 ft (95 percent), demonstrated performance significantly better than the standard derived from ATCBI-6 specification, 416 ft (95 percent), and considerably better than that for the Phase I system. The likely causes of this better performance were: (1) the lower flight altitudes involved (entirely less than 2000 ft), which minimized the effect of altitude errors cross-coupling into horizontal position errors (see Subsection 2.1.3); and (2) a tracker that was implemented for this test period, which reduced the frequency of large position errors (see next subsection) to approximately 10 percent of the measurements (versus approximately 15 percent during Phase I).

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* Flights were flown on June 12, to enable Sensis to assess (a) the range performance of the HITS RTs used to interrogate ATCRBS targets, and (b) how well the Phase II system provided target reports for helicopters with the same beacon code, to facilitate implementation of system improvements.

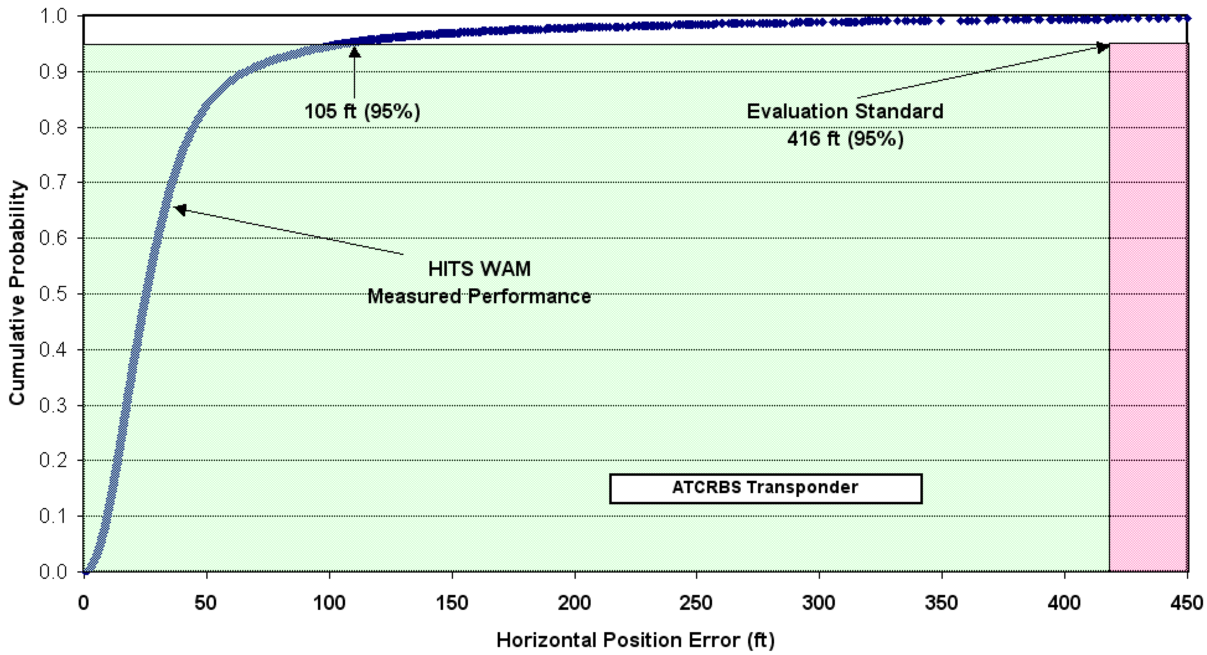

Figure 5-3 Phase II WAM Horizontal Position Accuracy with ATCRBS Transponder.

5.3.2 False Target Probability

Following the Phase I assessment, the target-processor (TP) software was modified to reduce the rate of false target reports, particularly for ATCRBS-equipped aircraft. A tracker (essentially, an algorithm that fit a curve to previous target reports) was implemented internal to the TP (i.e., its data were not output). The tracker predicted the position of each new target report (derived from time-of-arrival (TOA) measurements on transponder messages) by, in effect, extrapolation from earlier reports.* Then, the horizontal distance between the new report and tracker prediction was calculated. The TP withheld (did not output) target reports for which this difference was greater than 1000 ft. With this modification, only one false target report—as defined by horizontal distance greater than 1000 ft between a WAM report and the GPS reference—was found (figure 5-4). This performance satisfied the standard of less than 0.1-percent false target reports.

* The internal tracker may not correctly predict a new aircraft position as a result of (a) errors in previous position reports, and (b) unanticipated aircraft motion (typically, turns) between the time of the earlier measurements and the time corresponding to the prediction. Thus use of such a tracker entails the risk of eliminating valid reports as well as the benefit of eliminating "bad" reports.

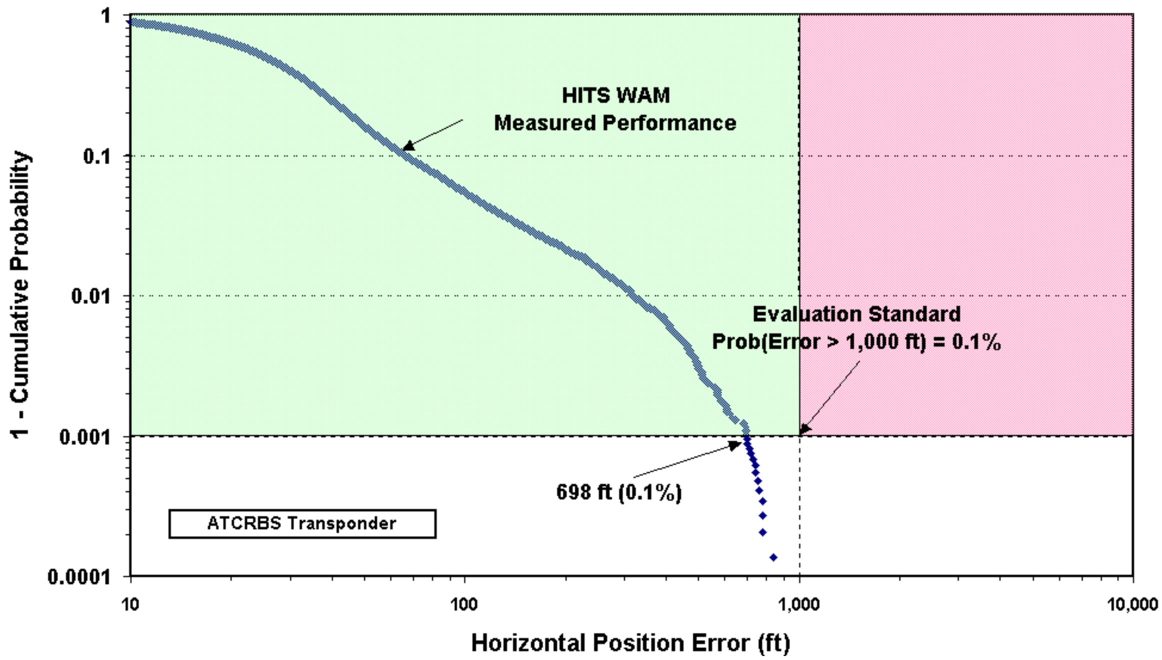

Figure 5-4 Phase II WAM False Target Probability with ATCRBS Transponder.

5.3.3 Update Intervals: Horizontal Position/Mode A Code and Mode C Code

Table 5-1 shows the update-interval statistics for the 4 evaluation flights. For both aircraft and both update types (horizontal position/Mode A and Mode C), the composite intervals (99-percent probability) did not meet the performance standard of 5 sec established for a system serving a terminal area. Position/Mode A updates occurred more frequently than Mode C updates, as a consequence of the HITS design (the former are necessary for the latter—see Subsection 2.1.5). Update performance for helicopter N2777D was consistently better than that for N906PH, suggesting that there may have been an issue with the transponder of the latter or its installation in the airframe. For N2777D, update performance was better on June 10 than on June 11, suggesting that update performance increases with altitude.

Table 5-1 Phase II WAM Isolated Target Update Intervals for ATCRBS

Aircraft	Day	Altitude	Position/Mode A		Mode C	
			99% Value*	No. of Intervals	99% Value*	No. of Intervals
N2777D	June 10	< 2 kft	4.8 sec	1580	6.3 sec	1410
	June 11	< 1 kft	5.8 sec	5053	6.5 sec	4480
	Composite		5.6 sec	6633	6.5 sec	5890
N906PH	June 10	< 2 kft	7.8 sec	1215	10.8 sec	1030
	June 11	< 2 kft	7.6 sec	1598	8.3 sec	1437
	Composite		7.7 sec	2813	9.3 sec	2467
Composite			**6.2 sec**	**9446**	**7.3 sec**	**8357**

* Intervals less than 0.5 sec and greater than 30 sec are not included in this statistic.

In 7 of the 8 combinations (of aircraft, flight, and ATCRBS mode) investigated, the update interval satisfied the 10-sec standard established for en route surveillance. Because some of the airspace used during this test period is under the jurisdiction of the Houston Air Route Traffic Control Center (ZHU ARTCC), the update evaluation standard could be considered to be overly stringent. The more-demanding terminal-area standard was employed in order to evaluate the Phase II configuration as representative of a WAM system that might be deployed as an alternative to a terminal radar.

Several factors were identified that may have degraded update performance for these tests. First, the N906PH helicopter transponder was replaced on June 10 after the morning flight (data for that flight are not included herein). Real-time viewing of the maintenance display terminal (MDT) had indicated that the aircraft transponder was not responding sufficiently to Mode A/C interrogations. Subsequently, the transponder was swapped for a higher-powered unit (600 W). Although the PHI avionics technician validated the transponder operation, subsequent results for N906PH were still not as good as those for N2777D.

Second, the flight profiles, particularly their low altitudes (2000-ft maximum), adversely affected update performance.* Table 5-2 shows that update performance generally improved as altitude increased. This is because at least three RUs must receive/decode a transponder Mode A message in order for a WAM update to occur. As aircraft altitude increases, line-of-sight access to all RUs improves.

Table 5-2 Phase II WAM Mode A / Mode C Update Intervals (sec, 99%) vs. Altitude

Aircraft	Flight \ Altitude (ft)	0 – 500	600 – 1,000	1,100 – 1,500	1,600 – 2,000
N2777D	June 10	3.8 / 4.1	5.3 / 7.1	4.1 / 5.6	N/A
	June 11	6.1 / 6.8	5.7 / 5.8	N/A	N/A
N906PH	June 10	N/A	15 / 21	7.8 / 10	6.7 / 7.7
	June 11	15 / 15	6.1 / 7.6	4.7 / 4.7	5.1 / 6.0

A third possible reason for the poor Phase II update results involves the location of transponder antenna on the PHI Bell 206 airframe. Obstructions are located on the underside of the airframe along with the transponder antenna (figure 5-5). Possible obstructions include: landing skids, other antennas, and a tank containing a flotation device. When combined with the low-altitude flight profiles and aircraft banking during the target-resolution tests, it is plausible that a significant fraction of interrogations and/or transmitted messages were obstructed.

Subsequent tests were conducted on September 10–11, 2003, using different helicopter airframes as targets of opportunity (Sikorsky S-76, Bell 407, and MBB BO-105). Preliminary results indicated improved update performance. However, the small data sample size and the inability to specify target maneuvers limited the strength of any conclusions that could be drawn.

* Note that low aircraft altitude tends to improve accuracy (reduce the effect of altitude errors on horizontal position calculations) but decrease update performance.

(a) Port View

(b) Front View

(c) Rear View

(d) Starboard View

Figure 5-5 Bell 206 Transponder Antenna Placement.

It is reasonable to ask whether a FAA secondary surveillance radar (SSR) would satisfy the update criteria employed herein, for equivalent conditions—same transponder/antenna/installation, same flight altitudes, and same aircraft-sensor distances. As discussed in Section 3.3, there is no assurance of an affirmative answer, because formal tests of radars are not conducted using airframes that have their transponder antennas blocked to the same extent as those on the test aircraft.

Qualitatively, because the secondary radar has more robust up and down links, owing primarily to its large antenna, it is more likely to get a response to any given interrogation. On the other hand, some factors favor the HITS Phase II configuration in an update performance comparison with SSR. During this test period, HITS interrogated each aircraft more often than an SSR (approximately 10 Mode A interrogations in a 5-sec interval, versus 8 for an older ATCRBS SSR). Moreover, HITS spread those interrogations approximately evenly over each 5-sec interval (whereas an SSR concentrates its interrogations into approximately 30 msec, when its antenna is pointed at the aircraft), providing more independent opportunities to avoid obstructions caused by maneuvers and nulls in the antenna pattern.

5.3.4 Mode C Code Correctness

Mode C code correctness was assessed during Phase II.* A Mode C code report was determined to be incorrect if it differed by more than 300 ft from the previous Mode C report from the same aircraft. Results, presented in table 5-3, show that the performance standard of 99-percent Mode C code correctness was satisfied. The table also shows that, of all target reports collected during Phase II testing, 83 percent contained Mode C information. This fraction is consistent with findings from the Phase I September 17–18, 2002, test period, where 85 percent of the target reports had altitude information.

Table 5-3 Phase II WAM Mode C Code Correctness

Aircraft	Flight	No. of Mode A Reports	No. of Mode C Reports	No. of Mode C Reports Incorrect	Percentage of Mode C Reports Correct
N2777D	June 10	2480	2021	20	99.0%
	June 11	8227	6834	0	100.0%
	Total / Ave.	10,707	8855	20	99.8%
N906PH	June 10	1631	1323	9	99.3%
	June 11	2338	2045	2	99.9%
	Total / Ave.	3969	3368	11	99.7%
Total or Average		**14,676**	**12,223**	**31**	99.7%

5.3.5 Target Resolution

Target-resolution tests were conducted with discrete Mode A codes assigned to the two aircraft. During these tests, N2777D flew a nominally straight track and N906PH crossed the straight track at 500 ft above. VFR conditions prevailed. Two pairs of flight sets were performed (figure 5-6)—a simple crossing with 90 deg between the tracks (test 1) and a series of crossings whereby N906PH repeatedly overtook N2777D (test 2).

Figure 5-6 shows that, qualitatively, HITS WAM performance for the target-resolution tests was quite good—there were no "target swaps," nor prolonged periods without reports. Table 5-4 summarizes the update interval and code-correctness performance for the resolution tests. Data for the table were limited to situations when the horizontal distance between the two aircraft was 1.6 nmi or less. For 5 of 8 combinations of crossing test, aircraft, and ATCRBS mode, the results met the evaluation standard of updates within 5 sec (98 percent). In all cases the 90-percent correct-code standard was met. All three failures to meet the update standard occurred for N906PH. This is consistent with table 5-1, which showed poorer update performance by N906PH during isolated target tests. The moderately substandard update performance on the target-resolution tests is consistent with that for Phase II as a whole (see Subsection 5.3.3).

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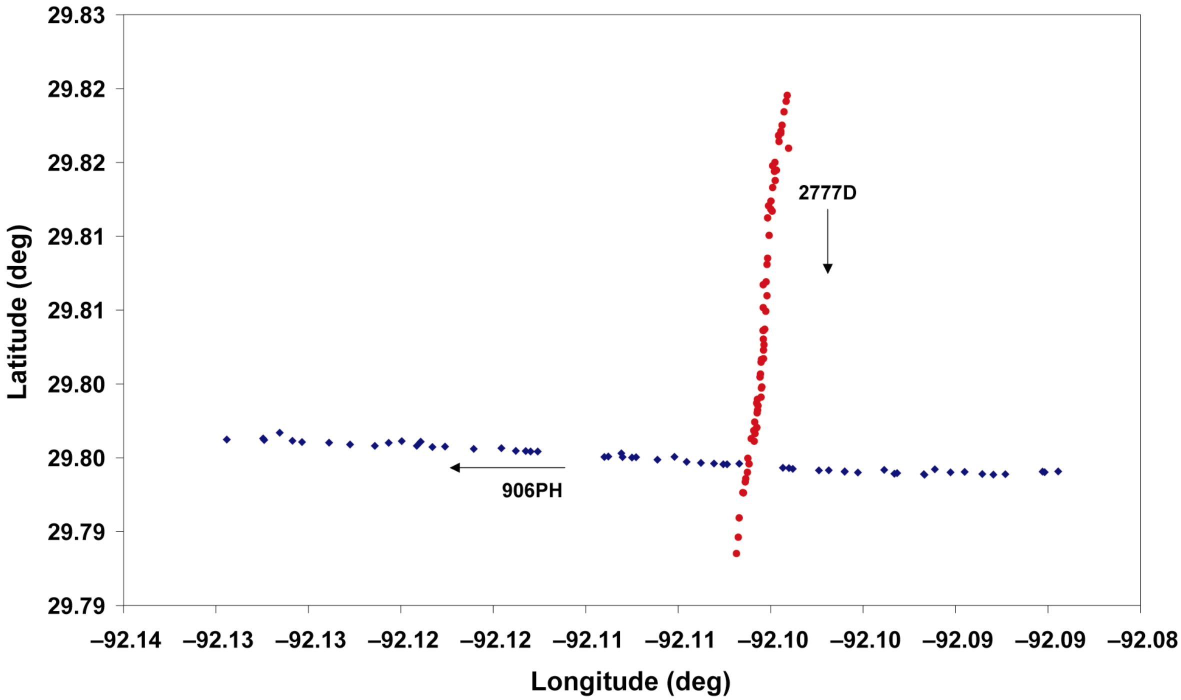
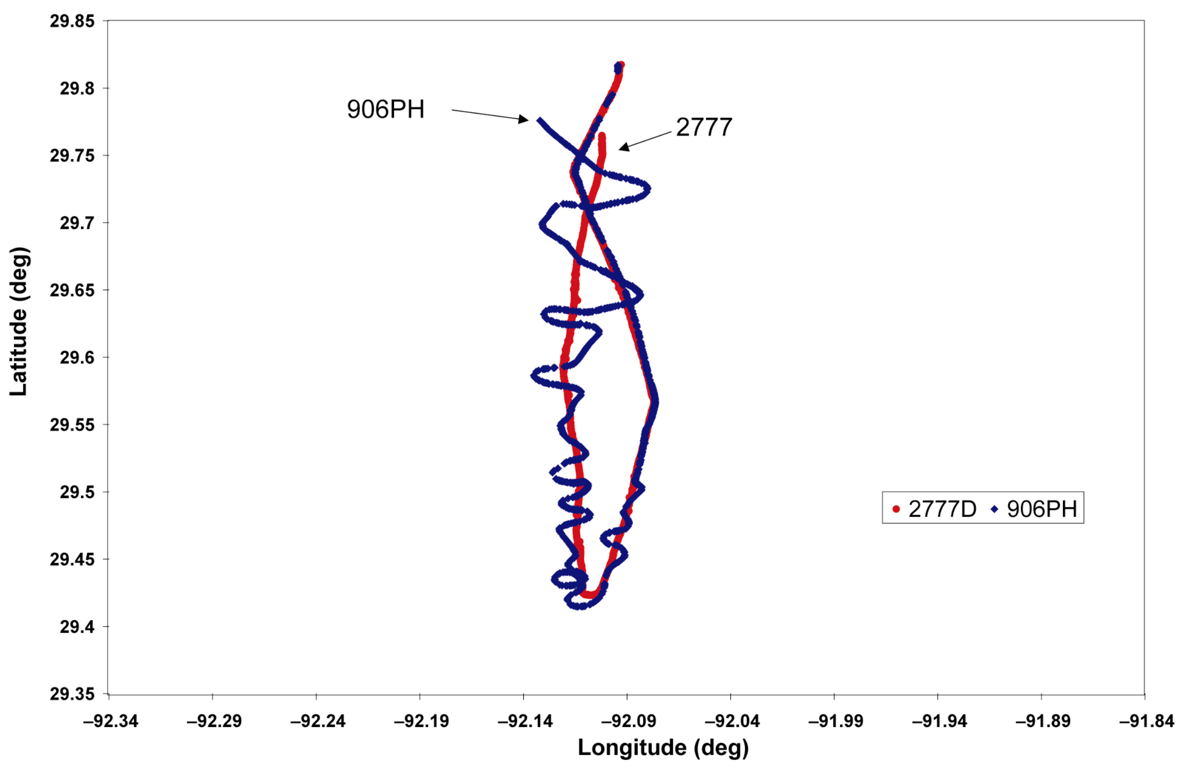
* As discussed in Section 2.1, Mode A/position reports were distributed by the TP only if the same Mode A code was received and decoded to the same result by three or more RUs. There is an extremely small likelihood of the same error occurring at each RU, so Mode A codes were assumed to be 100 percent correct.



(a) Crossing Test 1



(b) Crossing Test 2

Figure 5-6 Phase II Target-Resolution Test Ground Tracks (WAM Target Reports).

Table 5-4 Phase II WAM Target-Resolution Test Results

Aircraft & Parameter / Flight	N906PH				N2777D			
	Update Interval (98%)		Code Correctness		Update Interval (98%)		Code Correctness	
	Mode A	Mode C	Mode A	Mode C	Mode A	Mode C	Mode A	Mode C
Test 1	4.8 sec	7.5 sec	100%	100%	4.7 sec	4.8 sec	100%	100%
Test 2	6.1 sec	7.8 sec	100%	99%	3.8 sec	4.8 sec	100%	98%

5.3.6 Transponder Occupancy

Constraints on HITS use of the 1030- and 1090-MHz frequencies are discussed in Subsection 2.1.5. The FAA Office of Spectrum Policy and Management, the U.S. Government agency responsible for these frequencies, included in the license permitting HITS to radiate in the Gulf of Mexico region a requirement that the system not elicit more than 10 replies per second from any aircraft transponder. The FAA "Spectrum Office" also verbally expressed a desire that HITS WAM occupancy of any transponder be limited to 0.25 percent (also expressed as 2500 μsec/sec).*

The Phase II test, with its relatively high interrogation rate, was selected for evaluating HITS performance relative to these constraints. The test data were reviewed to determine the reply rate of the two test aircraft that could be attributed to HITS interrogations. Typically up to 4 replies/sec were observed. No instances were found where a test aircraft emitted 10 replies in a 1-sec interval.

Transponder occupancy was not measured during HITS testing. Instead, an analysis was performed to predict occupancy times for a Mode A/C transponder experiencing the high-rate interrogation scheme used for Phase II. A model was developed, based on transponder probability of detection, RF link margin, and line of sight from each RU to a postulated aircraft location. An aircraft transponder was assumed to be occupied if it received a Mode A/C interrogation, a Mode A/C suppression, or a Mode S discrete interrogation at a power level above the transponder detection threshold.

Figure 5-7 shows the predicted occupancy times (in units of μsec/sec) for a Mode A/C transponder at 5000 ft during a 1-sec interval. Possible target locations are separated by 5 nmi. RU 3 and RU 7 are assumed to be interrogating: each emits a 24-step whisper/shout sequence each second, and in combination they broadcast a total of 50 discrete Mode S interrogations (an upper limit for the HITS equipment).

Boldface values in figure 5-7 indicate the predicted occupancy time is greater than the performance standard of 2500 μsec/sec. The predicted maximum is 6220 μsec/sec, or a factor of 2.5 times the standard. However, this value should be viewed in the context of occupancy standard for TCAS, 10,000 μsec/sec. Inasmuch as an aircraft may be within range of multiple TCAS units, the occupancy standard for HITS requested by the FAA "Spectrum Office" appears to be overly stringent.

* Transponder occupancy is defined as the time when a transponder cannot reply to an SSR or Traffic Alert and Collision Avoidance System (TCAS) interrogation because it is being "occupied" by a WAM interrogation—either actually replying or inhibited ("suppressed") from replying.

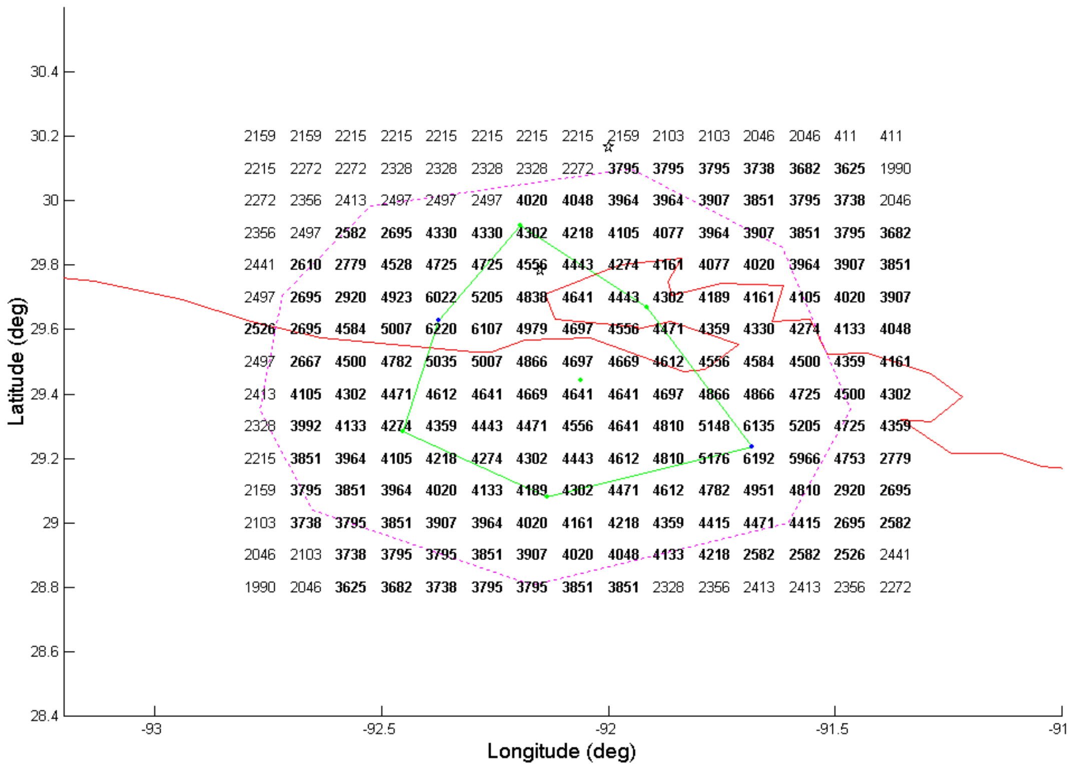


Figure 5-7 Predicted WAM-Induced ATCRBS Transponder Occupancy Times (μsec/sec).

5.3.7 Special Position Identification

An "Ident" capability is a requirement of both aircraft transponders and the ground equipment that receive and process transponder messages. When the Ident button is depressed in the aircraft, typically at the request of an air traffic controller, the end result is that the aircraft symbol on the controller's monitor temporarily changes in an easily distinguished way (e.g., flashes), enabling the controller to identify the aircraft. Electronically, when the Ident button is activated, a Mode A/C transponder message includes an additional Special Pulse Indicator (SPI) placed 4.35 μsec after the second framing pulse (termed F2).

During Phase II testing, a request was made from the PHI Communications Center to both N906PH and N2777D to press the Ident feature on their transponders. On the MDT display at the PHI facility, the symbols for both aircraft flashed for approximately 20 sec, indicating successful SPI pulse decoding by the Phase II HITS system.

5.3.8 Performance Summary

Table 5-5 summarizes the flight-test performance of the HITS Phase II system. For update performance, only data from helicopter N2777D are used, because there were unresolved questions concerning the transponder and its installation on N906PH. The criteria for horizontal accuracy, false target probability, Mode C code correctness, and SPI pulse detection were satisfied. Additionally, the HITS performed well on target-resolution tests. However, for Mode A and Mode C update intervals, the Phase II system did not meet the standard established for this effort. Additionally, the calculated transponder occupancy was in excess of the level requested by the FAA Spectrum Office. However, the performance shortfalls are not dramatically large, and options are available to address them.

Table 5-5 Phase II WAM Summary: ATCRBS Transponder, Low-Altitude Aircraft

Criterion / Perform.	Isolated Target						Target Resolution			
	Position Error		Update Interval (99%)		Code Correct		Update Int. (98%)		Code Correct	
	95%	>1000 ft	Beacon[‡]	Altitude	Beacon	Altitude	Beacon[‡]	Altitude	Beacon	Altitude
Standard[*]	416 ft	0.1%	5 sec	5 sec	99%	99%	5 sec	5 sec	90%	90%
Measured	105 ft	0.01%	5.6 sec	6.5 sec	100%	99.7%	4.0 sec	4.8 sec	100%	99%
Difference[†]	75%	90%	–12%	–30%	1%	0.7%	20%	4%	11%	10%

[*] Performance standard established for HITS evaluation—see Chapter 3 and appendix A.
[†] Difference is expressed as a percentage of the standard.
[‡] Same statistics apply to the horizontal-position update interval.

6. Phase III: High-Altitude Oceanic Surveillance System

6.1 Phase III Overview

6.1.1 Objectives and Challenges

Phase III focused on surveillance of aircraft in the Gulf high-altitude Oceanic sectors (figure 6-1). The Gulf Oceanic sectors begin approximately 75 nmi south of the U.S. coastline and extend southward to the boundaries with Flight Information Regions (FIRs) managed by Mexico and Cuba, 300–350 nmi from the U.S. coast. Vertically, the high-altitude sectors extend upward from FL180 to FL600. Flight operations in these sectors are entirely under instrument flight rules (IFR), controlled by the Houston Air Route Traffic Control Center (ARTCC) and Miami ARTCC.

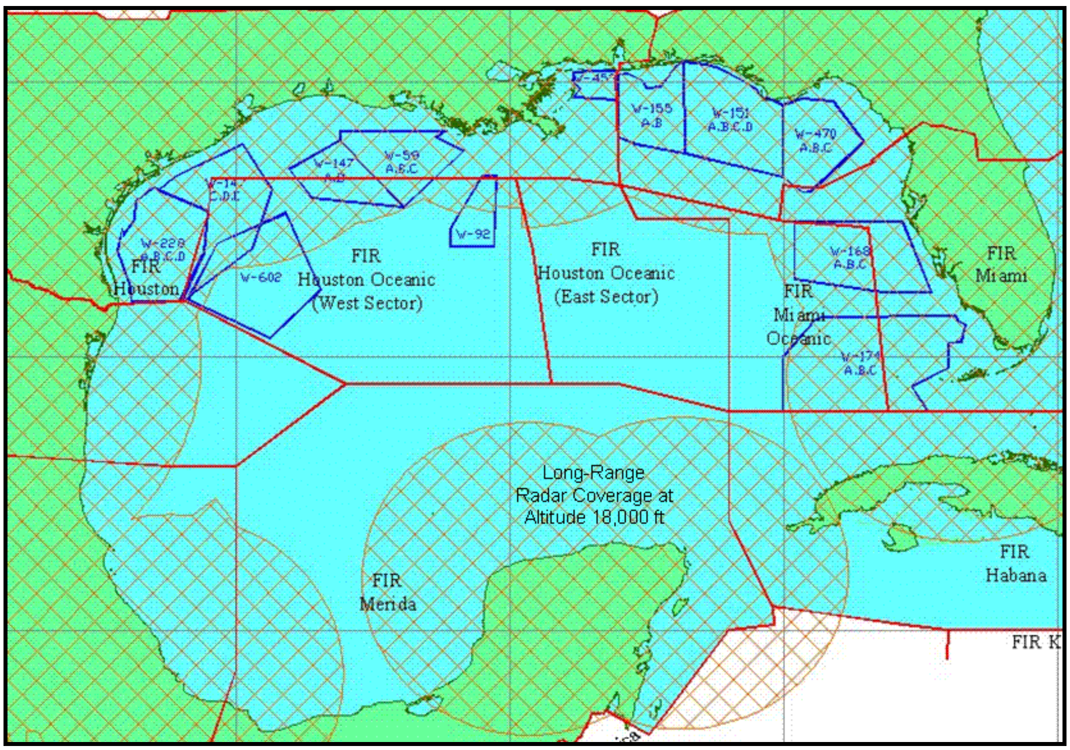


Figure 6-1 Gulf of Mexico Region Airspace.

Most of the two FIRs in Houston's airspace, and a portion of the Miami FIR, lack continuous surveillance coverage, significantly limiting their capacities. Aircraft traveling in nonradar airspace use time-based, oceanic in-trail separation standards* of 10 min (Houston West) and 15 min (Houston East and Miami). In terms of distance, these time separations are approximately equivalent to 50 to 100 nmi (depending upon aircraft speed), figures that are dramatically larger than the 5-nmi separation standard for radar-controlled domestic en route airspace. A consequence of large required separations is that, during busy traffic periods,

* The smaller minimum separation time in the Houston Oceanic West Sector is due to better availability/reliability of very-high-frequency (VHF) air-ground voice communications in this sector.

some aircraft departing from Gulf coast states and bound for Central/South American destinations cannot be assigned to their preferred altitudes (generally above FL300) without incurring 1- to 2-hour ground delays.

The Phase III Helicopter In-Flight Tracking System (HITS) deployment had two goals:

- Investigate the capability of automatic dependent surveillance – broadcast (ADS-B) to provide coverage throughout the entire U.S. high-altitude Oceanic sectors above 24,000 ft, and to overlap the coverage of Mexico's two long-range radars on the Yucatan Peninsula above 28,000 ft.
- Identify technical issues associated with, and assess the performance of, wide area multilateration (WAM) in high-altitude en route-like/oceanic domains.

This was the first U.S. WAM system configured and tested for operation in en route-like or oceanic airspace—possibly the first in the world. Phase I/II equipment operated in terminal-like airspace, and was not designed/intended to operate at the long ranges planned for Phase III. As a result, the Phase III deployment involved several new challenges:

- Deploying and operating HITS remote units (RUs) on deep-water platforms. These platforms are newer and more expensive to construct and operate than those closer to shore, with more restrictive rules for access and modification.
- Attaining greater RU reception range. Whereas the evaluation standard for RU range during Phases I/II was 50 nmi, the standard for Phase III was 200 nmi with a goal of 250 nmi, because greater range is needed for a system providing service to oceanic and en route airspace.
- Attaining greater RU interrogation range. Similarly, the Phase III standard was established at 200 nmi, with a goal of 250 nmi, rather than the 50 nmi employed during Phases I/II.
- Synchronize the RU clocks (needed for WAM capability) without using reference transponders. Distances between Phase III RUs were too great to allow use of reference transponders, which must have line-of-sight (LOS) visibility to multiple RUs.

6.1.2 Ground-System Architecture

For Phase III, a configuration with eight RUs was selected—five on shore and three on deep-water platforms. All locations were on the backbone of the network operated by telecommunications service provider Stratos Global Corporation. The selected sites were implementable within the available funding, minimizing communications cost (no additional network equipment was necessary), and providing reliable communications.

Each RU had the following equipment:

- 1090-MHz receiver capable of detecting/decoding Air Traffic Control Radar Beacon System (ATCRBS) Mode A and C, Mode S short squitter, and Mode S extended squitter transponder replies. To increase reception range, the Phase III receivers had 5-dB improved sensitivity over the Phase I/II units.
- Federal Aviation Administration (FAA) distance measuring equipment (DME) Model 5100A 1090-MHz antenna with 8-dB main-beam gain and omnidirectional azimuthal coverage. (To improve reception range, the lower-gain AS-177B antenna used during Phase I/II was not deployed for Phase III.)
- Global Positioning System (GPS) receiver and associated antenna, integrated with 1090-MHz receiver to provide a common time base for all receiver clocks.
- Uninterruptible power supply.

- High-speed digital router. This provided the interface linking the RU with the microwave communications system that networked the Phase III sites with the central processing site (CPS).

The Phase III CPS was located at the Houston ARTCC, enabling the entire controller workforce at the center to become familiar with HITS capabilities.

The Phase I/II RU reception range was predicted to be 100 nmi (Section 2.2), whereas the Phase I/II range was found during testing to be well over 100 nmi with a high-end, 500-W transponder (Subsection 4.5.1). As a result of the 5-dB improvement in RU receiver sensitivity (–80 to –85 dBm), the expected Phase III RU reception range was a factor of 1.8 larger than that for Phase I/II sites with the same DME 5100A antennas, and a factor of 3.2 larger than the reception range for Phase I/II sites with AS-177B antennas. Thus the Phase III downlink range was predicted to be between 200 and 250 nmi, at least with "high-end" transponders.

A power budget for the Phase III ground-to-air link, shown in table 6-1, provided a basis for projecting a 200-nmi interrogation range. Alternatively, the Phase III interrogation range can be estimated based on comparison with the Phase I/II capability. During Phase III a high-powered linear amplifier (3.2-kW peak output), procured from DRS Signal Solutions West (formerly Zeta Corporation), was integrated with the Sensis interrogator and installed at Morgan City, Louisiana. The output of the interrogator system drove an experimental 12-dB gain "super-DME" antenna. The factor-of-6.4 increase in transmitted power, combined with the 4 dB of additional gain provided by the super DME antenna, yielded a predicted factor-of-16 increase in radio frequency (RF) power in the antenna main beam. Assuming that all propagation losses were due to spherical spreading (the predominant signal attenuation mechanism at 1030 MHz), this would result in a factor-of-4 increase in interrogation range—i.e., the interrogation signal strength at an aircraft 200 nmi away would be the same as the power reaching an aircraft 50 nmi from a Phase I/II RT.

Table 6-1 Ground-to-Air Link Power Budget (Phase III, Without Multipath)

Link Element	Value		Comment
Transmitter power, 3.2 kW	65.0	dBm	Linear amplifier output level
Ground antenna gain	12.0	dB	Super DME antenna
Path loss, 200 nmi	–144.5	dB	Standard calculation
Aircraft antenna gain	0.0	dB	Standard assumption
Cable losses	–3.0	dB	Reasonable assumption
Received signal level	–70.5	dBm	Sum of above
Aircraft receiver MTL*	–74.0	dBm	Ref. 11, average value
Link margin	3.5	dB	Ref. 3 recommends 4 dB

* Minimum trigger level

Deployment of RUs on the deep-water platforms presented several challenges that did not arise during Phases I/II. The largest challenge was receiving approval from the owners to gain physical access. Platform access is almost completely restricted to personnel involved with the oil drilling/production operations. Moreover, the times when modifications to the platforms are permitted are limited. Owners of the deep-water platforms required that: (1) all personnel and companies visiting the platforms sign "hold harmless" waivers with regard to injury to personnel and damage to equipment; and (2) detailed engineering drawings be submitted and approved prior to commencing work on modification. An additional consideration was transportation cost: the cost of a round trip to/from a deep-water platform via helicopter ranged between $5000 and $8000.

Table 6-2 details the Phase III site locations selected. For perspective, the table also provides the ground range from each site to the nearest on-shore and deep-water RUs. Figure 6-2 depicts the site locations and the predicted ADS-B coverage at four altitudes above mean sea level (MSL).* The selected sites provided (predicted) coverage of all three U.S. FIRs at 24,000 ft, with the exception of a triangular-shaped area near the boundary separating the Houston East and Miami FIRs. The predicted coverage area at 24,000 ft was approximately 486,000 nmi^2, and the goal of overlapping Mexican radar coverage at 28,000 ft was achieved.

Table 6-2 Phase III Site Locations

Site Name	Location Type	Latitude (deg)	Longitude (deg)	Height MSL (ft)	Nearest Sites (nmi)	
					On Shore	Deep Water
North Padre Island, TX (NPI)	On shore	26.83358	–96.94037	230	GAL, 187	GBK, 271
Galveston, TX (GAL)	On shore	29.30692	–94.78995	346	NPI, 187	GBK, 171
Morgan City, LA (MCY)	On shore	29.70305	–90.76694	350	GAL, 212	BRT, 115
Apalachicola, FL (APL)	On shore	29.71163	–85.15187	250	PPK, 167	MSC, 233
Pinellas Park, FL (PPK)	On shore	27.82272	–82.8284	175	APL, 167	MSC, 340
Garden Banks (GBK)	Deep water	27.87570	–91.9863	250	MCY, 127	BRT, 71
Brutus (BRT)	Deep water	27.79371	–90.64746	300	MCY, 115	GBK, 71
Mississippi Canyon (MSC)	Deep water	28.17033	–89.22395	300	MCY, 123	BRT, 79

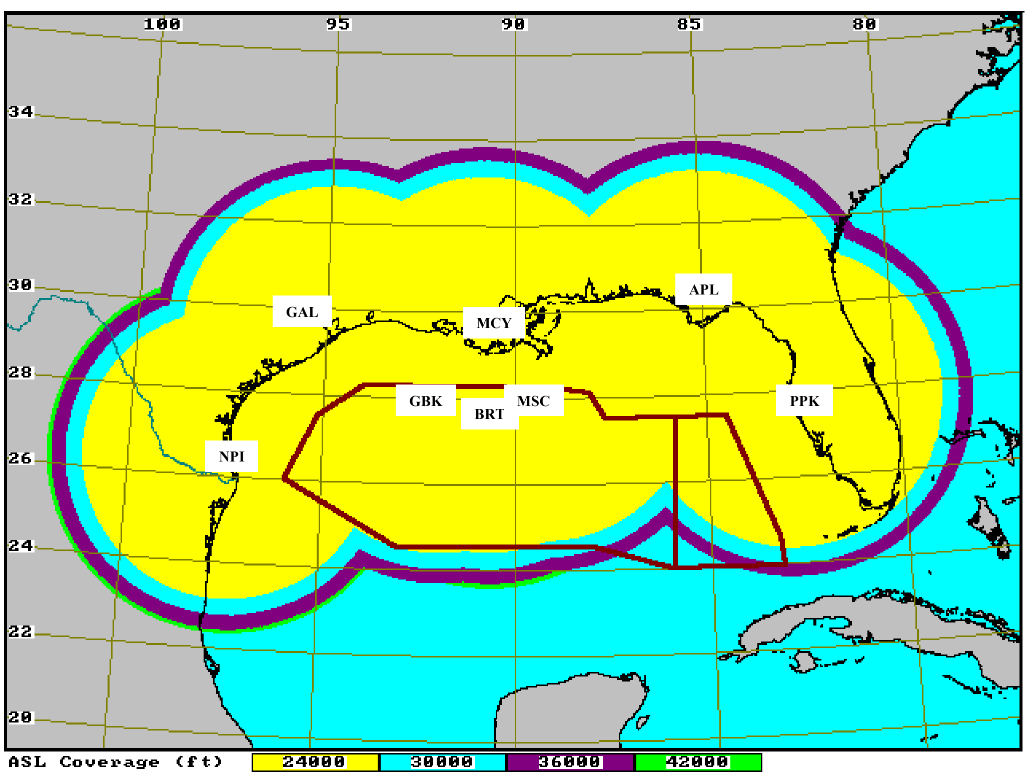


Figure 6-2 RU Site Locations and Predicted ADS-B Coverage.

* Surveillance system coverage predictions apply to geometric heights, whereas aircraft operate based on barometric altitudes. In comparing predictions with flight data, no attempt was made to adjust or account for difference in the two measures of altitude.

Although they provided good ADS-B coverage, these site locations were not optimal in this regard, because availability of physical space and communications were the most important factors in platform selection. Sites farther offshore and more widely spaced would have been chosen if they had been available. In particular, the site at Brutus added little to the coverage when the other two deep-water platform RUs were operating. (It was selected to ensure adequate coverage in the center of the Gulf even if one of the three sites failed.) An additional RU site at Key West, Florida, would have improved coverage of the U.S. FIRs. However, a coverage gap would have remained in the Houston sector.

Figure 6-3 illustrates the predicted HITS Phase III RU array WAM coverage for aircraft at 28,000-ft altitude. Coloring corresponds to the horizontal dilution of precision (HDOP), conservatively assuming that the reliable RU detection range is 200 nmi. Dark blue areas correspond to HDOPs of 4 or less, and were judged to be favorable for computing horizontal position in the en route/oceanic domains. If an aircraft in the blue areas was carrying a Mode S transponder, then analyses based on link budgets and HDOPs predicted that its horizontal position could be determined using the Traffic Alert and Collision Avoidance System (TCAS) (DF11) aircraft-to-ground squitters, without interrogating the aircraft.

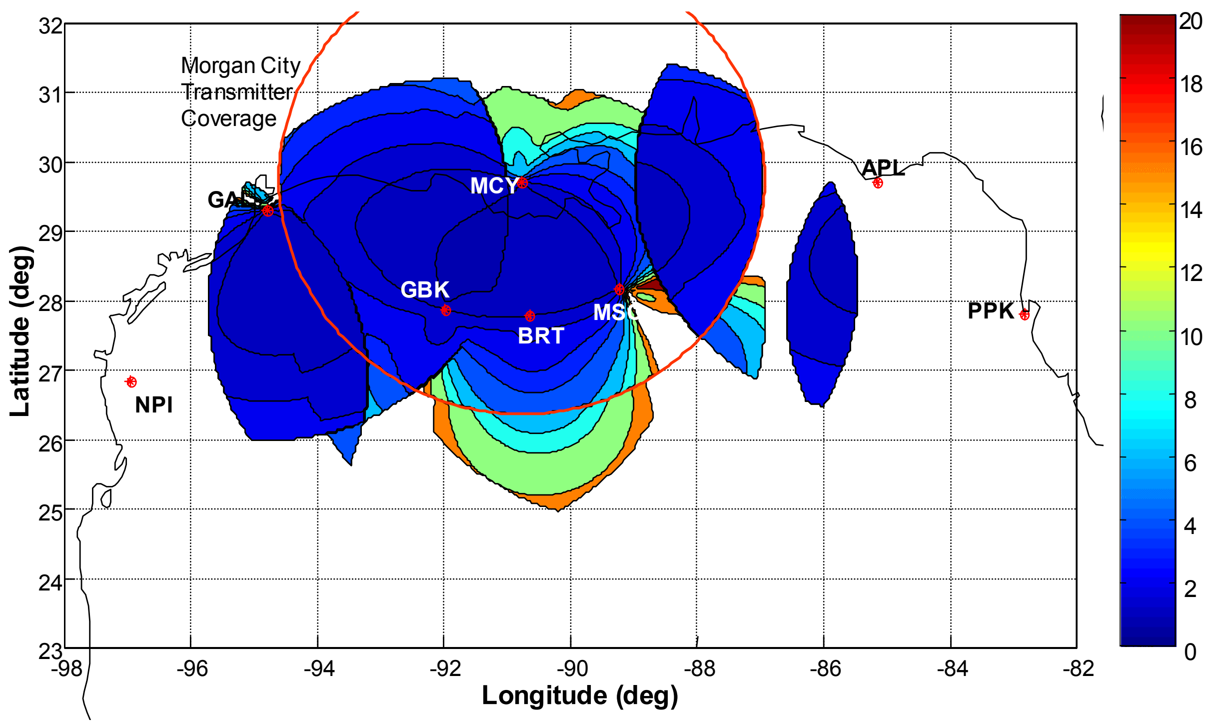


Figure 6-3 Predicted WAM HDOPs at 28,000-ft Altitude (200-nmi RU Range).

Figure 6-4 presents the altitude error cross-coupling factor (AECCF) for the Phase III array. AECCF (described in Subsection 2.1.3) is the multiplier that relates altimetry errors to horizontal-position errors, analogous to the way HDOP relates time-of-arrival (TOA) errors to horizontal position errors. In this context, "altimetry error" refers to the error in the knowledge of the target processor (TP) of the geometric height of the aircraft above the HITS model for the Earth's surface, which is taken to be MSL. AECCF values change more rapidly with position than HDOPs, particularly for locations near an RU. Also, AECCF values are significantly smaller than HDOPs. However, it should be noted that HDOPs typically scale TOA errors on the order of 20 ft, whereas AECCFs may scale errors that can be tens of thousands of feet (in cases where altitude is not known and zero is used). Thus altimetry error can be the dominant contribution to horizontal-position error.

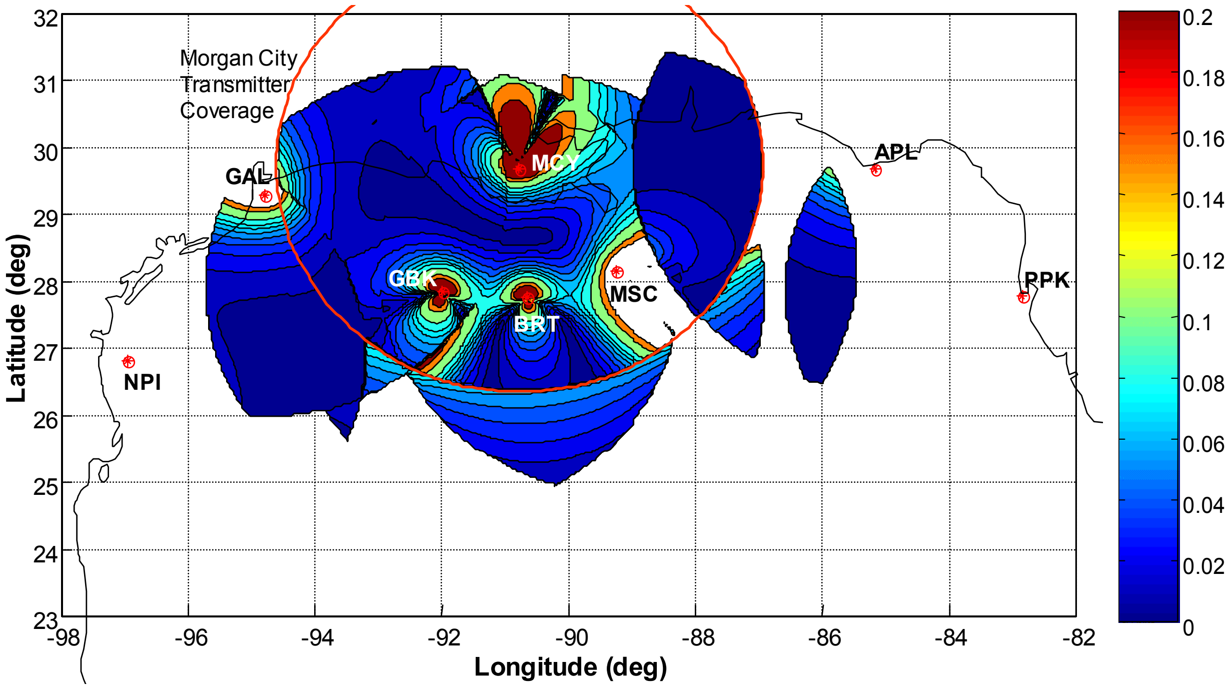


Figure 6-4 Predicted WAM AECCFs at 28,000-ft Altitude (200-nmi RU Range).

Good WAM coverage occurred roughly between –95 deg and –87 deg longitude and within a 3-deg latitude band. The area was approximately 93,300 nmi^2 at 24,000-ft altitude. These figures include coverage over land but not the "lens-shaped" region centered on –88-deg longitude (which would be of limited functional use). The southern boundary of the WAM coverage region was approximately 26.5-deg latitude. Both the area of WAM coverage region and its southern boundary compared unfavorably with those for ADS-B (486,000 nmi^2 and 24 deg).

For WAM to determine the position of an aircraft equipped with a Mode A/C transponder, as well as for WAM to determine the beacon and altitude codes of an aircraft carrying either a Mode A/C or Mode S short quitter transponder, one or more transmitters interrogating on 1030 MHz must be visible to and within signal range of the aircraft. The white circle in figure 6-3 corresponds to 200 nmi from the Phase III interrogator installed at Morgan City. Predicted full WAM functionality occurred in the dark blue regions within the white circle.

Selecting the Phase III sites to maximize ADS-B coverage (which requires only one visible RU) necessarily compromised WAM coverage (which requires three visible RUs with a favorable geometric arrangement). As discussed in Section 2.1, for WAM the ideal site arrangement is a grid comprising equilateral triangles. The adjacent RU separation is chosen to be the maximum distance consistent with providing coverage above the nearest sites at the minimum surveillance altitude. In this case, with a minimum surveillance altitude selected to be 24,000 ft, for optimum WAM coverage the sites would be 200 nmi apart. The distance between the RUs at Morgan City and Apalachicola, 293 nmi, significantly exceeded this guideline, causing a coverage gap at approximately –87-deg longitude. WAM coverage could have been improved significantly by relocating the Pinellas Park site to a position on the shoreline midway between Morgan City and Apalachicola. Some of the infeasible but desirable siting changes discussed in conjunction with ADS-B would also have improved WAM coverage—e.g., moving the deep-water sites even farther south, or relocating the Brutus site 200 nmi to the east.

6.1.3 Overview of Flight-Test Periods

The HITS Phase III system was subjected to three flight-test periods (table 6-3). The January test period was conducted primarily to enable Sensis to optimize HITS ADS-B performance prior to evaluation "for score." Those results are not reported herein. The February 2004 test period enabled the U.S. Government to evaluate ADS-B for en route/oceanic ranges. The February flight tests also provided an opportunity for Sensis to tune/evaluate WAM performance with the high-powered transmitter. The March test period was employed to further assess the Phase III system ADS-B performance and to assess its WAM performance for all three transponder types (ATCRBS Mode A/C, Mode S short squitter, and Mode S extended squitter).

Table 6-3 Phase III Flight-Test Periods

Dates	Aircraft	Transponder(s)	Altitude Regime	Scored?
Jan. '04	FAA Boeing 727	Mode S extended squitter	High	ADS-B ✗
Feb. '04	FAA Boeing 727	Mode S extended squitter and Mode A/C	High	ADS-B ✓ WAM ✗
Mar. '04	FAA Boeing 727	Mode S extended squitter and Mode A/C	High	ADS-B ✓ WAM ✓
	NASA Gulfstream III	Mode S extended squitter and Mode S short squitter	High	ADS-B ✓ WAM ✓

Two aircraft were used for Phase III tests (figure 6-5): a Boeing 727 (B-727), provided by the FAA Hughes Technical Center (Tech Center) for all three test periods; and a Gulfstream III (G-III), provided by NASA Dryden Flight Research Center for the March test period.

(a) FAA Boeing 727 **(b) NASA Gulfstream III**

Figure 6-5 Phase III Flight-Test Aircraft.

Flight profiles—ground tracks and altitudes—were selected to address a variety of objectives. These included determining the detection range capability of individual RUs and their consistency with the 4/3-Earth model commonly employed to predict sensor detection range. This is best done by flying a variety of flight altitudes, with tracks generally toward/away from an RU. A second goal was to explore the outer perimeter of the predicted ADS-B and WAM coverage areas for the entire RU array. This is best done by level flights with “zig-zag” ground tracks in/out of the predicted coverage region. A third consideration was to fly at desirable altitudes for air carrier aircraft, to demonstrate the potential operational use of ADS-B and WAM in the Gulf.

Operational considerations affected the profiles actually flown. Altitudes were assigned by FAA Air Traffic Control immediately prior to takeoff or while the aircraft was in flight, and (except between 10 PM and 6 AM) were not always the same as the requested altitude. Additionally, FAA pilots of the B-727 were restricted to flying established jet airways, which are not necessarily consistent with best testing of a surveillance system. Accounting for these factors involved several compromises. One was that no flights were conducted at the minimum design altitude of 24,000 ft. It was determined that if performance could be validated as consistent with predicted behavior at slightly higher, more operationally desirable altitudes (e.g., FL270 and FL280), then the performance at the minimum design altitude could safely be predicted by extrapolation.

6.1.4 B-727 Aircraft and Flight Profiles

The FAA Boeing 727-25C, tail number N40, is powered by three turbofan engines. For this airframe (manufactured in 1968), maximum cruise speed is approximately 0.9 mach, and the ceiling is approximately FL420 (ref. 12). During the Phase III tests, the aircraft was equipped with two transponders. ADS-B tests used a Rockwell Collins XS-950 Mode S extended squitter transponder interfaced with a GPS Wide Area Augmentation System (WAAS) receiver. An FAA Tech Center engineer verified the operation of the transponder at the Tech Center prior to flight testing; measured peak RF power was 480 W for the upper antenna and 417 W for the lower antenna. ATCRBS WAM tests used a Narco model AT 155 Mode A/C transponder. An FAA field engineer verified its operation before flight testing; peak RF power was 140 W for the single, lower antenna. To evaluate WAM position accuracy, the B-727 was equipped with an Ashtech (now Thales Navigation) Z-Xtreme GPS receiver that recorded nondifferentially corrected position reports.

Flight tracks from the February and March test periods are presented in appendices F (February) and G (March), and are summarized in table 6-4. ADS-B assessment flights followed published jet airways crossing the Gulf to and from U.S. airspace. Figure 6-6 (showing the February 12 PM flight from Miami International Airport (MIA) to Houston Intercontinental Airport (IAH)) and figure 6-7 (showing the March 24 PM flight that departed and arrived at Houston) are examples. Although these trajectories did not constitute a general coverage test, they were sufficient to demonstrate that actual ADS-B was consistent with figure 6-2.

Table 6-4 Phase III B-727 Flights "for Score"

Flight	Capability Tested	Altitude Regime	Transponder
Feb. 10 AM	ADS-B	FL280	Mode S extended squitter
Feb. 10 PM	ADS-B	FL280	Mode S extended squitter
Feb. 12 AM	ADS-B	FL370	Mode S extended squitter
Feb. 12 PM	ADS-B	FL360	Mode S extended squitter
March 23 AM	ADS-B & WAM	FL270	Mode S extended squitter
March 23 PM	WAM	FL270	ATCRBS
March 24 AM	ADS-B	FL280	Mode S extended squitter
March 24 PM	ADS-B & WAM	FL330	Mode S extended squitter
March 25 AM	ADS-B	FL330	Mode S extended squitter
March 25 PM	ADS-B & WAM	FL350	Mode S extended squitter

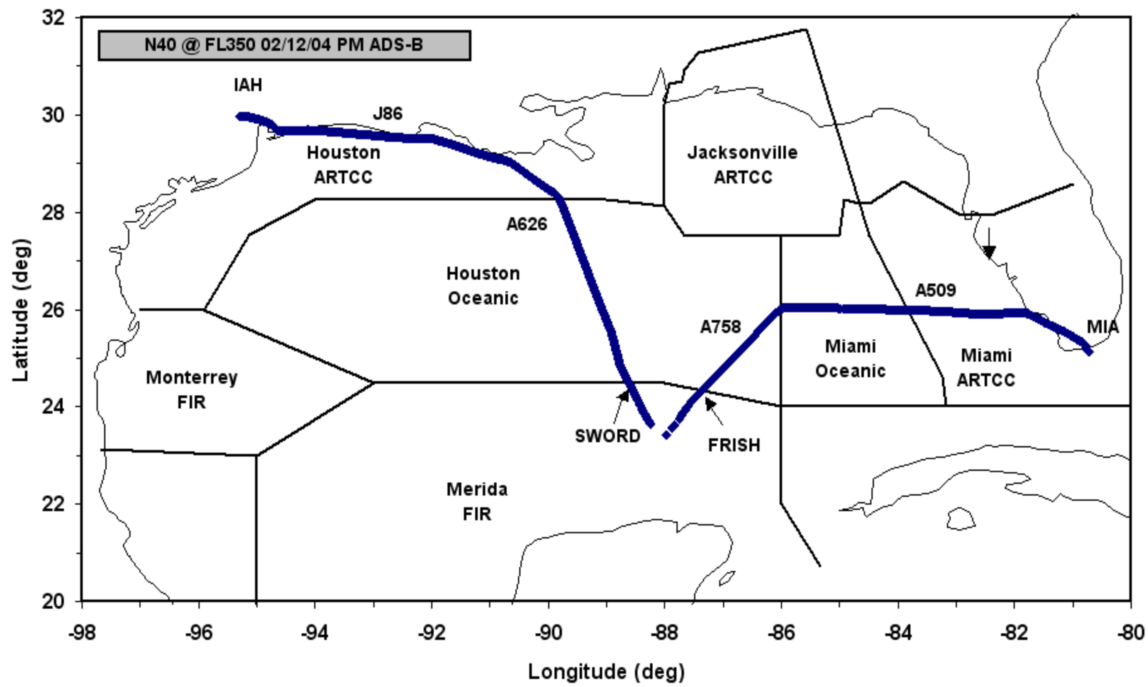


Figure 6-6 B-727 February 12 PM Flight at FL350 (ADS-B Ground Track).

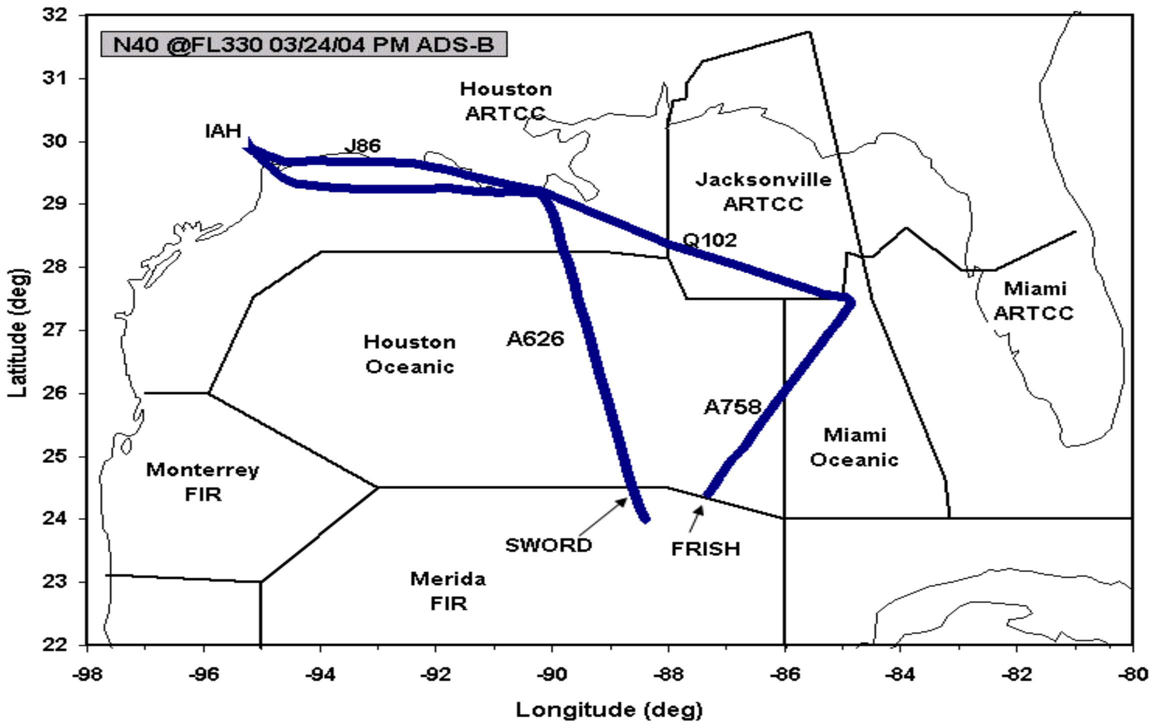


Figure 6-7 B-727 March 24 PM Flight at FL330 (ADS-B Ground Track).

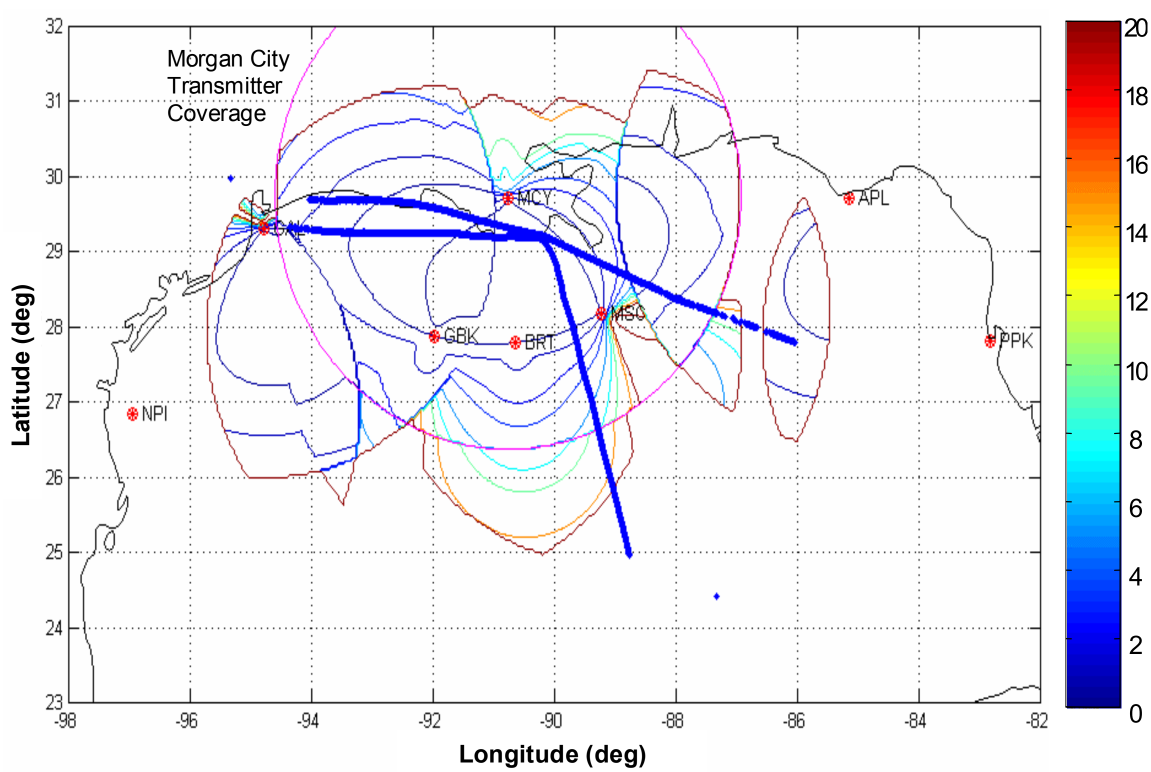


Figure 6-8 B-727 March 24 PM Flight at FL330 and HDOP Contours (WAM/Mode S ES Track).

A portion of the flights with the ADS-B transponder were designed to have tracks within the WAM coverage area, and thus also supported evaluation of WAM performance. Figure 6-8 shows an example of the WAM ground track for such a flight, together with the predicted HDOP contours for the flight altitude involved. Figure 6-8 can be compared to figure 6-7, which shows the ADS-B track for the same flight. The tracks are qualitatively consistent within the common coverage area. The WAM track is also reasonably consistent with the predicted coverage based on HDOP and link-budget analyses—in terms of both the extent of the two track segments and location of gaps in the tracks. (The loss of track near the departure/arrival airport at Houston occurs because the aircraft altitude is below the coverage limits of all RUs except GAL.) The exceptions to flight track-analysis model consistency are the track segments that extend beyond the predicted coverage to the south and east. One explanation is that the reception range for RUs on the deep-water platforms was better than predicted.

Figure 6-9 depicts the WAM track for the March 23 PM flight conducted to assess WAM performance with a Mode A/C transponder. Figure 6-9 also shows the predicted HDOP contours for the flight altitude (FL270), assuming that the reception range of the RUs was 125 nmi. The shorter RU reception range was based on the lower ATCRBS transponder power. (Based only on the transponder power ratio of three (417 W versus 140 W), the predicted ATCRBS reception range would be 200 nmi divided by the square root of three, or 115 nmi.) There is good agreement between the extent of the WAM tracks and the HDOP prediction, with the exception of the gap near –91 deg longitude and 29 deg latitude.

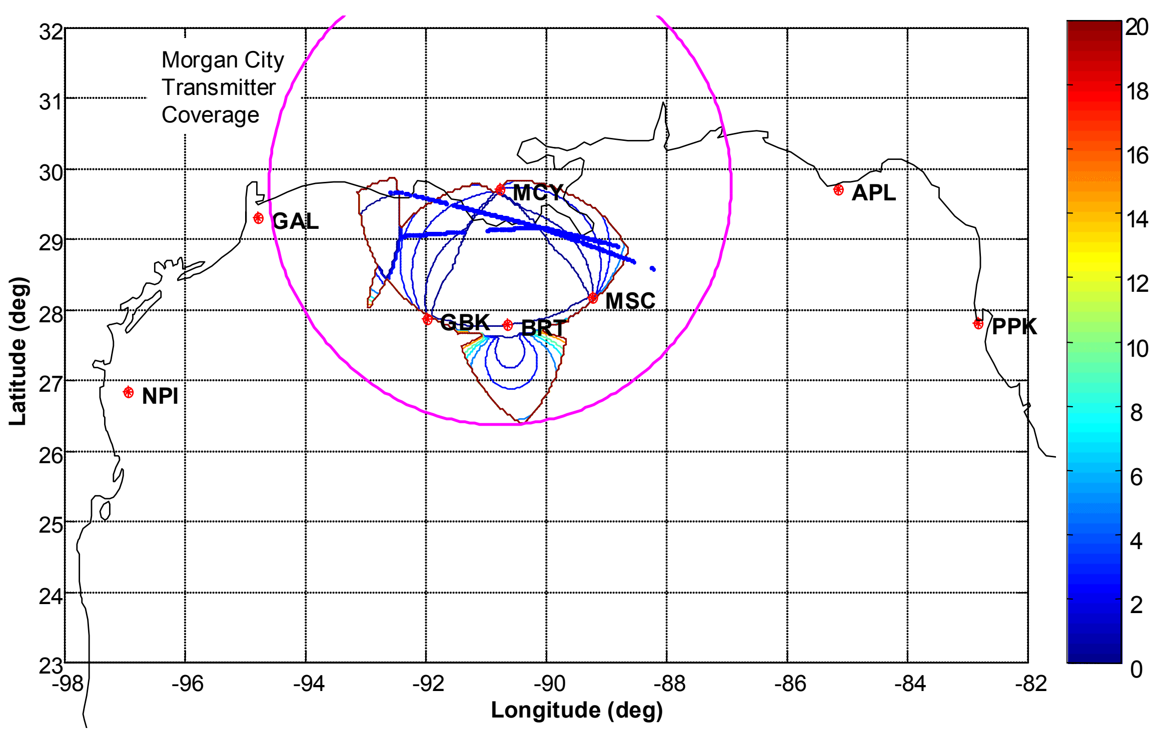


Figure 6-9 B-727 March 23 PM Flight at FL270 and HDOP Contours (WAM/ATCRBS Track).

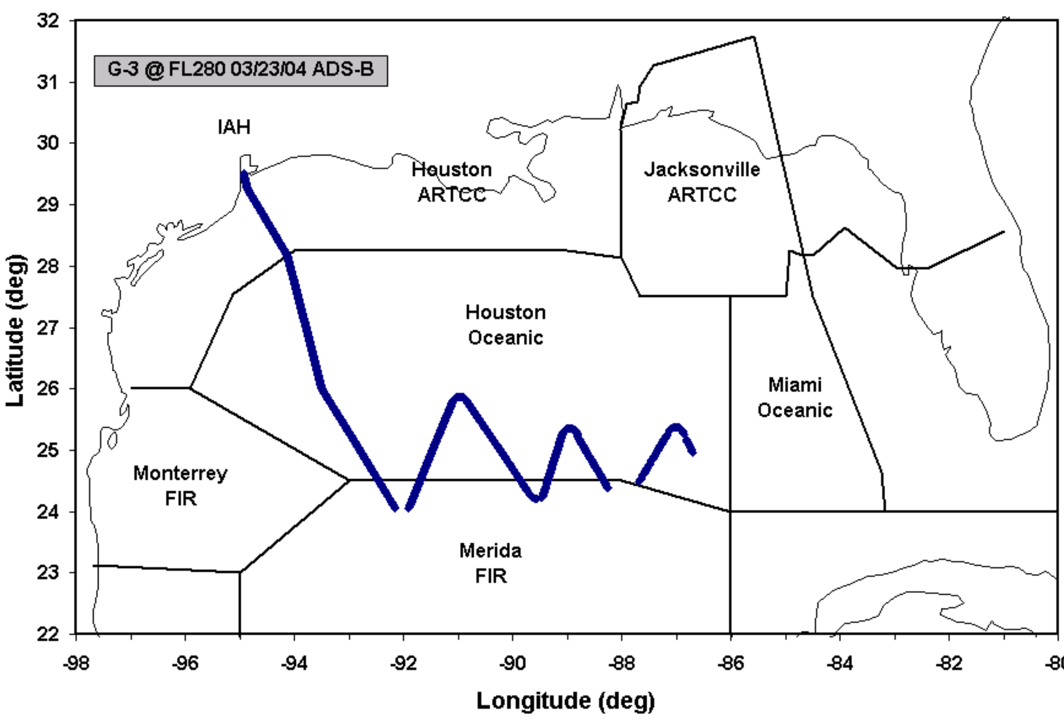
6.1.5 Gulfstream III Aircraft and Flight Profiles

The NASA G-III is powered by dual turbofan engines. Published maximum cruising speed is 500 kt; operating ceiling is 45,000 ft; and range with eight passengers is 4100 nmi. For Phase III, the G-III was equipped with both a Rockwell Collins TDR94 Mode S short squitter transponder and a Honeywell KT73 Mode S extended squitter transponder. The latter was interfaced with a Honeywell KLN 94 GPS Navigator that served as the information source for ADS-B reports. The KLN 94 also provided "position truth" for WAM tests. It was interfaced with the Volpe Airborne Data Collection System, which logged the GPS output data. Immediately following testing, a NASA engineer measured the short squitter transponder RF peak power at 300 W and the extended squitter transponder RF peak power at 150 W, at the antenna connector.

During the March test period, the G-III was employed to assess both ADS-B and WAM performance (table 6-5). The ADS-B flight probed coverage limits along the U.S./Mexican FIR boundary as well as the performance of individual RUs. Figure 6-10(a) shows ADS-B reports for the flight segment at FL280 from Houston (IAH) to near the boundary with the Miami Oceanic region. Figure 6-10(b) shows ADS-B reports during the return flight segment at FL390. Qualitatively, agreement with the predicted coverage within the U.S. FIRs (figure 6-2) is evident at FL280. As would be expected, coverage was better at the higher altitude.

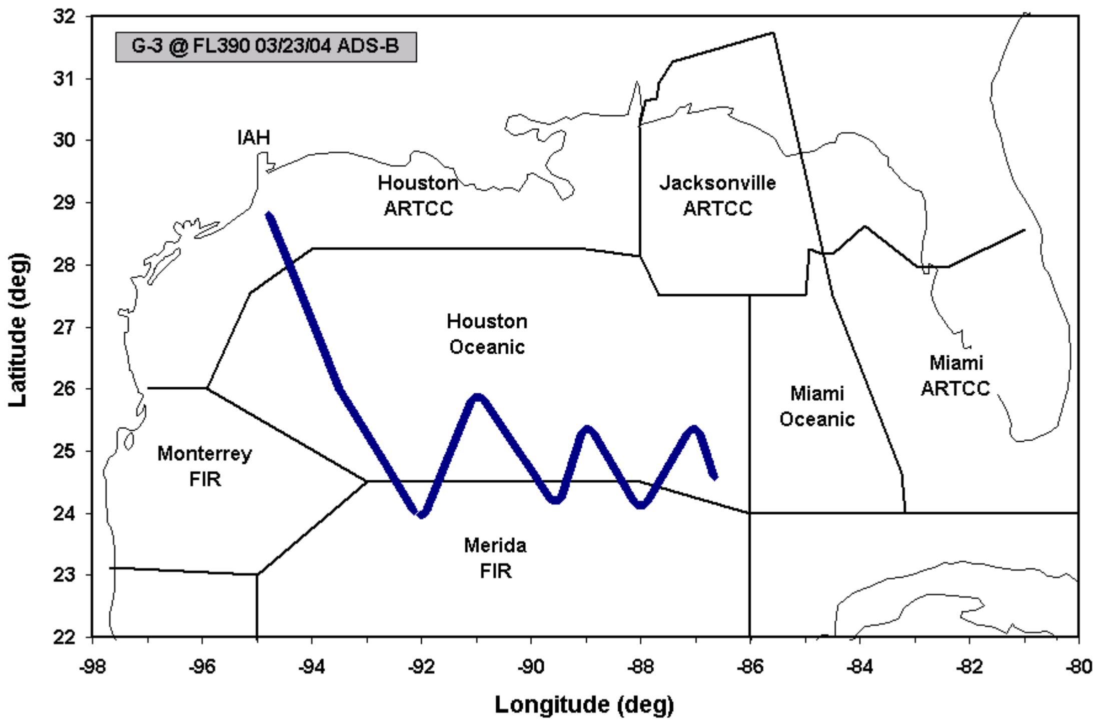
Table 6-5 Scored Phase III NASA G-III Flights

Flight	Purpose	Altitude Regime	Transponder
March 23	ADS-B test	FL280 (outbound) FL390 (inbound)	Mode S extended squitter
March 24	WAM test	FL280	Mode S short squitter



(a) Outbound from IAH at FL280

Figure 6-10 G-III March 23 Flight T (ADS-B Ground Track).



(b) Inbound to IAH at FL390

Figure 6-10 Concluded.

The WAM-determined ground track for the March 24 flight, conducted using a Mode S short squitter transponder, is shown in figure 6-11. This was the first test of HITS WAM capability with a conventional Mode S transponder. The figure also shows the predicted HDOP contours at the flight altitude, assuming that the downlink detection range is 200 nmi. The trajectory—essentially a set of parallel east-west tracks approximately 50 nmi apart—was designed to remain almost entirely within the WAM downlink coverage area, with most of the flight within coverage of the transmitter at Morgan City.

The agreement between WAM track and the HDOP contours—particularly the location of gaps in the WAM track near the boundaries in the predicted WAM coverage area—is quite good. The only "surprise" is the portion of the WAM track outside the predicted coverage area near –88 deg longitude and 26.5 deg latitude. This is consistent with figure 6-8, strengthening the hypothesis that coverage of the deep-water platform RUs was greater than 200 nmi.

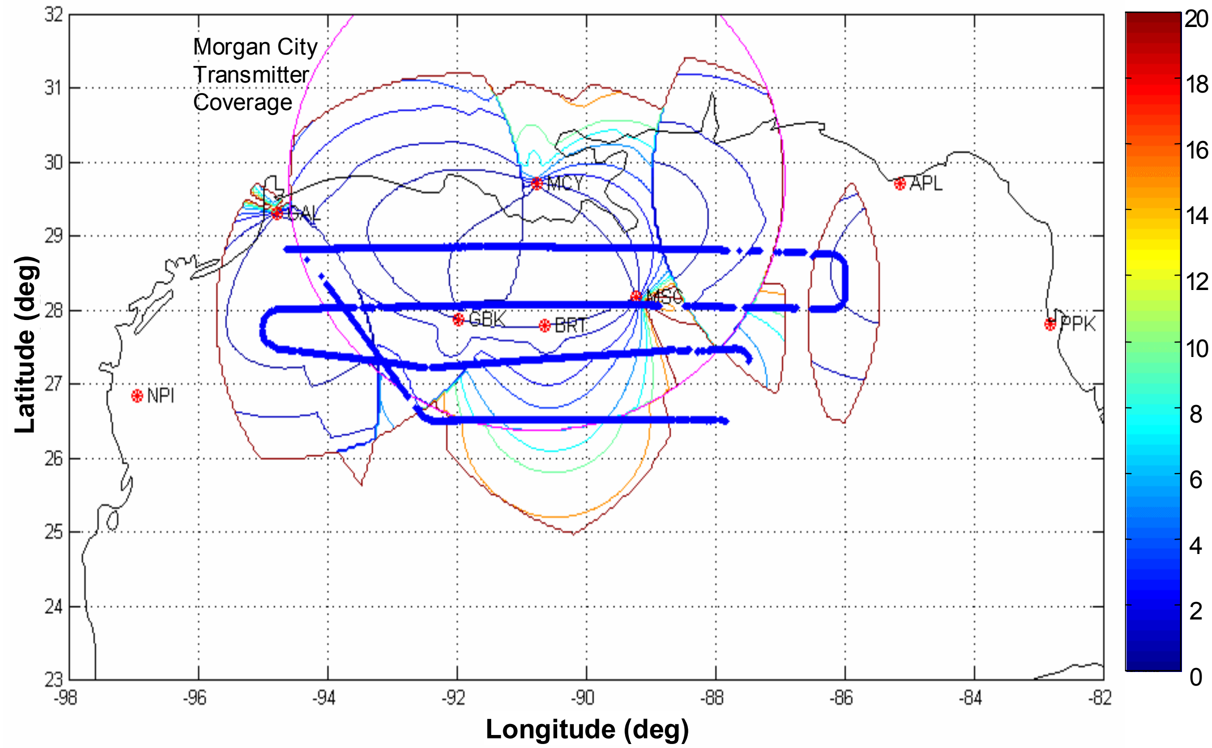


Figure 6-11 G-III March 24 Flight at FL280 and HDOP Contours (WAM/Mode S Track).

6.2 ADS-B Flight-Test Results

Based on flights during the February and March 2004 test period, HITS ADS-B performance was compared to the Air Traffic Control Beacon Interrogator, Model 6 (ATCBI-6) specification using the following parameters:

- RU reliable detection range
- Update interval
- Coverage volume

6.2.1 RU Detection Range

Five flight segments were analyzed to assess the range performance of the three RUs on offshore platforms (table 6-6). The "Predicted LOS" values in the table are the computed ranges of a hypothetical RU located at the maximum unobstructed receiving range based on the 4/3 spherical Earth model, assuming an antenna height of 275-ft MSL, which is representative for these offshore platforms. The columns labeled with the site names show the maximum distance from the RU to the aircraft when Mode S extended squitter messages were reliably received/decoded.

Table 6-6 Phase III RU Maximum Detection Range

Flight			Platform Detection Range (nmi)				Average (Station Range/LOS)
Date & Time	Aircraft	Altitude	Predicted LOS (275 ft)‡	Garden Banks (250 ft)‡	Brutus (300 ft)‡	Mississippi Canyon (300 ft)‡	
Mar. 23 AM	B-727*	FL270	222	223	232	234	103%
Mar. 23 PM outb'nd	G-III†	FL280	226	231	236	238	103%
Mar. 23 PM inbound	G-III†	FL390	263	259	277	276	104%
Mar. 24 PM	B-727*	FL330	243	248	267	256	106%
Mar. 25 AM	B-727*	FL330	243	263	268	258	108%
Mar. 25 PM	B-727*	FL350	250	267	254	262	104%
Average (Station Range / LOS)				103%	106%	105%	105%

* Rockwell Collins XS-950 Mode S extended squitter transponder (480 W upper / 417 W lower antenna).
† Honeywell KT73 Mode S extended squitter transponder (150 W).
‡ Platform antenna height, MSL.

As would be expected, there was a clear increase in RU detection range with aircraft altitude, and generally with platform antenna height. The reception range standard of 200 nmi was achieved in all cases, and the goal of 250 nmi was met in 11 of the 12 cases when the aircraft was at or above FL330 (i.e., where there was a reasonable chance of doing so). This favorable detection-range performance is consistent with: (a) results found during Phase I (Section 4.5.1), where the average detection range was 153 nmi; and (b) the factor-of-1.8 increase in detection range as a result of improved RU receiver sensitivity implemented for Phase III.

The last column and row in table 6-6 are the average of the ratio of the maximum detection range divided by the predicted LOS range for the aircraft altitude involved and an assumed 275-ft platform antenna height. These statistics indicate that RU range performance was not sensitive to differences in the aircraft transponders—B-727 (Rockwell CollinsXS-950, 417 W) and G-III (Honeywell KT73, 150 W)*—or the station equipment and its installation. The logical explanation is that the link was not operating at its signal-to-noise ratio limit, and that only LOS visibility limited detection range.

In 17 of the 18 cases (combinations of flights and RU platforms), the measured maximum reception distance exceeded the maximum distance predicted by the 4/3-Earth model. (The one exception involves the Garden Banks platform, which had a lower antenna height than was assumed for the "Predicted LOS" column.) This would seem to indicate that the 4/3-Earth model slightly underpredicts range. However, the 4/3-Earth model is based on geometric aircraft altitude, whereas barometric altitudes are used in table 6-6. This discrepancy alone could account for the performance-prediction difference. Small differences in the atmospheric density vertical profile from that assumed for the 4/3-Earth model could also account for the difference. In fact, the agreement between the measured ranges and the 4/3-Earth model is remarkably good, particularly considering that different aircraft transponders and times of day were involved. This suggests that the 4/3-Earth model can be used with reasonable confidence in other situations.

6.2.2 Position (Latitude/Longitude/Altitude) Update Performance

Table 6-7 shows update interval statistics for the ADS-B (DF17) message containing latitude/longitude/altitude information for five flight segments. Statistics in the table describe the time elapsed between receipt of an ADS-B message at any RU in the HITS array and receipt of the next message at any RU in the array. All "lat/lon/alt" received/decoded messages were considered for this analysis, regardless of the aircraft

* The detection range for the G-III Honeywell KT73 transponder was unexpectedly large, given its output power. One possible explanation is that the aircraft installation involved lower cabling/connector losses and greater antenna gain than were modeled.

altitude. Update intervals less than 0.5 sec were excluded from the probability calculations, because these were deemed to have no operational value. Also, when the aircraft was determined to be beyond the LOS of all RUs, then update interval "gaps" in that region were excluded.

Table 6-7 Phase III Array ADS-B Lat/Lon/Alt Message Update Performance

Flight Segment	Aircraft	Probability of Detection		
		99%	10 sec	5 sec
Feb. 10 AM	B-727	1.10 sec	99.9%	99.2%
Feb. 12 PM	B-727	2.55 sec	99.7%	98.9%
Mar. 23 PM (outbound)	G-III	0.98 sec	100.0%	100.0%
Mar. 23 PM (inbound)	G-III	3.16 sec	100.0%	99.3%
Mar. 24 AM	B-727	1.02 sec	100.0%	100.0%

The column labeled "Probability of Detection (99 percent)" contains the interval corresponding to the 99-percent point on the cumulative distribution of updates intervals, beginning with the smallest. The "Probability of Detection (10 sec)" column contains the percentage of instances when a position report was received within 10 sec of the previous report, and similarly the next column contains the percentage of instances when a position report was received within 5 sec of the previous report. Table 6-7 demonstrates that the Phase III HITS array ADS-B update performance easily satisfied the standard established for this effort—providing a report within 10 sec of the previous report with 99-percent probability.

In addition to three components of aircraft position, a radar target report also contains the aircraft beacon ("Mode A") code. Code performance was one of the HITS evaluation criteria (see chapter 3 and appendix A). However, the current ADS-B avionics standard (ref. 9) does not require that transponders broadcast the beacon code. Consequently, the associated performance could not be evaluated. It is expected that an update to reference 9 will be released during the next year, requiring broadcast of the beacon code.*

A second measure of ADS-B link performance is the fraction of messages broadcast by an aircraft that a particular RU receives/decodes as a function of range. This performance measure—termed message acceptance rate (MAR) in the communications field—was calculated for the B-727 March 24 PM flight and the three offshore platforms. It was assumed that the ADS-B transponders broadcast two squitters per second, in conformance with reference 9. Results of this calculation are shown in figure 6-12. The consistency of the curves indicates that the equipment and installation at each station are statistically similar. As expected, MAR performance degrades as range increases. However, a 50-percent message reception rate is attained at 250 nmi, which corresponds to an average position update rate of once per second, or more than adequate for an operational system functioning as an alternative to en route radar.

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* Mode S extended squitter transponders conforming to reference 9 also broadcast velocity messages twice per second, and flight ID messages once per ten seconds. (The flight ID is the radio call sign used in pilot-controller communications. For air carriers, it is the airline flight number; otherwise it is the aircraft tail number.) Currently, neither velocity nor flight ID information is included in a radar target report, and FAA automation systems software are not designed to use these items. Thus, they do not have roles in an evaluation of ADS-B capabilities relative to the ATCBI-6 specification. Moreover, instrumentation issues prevented their measurement during HITS. However, Eurocontrol has issued a directive that aircraft provide these parameters (and additional information as well—e.g., bank angle, rate of heading change) via the Mode S Aircraft Downlink Data (ADD) capability. Consequently, it would be appropriate for future ADS-B assessments to consider these parameters as well.

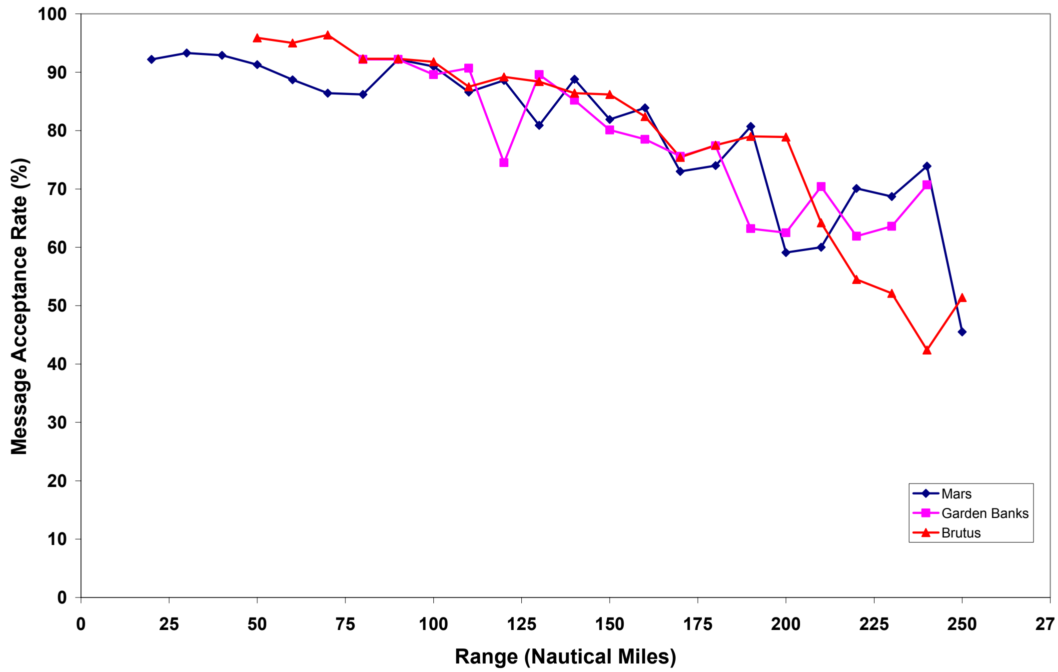
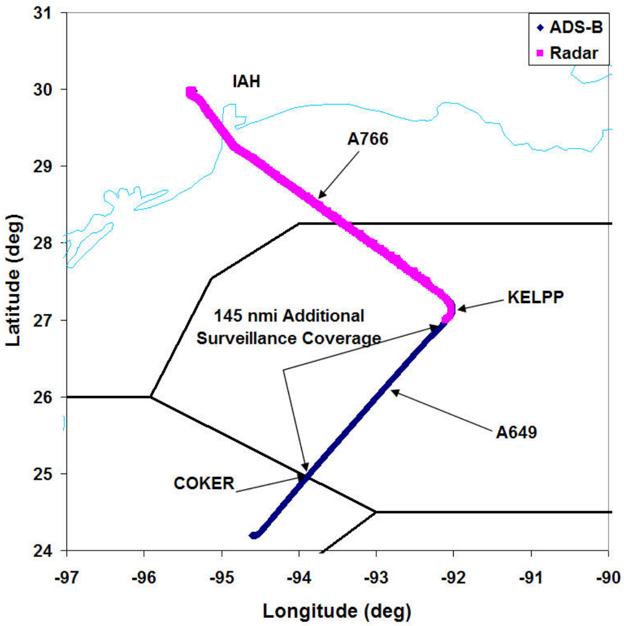


Figure 6-12 ADS-B MAR for B-727 March 24 PM Flight and Offshore Platforms.

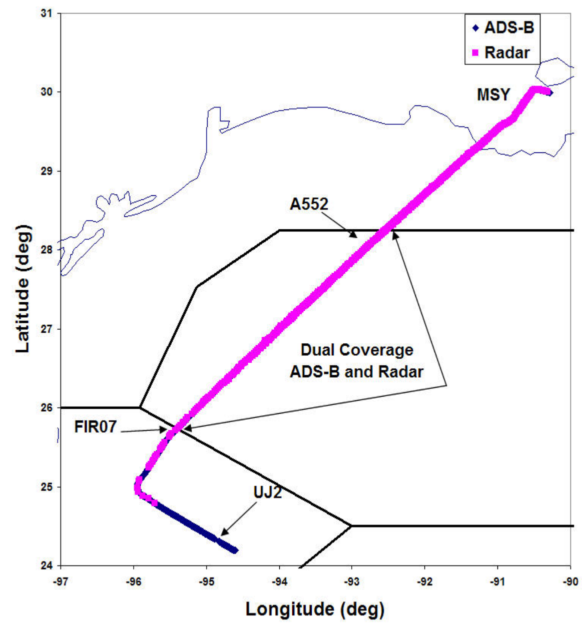
6.2.3 Coverage Volume

Several flights were conducted to (1) demonstrate the capability of HITS ADS-B to provide aircraft surveillance information beyond the range of installed FAA long-range radars, and (2) verify the predictions of ADS-B coverage. In support of the first objective, long-range radar data collected at the Houston ARTCC were obtained for 17 installations. These data included the following items: beacon code, barometric altitude, latitude, longitude, and Universal Time Coordinate (UTC). ADS-B and long-range radar target reports were correlated based on the aircraft beacon code, barometric altitude, and time of flight.

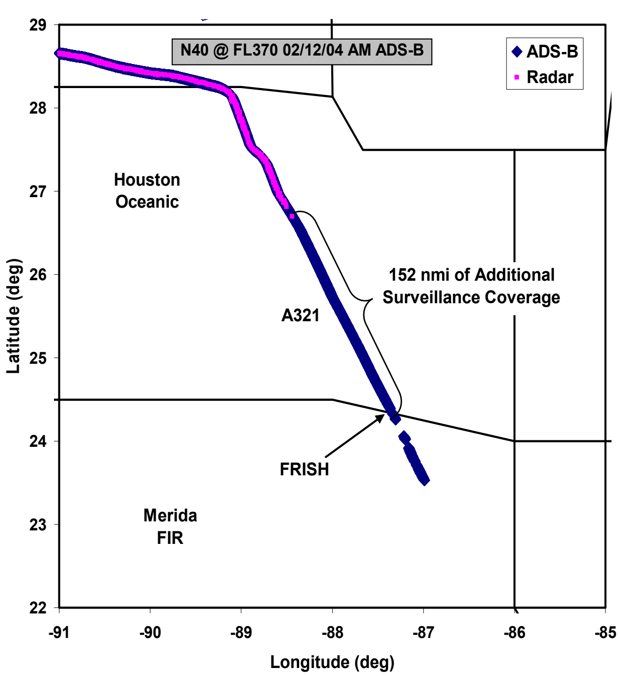
Radar and ADS-B ground tracks for six flight segments are presented in figure 6-13. Radar data are shown when a target report was received from any long-range radar interfaced with the Houston Center. Similarly, ADS-B data are shown when a DF17 message was received by any RU. Qualitatively, when the aircraft is with coverage of both sensor systems, the tracks coincide. The major difference is that ADS-B coverage extends farther south. For each of the jet airways displayed, the eight HITS RUs provided over 100 nmi more coverage of ADS-B aircraft than the set of 17 shore-based radars provided. The figure also shows that HITS/ADS-B coverage extended beyond the U.S. FIR into the Mexican FIR.



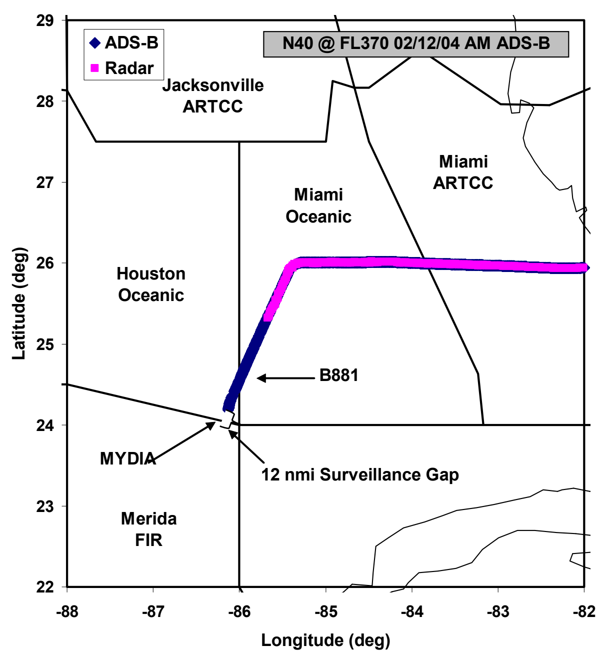
(a) B-727 Feb. 10 AM Flight (FL280)



(b) B-727 Feb. 10 AM Flight (FL280)

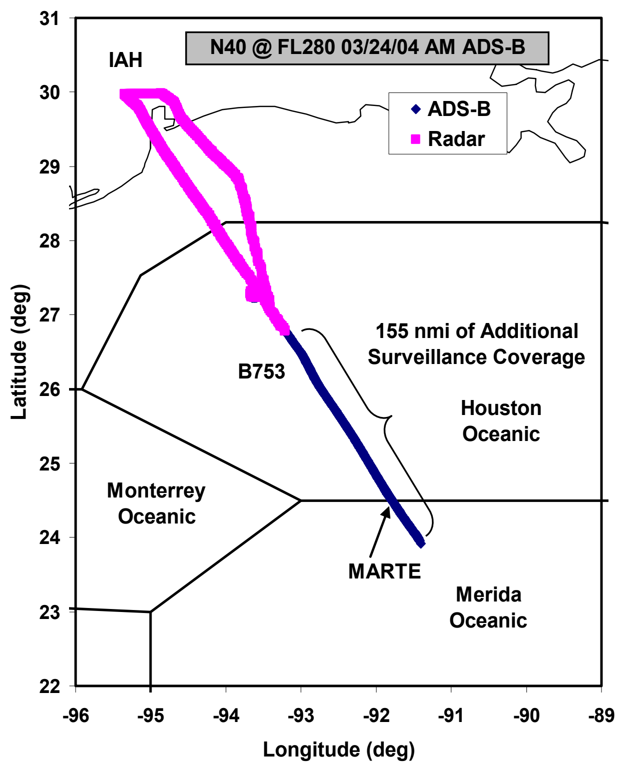


(c) B-727 Feb. 12 AM Flight (FL370)

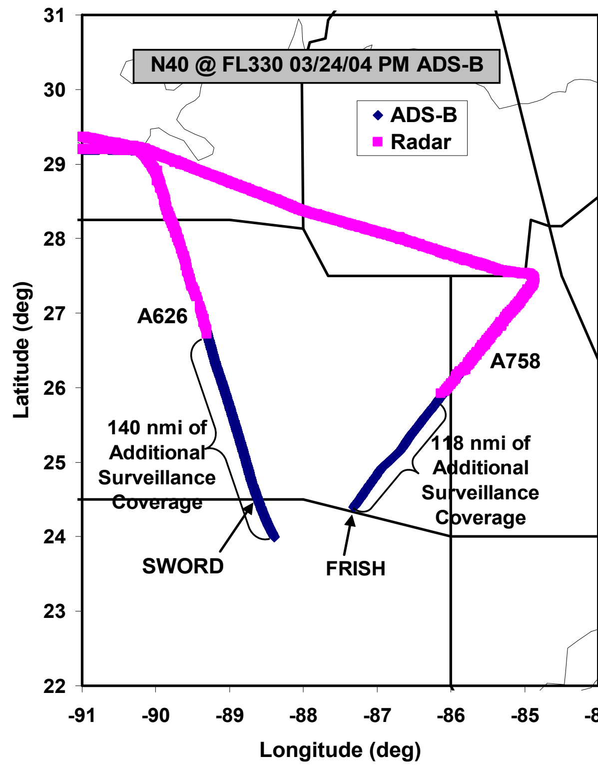


(d) B-727 Feb. 12 AM Flight (FL370)

Figure 6-13 Coverage Comparison: ADS-B vs. Long-Range Radar.



(e) B-727 March 24 AM Flight (FL280)



(f) B-727 March 24 PM Flight (FL330)

Figure 6-13 Concluded.

The Phase III RU configuration did not provide ADS-B coverage in the southeastern corner of the Houston Oceanic sector, as shown in figure 6-13(d) and figure 6-13(f). Figure 6-13(d) shows ADS-B position report within 12 nmi of the en route waypoint MYDIA in the U.S. FIR. Figure 6-13(f) shows the position of the aircraft being received at the en route intersection FRISH, but the track does not extend into the Mexican FIR.

The March 24 G-III test shown in figure 6-10 assessed ADS-B surveillance coverage along the U.S./Mexican FIR boundary at different flight levels. Full coverage on the U.S. side was achieved at FL280, and coverage well into the Mexican sector was achieved at FL390. This test also reinforced the conclusion made earlier that the range of the RUs was LOS-limited rather than signal power-limited. The coverage gaps at FL280 are not present when the aircraft is at FL390 while flying essentially the same ground track, proving that the Earth's curvature blocked the signal at the lower altitude.

6.2.4 ADS-B Performance Summary

ADS-B performance of the HITS Phase III system during flight tests was fully satisfactory. Ground-station range, lat/lon/alt update rate, and coverage met or exceeded the goals for these parameters (table 6-8). The flight tests also demonstrated the possibility of extending current long-range radar surveillance coverage into Mexican airspace, for ADS-B equipped aircraft. Complete ADS-B coverage within the Houston Oceanic sector would likely be possible with the installation of RUs in Mexico and the Florida Keys. Phase III ADS-B performance was sufficiently favorable that, at the conclusion of the NASA HITS effort, the FAA assumed management responsibility for the deployed HITS equipment.

Table 6-8 Phase III ADS-B Performance Summary

Performance \ Criterion	Detection Range	Update Interval (99%)			False Targets
		Position	Velocity‡	Flight ID‡	
Standard*	200 nmi	10 sec	10 sec	10 sec	0%
Measured	277 nmi	1.8 sec	N/A	N/A	0%
Difference†	39%	82%			0%

* Performance standard established for HITS evaluation—see chapter 3 and appendix A.

† Difference is expressed as a percentage of the standard, except when the standard is zero.

‡ For information purposes only; not part of evaluation.

It is noted that Phase III tests involved only high-altitude flights. Thus possible ADS-B performance limitations at low altitudes, as were observed for WAM, would not be revealed by these tests.

6.3 WAM Flight-Test Results

Five flights during the March 2004 test period were selected for the Phase III WAM evaluation: one involving an ATCRBS-equipped aircraft (B-727 on March 23), one involving a Mode S short squitter-equipped aircraft (G-III on March 24), and three involving ADS-B-equipped aircraft (all by the B-727). These flights were within the array "receive" coverage area, but were both inside and outside the coverage of the transmitter (figure 6-3). This was the first assessment in the U.S.—and possibly anywhere in the world—of a WAM system designed for en route/oceanic distances and/or that employed satellite signals (GPS) for RU time synchronization. The following criteria were used in the assessment:

- Horizontal position accuracy
- False target rate
- Horizontal position, Mode A, and Mode C update intervals
- Coverage

6.3.1 Horizontal-Position Accuracy and False Target Rate

Position accuracy and false target statistics are shown in table 6-9. The measured 95-percent position errors were much larger than those observed during Phases I/II (which were between 100 and 200 ft). However, they were comparable to the standard of 4375 ft established for en route/oceanic operations during this effort.

Table 6-9 Phase III WAM Horizontal Position Accuracy and False Target Rate

Flight Date	Aircraft	Transponder	Horiz. Position Error (95%)	False Target* Rate
March 23 AM	B-727	Mode S extended squitter	5077 ft	0.8%
March 23 PM	B-727	ATCRBS	1464 ft	0%
March 24	G-III	Mode S short squitter	3963 ft	2.2%
March 24 PM	B-727	Mode S extended squitter	4152 ft	0.1%
March 25 PM	B-727	Mode S extended squitter	4053 ft	0.8%

* Defined as horizontal position error greater than 10,000 ft

Accuracy for the ATCRBS transponder was much better (factor of 3 to 4) than accuracy for the two Mode S transponders. The cause of this difference appears to be the presence/absence of altitude information when the TP calculated the aircraft position from a set of TOA measurements. As discussed in Subsection 2.1.5, for ATCRBS aircraft, approximately 85 percent of the measurements on Mode A messages were accompanied by the aircraft Mode C code. Thus, most of the time, reported aircraft altitude was available for use in the horizontal-position calculation.

For the Mode S short squitter transponder, HITS used three separate messages (DF04, DF05, and DF11) to form WAM target reports. The DF11 message, broadcast once per second, was the most prevalent. However, the DF11 contained no altitude information, so that, in forming a WAM target report, the TP assumed that the aircraft was on the surface (zero altitude). The resulting large altitude error caused a significant error in the computed horizontal position. (The DF04 message did contain aircraft barometric altitude, but was transmitted only in response to interrogations from the ground, provided the aircraft was within range of the Morgan City interrogator.) For the Mode S extended squitter transponder, no altitude information was used.

As a consequence of the position error dependence on the availability of aircraft altitude, one could conclude that the error measured with the ATCRBS transponder is more representative of the accuracy of a more mature WAM system. For example, for Mode S short squitter messages, an alternative implementation could use the last available altitude information ("coast the altitude") when computing the horizontal position, with a resulting significant increase in accuracy. For Mode S long squitter messages, the software design could be changed to make use of the altitude information in the DF17 "lat/lon/alt" messages.

Aside from the presence/absence of altitude information, the immaturity of the ATCRBS position error suggests that there were residual errors of omission and commission in tested equipment. If these errors were corrected, one would expect the Phase III system position accuracy to be significantly better than was achieved with the ATCRBS transponder (and possibly approaching the accuracy demonstrated during Phases I and II).

Following Phase III testing, Sensis Corporation performed an assessment of its equipment, and found several factors that degraded performance (ref. 13). These included:

- CLX-type armored cable was used at the deep-water sites (because of platform safety regulations) instead of the Acutime 2000 cable shipped with the RUs. The CLX cable had a velocity of propagation (VOP) of 47 percent, which is significantly slower than the Acutime cable VOP of 80 percent.
- The TP software applied the wrong sign to the cable delay for all RUs. For example, the cable delay for the Galveston RU was configured as +500 nsec (equivalent to approximately 500 ft) and should have been –500 nsec.

These possible error sources are all plausible. However, additional testing would be required to confirm Sensis' analysis.

Data from the B-727 March 24 PM flight, using the Mode S extended squitter transponder, were analyzed to determine the relationship between the number of RUs contributing to a position solution and the horizontal position error. The result (figure 6-14)—indicating errors up to 7000 ft with three or four receiving RUs, but up to only 1000 ft with 5 or 6 RUs—is quite different from plots of the same type prepared during other WAM evaluations (ref. 14). In the referenced project, position error decreased more slowly and steadily as the number of receiving RUs increased, much as HDOP would decrease. The dramatically smaller errors achieved with 5 and 6 RUs—approximately a factor of seven—suggest that the error sources involved (whether those listed previously or others) are not random TOA measurement error, but are more deterministic/bias-like. This is consistent with erroneous altitude being the dominant contributor to horizontal position error, because the AECCF is essentially zero when many RUs are in view (figure 6-4).

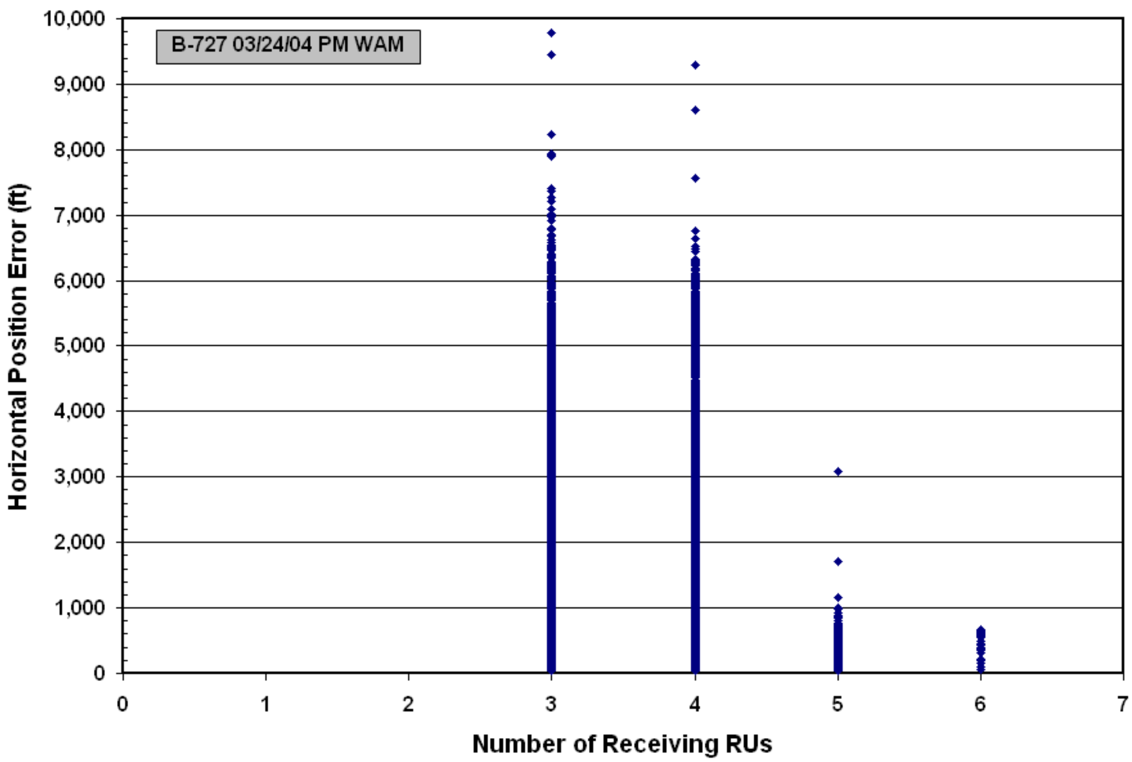


Figure 6-14 Number of RUs vs. Horizontal Position Error.

6.3.2 Position, Mode A, and Mode C Update Interval and Code Correctness

Table 6-10 presents HITS Phase III WAM update-interval and code-correctness statistics. The ATCRBS transponder had the largest (poorest) position update interval, not surprising considering that this unit: (a) had a shorter operating range than the Mode S transponders (figure 6-9), and (b) had to reply to an interrogation in order for its position to be calculated. Position-update performance for the Mode S transponders was consistent: the transponder that more frequently broadcasts squitters had a significantly shorter update interval. The extended squitter unit broadcast ADS-B position/velocity DF11 TCAS squitters at a combined rate of 5 Hz; in contrast, the short-squitter unit broadcast DF11 messages at 1 Hz.

Table 6-10 Phase III WAM Update Intervals and Code Performance

Flight Date	Aircraft	Transponder	Update Interval (sec, 99%)			Code Correct	
			Position	Mode A	Mode C	Mode A	Mode C
March 23 AM	B-727	Mode S extended squitter	1.9	N/A	14.4	N/A	100%
March 23 PM	B-727	ATCRBS	14.6	14.6	20.2	100%	100%
March 24	G-III	Mode S short squitter	4.1	29.4	32.8	100%	100%
March 24 PM	B-727	Mode S extended squitter	1.7	N/A	28.9	N/A	100%
March 25 PM	B-727	Mode S extended squitter	1.4	N/A	34.9	N/A	100%

To obtain a Mode A or Mode C code from a Mode S transponder requires a response to an interrogation. The HITS Phase III system was configured to interrogate for a Mode S transponder beacon code once every

2.4 sec and for its altitude code once every 2.1 sec. Given these interrogations, altitude-update performance for the Mode S transponders was unexpectedly poor. This indicates that at least one of the up/down links is not sufficiently robust.

Code correctness (essentially, decoding accuracy) was error-free.

6.3.3 WAM Coverage

The WAM coverage assessment is qualitative. Ground tracks for the five flights used in the evaluation (listed in table 6-10) are shown in figures 6-8, 6-9, 6-11, 6-15, and 6-16. Coverage for these flights was generally consistent with predictions based on standard analysis techniques—link power budgets and HDOP contours. Typically, coverage was better than predicted when the three deep-water RUs were involved, because these had better-than-expected receiving ranges.

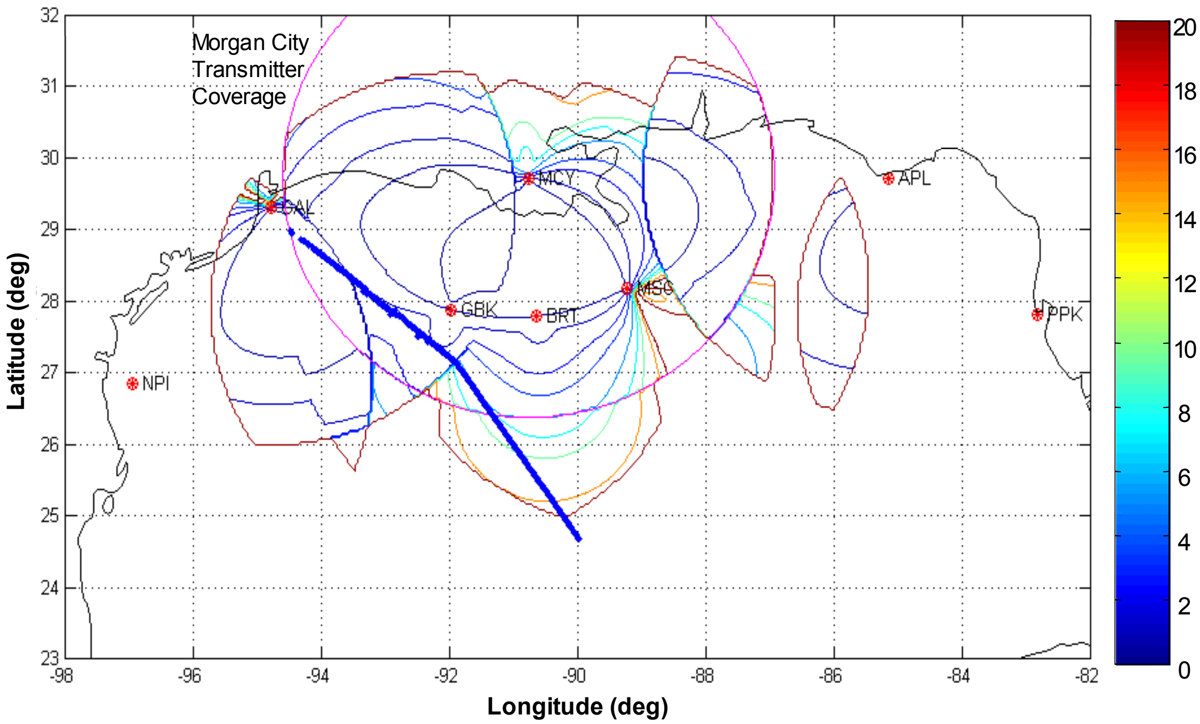


Figure 6-15 B-727 March 23 AM Flight at FL270 and HDOP Contours (WAM/Mode S ES Track).

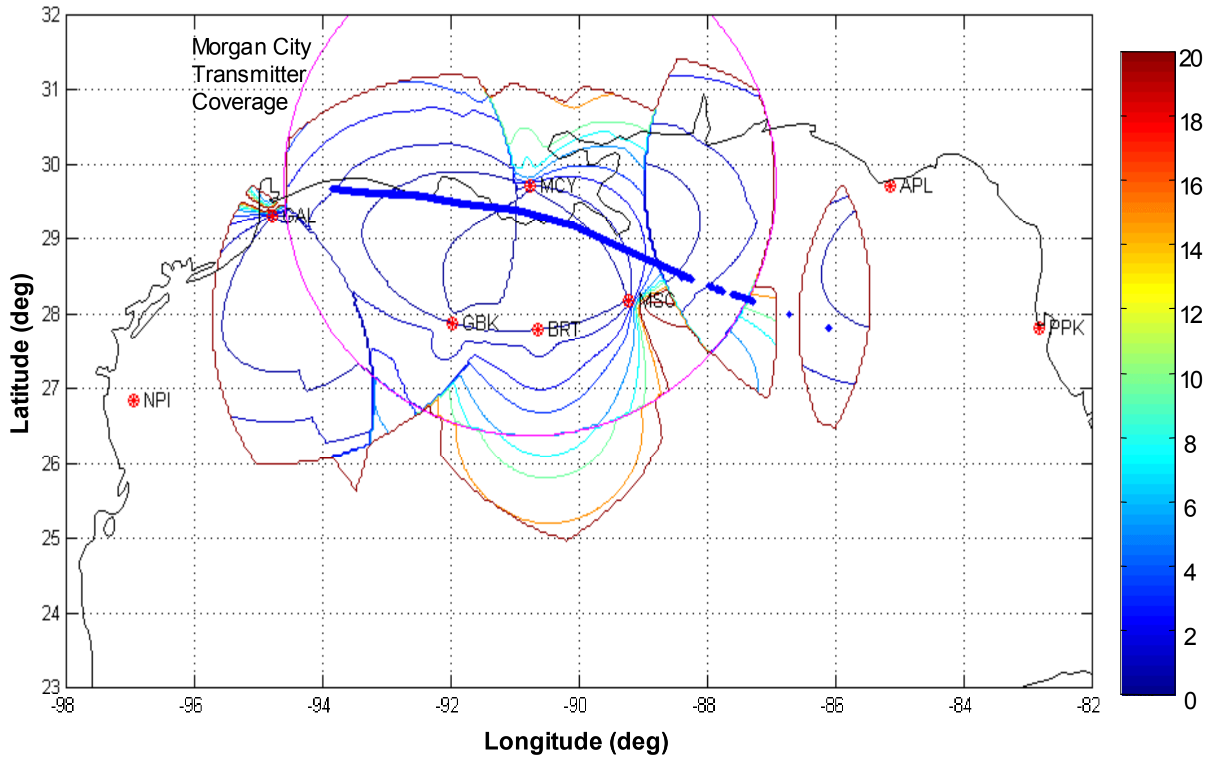


Figure 6-16 B-727 March 25 PM Flight at FL350 and HDOP Contours (WAM/Mode S ES Track).

6.3.4 WAM Performance Summary

The HITS Phase III system provided an opportunity to develop and mature WAM technology for en route/oceanic-like applications. The initial results, summarized in table 6-11, did not meet the standards established for this effort. This is not surprising in light of the fact that this was the first application of WAM technology to the large distances associated with en route-like and oceanic airspace. The contractor did demonstrate the integration of GPS timing synchronization into its RUs as well as the integration of an interrogator capable of eliciting replies at distances greater than 200 nmi.

In terms of improving accuracy, several modifications were identified that appear to be readily implementable with only software changes. Improving WAM update performance for widely separated sites will likely require additional/modified hardware—e.g., higher-gain ground antennas (possibly directional), more ground sites, and more frequent interrogations.

An option that should be considered in future WAM investigations/developments is determination of aircraft range to each receiving RU by measuring the time of transmission (TOT) of each interrogation and subtracting it from the measured transponder reply TOAs at the RUs. This approach—referred to as using range measurements rather than pseudorange (equivalent to TOA-only) measurements—requires software but not hardware changes. It has the practical advantage that the minimum number of receiving RUs needed to calculate aircraft position is reduced from three to two. Thus, either: (a) fewer RUs must be deployed for a given coverage area; or (b) if the same number is deployed, the update performance is improved.

Table 6-11 Phase III WAM Performance Summary

Trans-ponder	Criterion / Performance	Position Error 95%	Position Error >10k ft	Update Interval (99%) Position	Update Interval (99%) Beacon	Update Interval (99%) Altitude	Code Correct Beacon	Code Correct Altitude
Mode A/C	Standard*	4375 ft	0.1%	10 sec	10 sec	10 sec	99%	99%
	Measured	1464 ft	0%	14.6 sec	14.6 sec	20.2 sec	100%	100%
	Difference†	67%	100%	–46%	–46%	–102%	1%	1%
Mode S Short Squitter	Standard*	4375 ft	0%	10 sec	10 sec	10 sec	100%	100%
	Measured	3936 ft	2%	4.13 sec	29.4 sec	32.8 sec	100%	100%
	Difference†	10%	–2%	59%	–194%	–228%	0%	0%
Mode S Extended Squitter	Standard*	4375 ft	0%	10 sec	10 sec	10 sec	100%	100%
	Measured	4317 ft	0.6%	1.8 sec	N/A	27.8 sec	N/A	100%
	Difference†	1%	–0.6%	82%	N/A	–178%	N/A	0%

* Performance standard established for HITS evaluation—see chapter 3 and appendix A.
† Difference is expressed as a percentage of the standard, except when the standard is zero.

6.4 Overall Assessment and Summary

ADS-B performance of the HITS Phase III system was better than anticipated. RU receiving range was demonstrated to be LOS-limited rather than signal strength-limited. The RUs were able to receive and reliably decode messages at 250 nmi when the aircraft had sufficient altitude. It was demonstrated that 8 stations can provide coverage nearly throughout the 2 Houston FIRs.

WAM performance did not satisfy several performance standards established for this effort. However, basic functionality was proved and several candidate system improvements were identified.

7. HITS Deployment/Evaluation Synopsis

7.1 Purpose

In response to direction in the FY01 and FY02 budget acts, the National Aeronautics and Space Administration (NASA) deployed the Helicopter In-flight Tracking System (HITS) in Gulf of Mexico offshore and deep-water areas. HITS implemented two new aircraft surveillance technologies: wide area multilateration (WAM) and automatic dependent surveillance – broadcast (ADS-B).

To take advantage of the opportunity offered by the HITS deployment, NASA, with recommendations from other organizations, formulated several technical and operational goals. The most important were:

- Determine how well WAM and ADS-B perform in comparison to the specifications for traditional secondary surveillance radar (SSR) now deployed in the National Airspace System (NAS).
- Assess WAM capabilities to support low-altitude helicopter operations under instrument flight rules (IFR) in a terminal area and transiting to offshore platforms.
- Evaluate the capabilities of an ADS-B ground-station configuration to surveil the entire U.S.-managed portion of high-altitude Gulf airspace.
- Identify practical issues associated with deploying and operating air traffic control assets on nongovernmental, offshore platforms.

The U.S. Department of Transportation (DOT) Volpe National Transportation Systems Center (Volpe Center) served as the technical/operational evaluator and contracting agent. Sensis Corporation manufactured, installed, operated, and maintained the HITS equipment. At NASA's invitation, the Federal Aviation Administration (FAA) participated on a consultative basis in FY01–FY02, and actively in FY03–FY04. HITS deployment and testing were coordinated with Gulf aviation operators/organizations.

Evaluation criteria and numerical standards specific to this effort were developed by the Volpe Center based on the specifications for the FAA's Air Traffic Control Beacon Interrogator, Model 6 (ATCBI-6). Three surveillance system architectures were implemented. Their performance was evaluated against the HITS standards during nine separate flight-test periods. Results of those tests are summarized in Section 7.2. Conclusions (Section 7.3), Recommendations (Section 7.4), and then programmatic Lessons Learned (Section 7.5) follows. The posttest transfer of management of HITS assets from NASA to the FAA is described in Section 7.6.

7.2 Summary of Configurations and Flight-Test Findings

Test results are briefly described for the three deployment phases. Results depend most strongly on the following test conditions:

- Aircraft altitude regime: low (less than 3k ft), mid (approximately 10k ft), and high (greater than 20k ft)
- Analogous airspace type: terminal (ground sensors less than 50 nmi from aircraft), and en route/oceanic (ground sensors up to 250 nmi from aircraft)
- Measurement/transponder type:
  - WAM with Air Traffic Control Radio Beacon System (ATCRBS) transponder
  - WAM with Mode S short squitter transponder
  - WAM with Mode S extended squitter transponder
  - ADS-B with Mode S extended squitter transponder

Although of developmental value and technical interest, WAM capability with Mode S extended squitter transponder has operational use only as a backup to ADS-B for that equipment combination. Funding did not permit testing all combinations of conditions.

7.2.1 Phase I: Configuration Serving Helicopters/Offshore Platforms

Configuration Description—The Phase I system was the first U.S. deployment/test of a multilateration system for surveillance of in-flight aircraft. The architecture consisted of 21 remote units (RUs), with 17 on petroleum platforms. It was designed to provide WAM coverage of an area south of Intracoastal City, Louisiana—above 100 ft in altitude over a footprint of approximately 7000 nmi^2, and above 1000 ft over an additional footprint of 8750 nmi^2. This region is approximately 50-percent larger than the area covered by a terminal radar. ADS-B coverage was intended to extend over 100 nmi beyond the perimeter of the RUs. The central processing site (CPS) was located at Lafayette, Louisiana.

WAM Performance at Low Altitude with ATCRBS Mode A/C Transponder (Sept. 2002)—Flight tests conducted using two aircraft demonstrated satisfaction of most criteria derived from terminal SSR specifications. The composite horizontal position error—for both aircraft and flights up to 100 nmi from shore—was 172 ft (95 percent), significantly better than the standard of 416 ft (95 percent). Relative to SSR, WAM displayed exceptional performance for closely spaced/crossing targets.

An exception to the generally favorable performance was the target report (99-percent probability) update interval criteria. * For this test period, the interval between reports containing altitude ("Mode C") information was approximately one-half longer than the standard of 5 sec. The HITS RU antennas had a factor of 10 or less gain than a radar antenna. Consequently, the RU-aircraft communications link was more vulnerable to degradation by transmitter and receiver performance limitations, partial/full blockage of the signal path, and atmospheric effects. For this test period, the low-altitude flight trajectories (providing greater opportunities for signal loss and blockage), the use of general aviation ATCRBS transponders (typically having lower transmit power), and the relatively low interrogation rate (each receiver-transmitter (RT) broadcast one whisper-shout sequence every 2 sec) limited update performance.†

WAM Performance at Medium/High Altitude with Mode S Extended Squitter Transponder (Jan. 2003, Figure 7-1)—For flights at 10K and 22K ft of altitude, WAM satisfied all accuracy and update criteria with the (slight) exception of false target reporting. To address the false target issue, a software fix was identified and implemented for later tests. Relative to the September 2002 test period, target report update performance benefited from several changes: higher-altitude flight trajectories, use of a high-end transponder, a higher transponder message squitter rate (5 Hz total—2-Hz ADS-B position, 2-Hz ADS-B velocity, and 1-Hz Traffic Alert and Collision Avoidance System (TCAS) identification), and higher RT interrogation rate (1 Hz each for beacon and altitude code).

The HITS WAM and ADS-B functions used the same 1030- and 1090-MHz frequencies that are used by operational SSRs. Thus there was tradeoff inherent in choosing interrogation rates: Higher rates generally improved HITS update performance but increased the likelihood of disrupting aircraft tracking by nearby SSRs. To protect SSR operations, the FAA Office of Spectrum Policy and Management requested that HITS interrogators be configured so that their "transponder occupancy" (also called "victim transponder off-time"—the fraction of time an aircraft transponder was unavailable to a SSR because of HITS

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* Update performance for horizontal position, beacon code, and altitude code were evaluated separately.

† It is also relevant to observe that HITS performance was compared to SSR specifications. Although a SSR would be expected to perform better under these conditions, there is no assurance that it would have satisfied the update criteria.

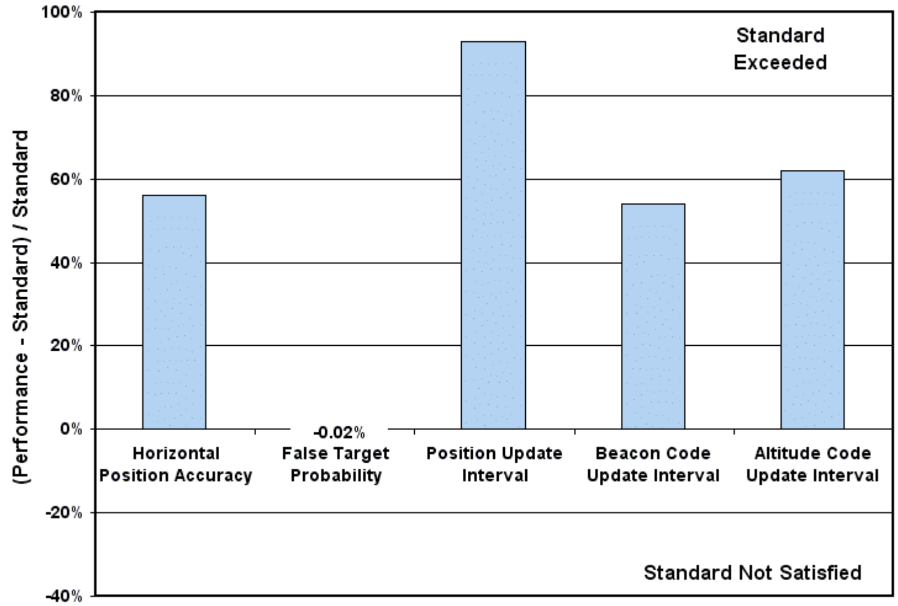

Figure 7-1 WAM Performance: High-Altitude, Terminal-Like Area, Mode S Extended Squitter Transponder.

interrogations) was 0.25 percent or less. This value is also a requirement for the Airport Surface Detection Equipment, Model X (ASDE-X) surface-surveillance system currently being deployed. For this test period, analysis predicted the worst-case HITS transponder occupancy to be 0.41 percent, about 1.6 times the FAA goal. (The equipment was not capable of measuring occupancy time.) This issue is discussed further in Subsection 7.2.2.

ADS-B Performance at Medium/High Altitude with Mode S Extended Squitter Transponder (Jan. 2003)—Reliable reception and message decoding was achieved for a target at Flight Level 220 (FL220) and ranges greater than 100 nmi. Limitations of the All-Purpose Structural EUROCONTROL Radar Information Exchange (ASTERIX) Cat 10 interface message format did not enable a complete assessment of the Mode S extended squitter message set.

Operational Benefit to Helicopter Fleet Operators—Most of the Gulf helicopter fleet is equipped with ATCRBS transponders. Standard practice is for FAA air traffic controllers to assign one beacon code to each fleet operator during visual flight rules (VFR) operations, making it impossible to automatically distinguish individual aircraft using WAM. As a consequence, when offered, operators showed little interest in receiving real-time feeds of HITS surveillance data.

Practical Issues for Offshore Deployment—Siting equipment on offshore platforms did not present inordinate problems. Over the period September 2002 to February 2003, the HITS RUs tolerated Gulf winter weather well, including a hurricane. However, attempting to maintain 24-hour communications between the RUs and CPS required frequent intervention to address issues such as lightning strikes on RUs and network changes by the commercial communications service provider.

7.2.2 Phase II: High-Density Helicopter Terminal Surveillance System

Configuration Description—The Phase II system consisted of seven RUs designed to provide WAM surveillance of helicopters operating from Intracoastal City. The coverage region—altitudes above 100 ft over a 1600-nmi^2 footprint, and altitudes above 1000 ft over an additional 5500-nmi^2 footprint—was comparable to that needed at several U.S. locations that do not currently qualify for a radar but could benefit from surveillance service. Typically, these airports have significant commercial (air taxi) traffic, frequent spells of poor visibility, and/or difficult terrain for approaches.

WAM Performance at Low Altitude with ATCRBS Transponder (June 2003, Figure 7-2)—Data for two leased Bell 206 Long Ranger helicopters equipped with ATCRBS transponders demonstrated satisfactory performance for most criteria while operating under 2000-ft altitude. The 105-ft (95 percent) horizontal-position error was the best achieved by WAM during the HITS effort, and was approximately one-quarter of the standard of 416 ft (95 percent). Resolution of closely spaced targets was also quite good. In contrast, target report update intervals were marginally longer (poorer) than the standard of 5 sec (99 percent), despite use of a high interrogation rate (aircraft were subjected to 2 whisper-shout sequences each second).

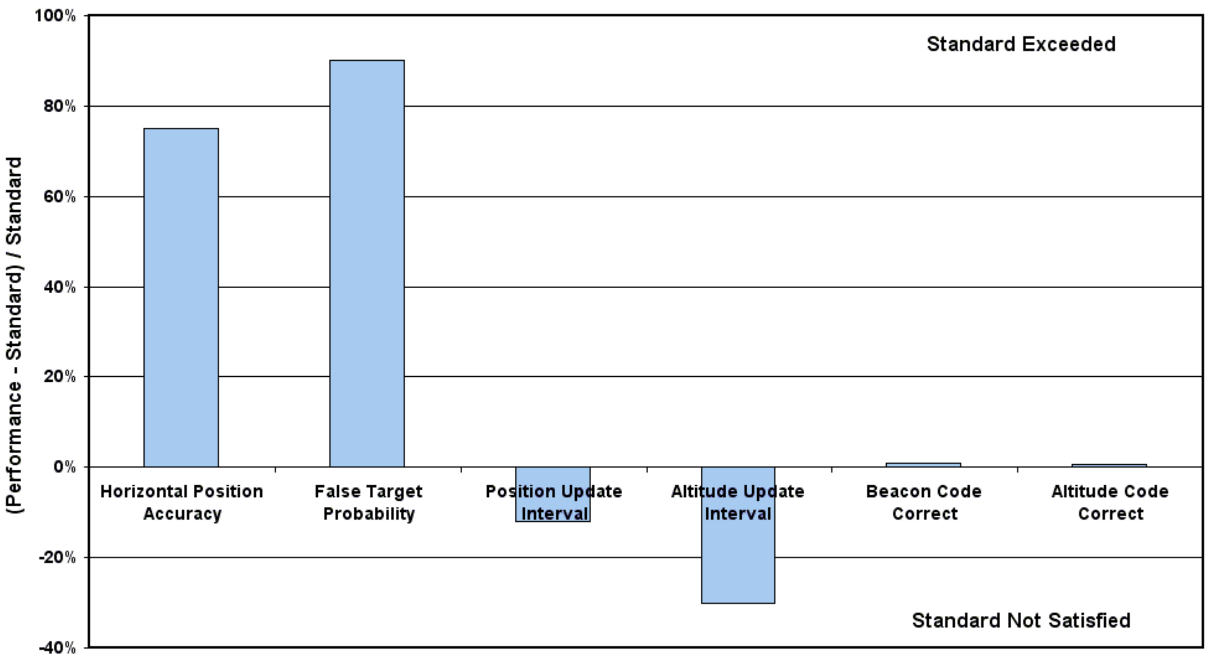

Figure 7-2 WAM Performance: Low-Altitude, Terminal-Like Area, ATCRBS Transponder.

The calculated transponder occupancy of 0.62 percent was 2.5 times the 0.25-percent maximum requested by the FAA. However, this value should be viewed in the context of the 1-percent TCAS occupancy standard. The TCAS standard was chosen to protect SSRs in high-traffic-density airspace such as Chicago. Given the lower aircraft density in the Gulf, the occupancy standard for HITS requested by the FAA "Spectrum Office" appears to be overly stringent. Moreover, the FAA is currently conducting studies to determine whether the ASDE-X system satisfies its 0.25-percent transponder occupancy requirement. Those studies indicate that, because of the relatively low rate of transponder responses to ASDE-X interrogations, calculated occupancy times using the methodology employed herein may be approximately a factor of two larger than actual occupancy times.

7.2.3 Phase III: Deep Gulf Surveillance System

Configuration Description—The Phase III system comprised eight RUs—three on platforms located over 100 nmi from the coastline and five on shore arrayed in an arc from Texas to Florida approximately 200 nmi apart. To improve reception, the RU receivers were made 5 dB more sensitive than the Phase I/II units, and omnidirectional 8-dBi gain antennas were deployed at all RUs. The CPS was located in the Houston Air Route Traffic Control Center (ZHU ARTCC). The Phase III configuration was designed to provide ADS-B coverage for most of the northern two-thirds of the Gulf (approximately 486,000 nmi^2), including the region in the center that lacks surveillance coverage. Currently, this region requires use of oceanic separation procedures for trans-Gulf operations, resulting in departure delays during peak traffic periods.

WAM was implemented where overlapping coverage from three or more RUs existed, with the expectation of surveilling approximately one-third of the ADS-B coverage region. Employing WAM technology over such a broad area required two significant technology enhancements: (1) GPS timing was introduced to synchronize the RU clocks, and (2) an experimental high-power interrogator was employed to elicit aircraft transponder replies. This was the first U.S. deployment/test of WAM for a region of comparable size and sensor-aircraft distances.

ADS-B Performance at High Altitude with Mode S Extended Squitter Transponder (Feb. and Mar. 2004, Figure 7-3)—HITS demonstrated reliable reception of Mode S extended squitter messages from targets up to 250 nmi away. ADS-B coverage was demonstrated within nearly the entire U.S. flight information region (FIR) at/above FL280, with the exception of the southeast corner of the Houston Oceanic East Sector area (this area lacks deep-water platforms or other means of locating a RU). Continuous high-altitude surveillance by a combination of HITS ADS-B and Mexican radar was demonstrated for flights between the U.S. southern coast and the Yucatan Peninsula along published jet airways.

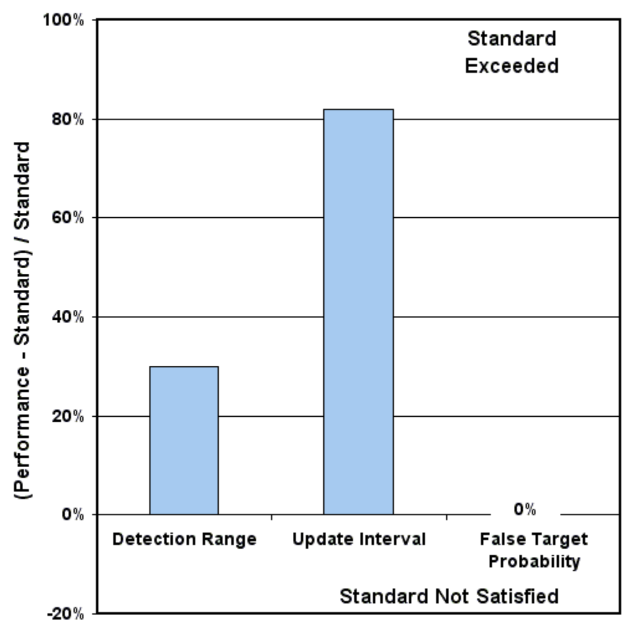

Figure 7-3 ADS-B Performance: High-Altitude, Oceanic-Like Area.

WAM Performance at High Altitude with Mode S Transponder (Mar. 2004)—The system demonstrated the capability of providing WAM data for Mode S short- and extended-squitter-equipped aircraft essentially throughout the predicted coverage region based on a 200-nmi RU reception range, including interrogating Mode S-equipped targets at distances greater than 200 nmi.

Quantitatively, the horizontal-position error was comparable to the standard established for en route/oceanic regions, 4375 ft (95 percent). Implementation issues were identified during posttest analyses that, if resolved, have the potential to improve accuracy significantly. The most significant of these was making better use of altitude information in the WAM calculations. Target report update performance for parameters requiring an interrogation-response cycle (beacon and altitude codes) did not meet the standard derived from SSR specifications. Achieved intervals for both codes were approximately 30 sec, three times the en route/oceanic standard of 10 sec (95 percent). Code update performance could be improved by deploying additional interrogators (including on platforms) and by use of higher-gain, nonomnidirectional antennas at sites on the perimeter of the coverage area.

WAM Performance at High Altitude with ATCRBS Transponder (Mar. 2004)—Functionally, the system demonstrated the capability to provide WAM data for an aircraft equipped with a general aviation class ATCRBS transponder essentially throughout the predicted coverage region based on a 125-nmi RU reception range. Quantitatively, the horizontal position error, 1464 ft (95 percent), was significantly smaller than that for Mode S aircraft because of better availability of altitude information. Target report update performance—which requires an interrogation-response cycle for formation of a report—did not meet the 10-sec (99 percent) standard established for this effort. Achieved intervals were approximately 15 sec (99 percent) for the beacon code and approximately 20 sec (99 percent) for the altitude code. As for HITS WAM performance with Mode S aircraft, target report update intervals could be improved by deploying additional interrogators and installing higher-gain antennas at some RUs.

Practical Issues for Deep-Water Deployment—Siting equipment on deep-Gulf platforms required more coordination and lead time than offshore platforms. Requirements for engineering drawings are more rigorous, and modifications can be made only during specific time windows.

7.2.4 Flight-Test Results Synopsis

Table 7-1 gives a synopsis of the results of flight tests of the ability of HITS to satisfy the evaluation criteria established for this effort. Additional information for each combination of airspace type, surveillance mechanism, and altitude regime can be found in earlier chapters, at locations cited in table 7-1.

Table 7-1 HITS Performance Conclusions, by Airspace/Surveillance Type/Altitude Regime

Airspace & Surv. Type / Altitude	Terminal-Like Airspace				En Route/Oceanic-Like Airspace			
	WAM with Transponder			ADS-B	WAM with Transponder			ADS-B
	ATCRBS	Mode S SS	Mode S ES	Mode S ES	ATCRBS	Mode S SS	Mode S ES	Mode S ES
< 3K ft	Note 1							
≈ 10K ft			Table 4-4	Table 4-7				
> 20K ft			Note 2	Table 4-7	Table 6-11	Table 6-11	Table 6-11	Note 3

Legend
SS = Short Squitter, ES = Extended Squitter
Black: Combination not tested.
Green: All evaluation criteria established for HITS were satisfied.
Yellow: Some evaluation criteria were satisfied, others were not.

Notes
1. See tables 4-3 and 5-5, and figure 7-2 (which is based on table 5-5).
2. See tables 4-5 and figure 7-1 (which is based on table 4-5).
3. See table 6-8 and figure 7-3 (which is based on table 6-8).

7.3 Conclusions

Wide Area Multilateration

- For terminal surveillance, WAM met most of the performance criteria. Horizontal-position error was consistently in the range 100–200 ft (95 percent), satisfying the standard of 416 ft (95 percent) by a large margin. Resolution of closely spaced targets was superior to that for radar. The major performance concern was the inability to obtain transponder messages from low-altitude aircraft as frequently as required for a SSR, particularly from aircraft equipped with low-end ATCRBS transponders.
- For en route/oceanic surveillance, WAM demonstrated potential for providing aircraft data in nonradar areas with more accuracy than a SSR. However, WAM target report update frequencies did not satisfy SSR specifications. As the first and only test period ever devoted to WAM surveillance of en route- or oceanic-like airspace, these results should not be taken as definitive of the capabilities of the technology.
- WAM performance with Mode S transponders was generally better* than that for ATCRBS transponders. This occurs for several reasons: (a) Mode S transponders broadcast a DF11 message once each second, from which the aircraft position can be estimated without an interrogation; (b) Mode S transponder messages contain a unique aircraft identifier, facilitating the clustering of detected versions of the same reply received at diverse geographical locations, and (c) Mode S transponders typically have higher performance capabilities than ATCRBS transponders.
- Interrogation schemes for beacon and altitude code data may need to be optimized to meet the transponder occupancy standard recommended by the FAA's Office of Spectrum Management. It would be appropriate to revisit/tailor this standard on a site-specific basis after the FAA has completed its study of ASDE-X transponder occupancy.

Automatic Dependent Surveillance – Broadcast

- For several extended flights above Flight Level 220, ADS-B satisfied the performance standards defined for this effort. No performance issues were identified that would preclude ADS-B from use as a sensor for mid- or high-altitude aircraft.
- Complete surveillance coverage of the Gulf of Mexico high-altitude airspace is limited by availability of RU locations—offshore platforms and possibly buoys—and not by surveillance-equipment performance.

Gulf of Mexico Environment

- HITS equipment operated with minimal disruption on petroleum platforms in an unfavorable weather environment.
- Communications from offshore platforms to a land-based facility by a commercial telecommunication service provider did not meet FAA availability standards.
- Approval for access to deep-water offshore platforms is generally challenging, and difficult at times.

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* The principal exception to this statement is the ATCRBS transponder WAM horizontal-position error during Phase III, which was approximately one-third of the error with Mode S transponders. This was due to the unavailability/ incorrect use of altitude information in WAM calculations using Mode S replies, and is not considered to be representative of the capabilities of WAM technology.

7.4 Recommendations

Based on the foregoing conclusions, the following actions are recommended to develop/improve WAM and ADS-B technologies:

Wide Area Multilateration

- Continue development/evaluation of WAM for en route applications, including correction of error sources observed during the Phase III test periods. Equipment changes can be tested with the currently deployed HITS RU locations and ADS-B-equipped targets of opportunity.
- Investigate the use of higher-gain, nonomnidirectional antennas at RUs on the perimeter of a WAM coverage area, such as the U.S. southern coast.
- Review the transponder occupancy time study being conducted by the FAA ASDE-X program, to determine its applicability to WAM use in terminal area and oceanic air space.
- Evaluate WAM processing based on range measurements (as opposed to the pseudorange measurements employed during HITS), as a means to (a) reduce the number of RUs, and (b) lessen the siting requirements on those that are deployed.
- Determine feasibility of integrating WAM as a supplement to SSR in high-density helicopter traffic areas, including interfacing WAM with current terminal automation systems.

Automatic Dependent Surveillance – Broadcast

- Conduct flight tests at altitudes up to 7000 ft, using airframe(s) and transponder(s) that operate in that regime, to determine whether the low-altitude target report update performance issues observed with WAM also occur with ADS-B.

7.5 Lessons Learned

Programmatic and technical issues arose during this effort that either proved beneficial or, if avoided, would have improved the overall program execution. These lessons include:

- **Award Contract on a Performance Basis**—The U.S. Government awarded the first HITS contract on a performance basis. This subsequently provided an incentive to the contractor in dealing with sensitive issues and resulted in better value to the taxpayer.
- **Be Skeptical of Commercial Off-the-Shelf (COTS) Equipment**—The HITS system was competitively awarded based partially on the availability of COTS equipment. However, less than one year into the effort, the RU receivers were redesigned. The U.S. Government detected a malfunction in the decoding of ATCRBS messages by the new receiver within a month of field installation. Replacement of all receivers added a three-month delay to the program.
- **Delineate the Evaluation Criteria and Test to Them**—The U.S. Government developed criteria for WAM and ADS-B evaluation based on existing SSR specifications. These provided a focus for the effort that would have been missing if the goal had been to demonstrate general functionality.
- **Flight Testing Is the Most Effective Evaluation Method**—Flight testing—rather than analysis or laboratory demonstration—proved to be the best way to assess performance and identify developmental issues. Examples of issues that were found by testing include (a) inability of RUs to detect ATCRBS-equipped aircraft, (b) significant WAM accuracy degradation with increasing aircraft altitude, (c) incorrect ADS-B message decoding for aircraft at ranges greater than 180 nmi, (d) inaccurate hardware clocks in the target processor (TP) computer, (e) sensitivity of WAM performance to the interrogation scheme, and (f) poor WAM accuracy with RUs using a Global

Positioning System (GPS) for timing. (Items (a)–(d) have been fixed; item (e) is site-specific and must be addressed for each deployment; item (f) is a recognized development area.)

- **Both Government and Contractor Engineering Add Value**—The best example is the Phase III configuration, which necessitated development/enhancement of capabilities in order to operate over much greater distances. To “hear” aircraft, the contactor successfully improved the sensitivity of the RU receivers. In order to “talk to” aircraft, the U.S. Government identified and required use of an interrogator from a third-party vendor that proved successful in field tests.

7.6 Transfer of Management of HITS Assets

Following the final flight-test period in March 2004, the four organizations involved in the conduct of the HITS effort—NASA, Volpe Center, Sensis, and the FAA—agreed that the most effective use of the remaining HITS assets was to transfer their management to the FAA. These assets consisted of the deployed Phase III equipment and spare equipment/parts. Additionally, sufficient funding remained to operate the Phase III equipment until March 2005 in support of tests managed by the FAA, to address issues associated with providing air traffic services to the Gulf with equipment similar to HITS. The first of those tests, being conducted at the FAA Technical Center, is directed at determining the viability of providing HITS ADS-B data in a radar-like format to the automation system (Host Computer System) installed at ARTCCs.

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Appendix A. Evaluation Criteria

This appendix provides detailed rationale for the Helicopter In-Flight Tracking System (HITS) evaluation criteria outlined in Chapter 3 of this report. Table 3-2 contrasts Air Traffic Control Beacon Interrogator, Model 6 (ATCBI-6) specification requirements (ref. 6) with those used to evaluate the HITS wide-area multilateration (WAM) and automatic dependent surveillance – broadcast (ADS-B) capabilities. The title for each subsection indicates the table 3-2 reference, and the applicable ATCBI-6 requirement is outlined next, prior to the explanation of how this requirement will be evaluated for WAM and ADS-B.

A.1 Coverage Volume

ATCBI-6 (ref. 6, Subsection 3.1.1, "Coverage Volume")—The ATCBI-6 shall provide surveillance coverage for the area defined as follows:

1. an altitude of 0 to 100,000 feet above ground level (AGL) as limited by the system elevation requirement specified herein;
2. an elevation from the local radar antenna horizon as determined by the Earth's curvature, atmospheric refraction, and as further limited by the terrain screening, to 40 deg with respect to the horizontal plane at the radar antenna;
3. a slant-range coverage from 0 to at least 125 nmi for terminal applications, and a maximum of 250 nmi in en route applications;
4. an azimuth of 360 deg.

WAM—WAM system coverage is inherently a more complex issue than radar coverage, because multilateration surveillance requires that (a) at least three remote unit (RU) sites be visible to the aircraft, and (b) the geometric arrangement of the RU sites be considered. Accordingly, three subcriteria are selected for this evaluation:

1. Each location in the HITS coverage volume must be within the coverage volume (as defined in criteria 2) of at least three RUs, and the system must provide an associated horizontal dilution of precision (HDOP) of
   - 1.5 or less within the polygon enclosing the perimeter RUs (primary coverage volume)
   - 4 or less with the area defined as the secondary coverage volume.
2. Each RU must provide reliable reception in a volume defined by:
   - altitude, 0 to 100,000 ft AGL;
   - elevation, horizon to 40 deg;
   - slant range, 0 to 50 nmi; and
   - azimuth, 360 deg.

   Reliable reception involves reception in accordance with Subsection A.2 of this appendix from transponders that comply with references 8 and 10.
3. Each location in the HITS coverage volume must be within the coverage volume (as defined in subcriteria 2) of at least one receive-transmit (RT) unit that interrogates (in accordance with Subsection A.5 of this appendix) transponders that comply with references 8 and 10.

The "geometry subcriterion" (first item) is taken from the Airport Surface Detection Equipment, Model X (ASDE-X) specification (ref. 7, Subsection 3.3.5), and is similar to requirements for most area navigation systems. HDOP is defined herein as the ratio of the horizontal position error to the time-of-arrival (TOA) measurement error in range units.

The “RU coverage subcriterion” (second item) is similar to that for the ATCBI-6. The maximum range value is changed from that for the ATCBI-6, based on engineering judgment and some published test results. It is clearly inappropriate to use the more stringent radar range requirement of 125 nmi or 250 nmi for a HITS RU, because (a) the HITS RU antennas have much lower gain, and (b) the HITS RT transmitter power is significantly less. Additional modification of the coverage subcriterion may be advisable based on test data and detailed antenna specifications and siting. A more limited approach to the HITS coverage volume subcriterion could require that each RU must provide reliable reception in a volume defined by (a) altitude, 0 to 60,000 ft AGL for an omnidirectional antenna and 0 to 100,000 ft AGL for a directional antenna; (b) elevation, horizon to 40 deg for both types of antennas; (c) slant range of 0 to 25 nmi for an omnidirectional antenna and 0 to 50 nmi for a directional antenna; and (d) azimuth of 360 deg for an omnidirectional antenna, and 0 to 180 deg for a directional antenna.

ADS-B—The ADS-B coverage criterion is based on the need for reliable communications with a single ground site, and is similar to the WAM RU subcriterion (second item) listed previously. Each remote site must provide reliable reception from a transponder compliant with reference 11 in a volume defined by: range, 0 to 50 nmi; azimuth, 360 deg; elevation, horizon to 40 deg; altitude, 0 to 100,000 ft.

A.2 Probability of Target Detection (Update Interval) and Probability of False Target Detection

ATCBI-6 (ref. 6, Subsection 3.1.2, “Probability of Target Detection (Pd) and Probability of False Target Detection”)—The ATCBI-6 shall achieve target detection greater than 99 percent for all aircraft within the detection volume as defined in Paragraph 3.1.1. The total of all Air Traffic Control Radar Beacon System (ATCRBS) false targets (reflections, multipath, splits, and false replies unsynchronized in time (FRUIT) disseminated by the monopulse secondary surveillance radar (MSSR) shall not exceed 1 for every 1000 real ATCRBS target reports disseminated (<0.1 percent of all ATCRBS targets disseminated can be false). The ATCBI-6 shall not report or disseminate any false Mode S target reports. This ability to detect targets and limit false targets shall be achievable in the presence of a steady-state environment of up to 11,000 ATCRBS and up to 1000 Mode S FRUIT per second, of which 100 percent are in the mainbeam.

The ATCBI-6 shall provide dynamic reflector processing for a minimum of 64 nonfixed reflectors and 64 fixed reflectors.

WAM—The probability of target detection, within 5 sec (terminal domain) or 10 sec (en route domain) of penetration into the HITS coverage volume, shall be greater than 99 percent for all transponder-equipped targets. Contained in each target report shall be current and correct Mode 3/A and Mode C code data. The probability of an ATCRBS false plot report shall be no greater than 0.1 percent within the coverage volume, including the effects of reflections, multipath, splits, and FRUIT. (There shall be, at most, one false ATCRBS plot report for every 1000 physical ATCRBS plot reports.) There shall not be any false Mode S or ADS-B plot reports.

For the HITS evaluation, it was determined that a target report whose target-position data diverges from target truth by more than 1000 ft (terminal domain) or 10,000 ft (en route/oceanic domain) shall be declared to be a false target. It was also determined that a report with 0.5 sec on the previous report would not be included in calculating the percentage of updates within 5 sec (terminal domain) or 10 sec (en route/oceanic domain), to avoid giving weight to reports that would have no operational utility.

ADS-B—The probability of target detection, within 5 sec (terminal domain) or 10 sec (en route domain) of penetration into the coverage volume, shall be greater than 99 percent for all airborne targets equipped with a 1090-MHz Mode S ADS-B transponder. There shall not be any false ADS-B plot reports. This performance shall be achieved in the radio frequency (RF) environment defined in the next entry. For the HITS evaluation, it was determined that a report with 0.5 sec on the previous report would not be included in calculating the percentage of updates within 5 sec (terminal domain) or 10 sec (en route domain), to avoid giving weight to reports that would have no operational utility.

RF Environment—The ability to detect targets and to limit false target generation shall be achievable with a steady-state transponder message density at each RU of up to 11,000 ATCRBS FRUIT per second, up to 1000 Mode S FRUIT per second, and up to 1000 ADS-B FRUIT (i.e., ADS-B targets) per second. The ATCRBS and Mode S FRUIT levels are specified in reference 6 which did not anticipate the introduction of ADS-B. The ADS-B FRUIT level for this evaluation is chosen to be equal to the Mode S level.

A.3 Target Plot Report Position Accuracy

ATCBI-6 (ref. 6, Subsection 3.1.3, "Accuracy")—The ATCBI-6 shall achieve the following range and azimuth accuracy:

Range Accuracy. The ATCBI-6 range errors, measured using beacon target reports, shall not exceed ±30 ft bias (including long-term drift) and the standard deviation of the range errors shall not exceed 25 ft. Transponder delay time variations from the nominal values specified in Federal Aviation Administration (FAA) Order 1010.51A , Section 2.7.11 shall not be included in the ATCBI-6 range bias measurement.

Azimuth Accuracy. The long-term combined sensor plus antenna azimuth accuracy shall not exceed the following values for the indicated antenna elevation angles:

1. Bias: For elevation angles <2 deg, the bias shall be within ±0.033 deg. For elevation angles equal or greater than 2 deg, the bias will be permitted to change as a function of the elevation angle due to the antenna beam widening. The sensor and antenna reported azimuth bias component change shall not exceed the change attributable to the antenna only.
2. Jitter: For all elevation angles less than 20 deg, the standard deviation of the azimuth errors shall not exceed 0.066 degree.

WAM (Terminal)—For applications in a terminal area, the HITS WAM subsystem shall calculate a two-dimensional (horizontal) position for ATCRBS, Mode S short squitter and Mode S extended squitter (including ADS-B) transponder messages. The plot report horizontal-position accuracy criterion is 416 ft (95 percent) for all transponder types. The rationale for this choice is presented immediately as follows.

Specified ATCBI-6 range errors are (see "Azimuth Accuracy"): bias, ±30 ft; and jitter, 25 ft rms. When combined, these yield a 95-percent range error of 80 ft (table A-1). The effect of uncertainty in the aircraft transponder time delay must be added to the radar range error. Reference 4 specifies ATCRBS transponder delay uncertainty to be ±0.5 µsec; reference 11 specifies Mode S transponder delay uncertainty to be ±0.25 µsec. Because the delay uncertainty applies to the round-trip elapsed-time measurement, the range error is one-half of the distance equivalent of the delay uncertainty. Combining the three error sources (table A-1) yields 95-percent range errors of 330 ft for ATCRBS transponders and 205 ft for Mode S transponders.

Table A-1 Summary of ATCBI-6 Range Errors

Radar Range Error Components (ft)			Transponder Error (ft)		Total Range Error (ft, 95%) by Transponder Type	
Bias	Jitter (rms)	Combined (95%)	ATCRBS	Mode S	ATCRBS	Mode S
±30	25	80	±250	±125	330	205

Specified ATCBI-6 angular errors are (see "Azimuth Accuracy"): bias, ±0.033 deg; and jitter, 0.066 deg rms. When combined, these yield a 95-percent error of 0.165 deg. Table A-2 presents the equivalent distance error, in the azimuth or cross-range direction, for three aircraft ranges.

Table A-2 Summary of ATCBI-6 Azimuth Errors

Angular Error Components (deg)			Linear Cross-Range Error (ft, 95%) Due to Combined Angular Error			
Bias	Jitter (rms)	Combined (95%)	@ 20 nmi [Note 1]	@ 40 nmi [Note 2]	@ 60 nmi [Note 3]	@ 250 nmi [Note 4]
±0.033	0.066	0.165	350	700	1050	4375

1. 20 nmi is the maximum distance between an airport and the Airport Surveillannce Radar (ASR) radar antenna for which ASR-radar-based instrument approaches are authorized.
2. 40 nmi is the maximum distance from a radar for which a 3-nmi minimum aircraft separation applies.
3. 60 nmi is the maximum usable range of a terminal radar.
4. 250 nmi is the maximum usable range of an en route radar.

The accuracy standard selected for HITS test data evaluation for terminal applications is based on the most stringent operation the ATCRBI-6 must support—providing information for radar-vector-based instrument approaches at the maximum distance the radar can be placed from an airport (20 nmi).

In computing the two-dimensional (horizontal) HITS accuracy standard, the radar range at 20 nmi of 330 ft (95 percent) applicable to an ATCRBS transponder and the azimuth/cross-range error of 350 ft (95 percent) are used. Both the range and cross-range errors are approximated by zero-mean Gaussian variates with a common standard deviation of 170 ft. [*] Then the corresponding two-dimensional (radial) error has a chi distribution whose 95-percent value is 416 ft.

WAM (En Route)—For applications in the en route domain, the HITS WAM subsystem two-dimensional (horizontal) position error shall be 4375 ft (95 percent) for all transponder types. The rationale for selecting this standard is that the principal operational function of en route radars is aircraft-to-aircraft separation. The maximum range at which separation services are provided is 250 nmi. As can be seen from tables A-1 and A-2, at large aircraft-radar separations, the radar measurement error in the range direction is negligible relative to the error in the azimuth or cross-range direction. Thus the WAM standard is selected to be the radar cross-range error at its maximum range.

ADS-B—This requirement is not applicable to the ADS-B subsystem, because it does not measure aircraft position.

[*] Treating the range and cross-range error components as Gaussian variates with zero-mean and rms value equal to the sum of the bias and jitter components is a common technique that leads to a mathematically tractable formulation without significantly altering the result that would be obtained by a more rigorous analysis. For the ATCBI-6, the range error could be more properly treated as a Gaussian variate with 25-ft standard deviation and an unknown mean constrained to ±280 ft (for an ATCRBS transponder). The mean could then be (a) set to its maximum value, or (b) treated as a random variate with uniform (or some other) distribution. The azimuth error could be treated similarly. The 95-percent horizontal position error could then be computed numerically for either approach (a) or (b). The approximation employed herein leads to results similar to approach (a) and appreciably larger (less stringent) than approach (b).

A.4 Target Resolution

ATCBI-6 (ref. 6, Subsection 3.1.4, “Resolution”)—Two closely spaced ATCRBS-equipped aircraft, with a uniform random distribution within a window described by a slant range separation less than 1.7 nmi and a simultaneous azimuth separation of less than 2.4 deg and greater than 1.2 deg, shall each be detected a minimum of 98 percent of the time. Two closely spaced ATCRBS equipped aircraft, with a uniform random distribution within a window described by a slant-range separation less than 1.7 nmi and a simultaneous azimuth separation of less than 1.2 deg, shall each be detected a minimum of 90 percent of the time. The code and altitude reported for each target detected in these closely spaced conditions shall be correct >90 percent of the time. Aircraft separated by greater than 1.7 nmi or greater than 2.4 deg in azimuth shall be detected and reported more than 99 percent of the time while meeting the detection volume, false target dissemination, and environmental conditions requirements described in Paragraph 3.1.2.

The ATCBI-6, when interrogating Mode S-equipped aircraft with discrete interrogations, shall resolve two Mode S-equipped aircraft or one Mode S and an ATCRBS-equipped aircraft 100 percent of the time.

WAM—Two closely spaced ATCRBS-equipped targets, defined as having 1.7 nmi or less separation, shall be resolvable 98 percent of the time. The identity (ID) and altitude codes reported for each of these targets shall be correct more than 90 percent of the time. ATCRBS targets separated by more than 1.7 nmi shall be detected and reported 99 percent of the time. All other combinations of closely spaced target pairs (i.e., one ATCRBS and one Mode S or ADS-B, or two Mode S, or two ADS-B, or one Mode S and one ADS-B) shall be resolvable 100 percent of the time. This criterion shall be satisfied in the presence of the RF environment specified in Subsection A.2 of this appendix.

ADS-B—Two closely spaced ADS-B-equipped targets shall be resolvable 100 percent of the time. This criterion shall be satisfied in the presence of the RF environment specified in Subsection A.2 of this appendix.

A.5 Interrogation Modes

ATCBI-6 (ref. 6, Subsection 3.1.5, “Interrogation Modes”)—The ATCBI-6 shall be capable of interrogating and processing replies from aircraft equipped with either ATCRBS or Mode S transponders. The ATCBI-6 shall interrogate and process replies from ATCRBS transponders in accordance with reference 4, Section 2.4. The ATCBI-6 shall interrogate and process replies from Mode S transponders in accordance with reference 10, Section 2.0. The ATCBI-6 shall be capable of providing a user-defined interrogation frame table (all-call and roll-call transmit/receive periods), with selectable interrogation period type and duration. The ATCBI-6 shall interrogate Mode S-equipped aircraft with a surveillance interrogation once per scan, with no more than a 10-percent reinterrogation rate. Interrogations shall be scheduled to fully and effectively use the available time.

WAM—HITS RTs shall be capable of interrogating and processing replies from aircraft equipped with ATCRBS or Mode S transponders. HITS RTs shall interrogate and process replies from ATCRBS replies using waveforms defined by reference 4, Section 2.4, and shall employ P4 pulses. RTs shall elicit Mode S replies using waveforms defined by reference 5, Section 2.0.

ADS-B—This criterion is not applicable to the ADS-B subsystem, because transponder messages are not elicited.

A.6 Multiple ATCRBS Reply Processing

ATCBI-6 (ref. 6, Subsection 3.1.6, “Multiple ATCRBS Reply Processing”)—The ATCBI-6 shall be capable of decoding at least four different replies simultaneously (i.e., where the F1 pulse of the fourth (last) reply precedes the Special Position Identification (SPI) pulse position of the first (earliest reply)).

WAM—Each HITS RU shall be capable of decoding at least four different ATCRBS replies simultaneously (i.e., where the F1 pulse of the fourth reply precedes the SPI pulse position of the first reply).

ADS-B—This criterion is not applicable, because the HITS ADS-B subsystem processes only Mode S extended-length messages.

A.7 Identity Code Reliability and Validation

Background—In addition to decoding a transponder message, the ATCBI-6 receiver outputs an associated "code validity" bit that indicates the level of confidence associated with the decoding process. (Decoding can be degraded because of a weak received signal and/or interference from overlapping FRUIT and garble.) Thus, when a transponder message is processed by a receiver, five outcomes are possible:

(a) Output message is correct (agrees with the code transmitted by the transponder) and is declared valid
(b) Output message is incorrect and is declared valid
(c) Output message is correct and is declared invalid
(d) Output message is incorrect and is declared invalid
(e) No output results from the transponder message.

ATCBI-6 (ref. 6, Subsection 3.1.7, "Code Reliability and Validation")**—**The ATCRBS Mode 3/A code detected and disseminated from the ATCBI-6 shall be correct (the same as what the aircraft transmitted) more than 99 percent of the time. The ATCBI-6 shall validate Mode 3/A codes a minimum of 99 percent of the time when the code is correct. Validation shall be declared less than 1 percent of the time when an incorrect code is disseminated. The ATCBI-6 shall correctly report the Mode S identification more than 99.9 percent of the time for Mode S-equipped aircraft.

WAM—For functional equivalence with the ATCBI-6, the HITS target processor (TP) shall have the capability to provide validity information for each plot report. Flight-test data collected will be analyzed to determine identity code reliability.

ADS-B—ADS-B identity information disseminated by HITS must be correct more than 99.9 percent of the time.

A.8 Altitude Report Reliability and Validation

ATCBI-6 (ref. 6, Subsection 3.1.8, "Altitude Report Reliability and Validation")—The ATCBI-6 shall correctly report the aircraft altitude more than 99 percent of the time. The ATCBI-6 shall validate that the altitude is correct more than 95 percent of the time. An incorrect altitude shall be validated less than 1 percent of the time. For Mode C replies with the D1 bit set or with C bits having values of 0, 5, or 7, the ATCBI-6 shall report an altitude of –99,900 feet.

WAM—For functional equivalence with the ATCBI-6, the HITS TP shall have the capability to provide validity information for each plot report. Flight-test data collected will be analyzed to determine altitude code reliability.

ADS-B—ADS-B altitude information disseminated by HITS must be correct more than 99.9 percent of the time.

A.9 ADS-B Navigation Data Reliability

ATCBI-6—This criterion is not applicable to ATCBI-6.

WAM—This criterion is not applicable to the HITS WAM subsystem.

ADS-B—HITS shall correctly report decoded ADS-B navigation information (latitude, longitude) more than 99.9 percent of the time.

A.10 Spectrum/Pulse Repetition Frequency (PRF)

ATCBI-6 (ref. 6, Subsection 3.1.9, "Spectrum/PRF")—All ATCBI-6 system performance requirements shall be met without exceeding a PRF of 200 Hz (2-mode interlace) and a maximum PRF of 300 (3-mode interlace). PRFs shall be selectable over the range of 50 to 400 Hz. This selection shall consist of at least 15 independent, fixed PRFs or equivalent, staggered PRF sets. The transmitter output waveform for ATCRBS interrogations as measured at the ATCBI-6 output port shall satisfy the waveform requirements of reference 6, Section 2.4. The radiated spectrum of any ATCRBS interrogation shall comply with reference 4, Section 2.4. The transmitter output waveform and spectrum as measured at the ATCBI-6 output port shall meet the requirements of reference 5, Section 2.4.1 for Mode S interrogations. The ATCBI-6 output port is defined as the RF connection for the RF cabling to the antenna rotary joint. This connection is after the RF ATCBI channel selecting relays.

WAM—The FAA Office of Spectrum Policy and Management is the governmental body responsible for managing the 1030- and 1090-MHz secondary surveillance radar (SSR) bands used by HITS. This office included, in the license to radiate on 1030 MHz in the Gulf of Mexico, the requirement that HITS not elicit more than 10 replies per second from any transponder. The FAA Spectrum Office also expressed a strong desire, verbally, that the HITS system be implemented in such a way that WAM interrogations would "occupy" a transponder for a maximum of 0.25 percent of the time (2500 µsec/sec). A transponder is occupied by HITS when it either is replying to a HITS interrogation or is inhibited from replying to another interrogation source as a result of a HITS suppression pulse sequence.

ADS-B—This criterion is not applicable because the HITS ADS-B subsystem does not transmit.

A.11 Target Capacity

ATCBI-6 (ref. 6, Subsection 3.1.10, "Target Capacity/Overload Processing")—The ATCBI-6 shall provide target processing capacity as defined below:

1. 1400 beacon (ATCRBS or Mode S) equipped aircraft targets (uniformly or nonuniformly distributed in range and azimuth) per 360-deg antenna scan (See "Note" after number 5); and
2. in addition to (1) the ATCBI-6 shall process target reports from a colocated primary radar for at least 700 primary target reports corresponding to the beacon targets specified in (a) plus an additional 300 false primary reports per 360-deg azimuth antenna scan. The primary target reports and false primary reports may be uniformly or nonuniformly distributed in range and azimuth; and
3. a peak of 350 beacon targets plus 350 primary radar targets corresponding to the beacon targets and 200 false primary reports all uniformly distributed in a 90-degree sector; and
4. a peak of 100 beacon targets plus 100 primary radar targets corresponding to the beacon targets and 100 false primary targets uniformly distributed across two contiguous 11.25-degree sectors; and
5. a peak of 32 beacon targets per 2.4-degree wedge plus 32 primary targets corresponding to the beacon targets and 32 false primary targets per 2.4-degree wedge.

Note: Under the conditions described in (1), the processing throughput reserve requirement of reference 6, Paragraph 3.1.12.3 shall be 33 percent.

WAM and ADS-B—HITS equipment shall have target processing capacity based on that for the ATCBI-6 when used in terminal operations (i.e., 5-sec period and 125 nmi). The primary radar target aspect of the ATCBI-6 specification is not pertinent to the HITS. Separate subcriteria are established for individual RUs and the full HITS.

1. Each HITS RU must have the capability to process returns from a total of 1400 transponder-equipped targets (total of ATCRBS, Mode S and ADS-B) within a 5-second update interval. Target capacity of 1400 for the RU will be verified during Factory Acceptance Testing (FAT) at Sensis without communications bandwidth restrictions.
2. The full HITS system, including inter-site communications and the TP, must have the capability to process:
   a. An average of one transponder target per 35 nmi^2 within the full coverage area, and
   b. A peak of one transponder target per 10 nmi^2 within 1 percent of the coverage area.

A.12 Overload Processing

ATCBI-6 (ref. 6, Subsection 3.1.10, "Target Capacity/Overload Processing")—The ATCBI-6 equipment shall provide a capability to automatically sense and protect against target overload situations. When a target overload condition occurs, it shall be declared and reported to the remote system control terminal as well as to the NAS Infrastructure Management System (NIMS) manager. During this situation, target processing shall be discriminately and dynamically reduced in a manner assuring optimum operational capability. When the overload condition is no longer present, overload reports to the remote system control terminal and NIMS manager shall be cleared and full beacon target processing shall automatically be restored.

WAM and ADS-B—The HITS equipment shall provide a capability to automatically sense and protect against target overload situations. When a target overload situation occurs, the HITS will declare and report the condition to the TP, and target processing shall be discriminately and dynamically reduced in a manner assuring optimum operational capability. When the overload condition is no longer present, overload detection and reporting shall be cleared and full target detection and processing will resume.

A.13 Data Latency

ATCBI-6 (ref. 6, Subsection 3.1.11, "Data Timeliness")—Time for the ATCBI-6 to process incoming secondary beacon replies, weather reports, and primary radar reports shall be defined as the interval from the time when antenna boresight passes a target measured azimuth to the time that a target report is output to the automation system. For terminal-configured ATCBI-6 all data shall be processed and available for transmission from the sensor to the air traffic control (ATC) facilities no later than 3/32 of a scan period, nor sooner than 5/64 of a scan period, after their acquisition by the ATCBI-6. The ATCBI-6 shall also accept external radar data derived from a colocated primary radar system for the purpose of performing radar/beacon report correlation and merge function. All radar data that is received within 3/64 of a scan from the radar system shall be processed by the correlation function. These requirements shall be met while the ATCBI-6 is processing a capacity target load as specified in Paragraph 3.1.10. For en route-configured ATCBI-6, data shall be buffered for up to 6 seconds, and that data shall be throttled in a priority order under capacity overload (including exceeding of communications capacity) conditions. Weather data shall be buffered and delivered at a rate of less than 32 messages/second. Weather messages shall be dropped before primary search messages. Primary search messages shall be dropped before beacon messages.

WAM and ADS-B—Time for the HITS to process incoming transponder messages shall be defined as the interval from the time when a transponder emits a message to the time that a target report is output to the automation system. The HITS shall detect and process ATCRBS and Mode S transponder replies, and transmit target reports within 0.5 second of the transmission time of each transponder.

A.14 RU Clock Calibration

ATCBI-6 (ref. 6, Subsection 3.2.10.7, "Beacon Parrot")—The ATCBI-6 system shall include a beacon parrot transponder capability to be located at two fixed locations relative to the ATCBI-6 antenna. Conventional ATCRBS transponder Mode 3/A and C capability, plus selective addressing capability, shall be provided by the parrot at each of these two fixed locations. Mode S modes shall include the All-Call and surveillance uplink and downlink transmission capabilities as specified in FAA Order 6365.1A.

WAM—This criterion is based on the ASDE-X specification (ref. 7, Subsection 3.3.36). The HITS WAM subsystem shall include a means to synchronize the time-of-arrival (TOA) clocks of the RUs. If each RU clock takes the form of an internal counter of the cycles of an internal oscillator, then the calibration function shall compute the offsets and offset rates among the respective RU counters. If calibration transponders are used for this purpose, the system shall have the capability to use multiple transponders, and each transponder shall have at least one RU in common with another transponder.

ADS-B—This criterion is not applicable because the HITS ADS-B subsystem does not perform measurements.

A.15 Continuous Certification

ATCBI-6 (ref. 6, Subsection 3.2.12, "System Calibration")—The ATCBI-6 shall include provisions for the accurate north mark alignment, and calibration of the range and azimuth measurements in an automated process. This alignment and calibration shall include the use of permanently installed beacon transponders that are sited within the normal coverage volume of the system. Calibration shall ensure that target reports are correctly reported with reference to north and that all targets are reported in accordance with the accuracy requirements of reference 6, Paragraphs 3.1.3.1 and 3.1.3.2. The ATCBI-6 shall allow for correction of target report data to either true north or magnetic north.

WAM—HITS shall provide the capability to continuously certify (verify) that the WAM subsystem is operating properly. This can be accomplished by installation of external transponder message sources within the coverage volume of each RU triad or by including a transponder-like RF generator within each RU.

1. External WAM "parrots" should routinely broadcast transponder messages conforming to Mode A, Mode C, Mode S short length, and Mode S extended length without being elicited. External parrots should have unique identities, and should be placed at fixed, surveyed locations such that (a) each RU is in radio contact with at least one physical parrot, and (b) each physical parrot is in radio contact with at least three RUs.
2. Internal WAM "parrots" should be built-in target generators that routinely inject RF signals into each RU receiver that conform to Mode A, Mode C, Mode S short-length, and Mode S extended-length messages. Each message has an associated known identity and software-generated TOA that should be selected to correspond to known, specified locations (e.g., the center of each RU triad).
3. Internal WAM "parrots" should be analogous to the internal test generators built into distance measuring equipment (DME) ground transponders, and to a lesser extent to the internal monitors built into the instrument landing system (ILS) localizer and glide-slope equipment deployed throughout the National Airspace System (NAS). A disadvantage of internal WAM parrots is that they do not detect RU position changes.

ADS-B—HITS shall provide the capability to continuously certify (verify) that the ADS-B subsystem is operating properly. This may be accomplished through the use of either externally or internally generated ADS-B transponder messages:

1. External ADS-B "parrots" should routinely broadcast known ADS-B messages (i.e., known identity and location) without being elicited. External parrots should be placed such that each RU is in radio

contact with at least one physical parrot. If external parrots are used, each parrot shall have at least one RU in common with another parrot.

2. Internal ADS-B “parrots” should be target generators built into each RU that routinely injects RF signals in each RU receiver that contains known ADS-B messages (i.e., known identity and location, possibly different for each RU).

Internal ADS-B “parrots” should be analogous to the internal test generators built into several NAS navigation aids.

A.16 Processing and Display of SPI Responding Targets

ATCBI-6 (refs. 6 (Sections 1.3.4 and 2.6.3), and 11 (Section 2.2.4.1), related to the Special Position Identification (SPI) pulse)—The ATCBI-6 along with other SSR systems are designed to process and specifically display transponder responses that are accompanied by an SPI pulse (located 4.35 microseconds after the last framing pulse). The SPI pulse is available for transmission upon request of the ground surveillance authority. In addition to the 4096 discrete reply codes, the SPI pulse can be added to any responding mode with the exception of the Mode C. When the pilot depresses the transponder Ident button, the transponder transmits the SPI pulse (for approximately 15–30 seconds) and it is received and processed by the secondary surveillance radar receiver. In the case of a simple Plan Position Indicator (PPI), the SPI results in a much wider beacon slash being displayed for several sweeps of the radar antenna. This capability is used as a more positive means of aircraft identification.

WAM—HITS shall provide the capability to process and uniquely display targets responding with the SPI pulse.

ADS-B—This criterion is not applicable.

Appendix B. Airborne Data-Collection System

The Volpe Center developed an Airborne Data Collection System (ADCS) to record precise aircraft three-dimensional position as a function of time for installation on instrumented/controlled flight-test aircraft. The ADCS provided aircraft "position truth" information to be used in evaluating the performance of the Helicopter In-Flight Tracking System (HITS) wide-area multilateration (WAM) and automatic dependent surveillance – broadcast (ADS-B) functions.

Aircraft instrumented with the ADCS included several helicopters (leased from Petroleum Helicopters, Inc. (PHI)) and a light fixed-wing aircraft operated by Volpe. The helicopters all were Bell model 206 Long Rangers, and were equipped with Air Traffic Control Radar Beacon System (ATCRBS) Mode A/C transponders and very-high-frequency (VHF) radios. The fixed-wing aircraft was a Piper Aztec twin-piston-engine air vehicle equipped with a Bendix-King model KT76 Mode A/C transponder and three VHF radios.

The HITS ADCS (figure B-1) included the following:

- Differential-capable single-frequency Global Positioning System (GPS) aircraft receiver (Trimble Ag132) interfaced with a demodulator that receives GPS corrections generated by Omnistar and broadcast over a geostationary L-Band satellite
- Dual-band "patch" type antenna to simultaneously receive the GPS signal and Omnistar correction data
- Laptop computer for data recording, control, and display functions

The Omnistar real-time differential GPS system is advertised to have a position accuracy of 3 ft.

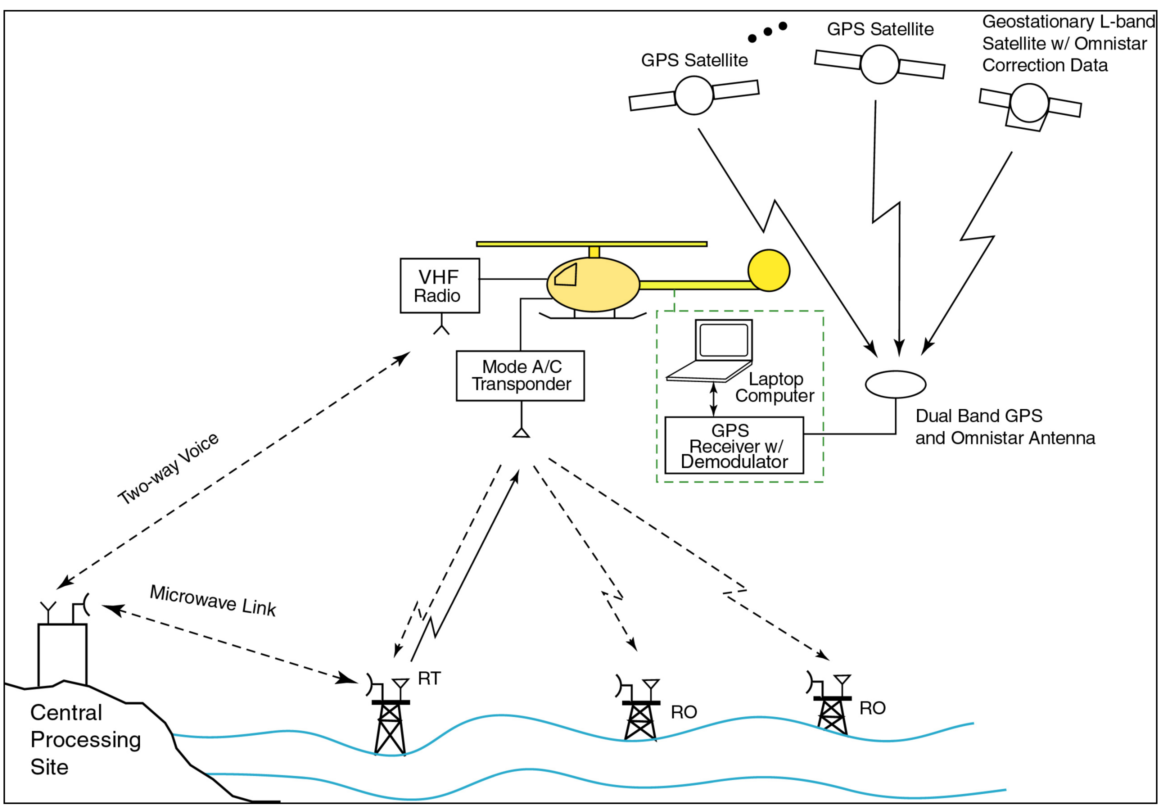


Figure B-1 Airborne Data Collection System (NOTIONAL).

Appendix C. September 17–18, 2002, Flight-Test Aircraft Tracks

During the September 17–18, 2002, flight-test, seven flight segments were conducted for the purpose of evaluating HITS WAM performance for low-altitude aircraft equipped with Air Traffic Control Radar Beacon System (ATCRBS) Mode A/C transponders. This appendix presents a tabular summary of the flight segments (table C-1) and plots of their ground tracks (latitude and longitude coordinates) and altitude profiles (figures C-1 through C-7). Figures containing plots of the ground tracks also show the remote-unit (RU) locations and the predicted WAM inner and outer coverage areas.

Table C-1 September 2002 Flight Summary

Flt Segment	Purpose	Aircraft	Altitude Regime	Transponder	Scored?
Helo 1	WAM test	PHI Bell 206	Low (< 2000 ft)	ATCRBS	✓
Helo 3	WAM test	PHI Bell 206	Low (< 1500 ft)	ATCRBS	✓
Helo 4	WAM test	PHI Bell 206	Low (< 2000 ft	ATCRBS	✓
Helo 5	WAM test	PHI Bell 206	Low (< 1500 ft)	ATCRBS	✓
Piper Aztec 2	WAM test	Volpe Piper Aztec	Medium (< 10,000 ft)	ATCRBS	✓
Piper Aztec 3	WAM test	Volpe Piper Aztec	Low (< 4000 ft)	ATCRBS	✓
Piper Aztec 4	WAM test	Volpe Piper Aztec	Medium (< 10,000 ft)	ATCRBS	✓

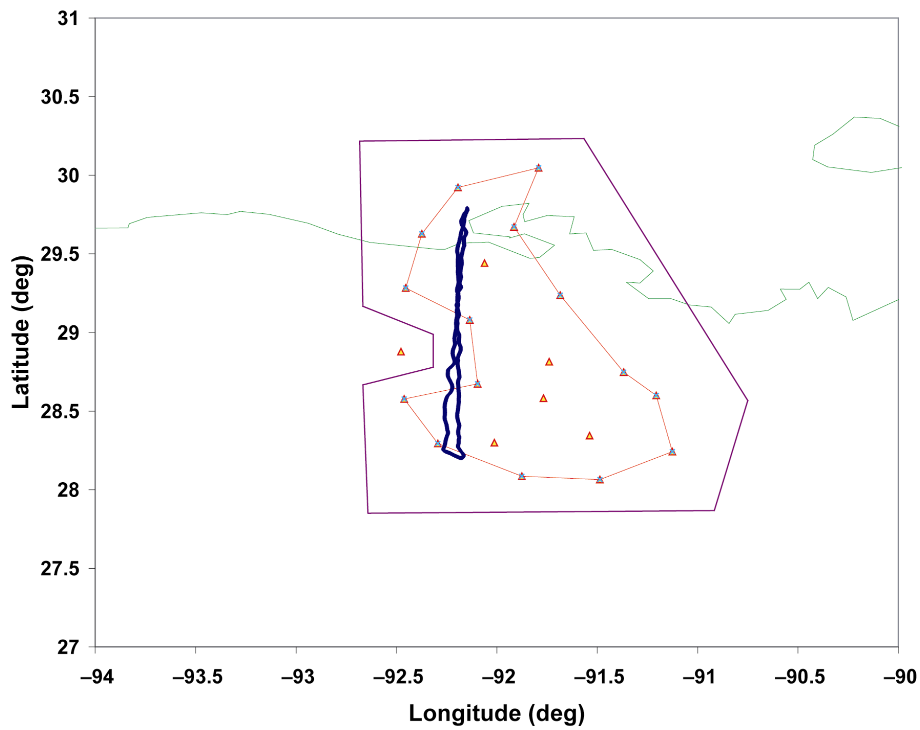


Figure C-1(a) Helo 1 Ground Track (WAM Target Reports).

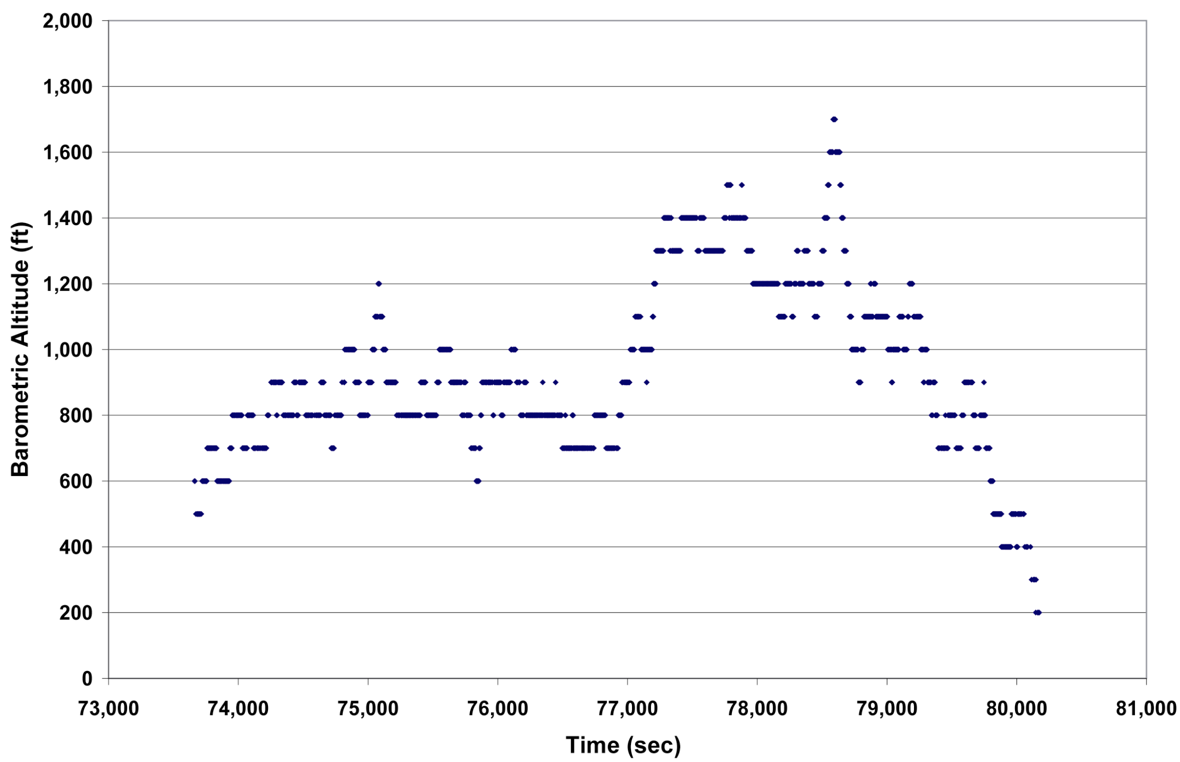


Figure C-1(b) Helo 1 Altitude Profile (Transponder Barometric Data).

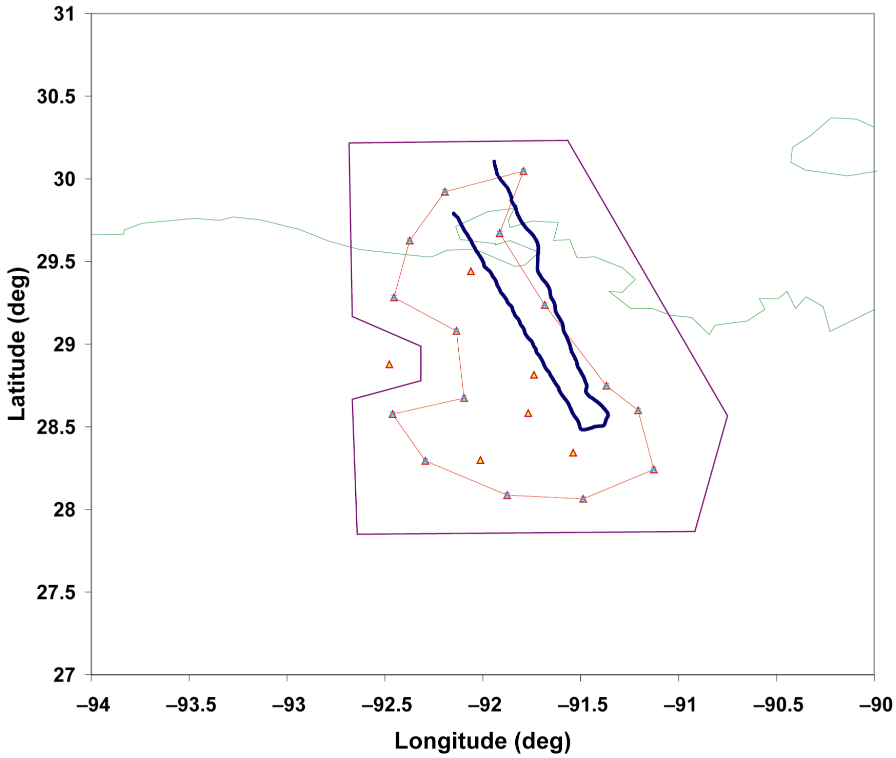


Figure C-2(a) Helo 3 Ground Track (WAM Target Reports).

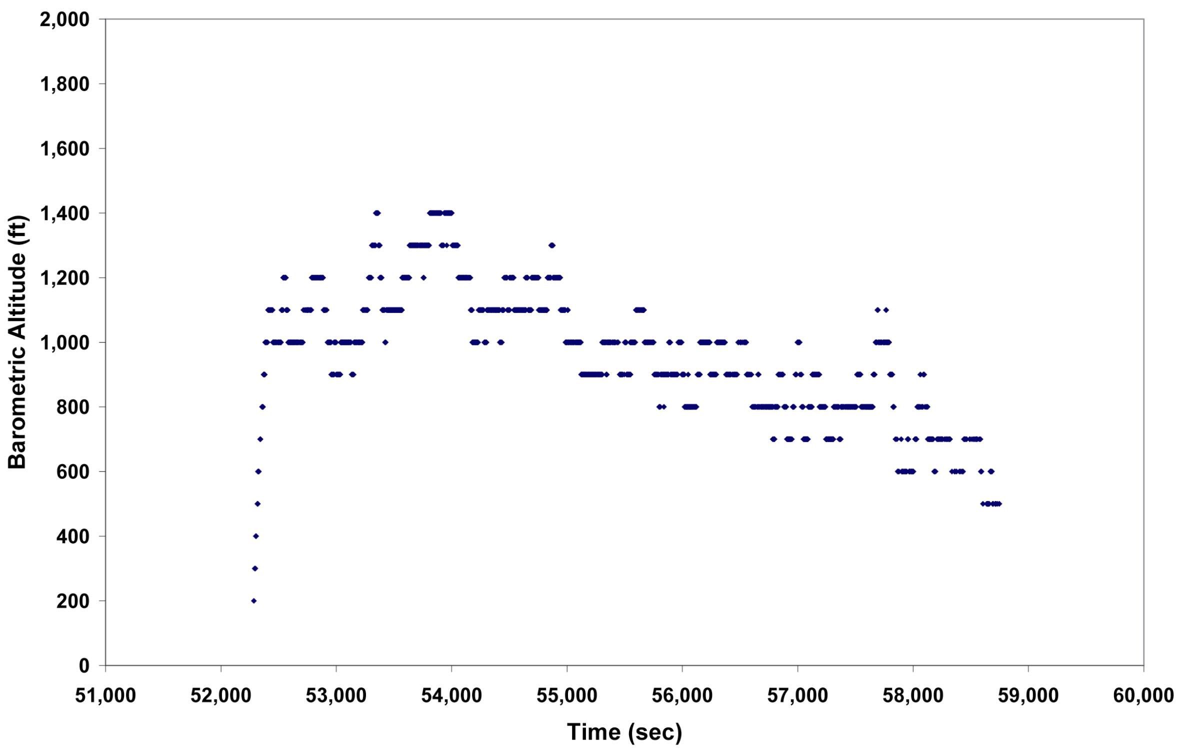


Figure C-2(b) Helo 3 Altitude Profile (Transponder Barometric Data).

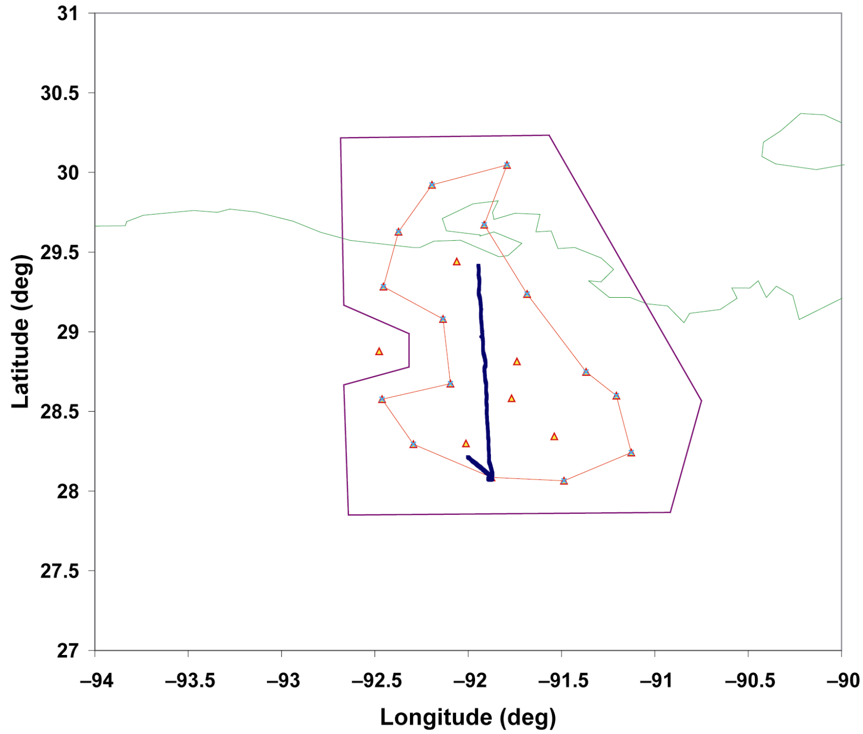


Figure C-3(a) Helo 4 Ground Track (WAM Target Reports).

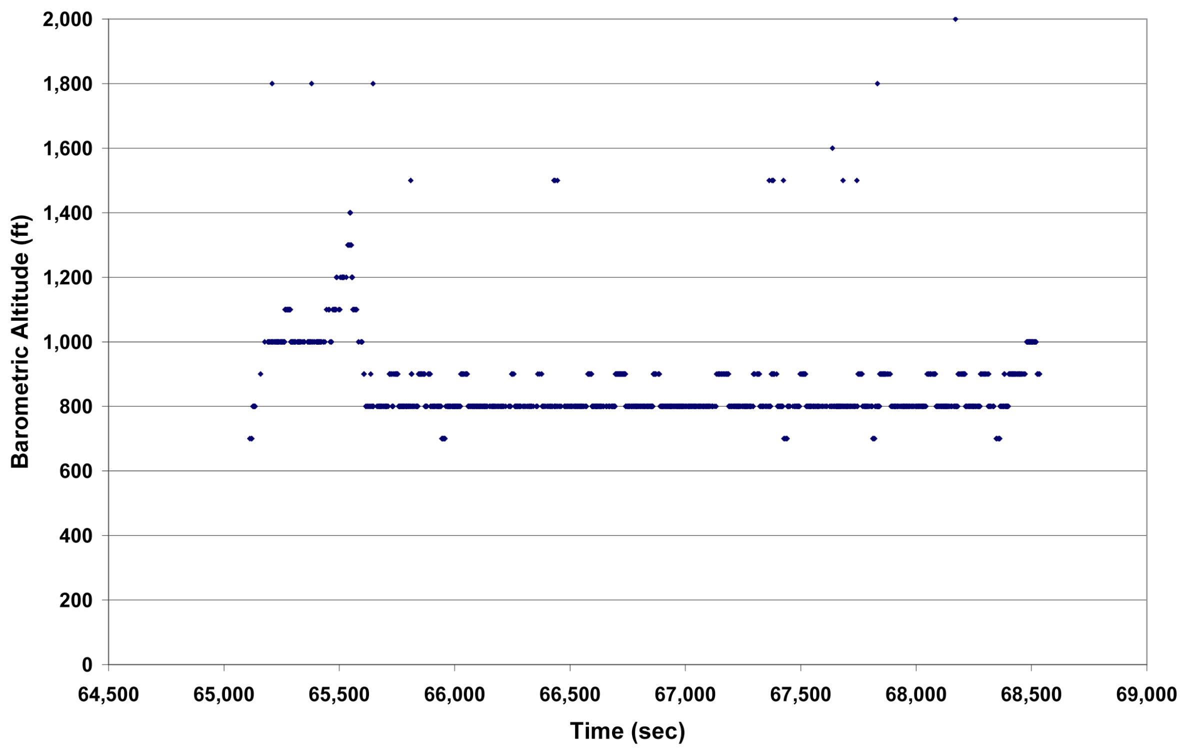


Figure C-3(b) Helo 4 Altitude Profile (Transponder Barometric Data).

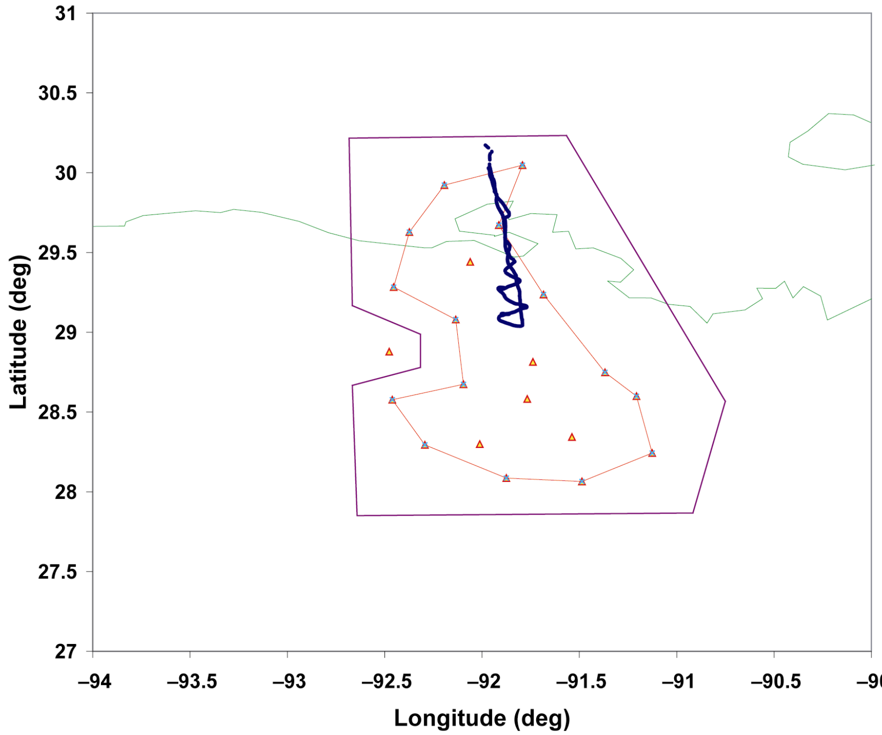


Figure C-4(a) Helo 5 Ground Track (WAM Target Reports).

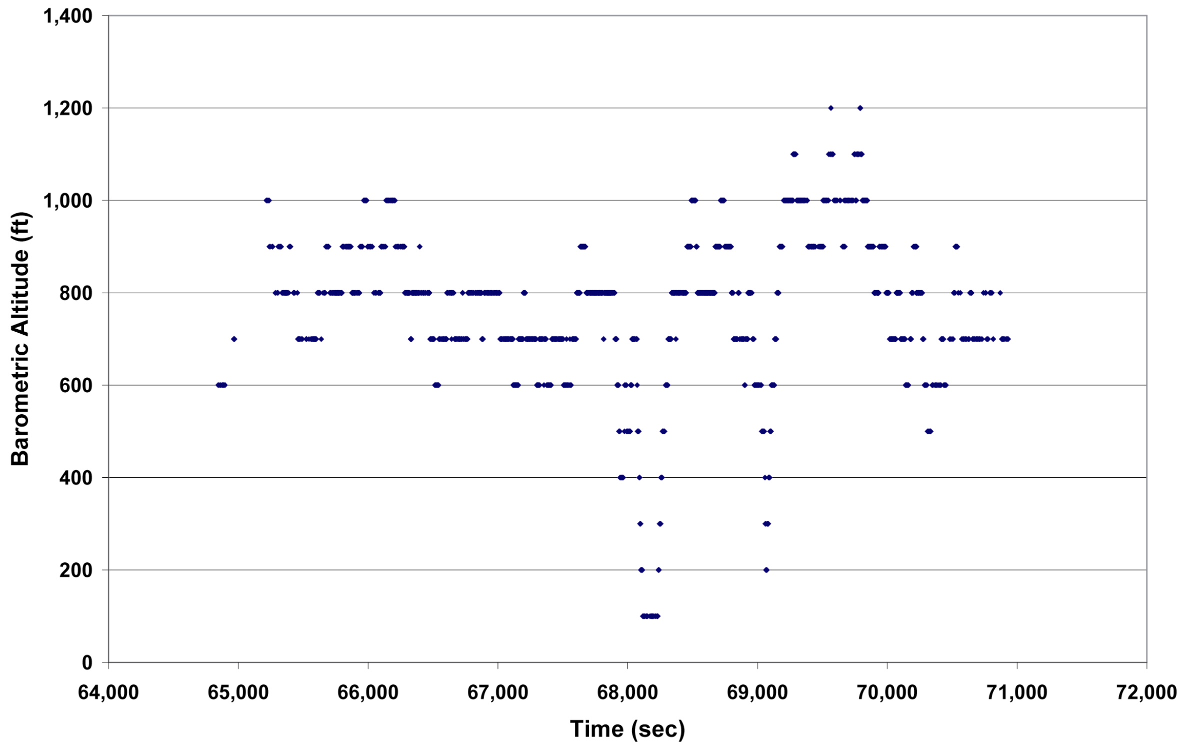


Figure C-4(b) Helo 5 Altitude Profile (Transponder Barometric Data).

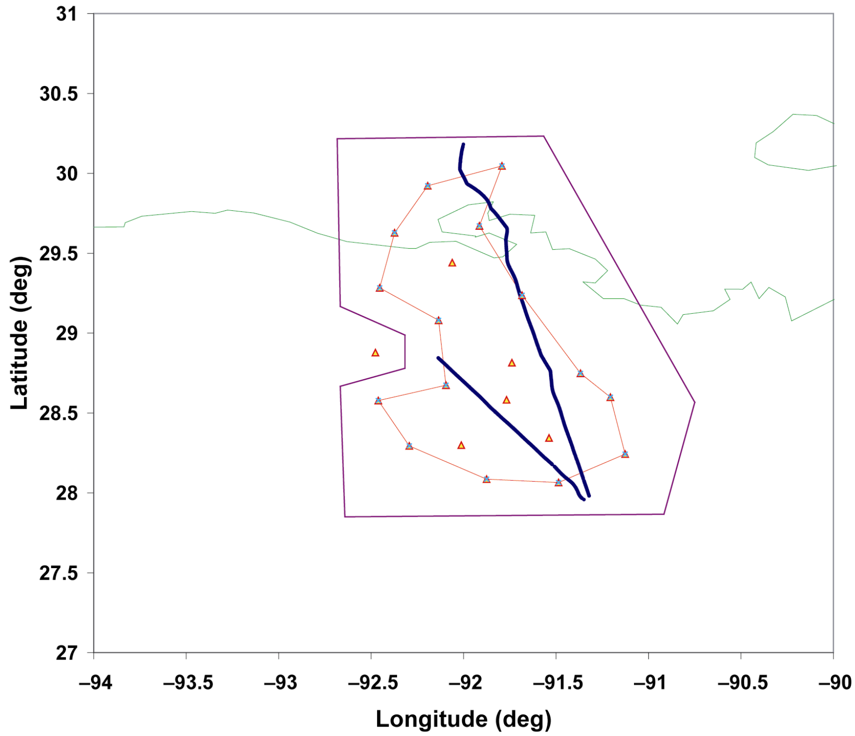


Figure C-5(a) Piper Aztec 2 Ground Track (WAM Target Reports).

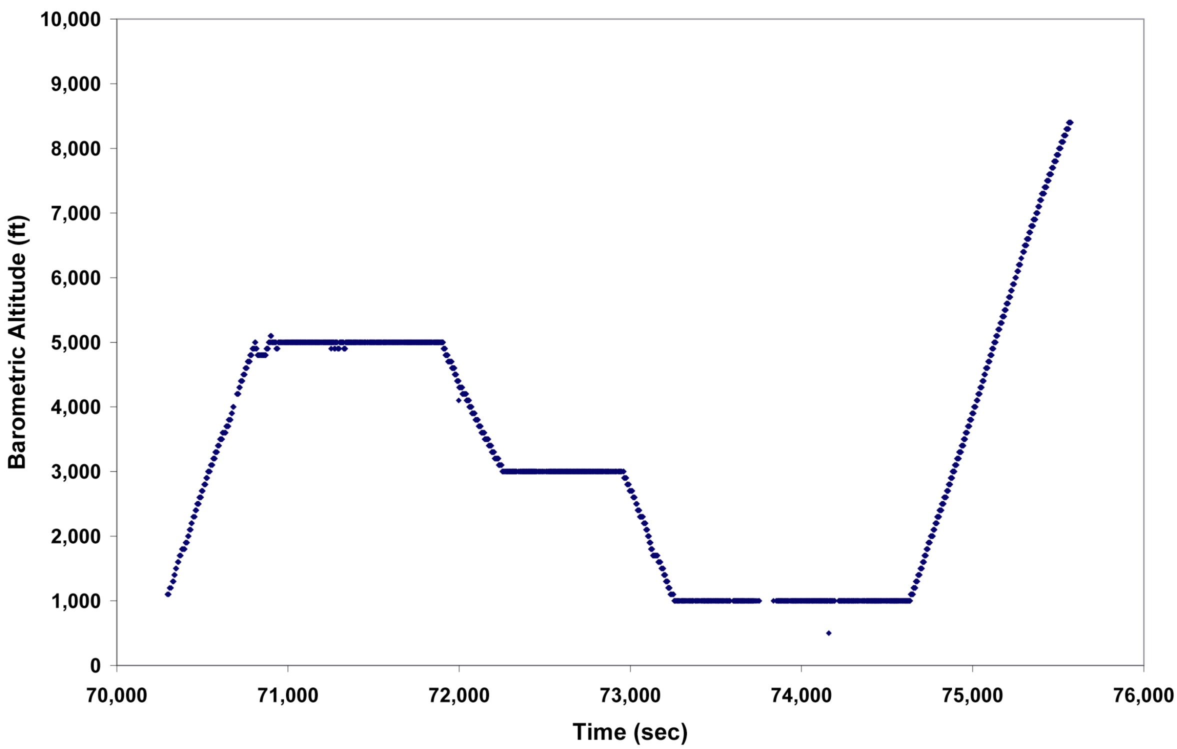


Figure C-5(b) Piper Aztec 2 Altitude Profile (Transponder Barometric Data).

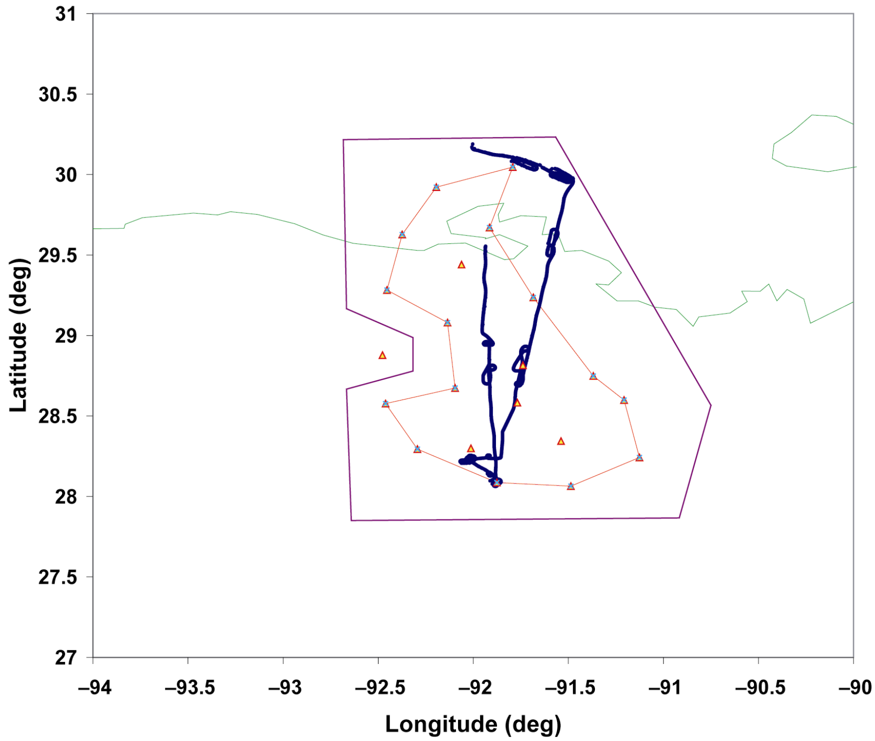


Figure C-6(a) Piper Aztec 3 Ground Track (WAM Target Reports).

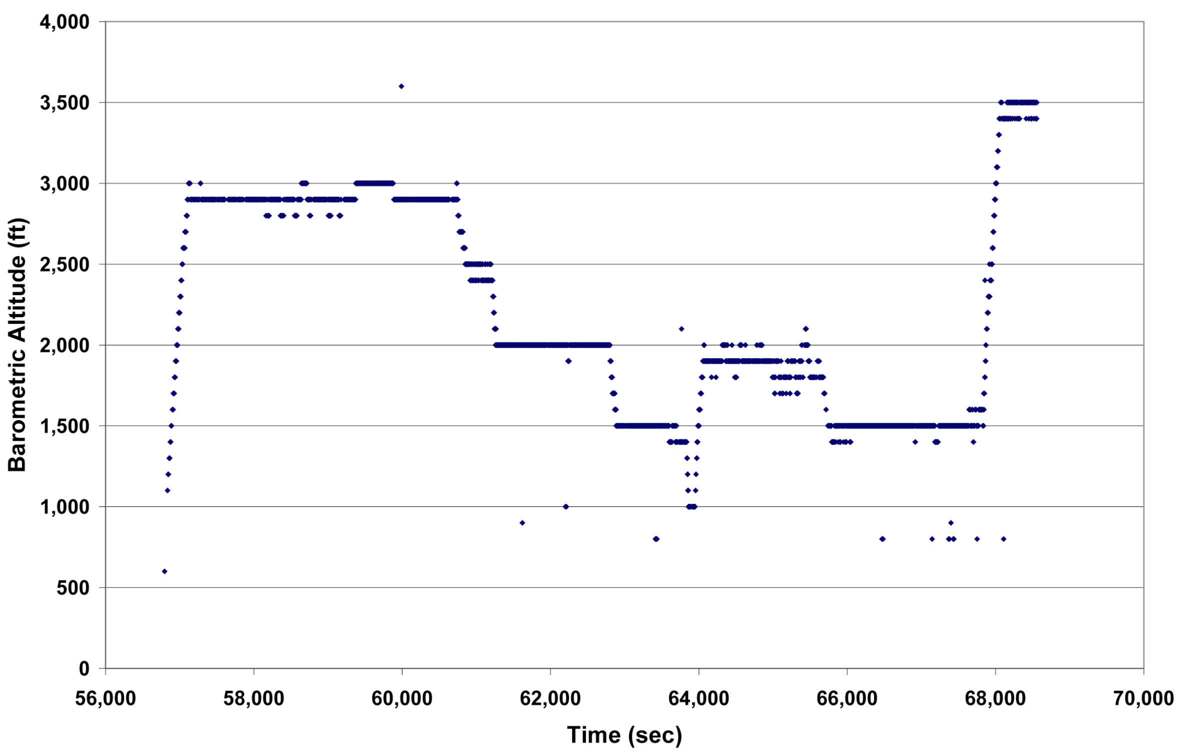


Figure C-6(b) Piper Aztec 3 Altitude Profile (Transponder Barometric Data).

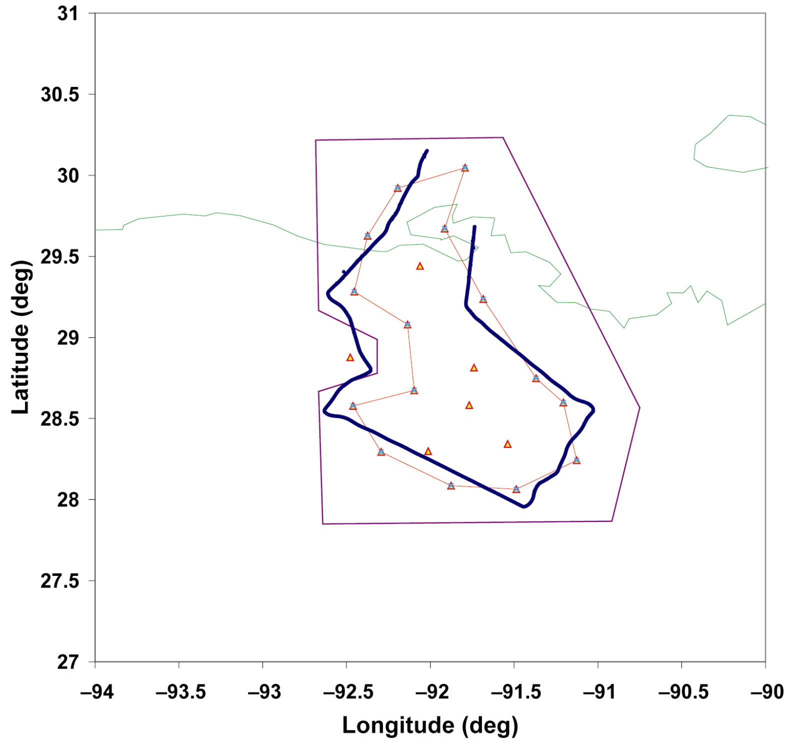


Figure C-7(a) Piper Aztec 4 Ground Track (WAM Target Reports).

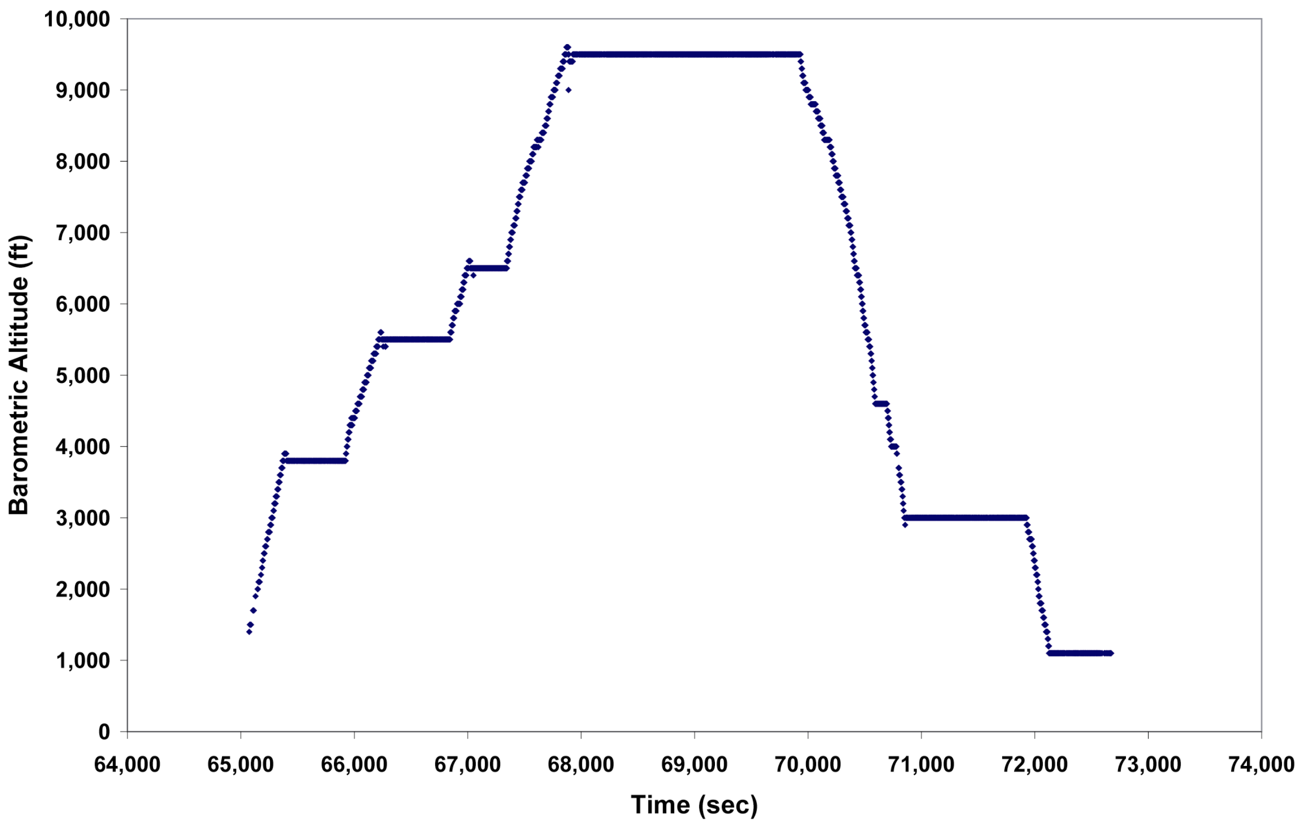


Figure C-7(b) Piper Aztec 4 Altitude Profile (Transponder Barometric Data.

Appendix D. January 28–29, 2003, Flight-Test Aircraft Tracks

During the January 28–29, 2003, flight test, three flights were conducted for the purpose of evaluating Helicopter In-Flight Tracking System (HITS) wide-area multilateration (WAM) and automatic dependent surveillance – broadcast (ADS-B) performance. This appendix presents a tabular summary of the flights (table D-1) and individual plots of the flight ground tracks (latitude and longitude coordinates) and altitude profiles (figures D-1 through D-5). Additionally, ground tracks are shown for six flight segments extracted from the January 28 flights for analysis purposes. Figures containing plots of the ground tracks also show the predicted WAM inner and outer coverage areas.

Table D-1 January 2003 Flight-Test Summary

Flight	Purpose	Aircraft	Altitude Regime	Transponder	Scored?
January 28 AM	WAM test	FAA Tech Center Convair 580	High and low alt (FL220 and 10k ft)	Mode S extended squitter	✓
January 28 PM	WAM test	FAA Tech Center Convair 580	Low alt (10k ft)	Mode S extended squitter	✓
January 29	ADS-B test	FAA Tech Center Convair 580	Low to high alt (<FL210)	Mode S extended squitter	✓

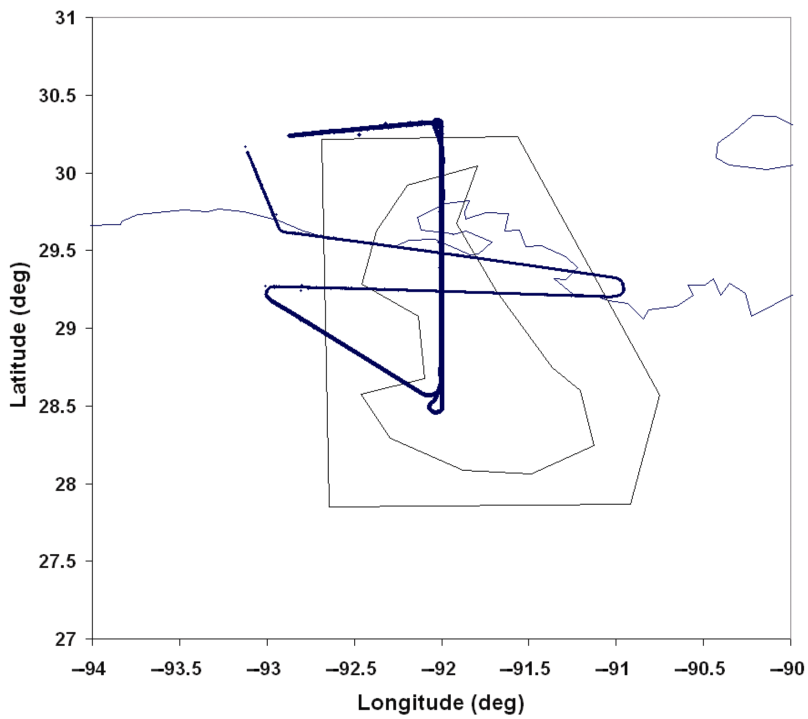


Figure D-1(a) January 28 AM Flight Ground Track (WAM Target Reports).

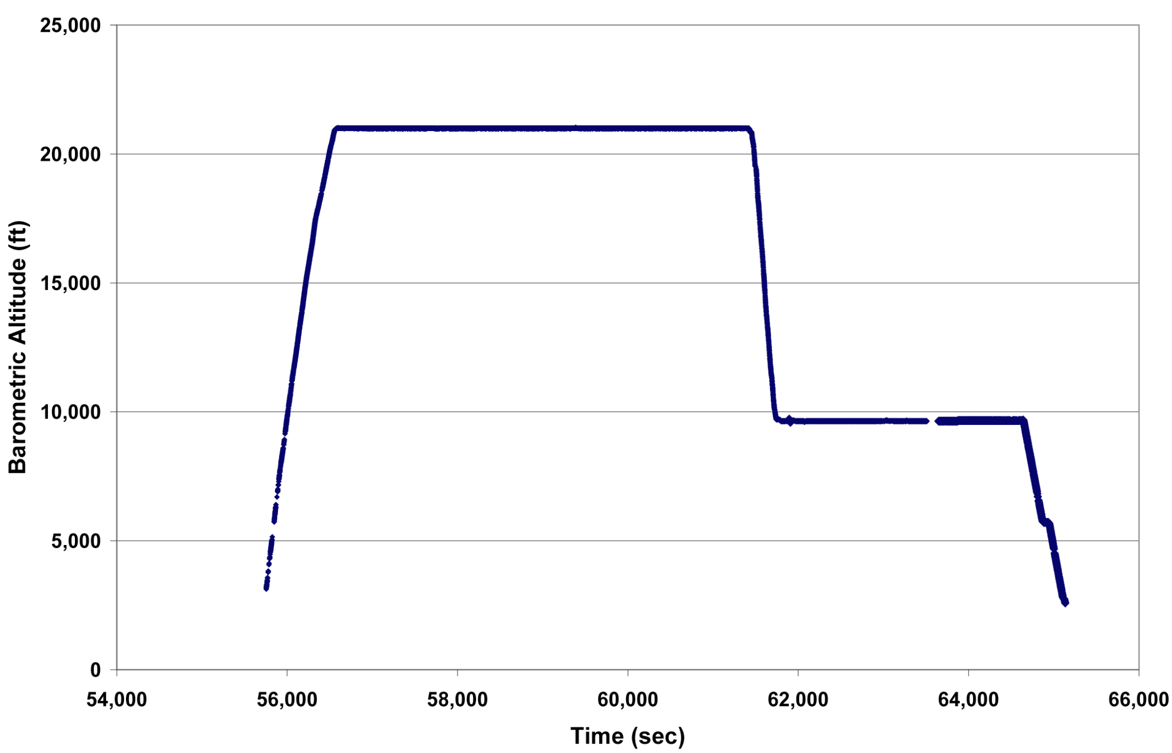
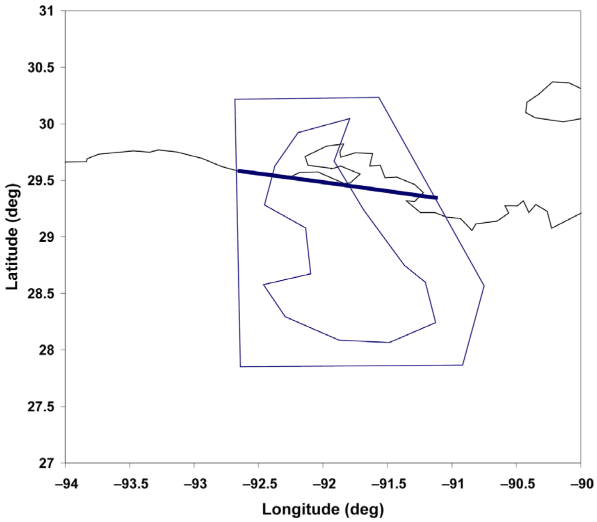
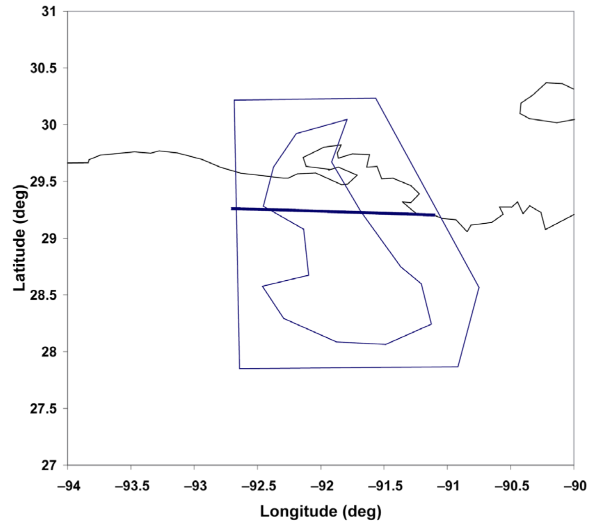


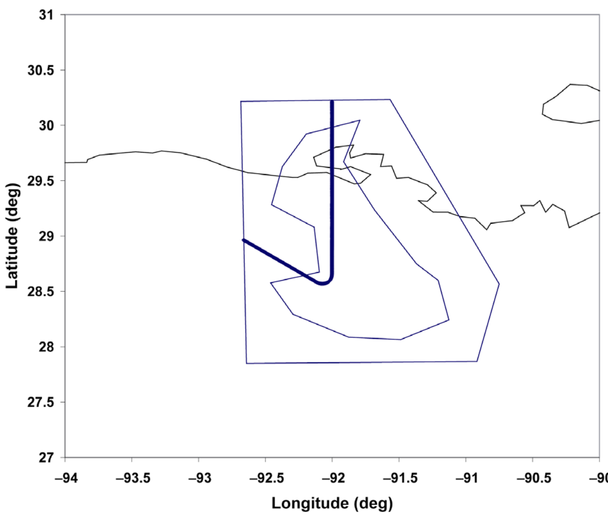
Figure D-1(b) January 28 AM Flight Altitude Profile (Transponder Barometric Data).



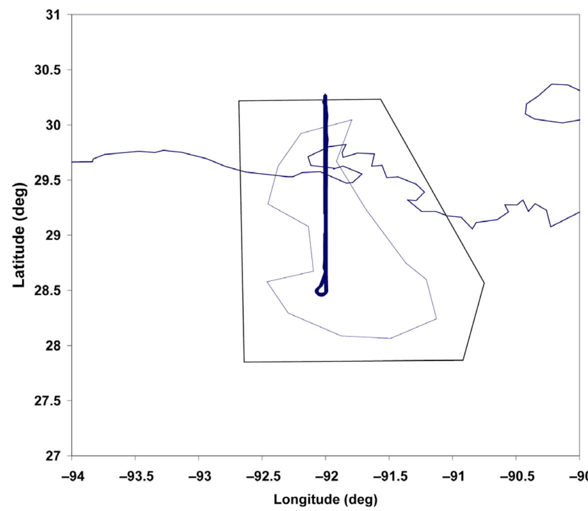
(a) AM 1 Segment Ground Track



(b) AM 2 Segment Ground Track



(c) AM 3 Segment Ground Track



(d) AM 4 Segment Ground Track

Figure D-2 January 28 Morning Flight Segments (WAM Target Reports).

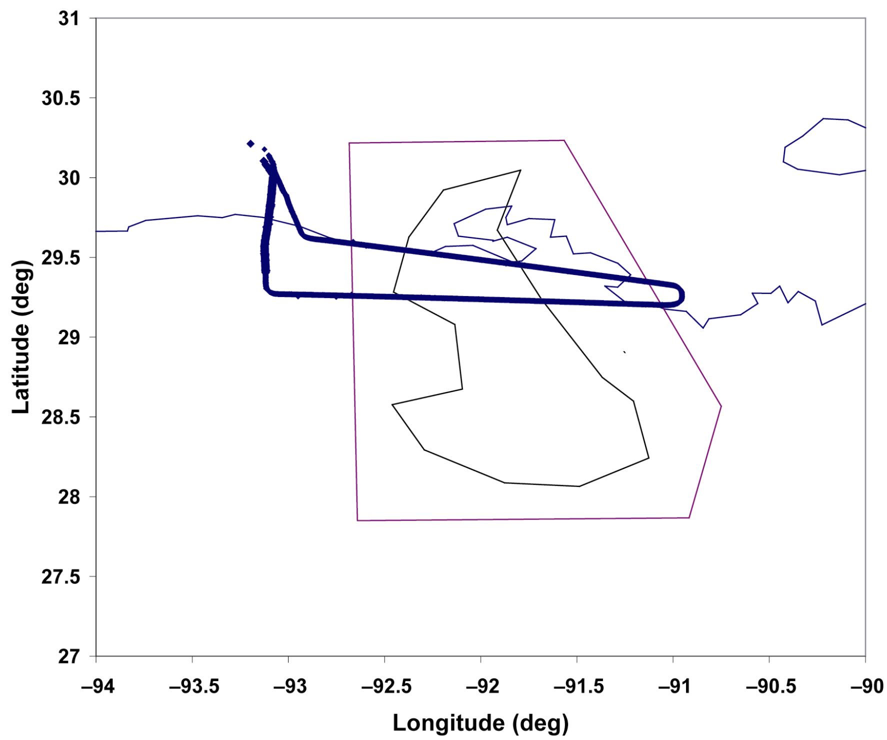


Figure D-3(a) January 28 PM Flight Ground Track (WAM Target Reports).

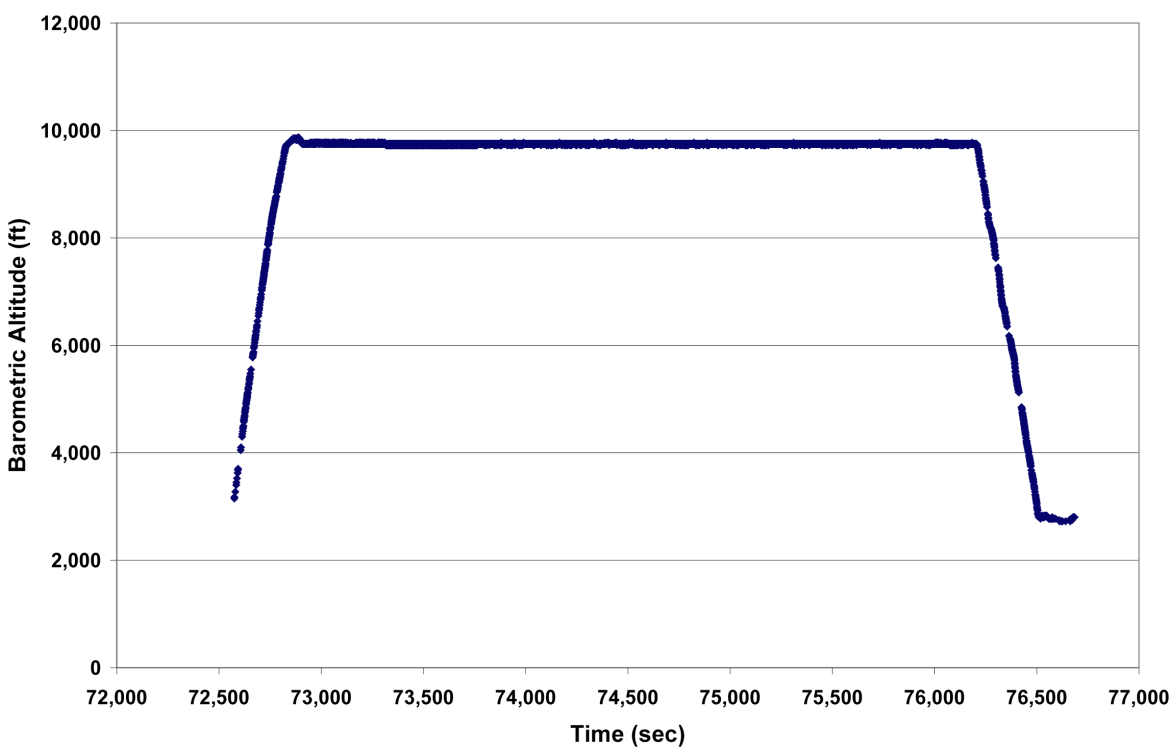
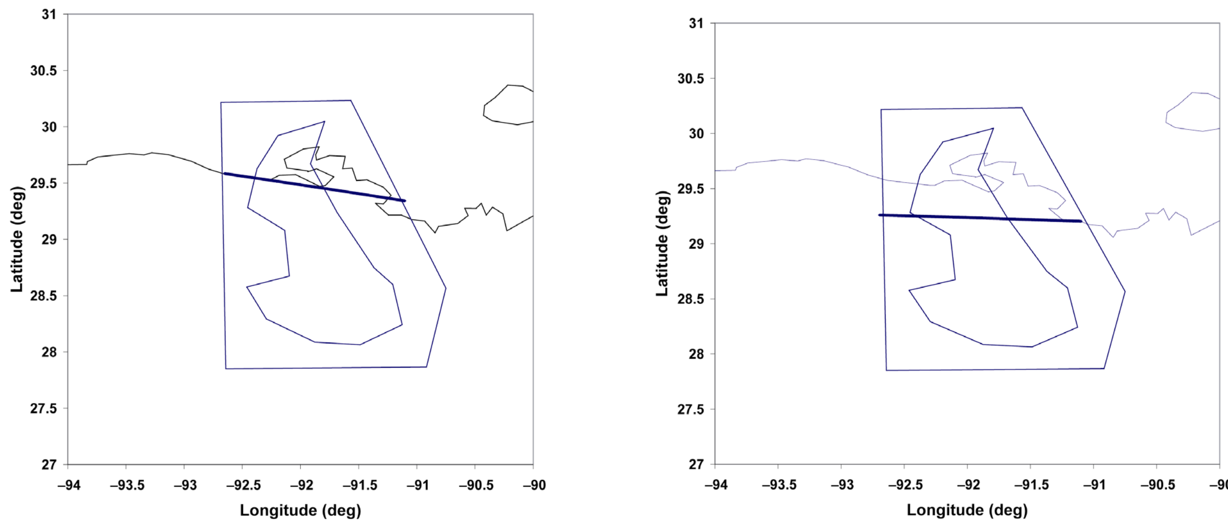


Figure D-3(b) January 28 PM Flight Altitude Profile (Transponder Barometric Data).



(a) PM 1 Segment Ground Track

(b) PM 2 Segment Ground Track

Figure D-4 January 28 Afternoon Flight Segments (WAM Target Reports).

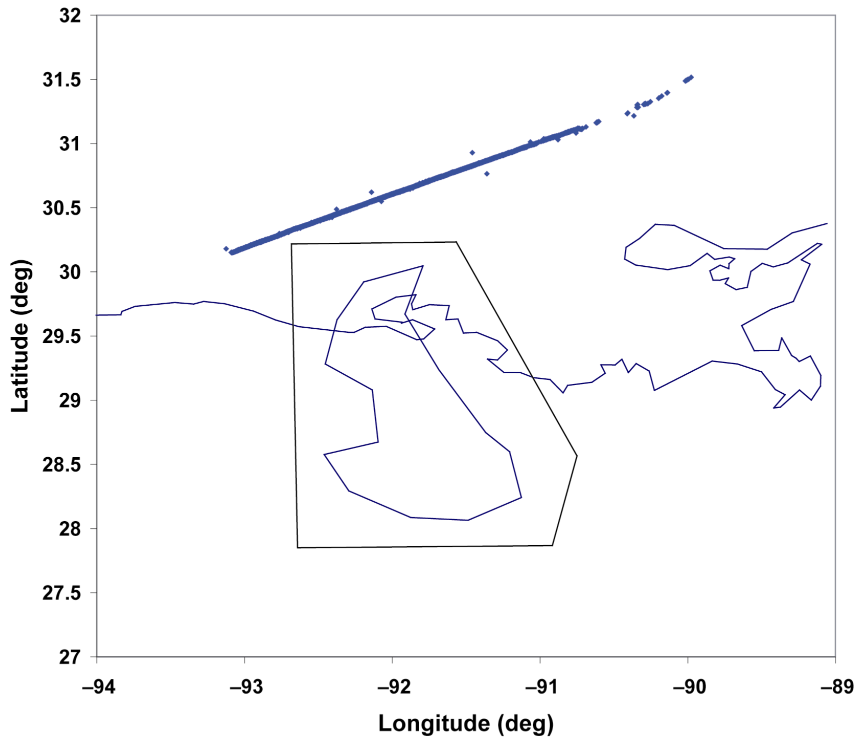


Figure D-5(a) January 29 Flight Ground Track (WAM Target Reports).

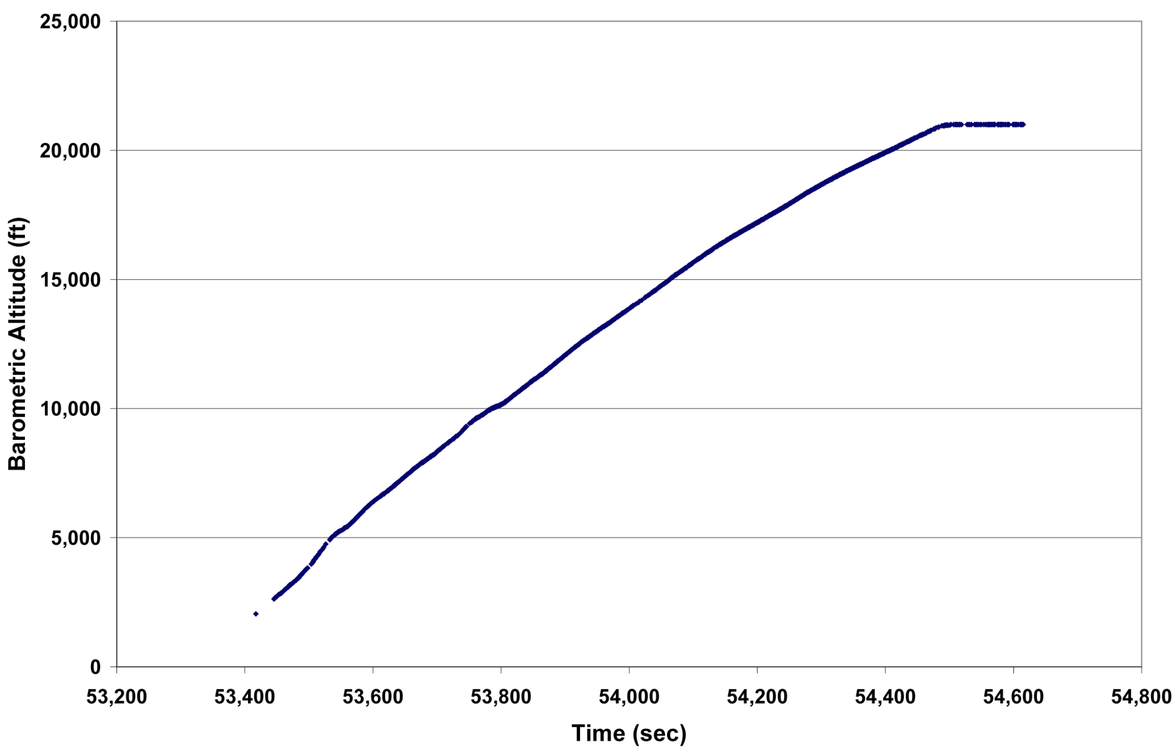


Figure D-5(b) January 29 Flight Altitude Profile (Transponder Barometric Data).

Appendix E. June 10–11, 2003, Flight-Test Aircraft Tracks

During the June 10–11, 2003, flight test, four flight segments were conducted for the purpose of evaluating Helicopter In-Flight Tracking System (HITS) wide-area multilateration (WAM) performance for low-altitude aircraft equipped with the Mode A/C transponder. This appendix presents a tabular summary of the flight segments (table E-1) and plots of their ground tracks (latitude and longitude coordinates) and altitude profiles (figures E-1 through E-4). Figures containing plots of the ground tracks also show the remote-unit (RU) locations and the outer boundaries of the predicted WAM inner and outer coverage areas.

Table E-1 June 2003 Flight Summary

Flt Segment	Purpose	Aircraft	Altitude Regime	Transponder	Scored?
N906PH					
June 10	WAM test	PHI Bell 206	Low (< 2000 ft)	ATCRBS	✓
June 11	WAM test	PHI Bell 206	Low (< 2000 ft)	ATCRBS	✓
N2777D					
June 10	WAM test	PHI Bell 206	Low (< 2000 ft)	ATCRBS	✓
June 11	WAM test	PHI Bell 206	Low (< 1000 ft)	ATCRBS	✓

* Portions of these flight segments were used for the target-resolution test.

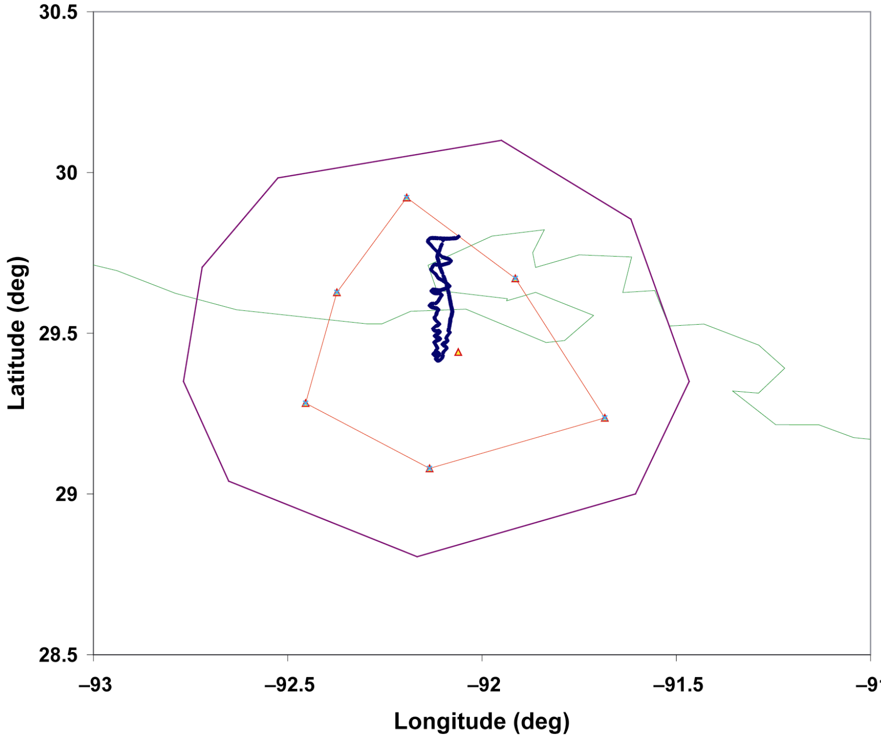


Figure E-1(a) N906PH June 10 Ground Track (WAM Target Reports).

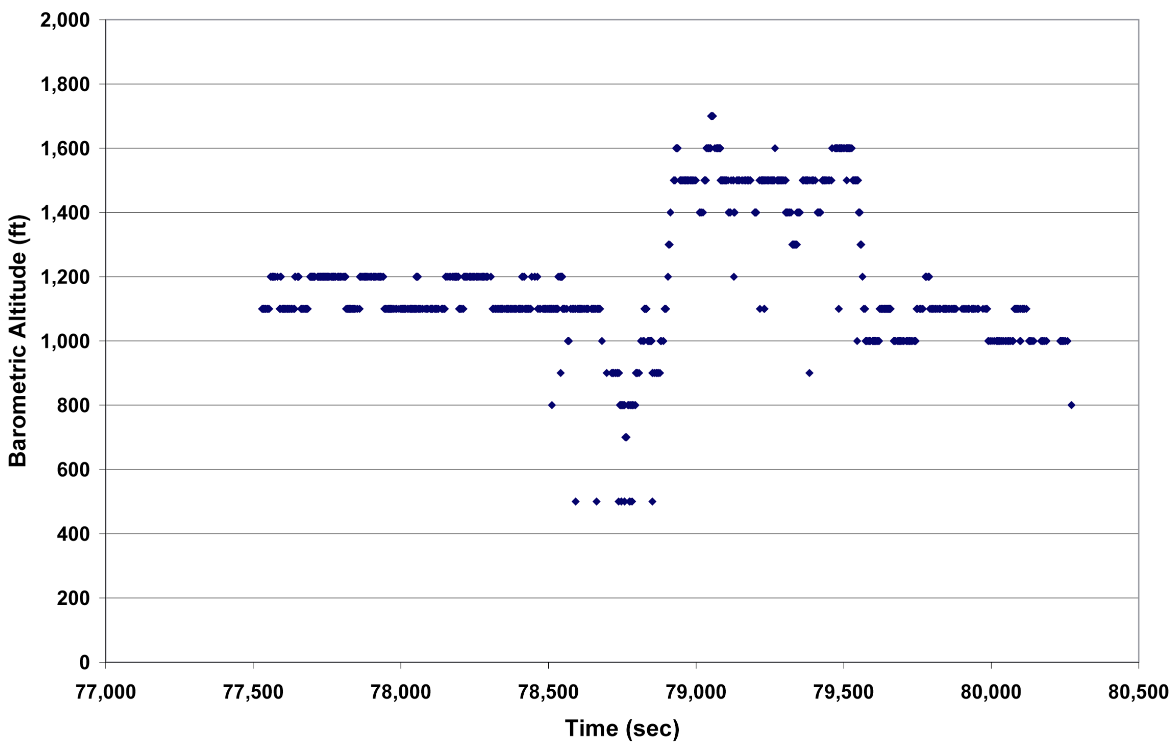


Figure E-1(b) N906PH June 10 Altitude Profile (Transponder Barometric Data).

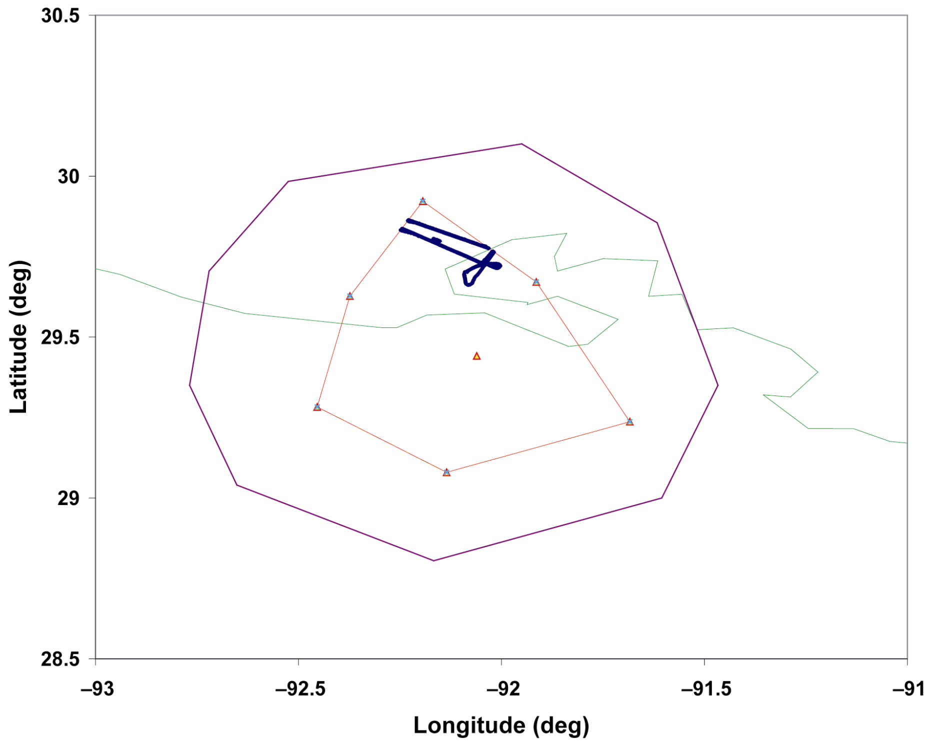


Figure E-2(a) N906PH June 11 Ground Track (WAM Target Reports).

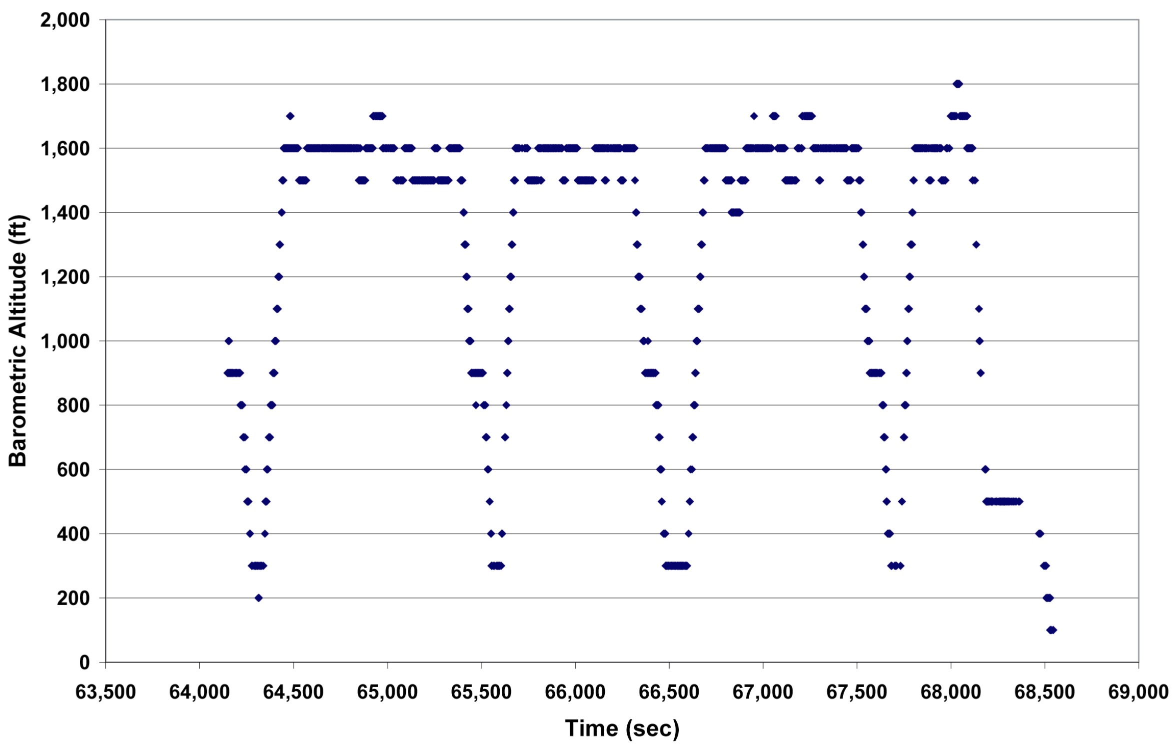


Figure E-2(b) N906PH June 11 Altitude Profile (Transponder Barometric Data).

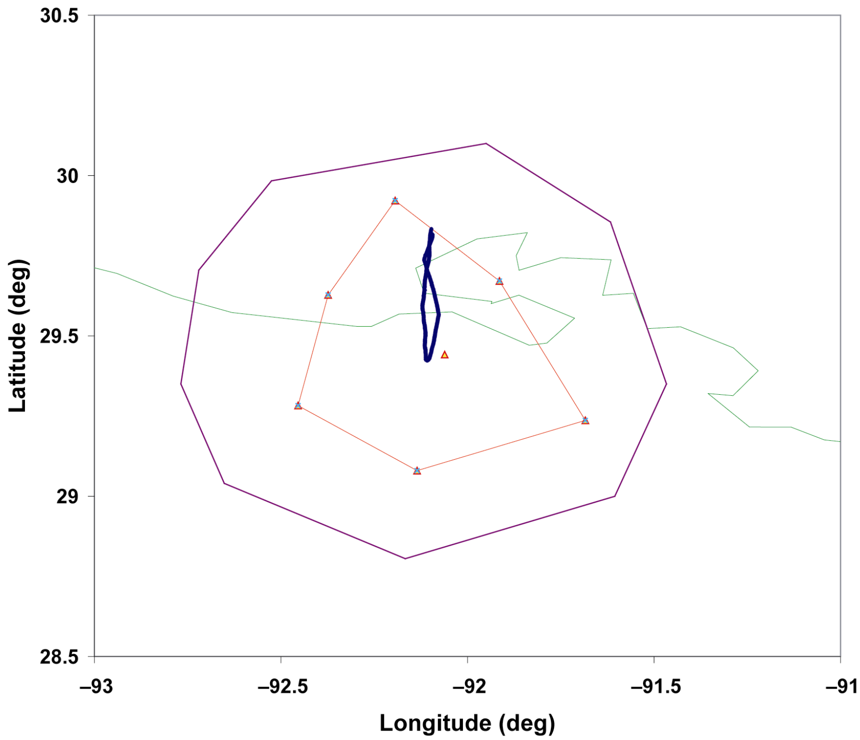


Figure E-3(a) N2777D June 10 Ground Track (WAM Target Reports).

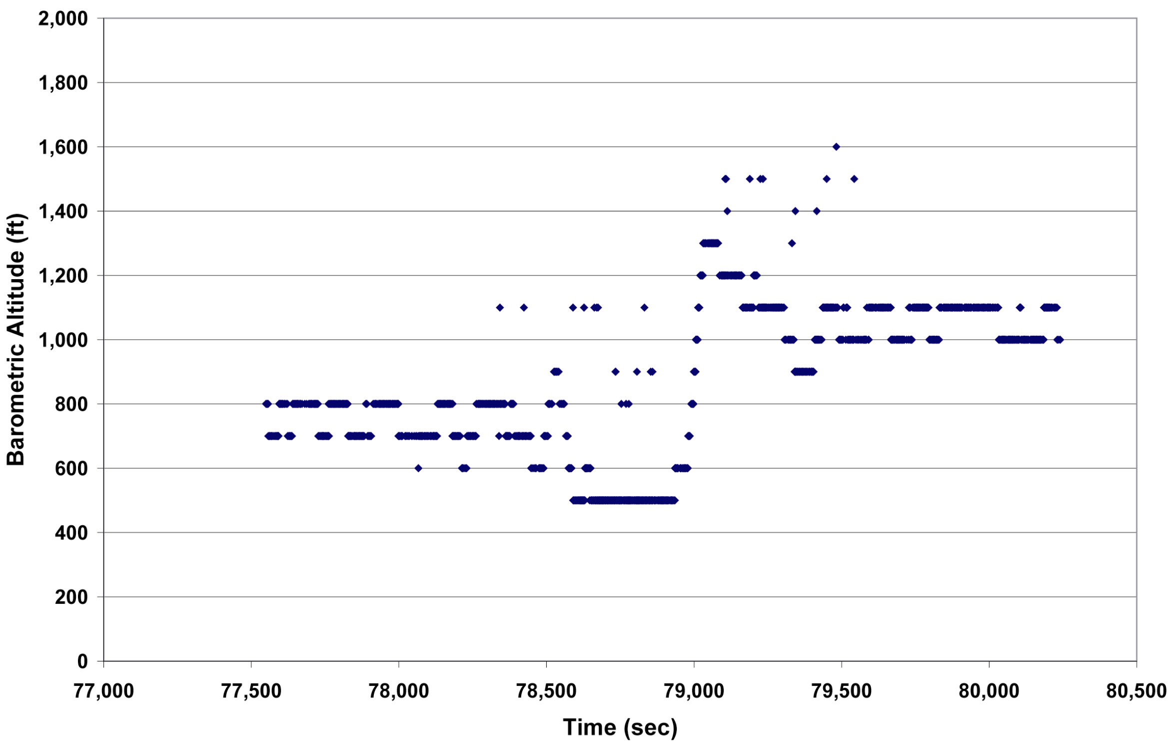


Figure E-3(b) N2777D June 10 Altitude Profile (Transponder Barometric Data).

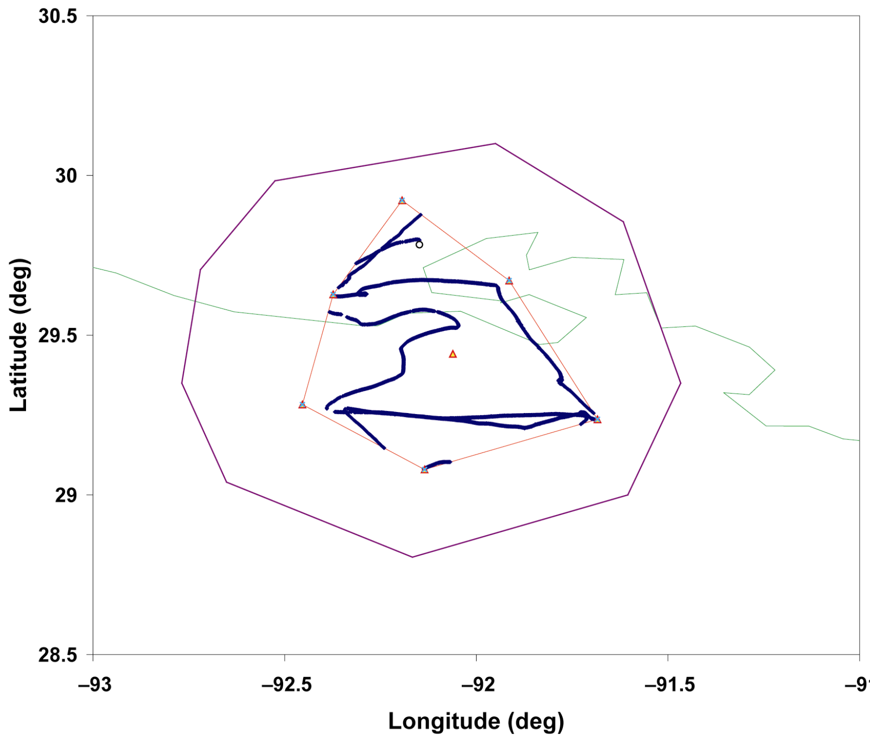


Figure E-4(a) N2777D June 11 Ground Track (WAM Target Reports).

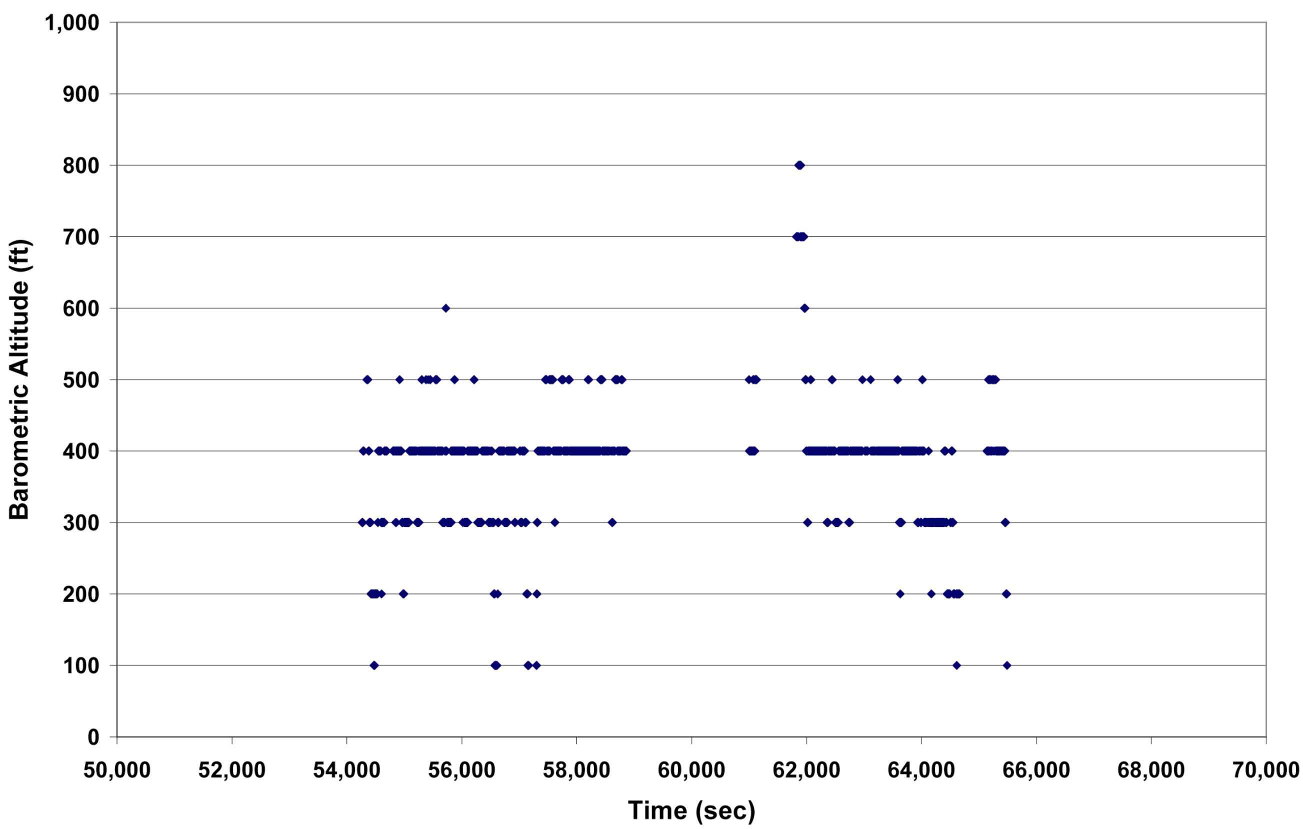


Figure E-4(b) N2777D June 11 Altitude Profile (Transponder Barometric Data).

Appendix F. February 10–12, 2004, Flight-Test Aircraft Tracks

During the February 2004 test period, six flights were conducted for the purpose of evaluating Helicopter In-Flight Tracking System (HITS) performance during high-altitude flight. The aircraft, FAA Boeing 727, was equipped with a Mode S extended squitter transponder for automatic dependent surveillance – broadcast (ADS-B) tests, and an Air Traffic Control Radar Beacon System (ATCRBS) transponders for wide-area multilateration (WAM) checkout. This appendix presents a tabular summary of the flights (table F-1) and individual plots of the flight tracks (latitude and longitude coordinates) and altitude profiles (figures F1 through F6).

Table F-1 February 2004 Flight Summary

Flight	Purpose	Altitude Regime	Transponder(s)	Scored?
Feb. 10 AM	ADS-B test	FL280	Mode S extended squitter	✓
Feb. 10 PM	ADS-B test	FL280	Mode S extended squitter	✓
Feb. 11 AM	WAM test	FL330	ATCRBS/Mode S short squitter	✗
Feb. 11 PM	WAM test	FL280	ATCRBS/Mode S short squitter	✗
Feb. 12 AM	ADS-B test	FL370	Mode S extended squitter	✓
Feb. 12 PM	ADS-B test	FL360	Mode S extended squitter	✓

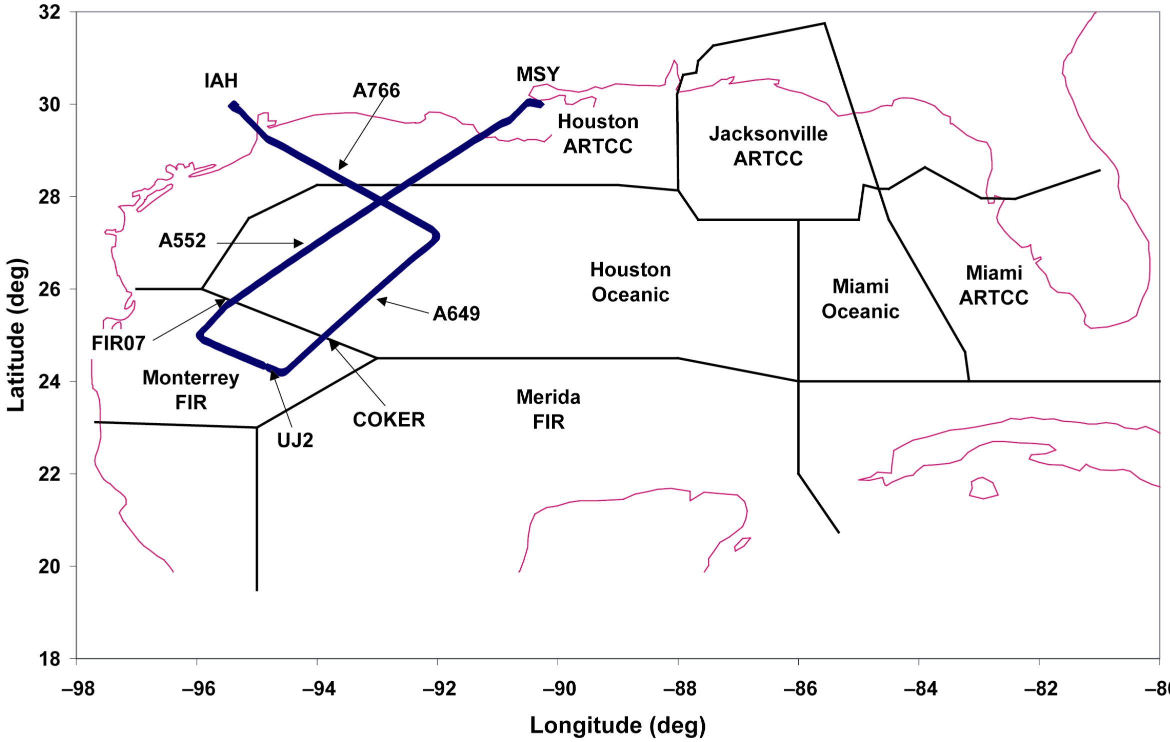


Figure F-1(a) Feb. 10 AM Ground Track (ADS-B Data).

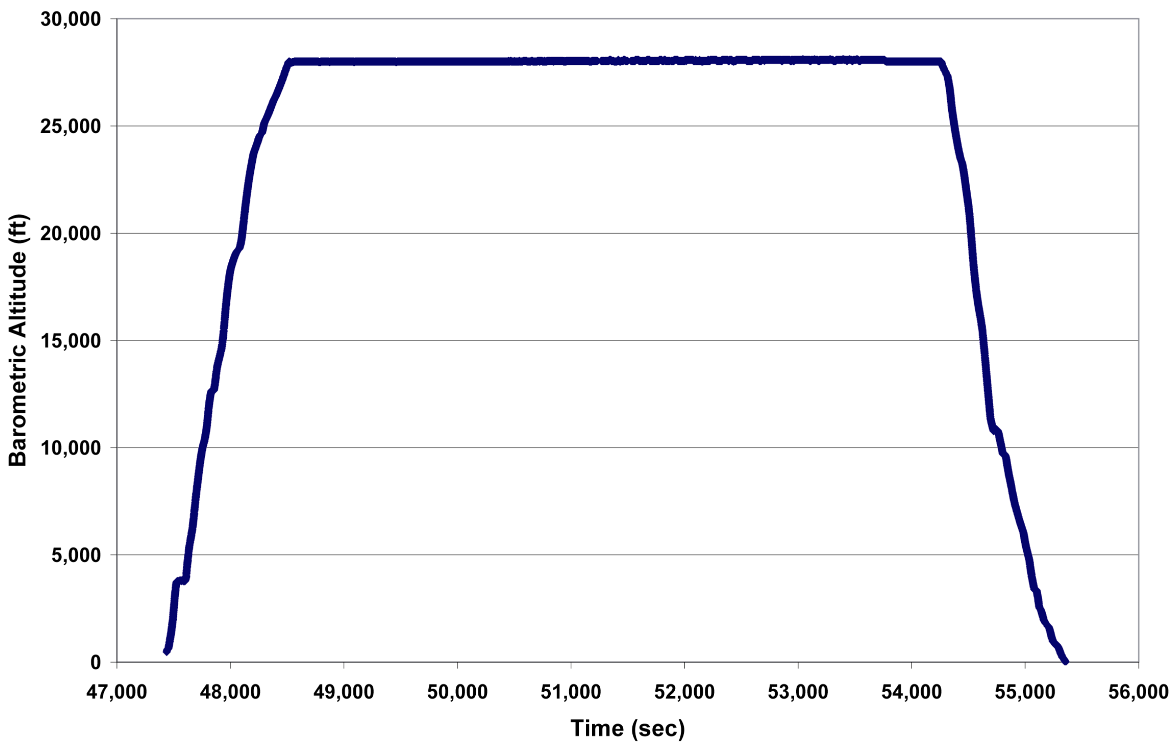


Figure F-1(b) Feb. 10 AM Flight Altitude Profile (Transponder Barometric Data).

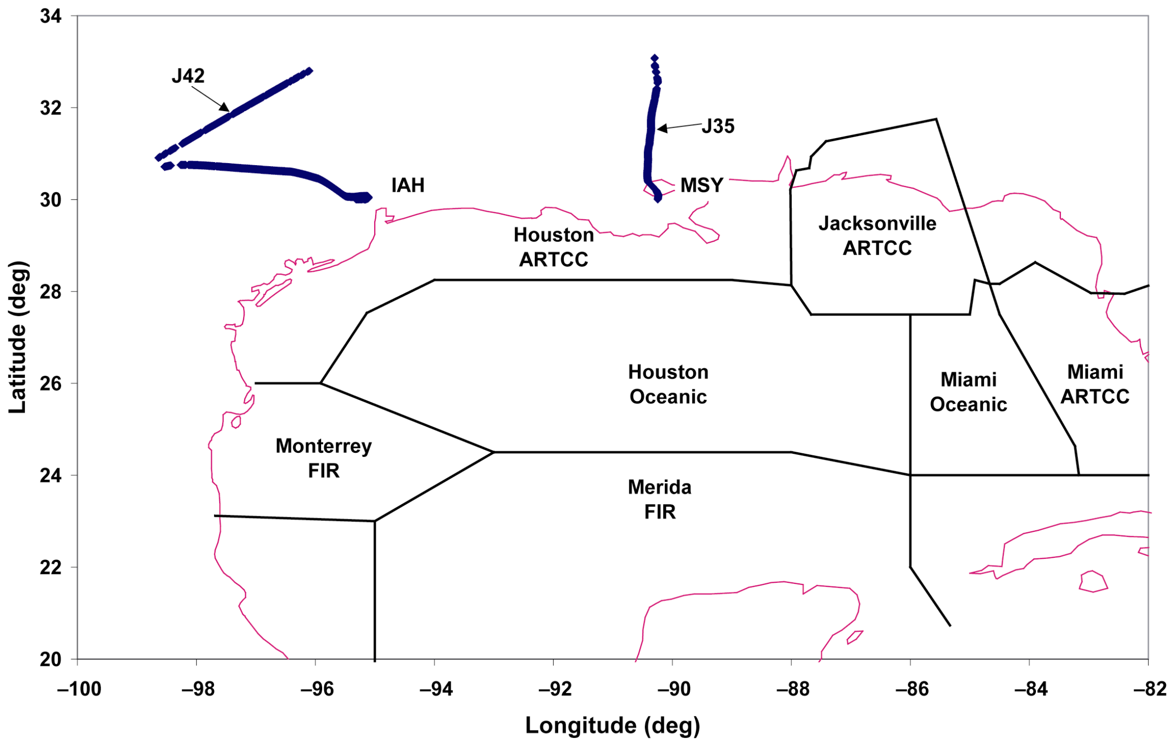


Figure F-2(a) Feb. 10 PM Flight Ground Track (ADS-B Data).

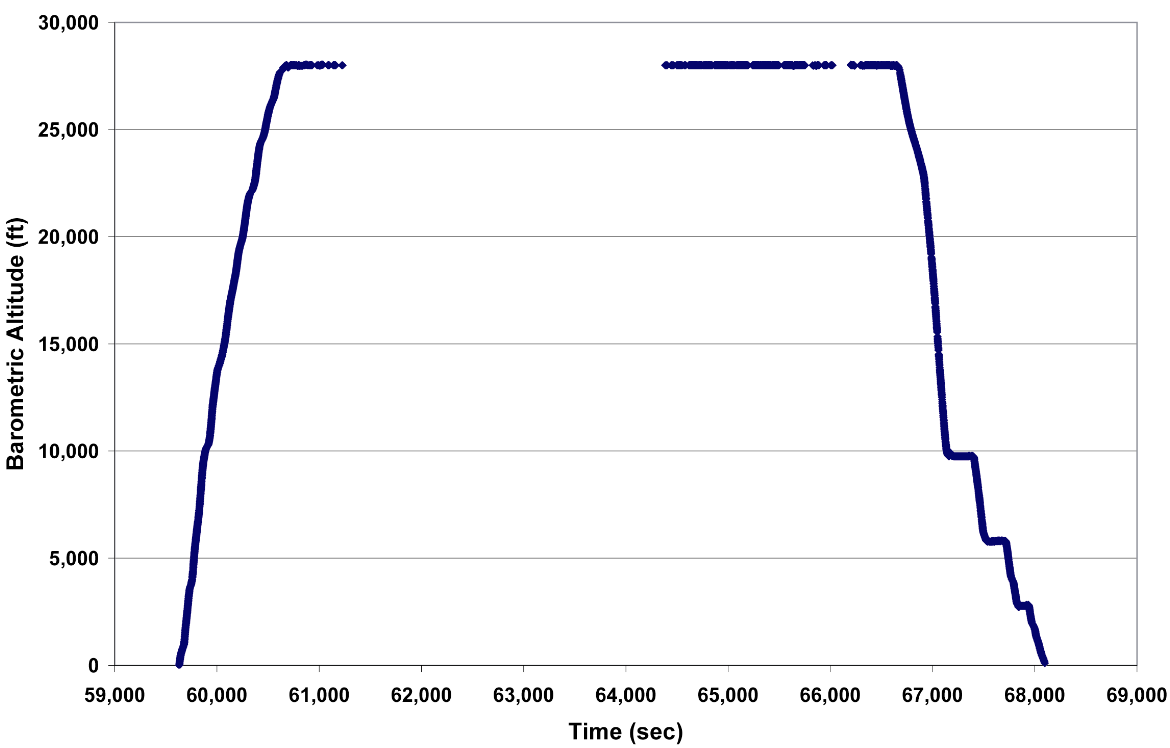


Figure F-2(b) Feb. 10 PM Flight Altitude Profile (Transponder Barometric Data).

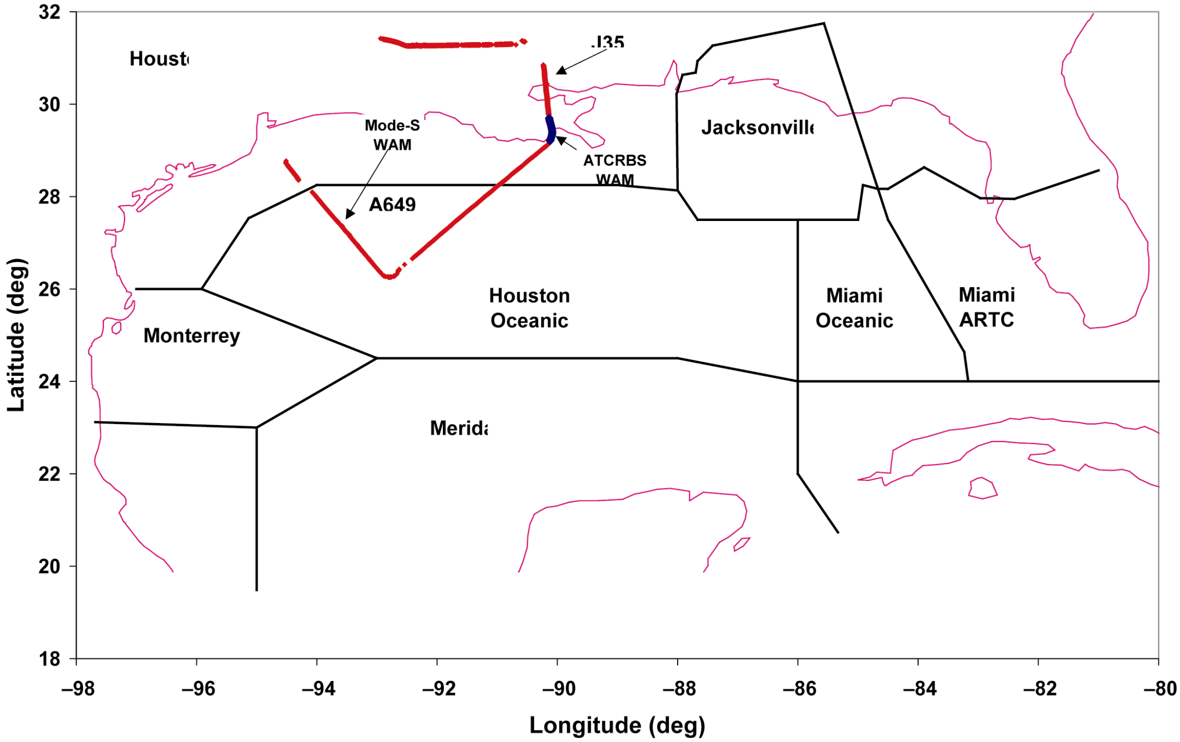


Figure F-3(a) Feb. 11 AM Flight Ground Track (WAM Target Reports).

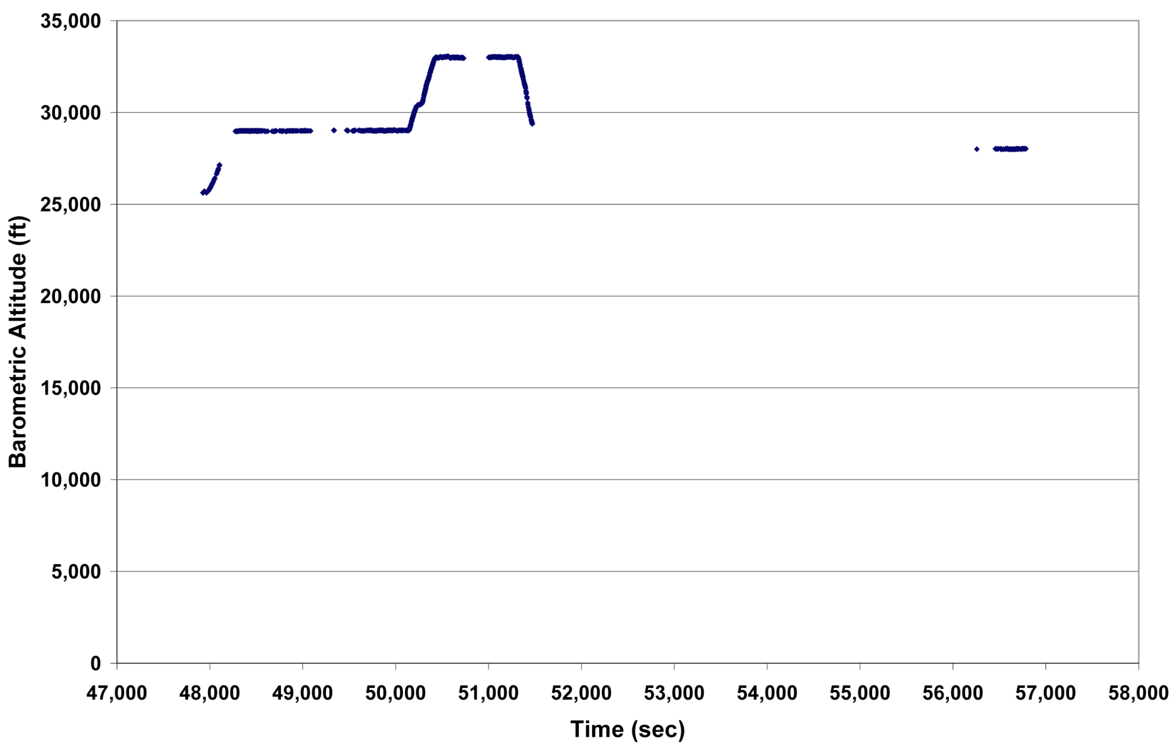


Figure F-3(b) Feb. 11 AM Flight Altitude Profile (Transponder Barometric Data).

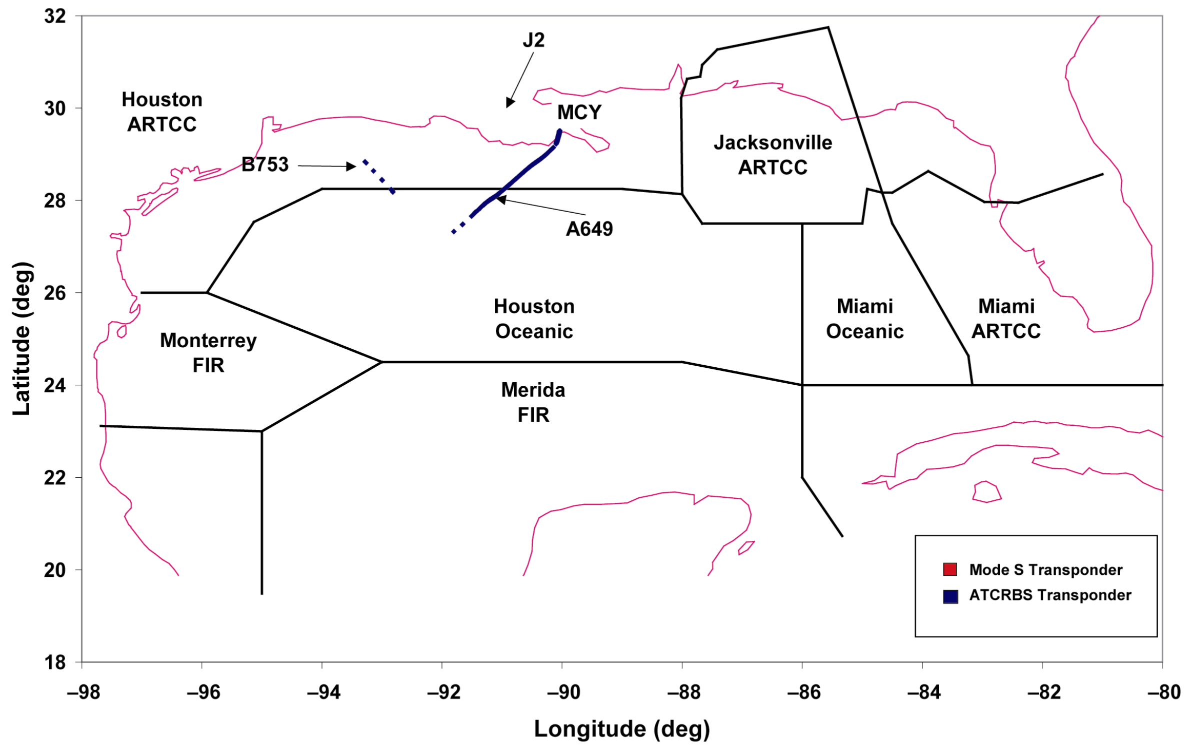


Figure F-4(a) Feb. 11 PM Flight Ground Track (WAM Target Reports).

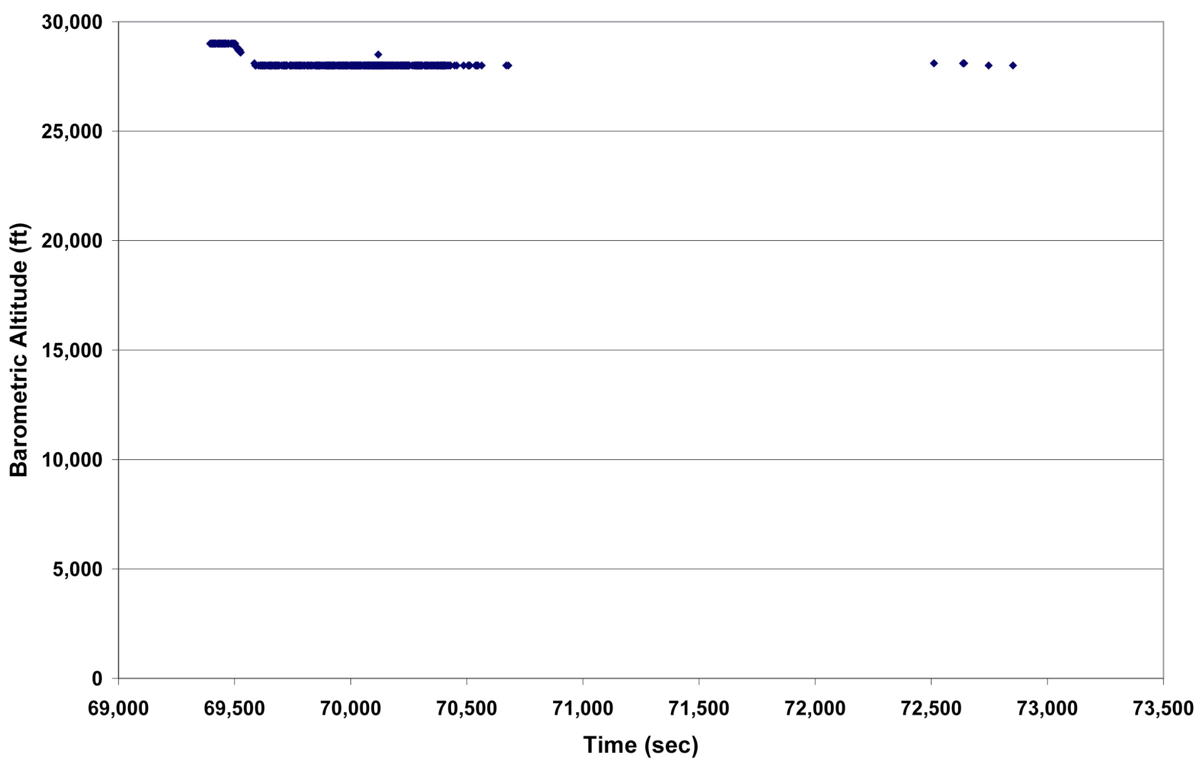


Figure F-4(b) Feb. 11 PM Altitude Profile (Transponder Barometric Data).

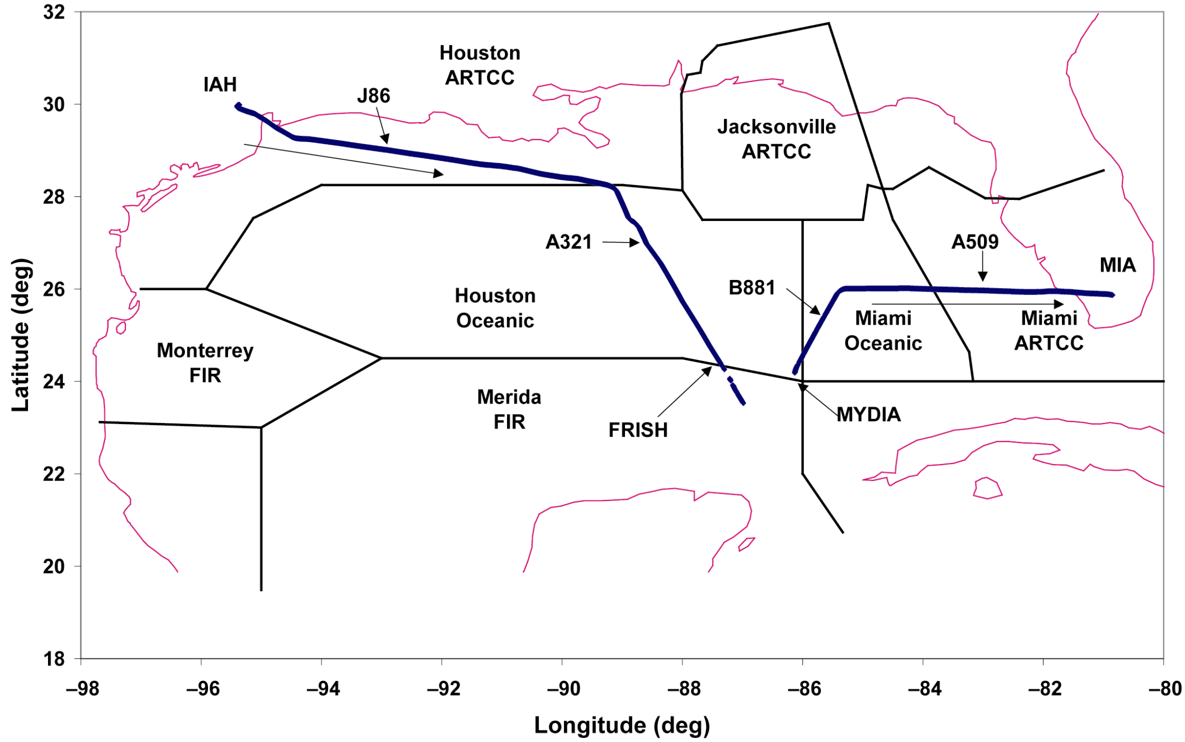


Figure F-5(a) Feb. 12 AM Flight Ground Track (ADS-B Data).

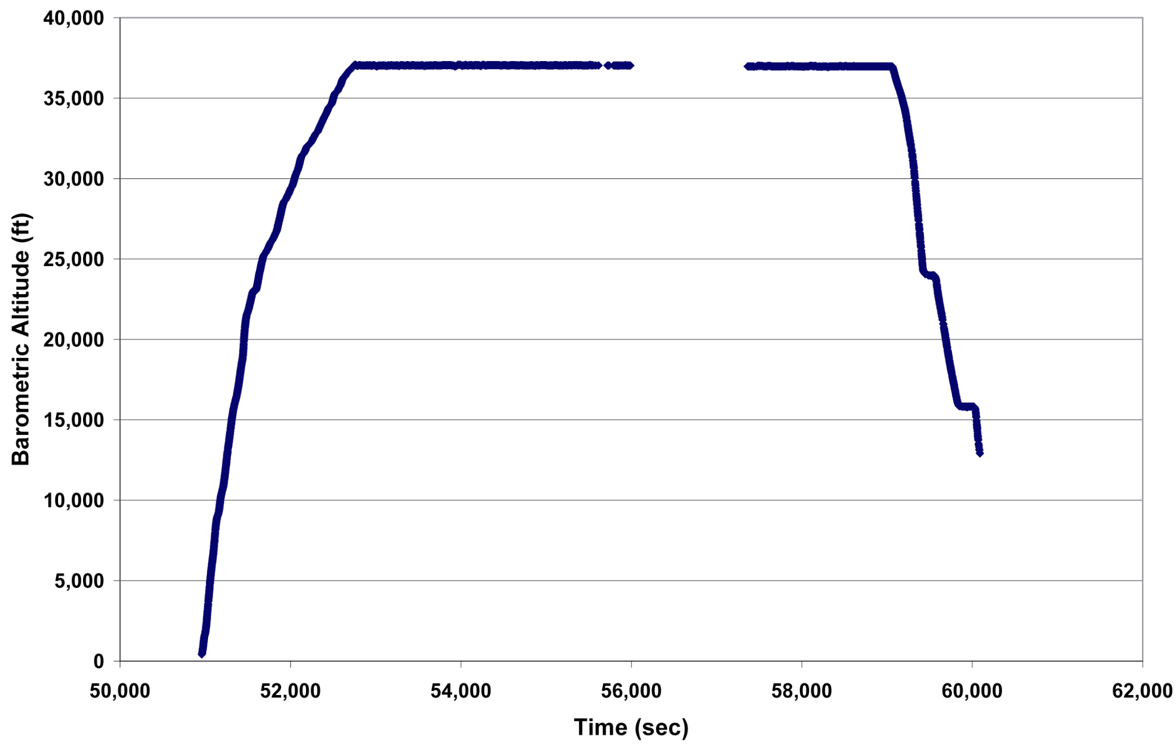


Figure F-5(b) Feb. 12 AM Flight Altitude Profile (Transponder Barometric Data).

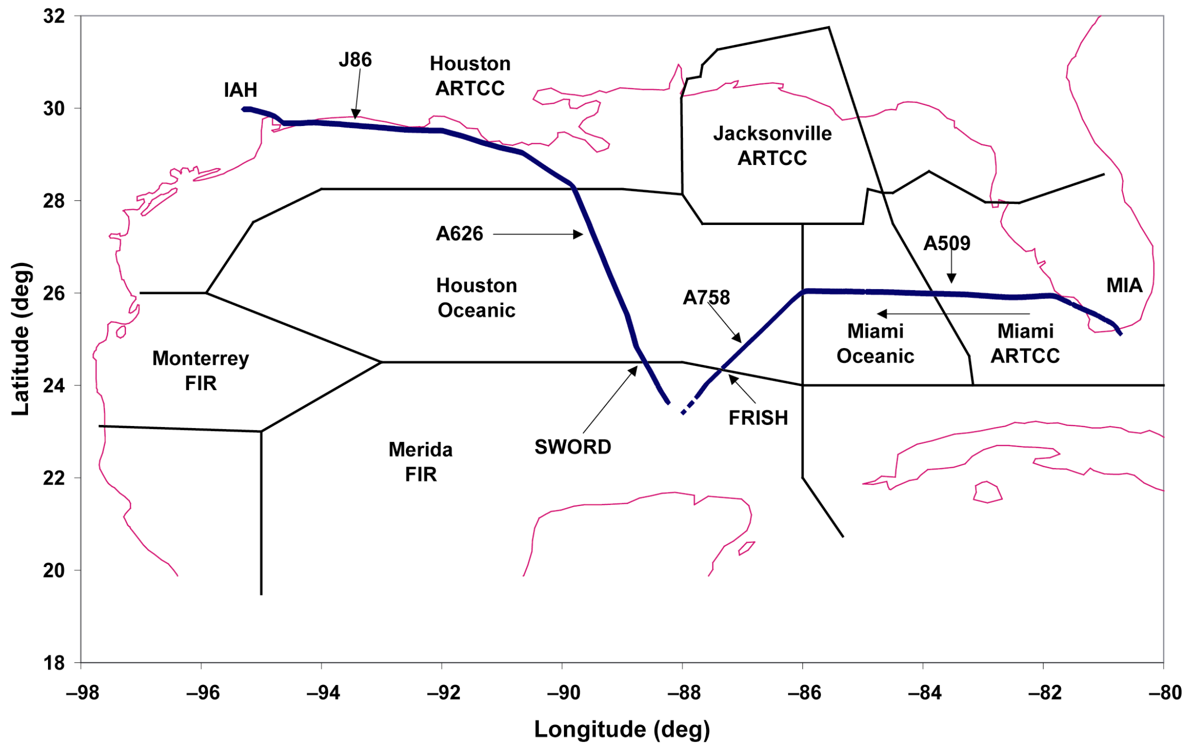


Figure F-6(a) Feb. 12 PM Flight Ground Track (ADS-B Data).

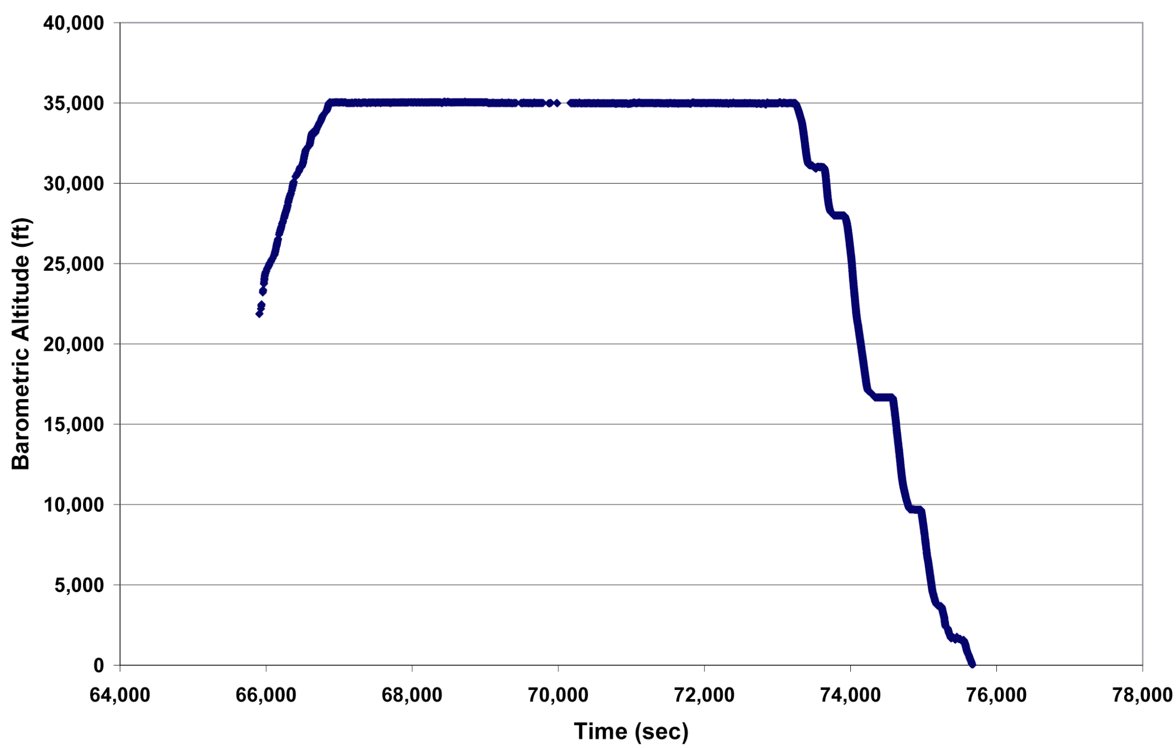


Figure F-6(b) Feb. 12 PM Flight Altitude Profile (Transponder Barometric Data).

Appendix G. March 23–25, 2004, Flight Test Aircraft Tracks

During the March 2004 flight test, eight flights were conducted for the purpose of evaluating Helicopter In-Flight Tracking System (HITS) automatic dependent surveillance – broadcast (ADS-B) and wide-area multilateration (WAM) performance for high-altitude aircraft equipped with Mode S extended squitter, Mode S short squitter, and Air Traffic Control Radar Beacon Soystem (ATCRBS) transponders. This appendix presents a tabular summary of the flights (table G-1) and individual plots of the flight tracks (latitude and longitude coordinates) and altitude profiles (figures G-1 through G-8).

Table G-1 March 2004 Flight Summary

Flight	Purpose	Aircraft	Altitude Regime	Transponder	Scored?
FAA March 23 AM	ADS-B test	FAA Tech Center B-727	FL270	Mode S extended squitter	✓
FAA March 23 PM	WAM test	FAA Tech Center B-727	FL270	ATCRBS	✓
NASA March 23	ADS-B test	NASA Gulfstream III	FL280 (out) FL390 (in)	Mode S extended squitter	✓
FAA March 24 AM	ADS-B test	FAA Tech Center B-727	FL280	Mode S extended squitter	✓
FAA March 24 PM	ADS-B test	FAA Tech Center B-727	FL330	Mode S extended squitter	✓
NASA March 24	WAM test	NASA Gulfstream III	FL280	Mode S short squitter	✓
FAA March 25 AM	ADS-B test	FAA Tech Center B-727	FL330	Mode S extended squitter	✓
FAA March 25 PM	ADS-B test	FAA Tech Center B-727	FL350	Mode S extended squitter	✓

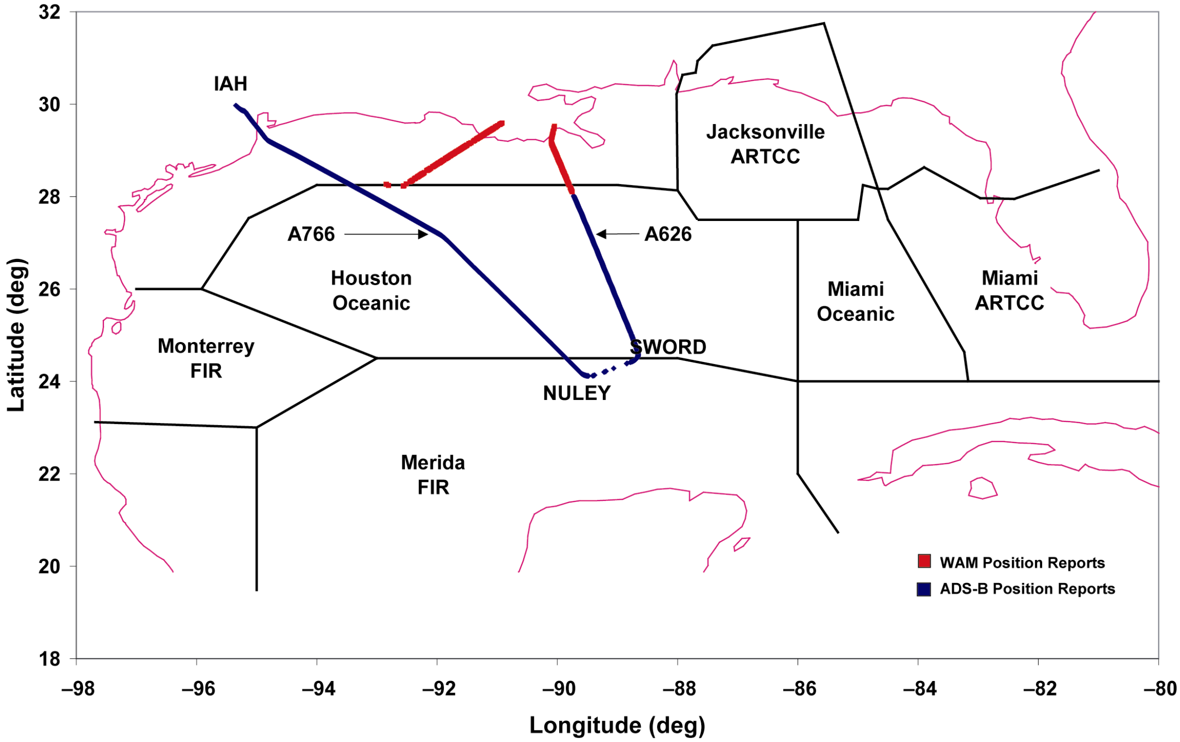


Figure G-1(a) FAA March 23 AM Flight Ground Track (ADS-B Data).

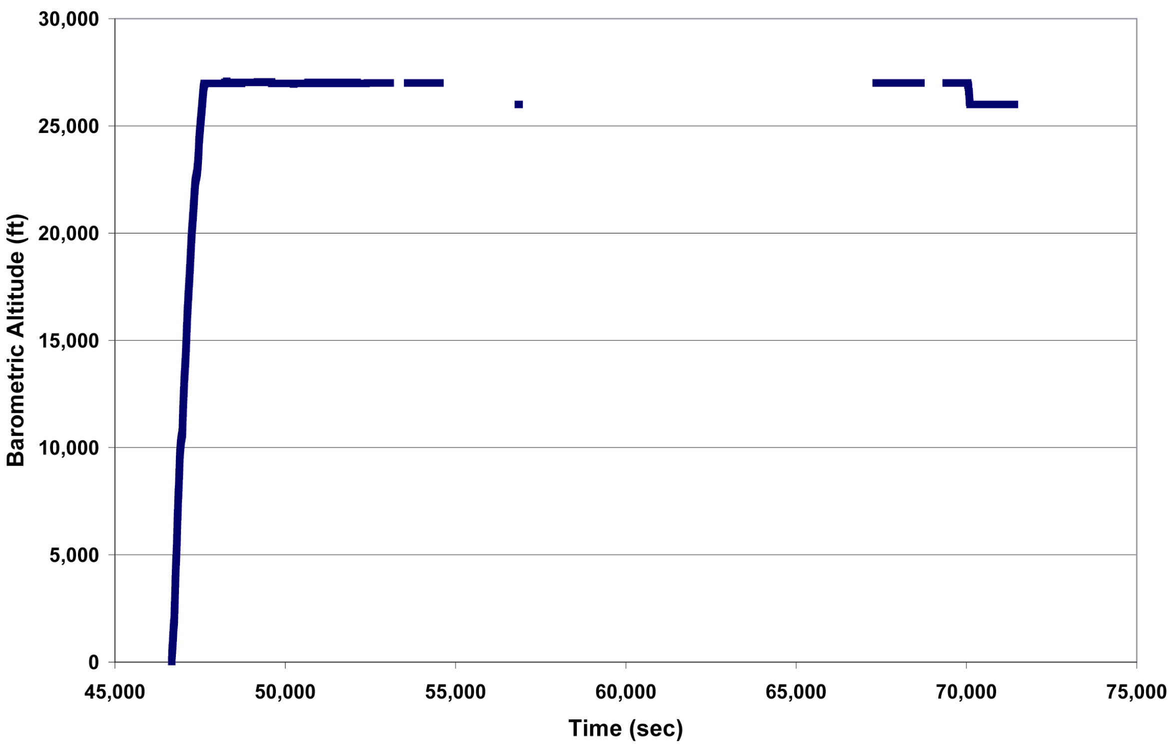


Figure G-1(b) FAA March 23 PM Flight Altitude Profile (Transponder Barometric Data).

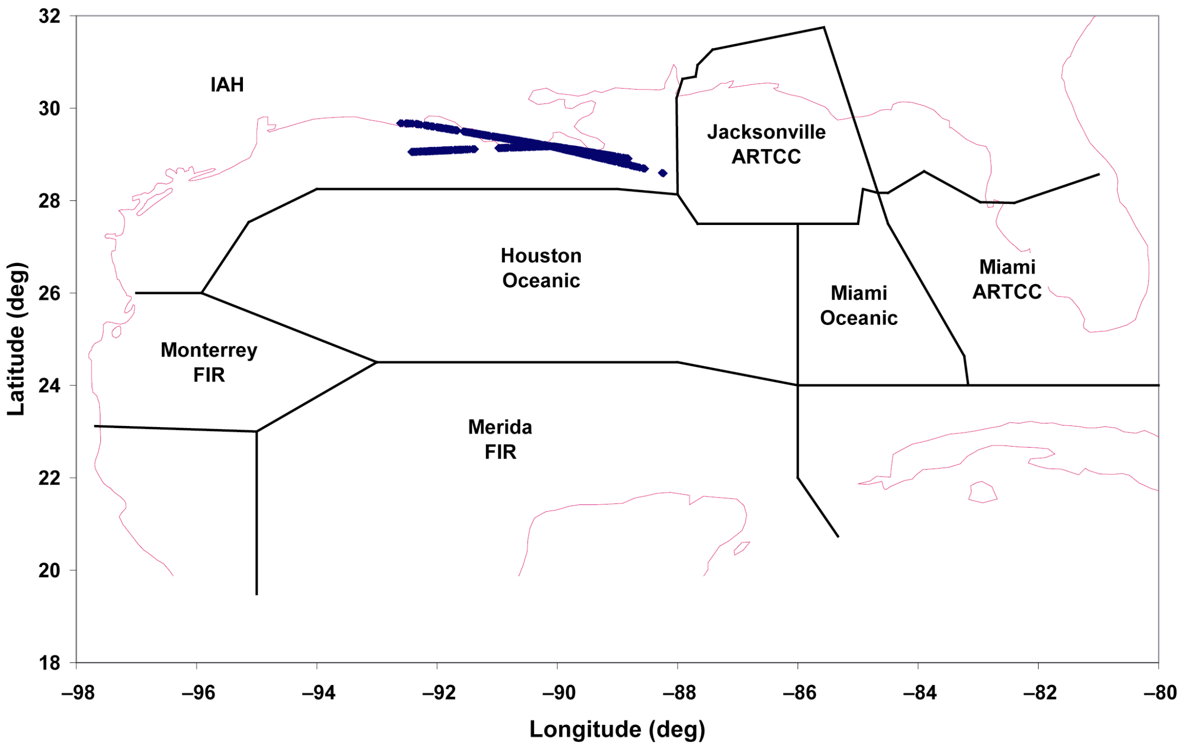


Figure G-2(a) FAA March 23 PM Flight Ground Track (WAM Target Reports).

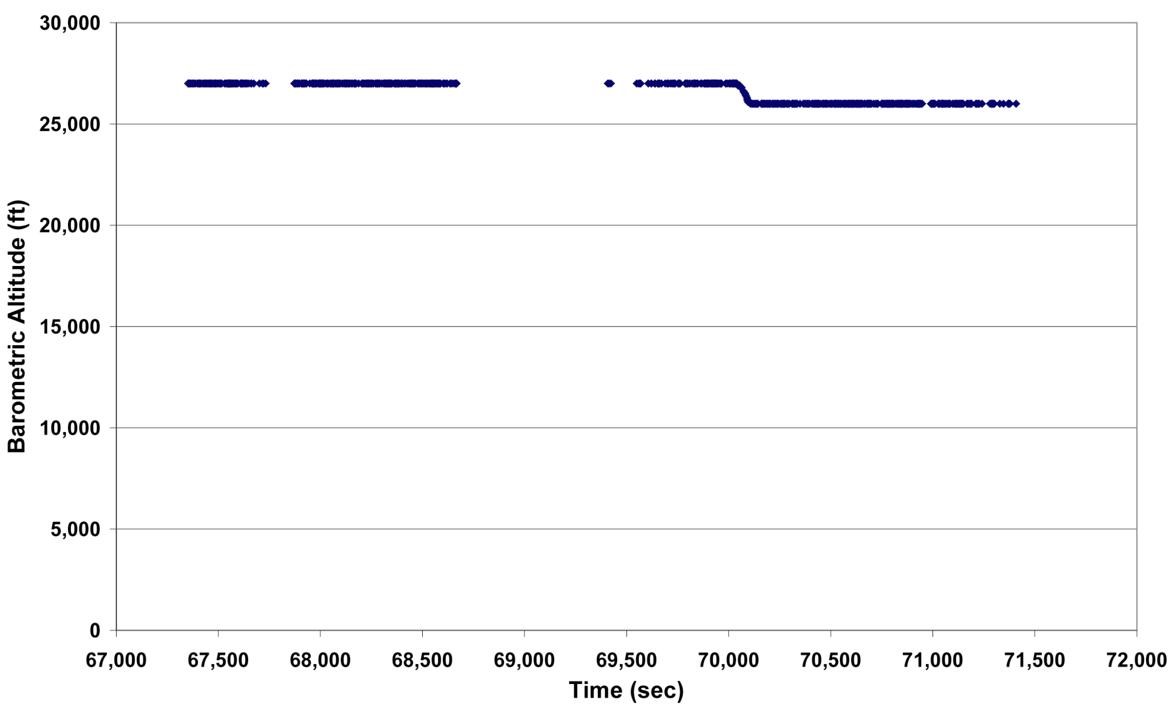


Figure G-2(b) FAA March 23 PM Flight Altitude Profile (Transponder Barometric Data).

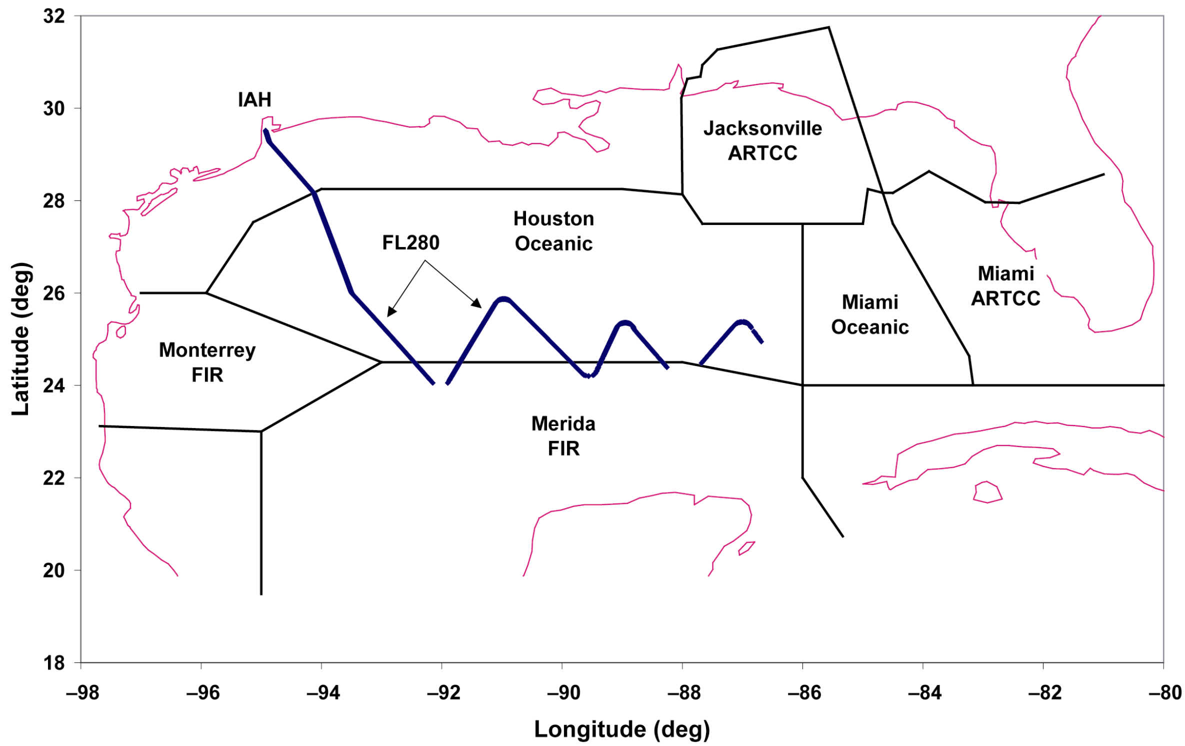


Figure G-3(a) NASA March 23 Outbound Flight Ground Track (ADS-B Data).

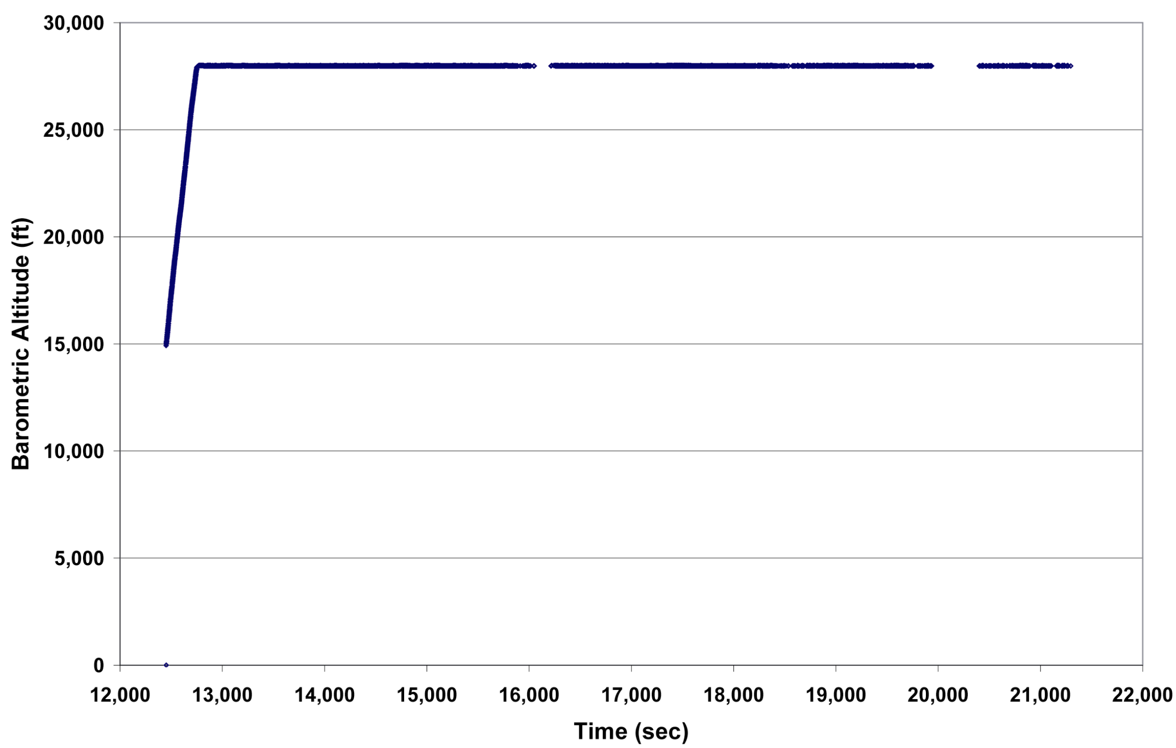


Figure G-3(b) NASA March 23 Outbound Flight Altitude Profile (Transponder Barometric Data).

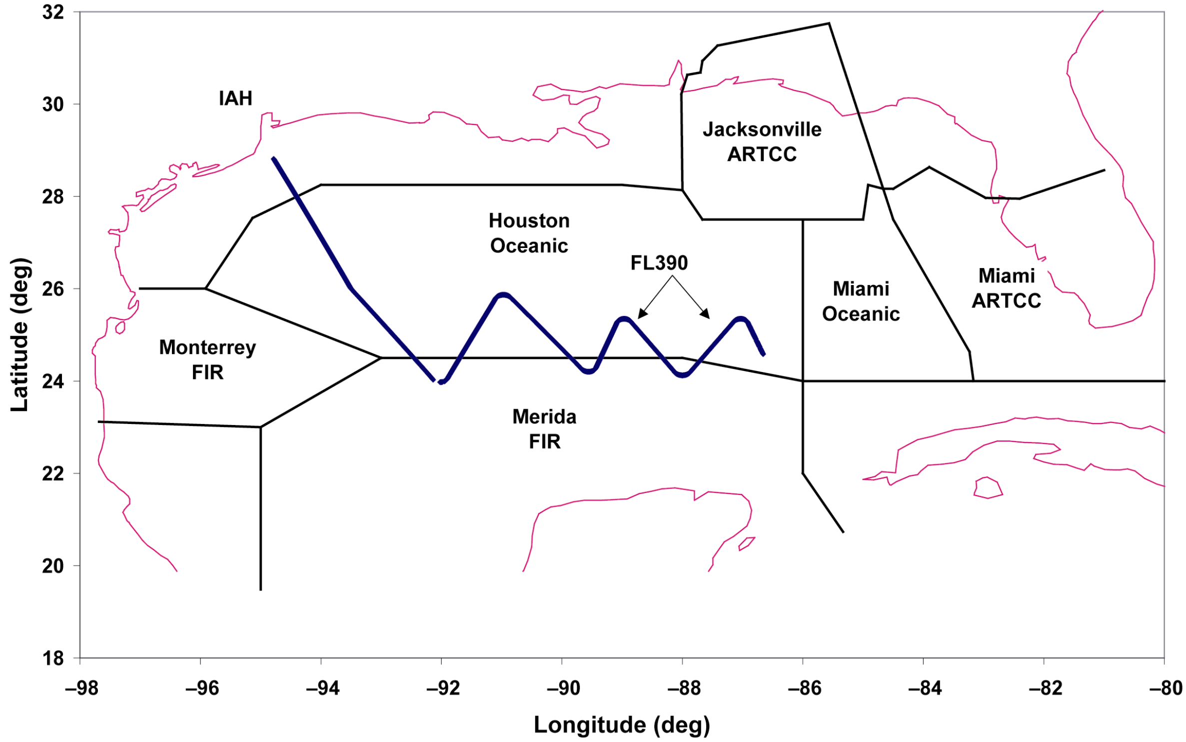


Figure G-3(c) NASA March 23 Inbound Flight Ground Track (ADS-B Data).

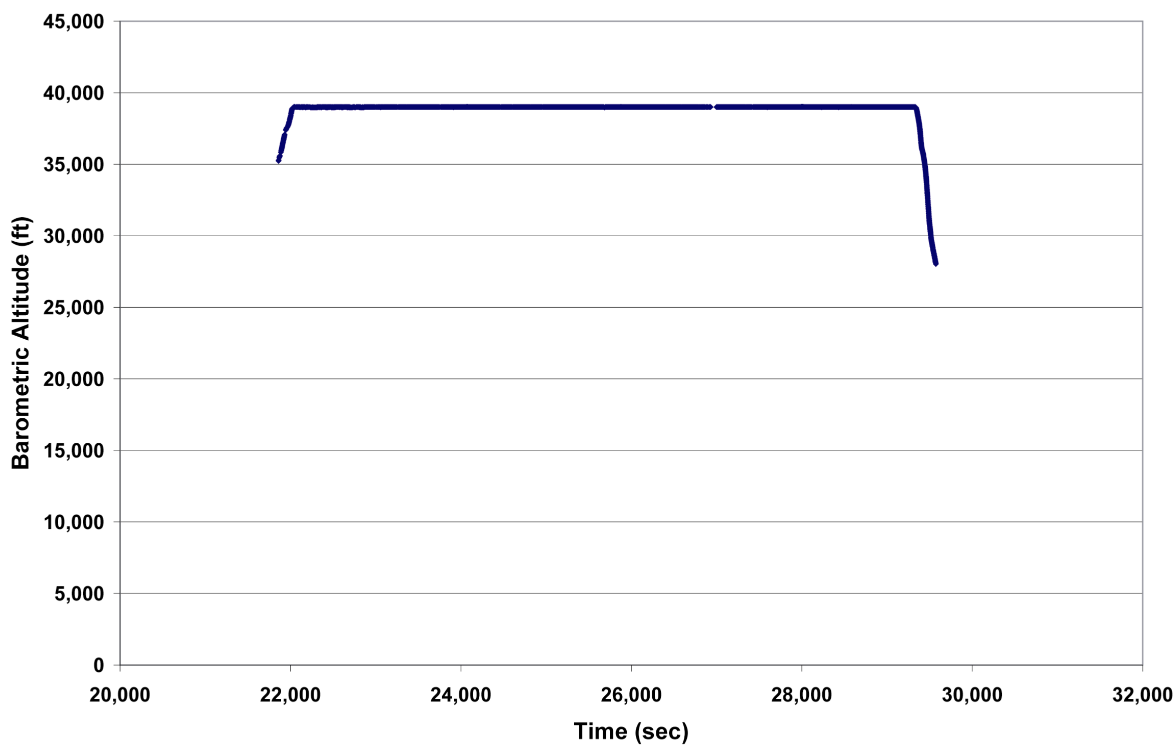


Figure G-3(d) NASA March 23 Inbound Flight Altitude Profile (Transponder Barometric Data).

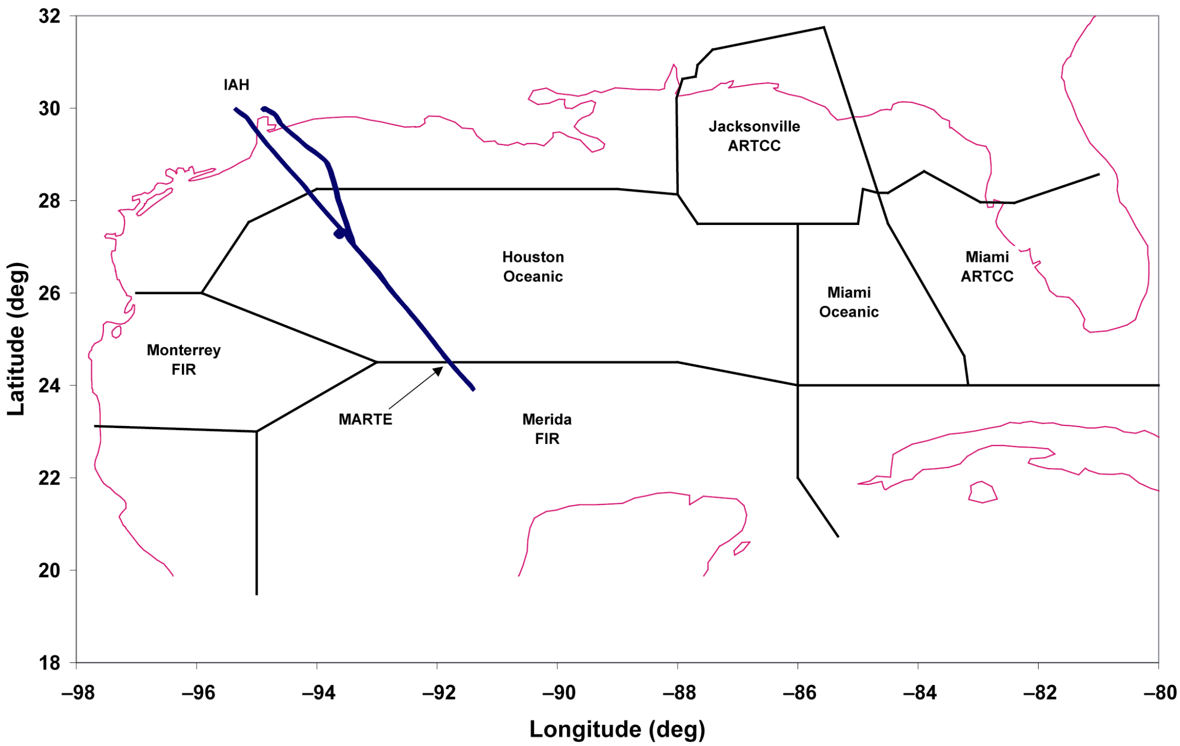


Figure G-4(a) FAA March 24 AM Flight Ground Track (ADS-B Data).

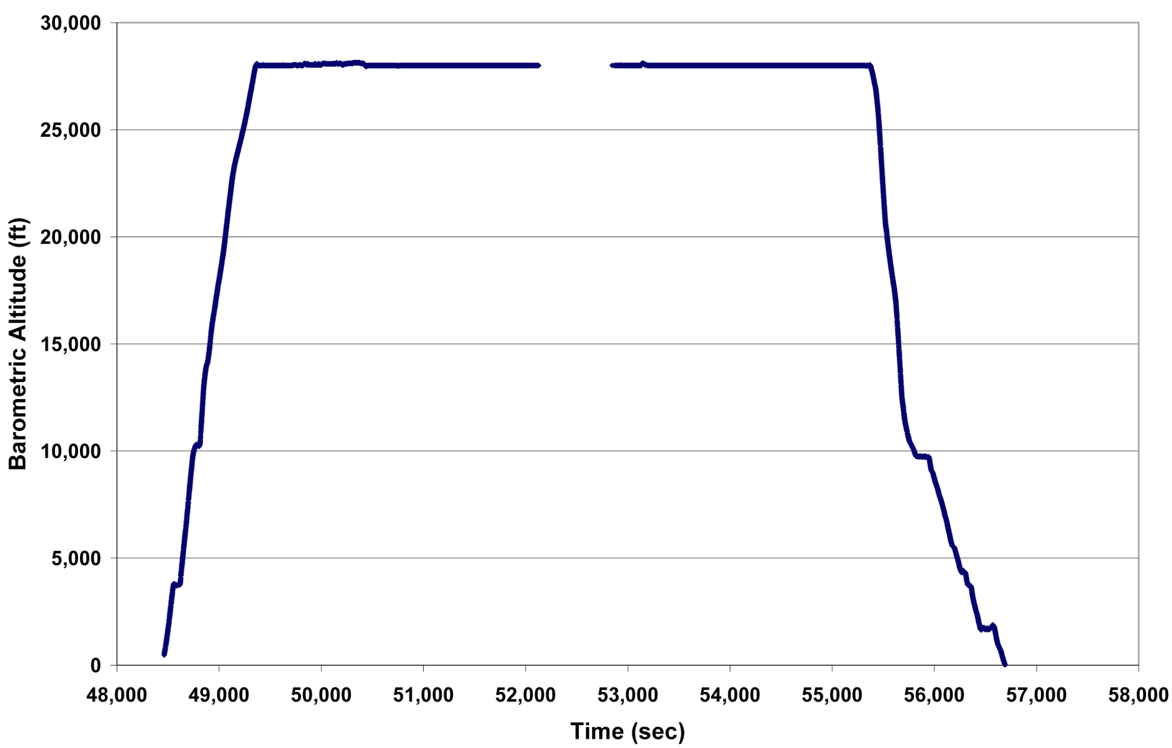


Figure G-4(b) FAA March 24 AM Flight Altitude Profile (Transponder Barometric Data).

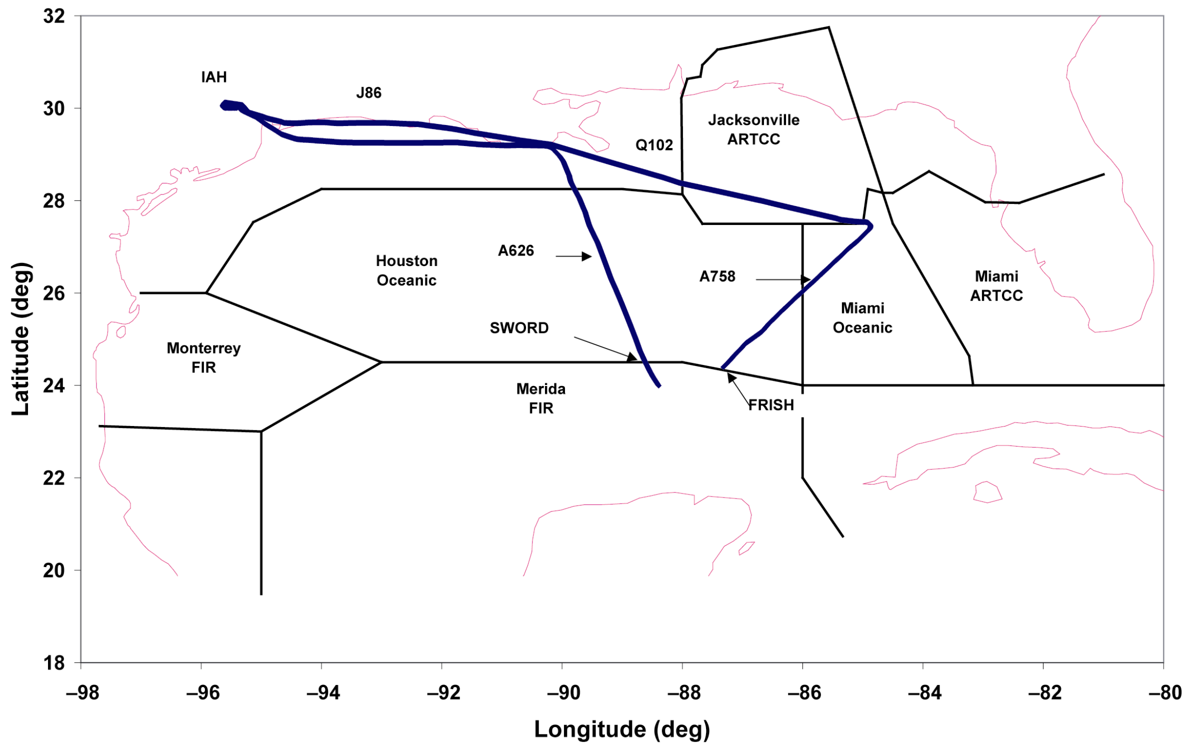


Figure G-5(a) FAA March 24 PM Flight Ground Track (ADS-B Data).

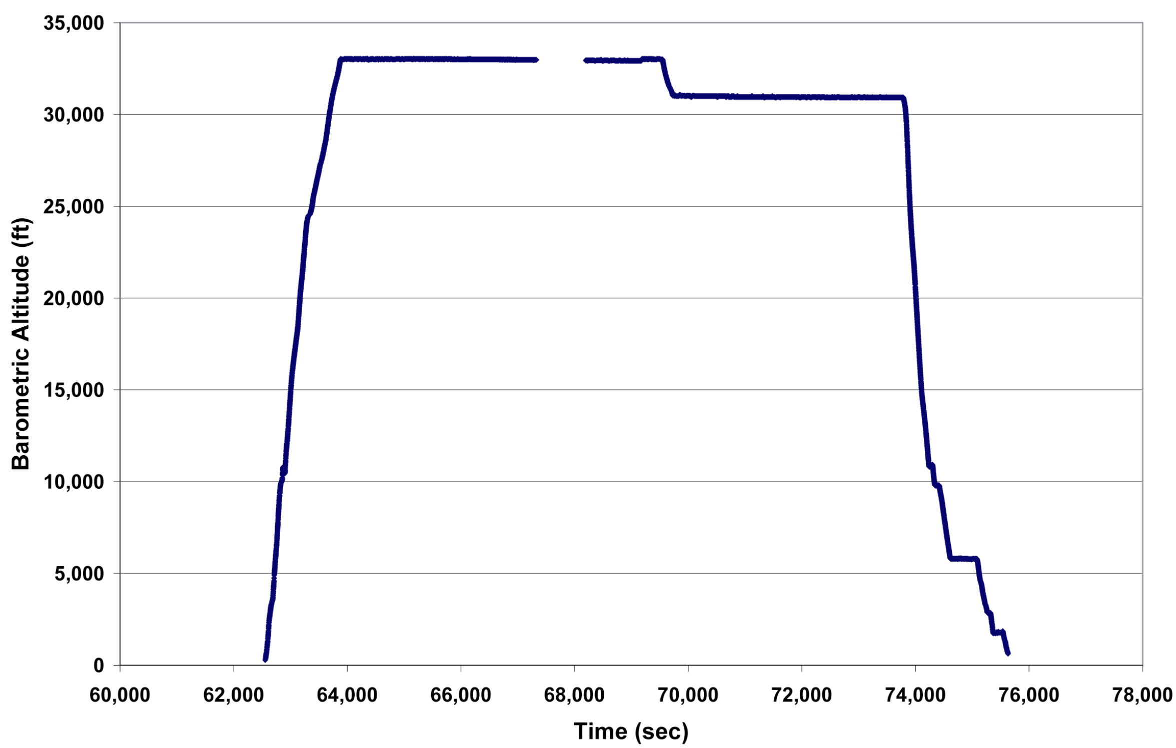


Figure G-5(b) FAA March 24 PM Flight Altitude Profile (Transponder Barometric Data).

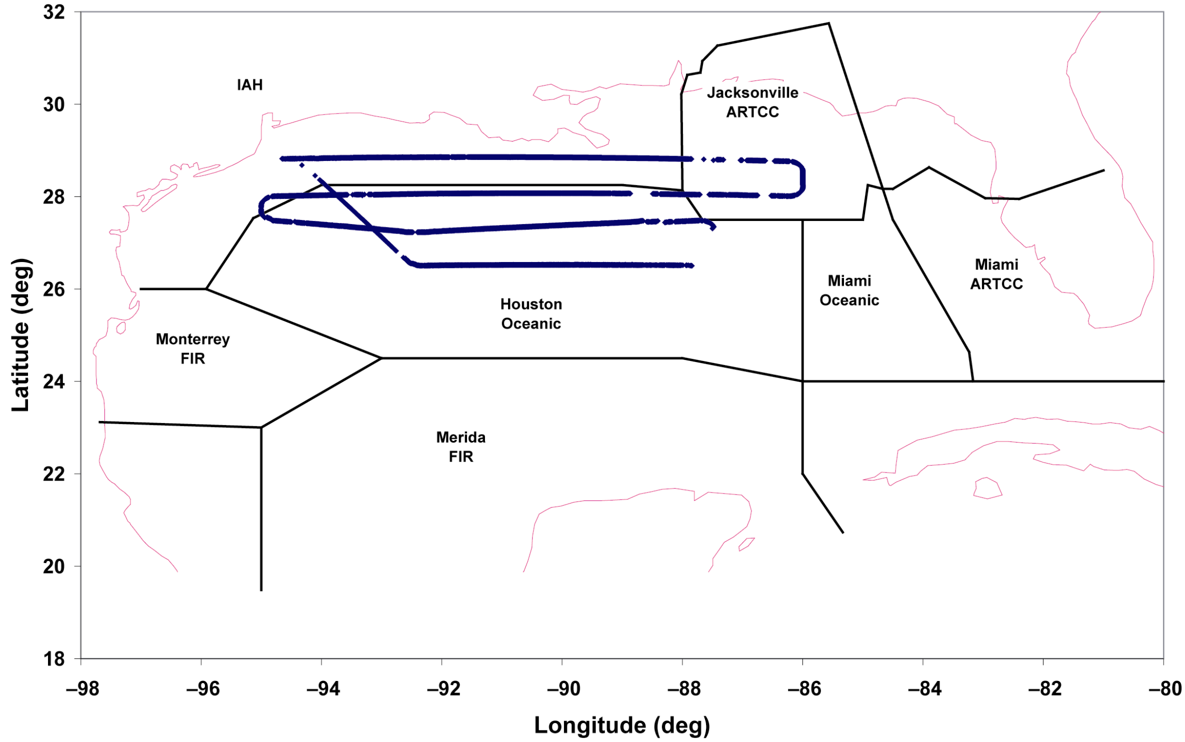


Figure G-6(a) NASA March 24 Flight Ground Track (WAM Target Reports).

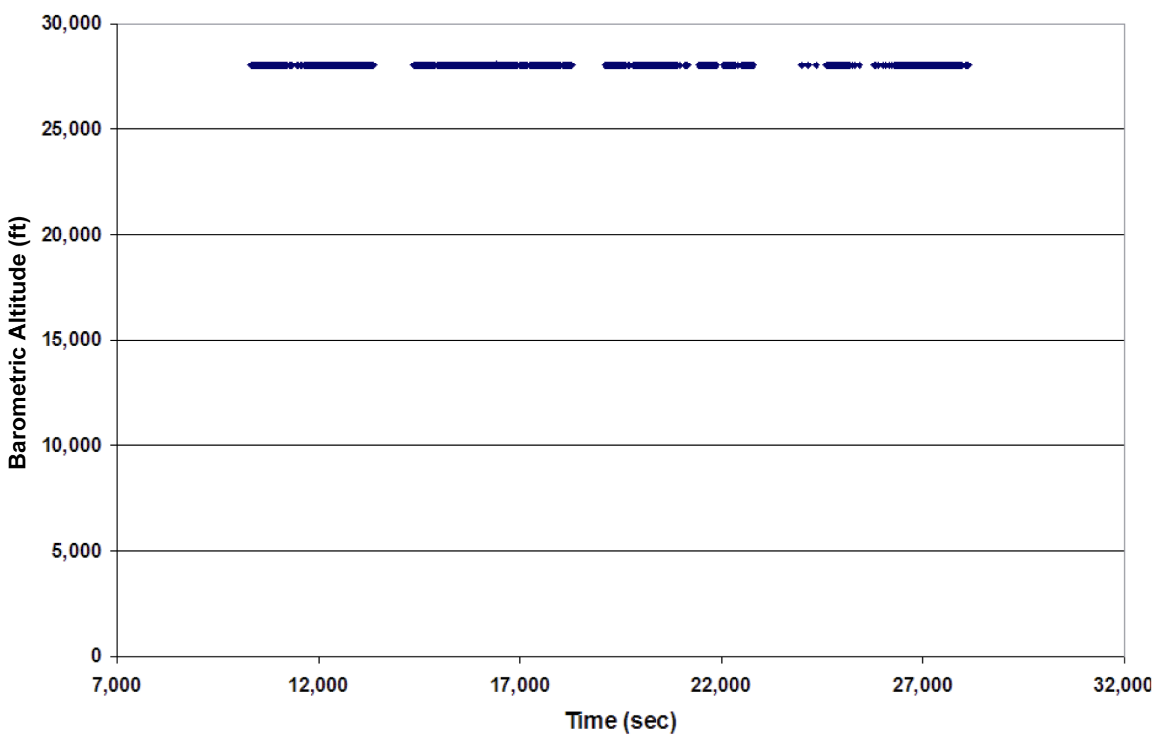


Figure G-6(b) NASA March 24 Flight Altitude Profile (Transponder Barometric Data).

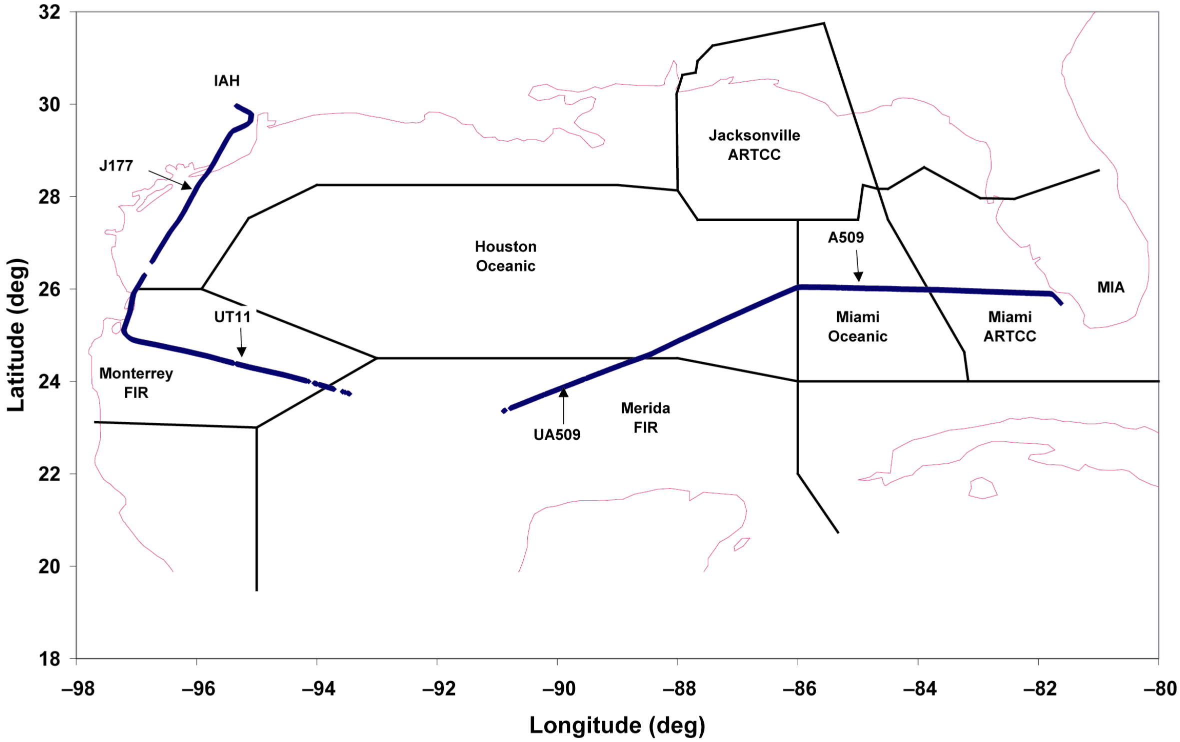


Figure G-7(a) FAA March 25 AM Flight Ground Track (ADS-B Data).

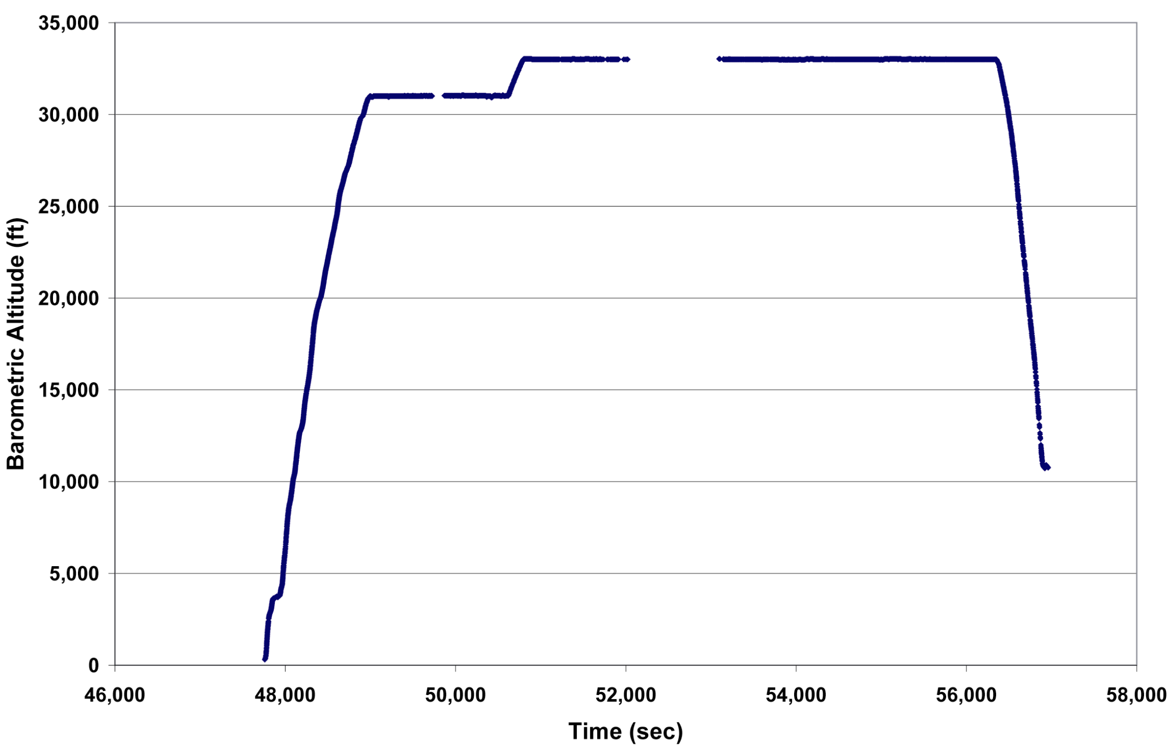


Figure G-7(b) March 25 FAA 1 Flight Altitude Profile (Transponder Barometric Data).

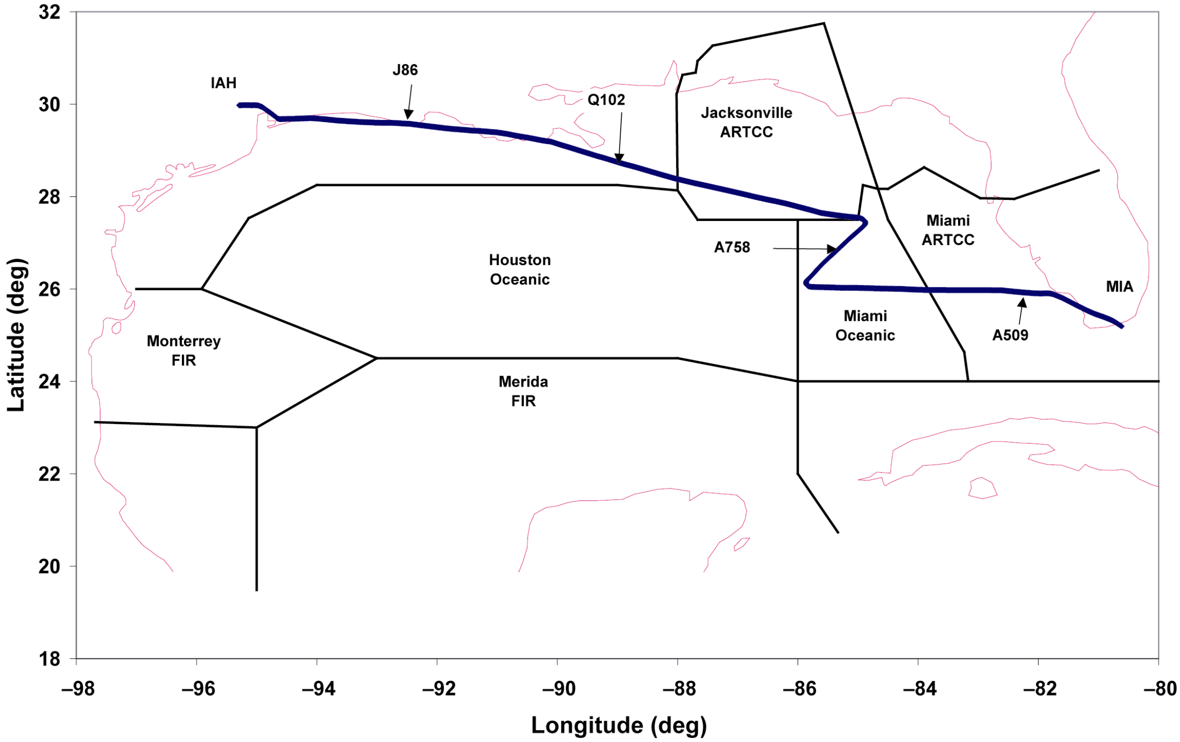


Figure G-8(a) FAA March 25 PM Flight Ground Track (ADS-B Data).

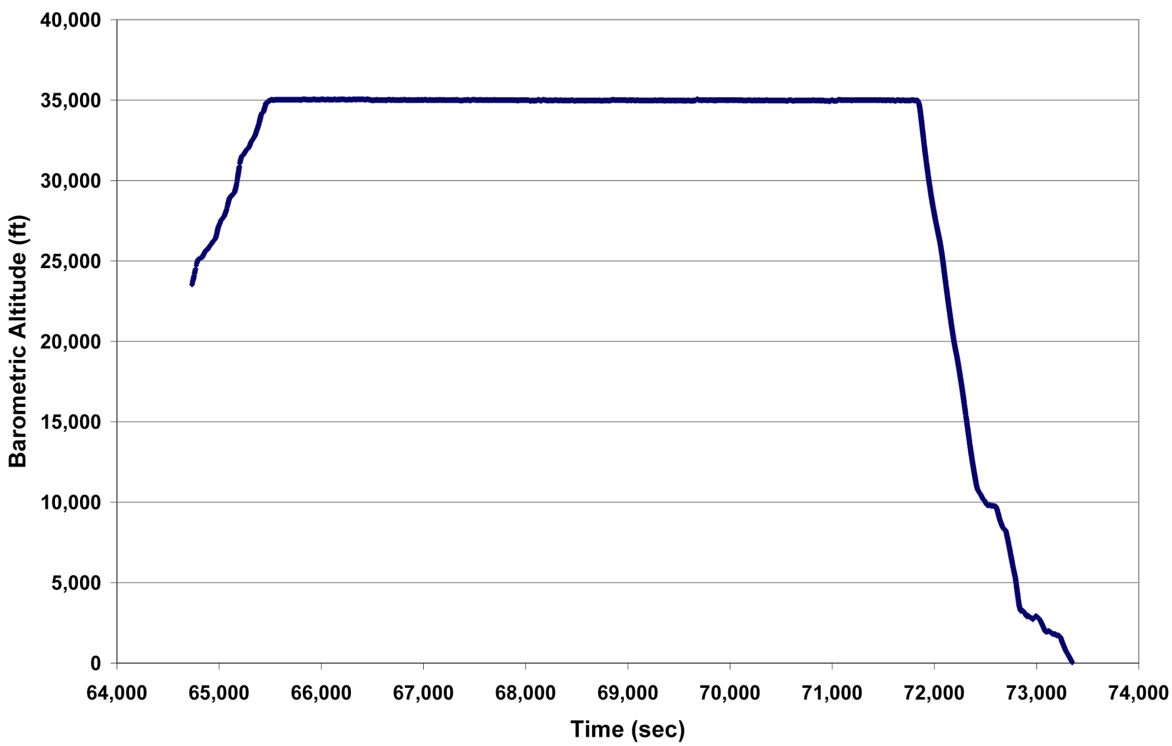


Figure G-8(b) FAA March 25 PM Flight Altitude Profile (Transponder Barometric Data).

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14. ABSTRACT
The Gulf of Mexico airspace has two major operating regions: low altitude offshore (below 7,000 ft) and high altitude oceanic (above 18,000 ft). Both regions suffer significant inefficiencies due to the lack of continuous surveillance during Instrument Flight Rules operations. Provision of surveillance in the offshore region is hindered by its low-altitude nature, which makes coverage by conventional radars economically infeasible. Significant portions of the oceanic sectors are inaccessible to shore-based sensors, as they are beyond line-of-sight.

Two emerging surveillance technologies were assessed that are relatively low cost and can be deployed on offshore platforms—Wide Area Multilateration and Automatic Dependent Surveillance – Broadcast. Performance criteria were formulated using existing FAA specifications. Three configurations were developed and deployed—representative of systems serving full-size and reduced-sized domestic terminal areas and an en-route/oceanic region. These configurations were evaluated during nine flight test periods using fixed- and rotary-wing aircraft.

15. SUBJECT TERMS
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