Automatic Dependent Surveillance–Broadcast in the Gulf of Mexico

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The Federal Aviation Administration is adopting Automatic Dependent Surveillance–Broadcast (ADS–B) to provide surveillance in the National Airspace System (NAS). Aircraft separation services are currently provided by a system of en route and terminal radars, and the performance of these radars in part dictates the separation distance required between aircraft. ADS–B is designed to provide comparable service in areas where no radar coverage exists. It will eventually be the primary surveillance source in the NAS, if it is proven to provide performance equal to or better than radar.

» **Growing air traffic congestion and delays** in the National Airspace System (NAS) require significant restructuring of the current Air Traffic Control (ATC) system. The Federal Aviation Administration (FAA) plans include the Next Generation Air Transportation System (NextGen), a Joint Planning Development Office multiagency effort established by Congress to transform the air transportation system into a more flexible, adaptive, and highly automated system capable of handling two to three times the current traffic. Automatic Dependent Surveillance–Broadcast (ADS–B) will provide the surveillance that NextGen needs to tackle these problems. Surveillance in today's NAS is provided by a system of terminal and en route radars. The FAA is seeking to augment this system by using ADS–B for aircraft surveillance and separation, and plans to implement ADS–B over the next 20 years to track all aircraft. ADS–B, a satellite-based system that provides accurate surveillance and state information to controllers on the ground and to the cockpits of equipped aircraft, is a key enabler of NextGen.

Primary and secondary surveillance radars have provided positive position information to air traffic controllers ever since being introduced for commercial aircraft separation services in the early 1950s (see Figure 1). Improvements in radar system performance and the proliferation of coverage have served the FAA well. But radars are expensive to maintain, are subject to terrain blockage, and cannot provide coverage in areas where there is no line of sight. The accuracy of radars in determining position degrades at long range, and errors in measured separation between aircraft are introduced when different aircraft are tracked by different radars.

FIGURE 1. Air traffic controllers monitor the radar sensors in their region. The multisecond scans of the radars are converted to sweeps on the scope in front of each controller, showing the objects located by the radar.

Essentially, the FAA wants to move to the operations shown in Figure 2. Traditional and current technology comprises a radar sensor with a periodic sweep time of several seconds, and the detected aircraft are shown on the display. Under optimum conditions, the controller receives azimuth, range, and altitude data on the aircraft, as well as information unique to each aircraft (e.g., flight number, type of aircraft). Aircraft must depend on the controllers to separate them from other aircraft. The expectations for ADS–B include all the same information as radar sensors provide, but more rapidly and with significantly more accuracy. By broadcasting aircraft position information to a ground station, ADS–B can also provide coverage in areas that don't have radar coverage. In addition—and fundamental to the improvements expected for NextGen—ADS–B provides trajectory information, or four-dimensional data, that includes speed and direction of motion.

ADS–B depends on the aircraft broadcasting their self-determined positions to air traffic controllers. ADS–B, as being implemented by the FAA, will employ two different data links: one uses the Mode Select (Mode S) 1090 MHz squitter (Mode S Extended Squitter, or Mode S ES) designed by Lincoln Laboratory [1] and intended primarily for commercial aircraft, and the second uses a UHF data link known as the Universal Access Transceiver, designed primarily for small general aviation aircraft. Mode S transponders send out spontaneous signals known as squitters that enable aircraft equipped with the Traffic Alert and Collision Avoidance System (TCAS) [2] to acquire the signals and determine if they are a threat and to coordinate resolutions. TCAS and Mode S radars can selectively interrogate Mode S transponders to avoid interference from other transponders. ADS–B makes use of these squitters by making them larger (extended squitters) so that position and state data can be included in the squitter. The integrated ADS–B system allows aircraft to broadcast their position, intent, and status information on the order of twice per second.

Lincoln Laboratory Role

Lincoln Laboratory played a critical role in conception, development, and testing of the 1090 MHz Mode S Extended Squitter data link for ADS–B [1] and continues to support the FAA's national implementation program [2, 3]. In 1992, Lincoln Laboratory proposed to the FAA the use of Mode S ES for the transmission of aircraft-derived position. This concept has evolved into the current ADS–B 1090 MHz data link that allows aircraft to broadcast and receive ADS–B information by using

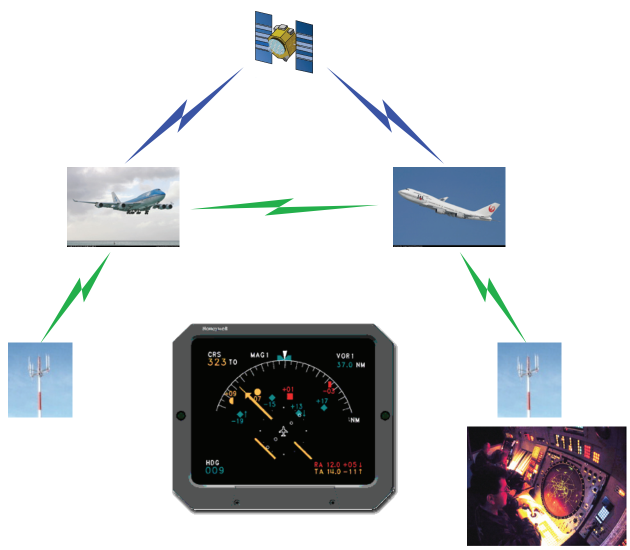

FIGURE 2. Automatic Dependent Surveillance–Broadcast (ADS–B)–driven technology still includes the air traffic controllers shown in the bottom right, but the information presented to the controller is obtained from ADS–B connections to global positioning sensors and ground-based transceivers. Aircraft that have ADS–B equipment can send and receive the same information directly to and from other similarly equipped aircraft and can observe all the information on nearby aircraft on the monitors in their cockpits (center).

existing transponder equipment. It has been adopted worldwide as the commercial fleet's standard for ADS–B implementation.

The FAA asked Lincoln Laboratory to develop a model and testing procedure for assessing ADS–B's ability to perform adequately in several environments. The FAA awarded a contract to the team led by ITT Corp. to install ADS–B at four key sites. On the basis of the performance at these sites, the FAA will make a decision for nationwide deployment in 2010, to be completed by 2013. The four sites of interest are Philadelphia (a busy terminal); Louisville, Kentucky (a nighttime hub for United Parcel Service aircraft that are all ADS–B equipped); Juneau, Alaska (mountain blockage); and the Gulf of Mexico (regions of no radar coverage). Before ADS–B can be implemented either in a mixed ADS–B/radar environment or a radar-independent environment, it is essential that we verify that ADS–B's ability to support separation services is equal to or better than the same information obtained from radars.

The approach we are taking in this article is to first model the performance that would be achieved if there were radar coverage across the Gulf of Mexico (GoMex) and compare that to the proposed implementation of ADS–B coverage across the Gulf. GoMex was chosen as a key case because it has gaps in radar coverage in the center of the Gulf that could be covered by ADS–B. The coverage range for ADS–B extends well beyond the Gulf coast, as shown in Figure 3. The model determines the current surveillance system baseline performance that could be achieved if there were, in fact, radar coverage on the Gulf. Next, the performance of ADS–B separated from ADS–B aircraft and ADS–B aircraft separated from aircraft under radar surveillance is simulated for the same flight paths. Results are then compared to determine if the new system performs as well as the current surveillance baseline. The performance metrics are position-estimation errors and measured-separation errors. This approach was used in earlier work on the analysis of Required Surveillance Performance (RSP) [4–6]. (See also the sidebar, "Required Surveillance Performance," on page 58.)

ADS–B Technology

ADS–B uses global positioning systems (GPS) to report known positions and state vectors instead of being interrogated by radar [7]. ADS–B combines the data obtained from GPS and other equipment on the aircraft to produce a three-dimensional positioning and state vector data. ADS–B compiles these data and continually updates—about twice per second—the following information: aircraft identification (fixed), time, physical position by latitude and longitude and altitude, heading, velocity, vertical rate of climb or descent, and rate-turn indication. The many benefits of ADS–B cited by the FAA include providing surveillance to remote areas not covered by radar, potentially reducing separation, supporting current horizontal and vertical separation standards, improving controllers' ability to manage traffic and plan arrivals and departures, reducing cost of operations, reducing air travel time, and saving fuel costs.

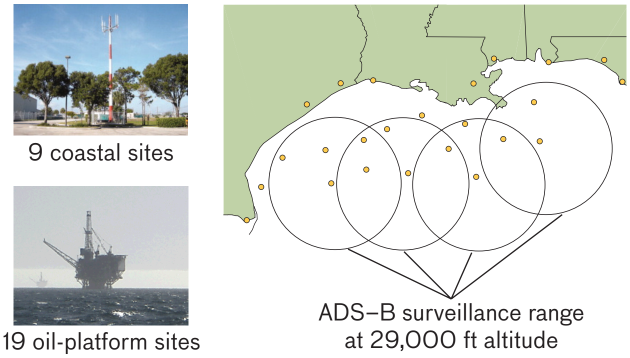

FIGURE 3. ADS–B relies on the global positioning system (GPS) and ground-based locations for the aircraft's four-dimensional information that has to be transmitted to air traffic control. Here in the Gulf of Mexico (GoMex), there are coastal and oil-platform transponder sites that will provide additional positioning information resources as well as communication points.

In addition to reporting aircraft position, the messages also include estimates of accuracy encoded into categories called the Navigation Accuracy Category for position and velocity, or NAC_p and NAC_v. The NAC_p and NAC_v determine the air traffic services that can be supported. For instance, closely spaced parallel approaches to runways would require more accuracy than en route five-nautical-mile* separation.

This basic surveillance system, known as ADS–B "out," is supplemented with ADS–B "in," which allows the aircraft to receive traffic information from the ground as well as real-time graphical weather products. In simple

* All subsequent references in this article to distances in miles are nautical miles.

Required Surveillance Performance

Preliminary work has set the criteria for evaluating ADS–B performance.

Flight simulations were run with various test cases and radar configurations to document ADS–B and radar performance. The radar error models (validated in our previous work [a]) used to compute radar position errors in the simulation runs are summarized in Table A. In the simulation, bias errors are sampled once and held constant for the entire flight, and jitter errors are resampled for each update.

The flight path used to validate radar error models developed for the Required Surveillance Performance (RSP) analysis is shown in Figure A. This flight went through the Boston Air Route Traffic Control Center (ARTCC) airspace and involved two jet aircraft flying in-trail approximately 3 miles apart. The flight path included both long-range and short-range sliding-window and monopulse secondary surveillance radars (SWSSRs and MSSRs). During the validation flight test, the true locations of the aircraft were determined by onboard Ashtech global positioning system (GPS) receivers. The radar position reports were used to validate the radar-position error models and to determine errors in measured separation.

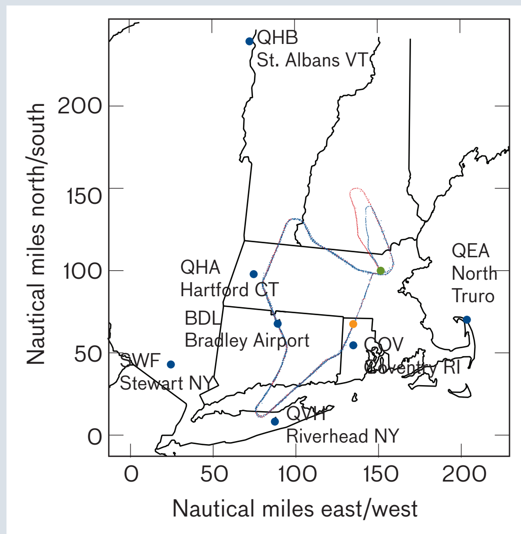

FIGURE A. **The flight test data for the Falcon 20 and Gulfstream G2 aircraft were used to validate the radar error models. The Falcon 20 is depicted in red, and the Gulfstream G2 is in blue.**

The radar-antenna-mast starting points are randomly set, and the rotation rates are randomly selected from the specification limits (4 to 5 s for short-range radars and 10 to 12 s for long-range radars). Unless otherwise noted, the radar closest to the aircraft is used for position estimates. The metrics of performance are geographic positional accuracy and the error in measured separation between aircraft. A position-accuracy scatter plot and a separation-error histogram are generated. Separation error compares the last measured separation to the true separation of the aircraft at that time, and the corresponding histogram is generated by a random sampling over the entire flight. Figure B shows the probability distribution of separation of the two aircraft in the RSP analysis as a function of distance away from a radar sensor.

The errors measured here are sensor measurement errors. The errors that may be associated with the processing of the measurements for display are not included, because the analysis is intended to compare radar performance with radar and ADS–B in a mixed radar environment and to determine requirements for the ADS–B reports on the basis of the radar sensor performance. Any of a number of different display processing systems could be involved and, depending on how those systems are designed and implemented, additional errors could be introduced for radar or ADS–B reports.

REFERENCE

a. S.D. Thompson, J.W. Andrews, G.S. Harris, and K.A. Sinclair, "Required Surveillance Performance Accuracy to Support 3-Mile and 5-Mile Separation in the National Airspace System," Lincoln Laboratory Project Report ATC-323, Nov. 1, 2006.

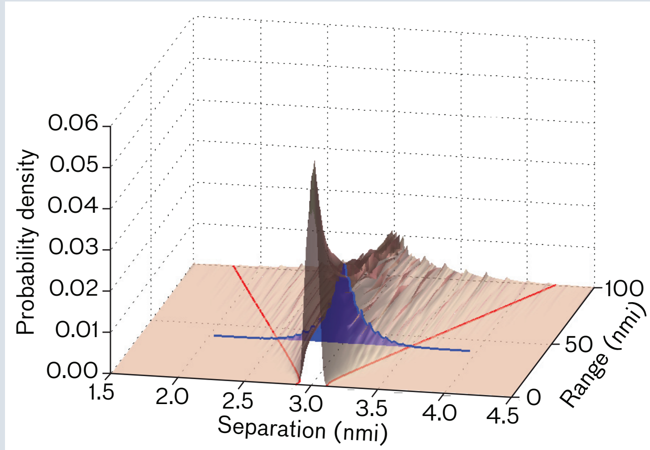

FIGURE B. Probability density of measured separation as a function of range for an ATC Radar Beacon System (ATCRBS) sliding-window short-range sensor and two aircraft separated by three miles. The blue slice shows the measured separation of two aircraft at 40 mi distance. It is clear from this information that as aircraft move further away from a radar, the precision of the positions and separations is degraded.

Table A. Radar Errors in Model for Beacon Sensors

		MSSR		SWSSR	
		Short range	Long range	Short range	Long range
Registration errors	Location bias	200 ft uniform in all directions σ = 115 ft (0.019 nmi)			
	Azimuth bias	$\pm$0.3° uniform σ = 0.173°			
Range errors	Radar bias	$\pm$30 ft uniform σ = 17 ft			
	Radar jitter	25 ft root mean square Gaussian σ = 25 ft			
Azimuth error	Azimuth jitter	Gaussian σ = 0. 068°		Gaussian σ = 0.230°	
Uncorrelated sensor scan-time error		4–5 s uniform	10–12 s uniform	4–5 s uniform	10–12 s uniform

Transponder Range Errors in Model

Mode S	ATC Radar Beacon System
$\pm$125 ft uniform: σ = 72 ft	$\pm$250 ft uniform: σ = 144 ft

Data Dissemination Quantization

One azimuth change pulse is 1/4096 of a scan, or approximately 1.5 milliradians

Range step size is 1/64 nmi for short-range radars and 1/8 nmi for long-range radars terms, ADS–B gives an aircraft the ability to broadcast: "I know exactly where I am and what I am planning to do. Why don't I just tell air traffic control (and anyone else out there who might be interested)?"

For the full benefits of ADS–B to be achieved, however, universal equipage is required. To achieve this mandate, the FAA would like to offer some incentives for aircraft operators to equip early. The first operators to equip with ADS–B will not reap all the advantages described above; thus they need to see some initial benefits before adopting the equipment—they don't want to be the first users if they don't get some payback.

ADS–B Key Site Applications

The FAA recently awarded a contract to the ITT Corp. for initial installations of ADS–B at four key sites: GoMex, Philadelphia, Louisville, and Juneau. After validation of the required performance, nationwide implementation will begin and is expected to be completed by 2013. The FAA's Surveillance and Broadcast Services program office is in charge of implementing ADS–B and is interested in early voluntary equipage by users. Realizing the full potential of the ADS–B system will require nearly universal equipage.

The challenge is to provide benefits to those who choose to equip early. Philadelphia is being evaluated because it is a convenient terminal near the FAA Technical Center in Atlantic City, New Jersey, and happens to have some USAir planes that are equipped with 1090 MHz Mode-ES ADS–B. Juneau provides a second location where there is an incentive for ADS–B implementation (radar tracking is impeded by surrounding mountains).

An example of a niche benefit is nighttime operations in Louisville, where the United Parcel Service (UPS) has chosen to equip all its aircraft with ADS–B units early. During the night rush into Louisville, nearly all of the arrivals and departures are UPS aircraft. By equipping its aircraft, UPS has been able to actively participate with ATC in the optimum sequencing, merging, and spacing of arrivals and departures. UPS is able to give some aircraft priority to achieve optimum package sorting. ADS–B reports are also received by the UPS operations center to optimize surface movement and ramp control.

Another potential benefit can be achieved in GoMex, where we were asked to focus our current efforts. At present, there is no radar surveillance in the middle of the Gulf; aircraft that desire to transit from North America to Central or South America through the Gulf must be separated procedurally. This separation creates a bottleneck and consequently causes delays across the Gulf. For an enticement to equip with ADS–B, the FAA is planning to implement special routes for aircraft under ADS–B surveillance; these routes would allow such aircraft to cross the Gulf without the normal delays. Separation services would be provided just as they are now: under radar coverage until the aircraft transitioned into coverage by Mexican radar. Initial estimates by the FAA are that the high-altitude capacity can be increased from 60 to 80 aircraft per hour (constrained by Mexico's airspace capacity), with savings of approximately $85 million dollars per year from increased capacity and optimal routing.

Modeling

We developed a radar error model based on our RSP work [4, 5] and added an ADS–B error model and the capability to model what the automation will do with the ADS–B reports. For the reference system approach, we compare a new concept for providing a service to a reference system that has already proven to safely and satisfactorily provide that service. For the purposes of this article, the new concept is using ADS–B to establish aircraft separation in the airspace, and the reference system is radar. The analysis uses error characteristics for the radars to set a baseline against error characteristics derived for ADS–B. The performance for aircraft using ADS–B for surveillance is compared with the performance for aircraft under radar surveillance. The case in which one aircraft is under ADS–B surveillance and the other aircraft being separated is under radar surveillance is also compared. Performance for ADS–B is analyzed for different NAC_p values. The concept taken in the GoMex analysis is that it would be acceptable if long-range MSSRs were in fact installed in the Gulf, thus affording surveillance coverage. Therefore, if the ADS–B performed as well as long-range MSSRs in the Gulf, then ADS–B would be equally acceptable.

This proposal requires that Houston's Air Route Traffic Control Center (ARTCC) be able to integrate the ADS–B position reports into the current radar surveillance system. The FAA is currently in the process of upgrading the automation at ARTCCs to the new En Route Automation Modernization architecture (ERAM).

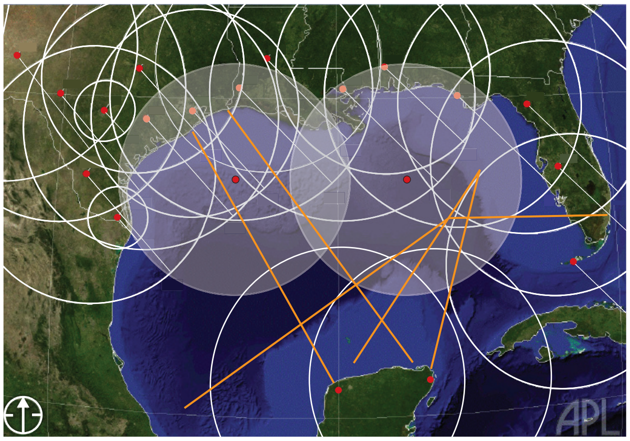

FIGURE 4. The gap between the Gulf coast radars and those on the Yucatan peninsula is covered with the addition of two virtual monopulse secondary surveillance radars, as shown by the filled circles. The five most heavily traveled high-altitude routes, shown in orange, all cross the region that is not monitored by current radars. The original of this figure was produced by the Applied Physics Laboratory (APL) of The Johns Hopkins University.

This automation is responsible for coordinating all of the radar inputs and assigning tracks and data blocks to the aircraft on the controller's display. This upgrade will not occur in Houston ARTCC in time to support the near-term implementation of ADS–B in the Gulf; therefore, the ADS–B reports must be integrated into the current automation system, which is called Host.

Because the Host automation software was written in the early 1980s and will soon be upgraded with ERAM, it doesn't make sense to attempt any major changes at this time. Thus the decision has been made to have the ADS–B reports appear as if they were from two long-range MSSRs, shown in Figure 4, located strategically in the Gulf to cover airspace not currently covered by radars. These virtual radars would have to appear like any other long-range MSSR sensor to the Host automation. This process requires that a sweep of the virtual antenna update the targets every 12 s as the virtual antenna passes the target and that the reports be made in terms of range and azimuth from the virtual-radar site and in a format known as Common Digitizer 2 (CD2). CD2 reports the azimuth to the nearest azimuth change pulse (1/4096 of a circle) and range to the nearest 1/8 mile. This approach requires that our modeling must provide automation outside of the Host to collect the individual reports from the ADS–B sensors distributed in the Gulf and convert them to virtual-radar reports. Figure 5 shows how this conversion functions.

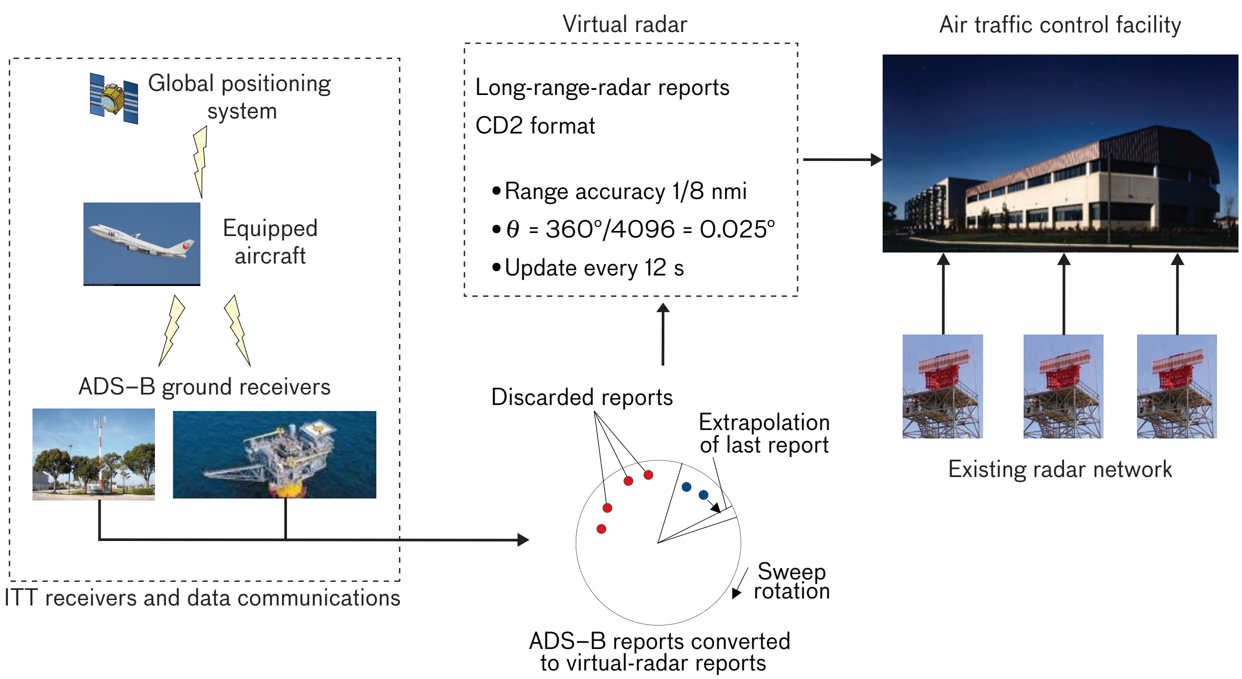

FIGURE 5. The ADS–B data must appear as if they were from a radar. There should be no distinction between existing radars and the ADS–B virtual-radar data. The model updates every 12 s as if the data were from a sweep radar, reports the position in terms of range and azimuth from a virtual radar, and converts the ADS–B data into Common Digitizer 2 (CD2) format.

For radar-site mapping and aircraft tracking, a stereographic plane (SP, a stereographic projection onto a plane tangent to the earth's surface, centered on the extended GoMex airspace) was created, and the radar locations of the real and virtual radars were specified in a Cartesian coordinate system on that SP. This mapping simulates what is done by the Host automation system. Two long-range MSSRs were modeled at the locations of the virtual radars.

The Lincoln Laboratory model simulates a flight through a modeled airspace and then measures statistics on the results. The airspace is modeled as a Cartesian SP coordinate system with radars placed in positions to model a real or generic airspace. The radars are modeled as either MSSR or long- or short-range sliding-window radars. Virtual-radar sites for ADS–B use are also located in the airspace model. Flight plans are stored as waypoints, and a flight plan generator is used to create the true position of the aircraft versus time, with realistic turns based on airspeed and commercial flight-management systems limits. The aircraft equipage is specified for each of two aircraft. This information includes whether the aircraft is transponder equipped and, if so, with what type of transponder. The aircraft is declared to be ADS–B-equipped—capable of making ADS–B position reports—or nonequipped. An image of the graphical user interface is shown in Figure 6.

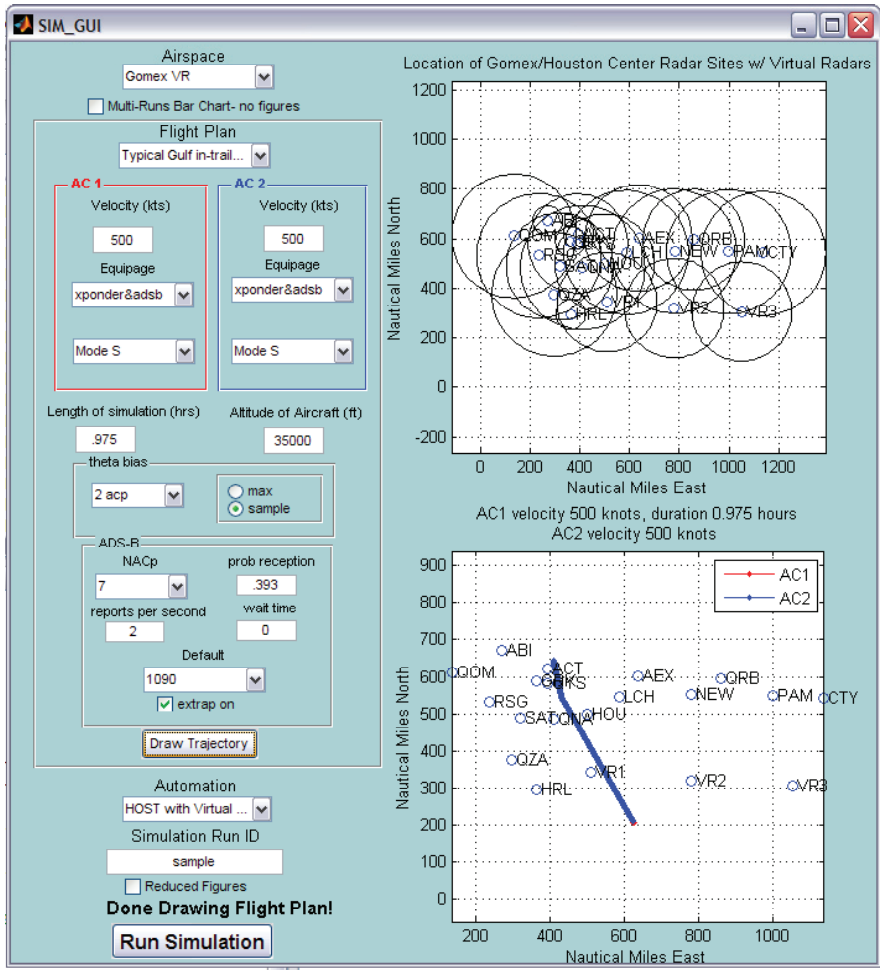

FIGURE 6. The graphical interface to the modeling program provides the user with a series of options on the left (for the individual aircraft and for the overall test run). The graphs on the right depict the active radars and aircraft tracks for the test.

The Host automation system at an ARTCC uses the SP. All sensor reports received by the Host are represented on that flat plane. The plane is divided up into 16 mi × 16 mi sort boxes, and each sort box is assigned a preferred sensor. The position reports from each sensor are displayed if that sensor is tracking the aircraft in its sort box. In the event that the preferred sensor loses track, the designated secondary sensor can display the measured position. Because the preferred sensor is normally the closest sensor, the sort boxes with the same preferred sensor are usually contiguous areas closest to that sensor. Thus, as aircraft travel across the ARTCC airspace, they are generally tracked by the same sensor until they cross a sort-box boundary into another area of contiguous sort boxes with a different preferred sensor. This process is simulated by having the nearest sensor track the aircraft in the simulation. For two aircraft being separated, there may be times when the two aircraft are being tracked by different sensors and thus the bias errors of the sensors and the asynchronous updates will add to errors in measured separation during that period.

The simulation for GoMex was based on a modification of the simulation used for the RSP analysis and verification. Houston ARTCC radars were converted to the SP, and two additional virtual MSSR radars were placed in the middle of GoMex to serve as a baseline for radar performance. The simulation could then place ADS–B virtual-radar coverage at the same spot in the Gulf to see what equivalent level of service was achieved by the use of ADS–B.

The proposed implementation at Houston was to have the ADS–B virtual radars be the preferred sensor for sort boxes where they were the nearest sensors, as is commonly done with other radars. If the virtual radars were, in fact, the MSSRs that they were emulating, then performance similar to that observed in the remainder of Houston ARTCC airspace would be expected. All commercial aircraft are transponder equipped, and they would all be tracked by the same radar except when crossing sort-box boundaries where the preferred sensor changes. When the aircraft being separated are tracked by the same radar, error values in measured separation are smaller because position measurement bias errors do not contribute to errors in separation and because the aircraft position measurements are synchronized. When different radars track the two aircraft being separated, error values in measured separation are larger because the radars will have different position bias errors that add to separation error and because the position measurements are not synchronized. The aircraft are changing position with time; therefore, they will change position relative to each other between the asynchronous updates.

The proposed implementation using virtual radars presents a problem because only some aircraft will be ADS–B equipped. Thus, in sort boxes where the virtual radars are the preferred sensor and radar is the secondary sensor, the ADS–B aircraft will be tracked by the virtual radars and the non-ADS–B-equipped aircraft will be tracked by the nearest real radar. Although the virtual radars will not have a bias, the actual radar bias will degrade separation-measurement performance when one aircraft is being tracked by virtual radar and one aircraft by real radar. In addition, the aircraft position reports won't be synchronized, and this factor will add to the errors in measured separation.

Simulation Testing

Lincoln Laboratory was asked to analyze the performance of this proposed system of virtual radars to see if their integration into Houston ARTCC would support current

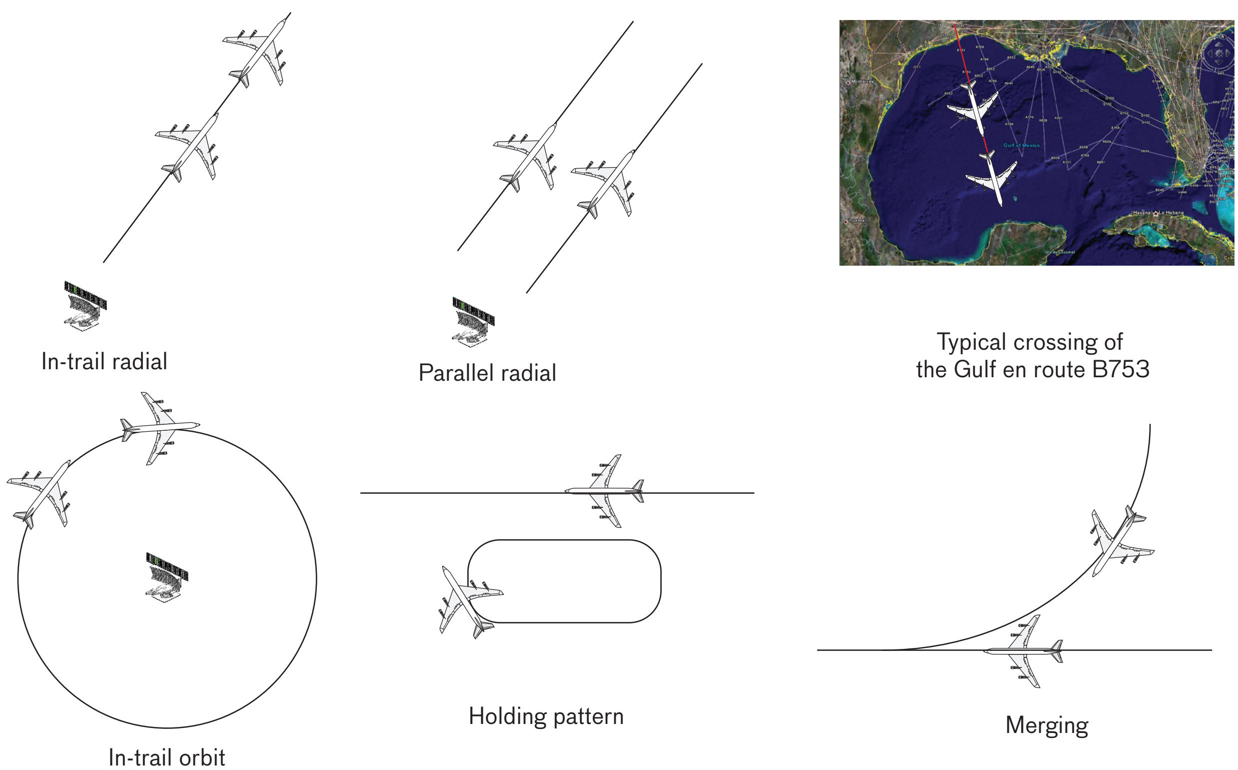

FIGURE 7. Various scenarios were simulated and evaluated. Some of the configurations shown above were in regions covered by radar and ADS–B virtual radars. In the crossing of the Gulf, it is assumed that both aircraft have ADS–B equipment.

separation services across the Gulf. We had previously developed a Monte Carlo simulation model in support of the RSP program [4]. RSP resulted in demonstrating that the newer MSSR radars had better performance than the currently acceptable sliding-window sensors and that 3 mi separation could safely be extended to a range of 60 mi from MSSR sensors instead of the 40 mi limit for sliding-window sensors.

The simulation is run for various operational scenarios. Scenarios are input into the simulation as a series of waypoint coordinates for the aircraft to fly. Turns are simulated by a number of waypoint coordinates input in a circle based on a radius of turn derived from the airspeed of the aircraft; a standard turn rate (3°/s) is assumed up to a maximum bank angle of 25°. The simulation time step is 0.01 s. The operational scenarios run in GoMex are shown in Figure 7. The relative geometries between the aircraft and the radar have a significant impact on the errors in measured separation; therefore, it is best to study a variety of operational scenarios and present the results.

For each simulation run, the initial radar-mast orientations are randomly sampled and the rotation rate sampled within limits based on radar type. The result is that the radars are unsynchronized. Radar bias errors are sampled individually for each of the radars and held constant for all measurements by that radar. These effects, as well as statistical errors, are shown in Figure 8. Aircraft transponder turnaround errors, based on transponder type, are sampled once and held constant for each aircraft. The radar closest to the aircraft is assumed to be the reporting radar, taking into account the cone of silence directly above the radar site.

The sensor-error measurement models are based on specifications and field measurements made primarily by Arcon Corp. [8] and validated with flight tests in the Boston area as part of the RSP program [4, 5]. The aircraft are flown according to the flight plan, and the times of measurement for all radars are computed for the period of time the aircraft are within range of the radars and not within the cone of silence. The true position of the aircraft is recorded, and the random errors associated with the position measurement are sampled for range and azimuth. The estimated position is then recorded in CD2 format (for submission to ARTCC).

The ADS–B reports are generated in the simulation according to a rate, a probability of reception for each

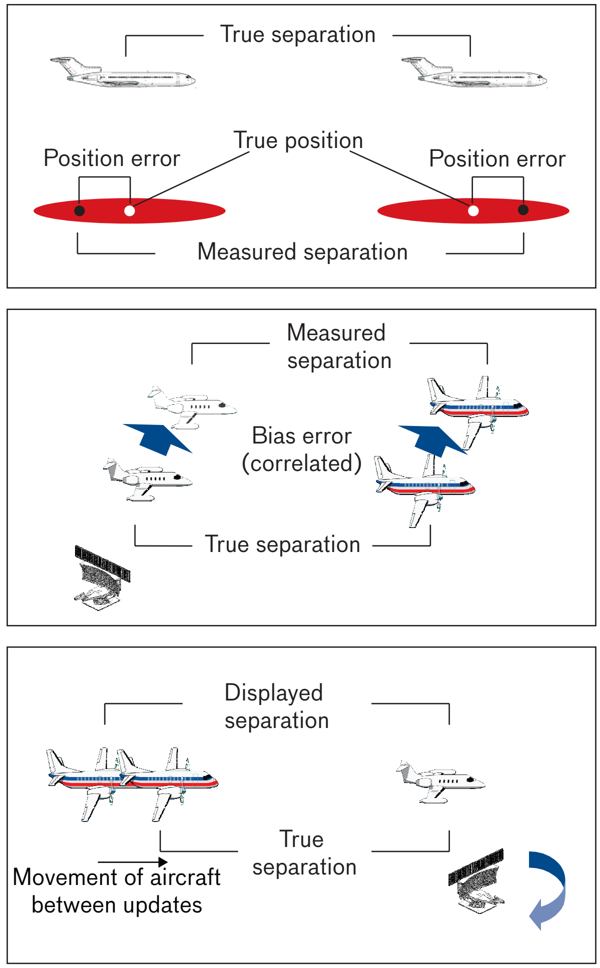

FIGURE 8. Three of the sources of separation errors are statistical (top), radar bias (middle), and radar sweep updating (bottom). Both the statistical errors and radar update errors can cause the measured separation to be less (or greater) than the true separation. Radar bias errors are identical for all aircraft monitored by a single radar and therefore do not affect the separation estimate.

report, and a wait time. The wait time is the minimum time after a report is received before a new report will be accepted. The position errors associated with an ADS–B report are sampled on the basis of the upper limit of NAC_p position-accuracy categories.

All of the reports of the radars and ADS–B are recorded and, according to the automation scheme chosen, converted to the reports displayed to a controller. For instance, if the "radar only" automation is chosen, then only the radar reports are considered and the nearest tracking radar is used to report the estimated position. If "ADS–B virtual-radar" automation is chosen, then the ADS–B reports are converted to virtual-radar reports,

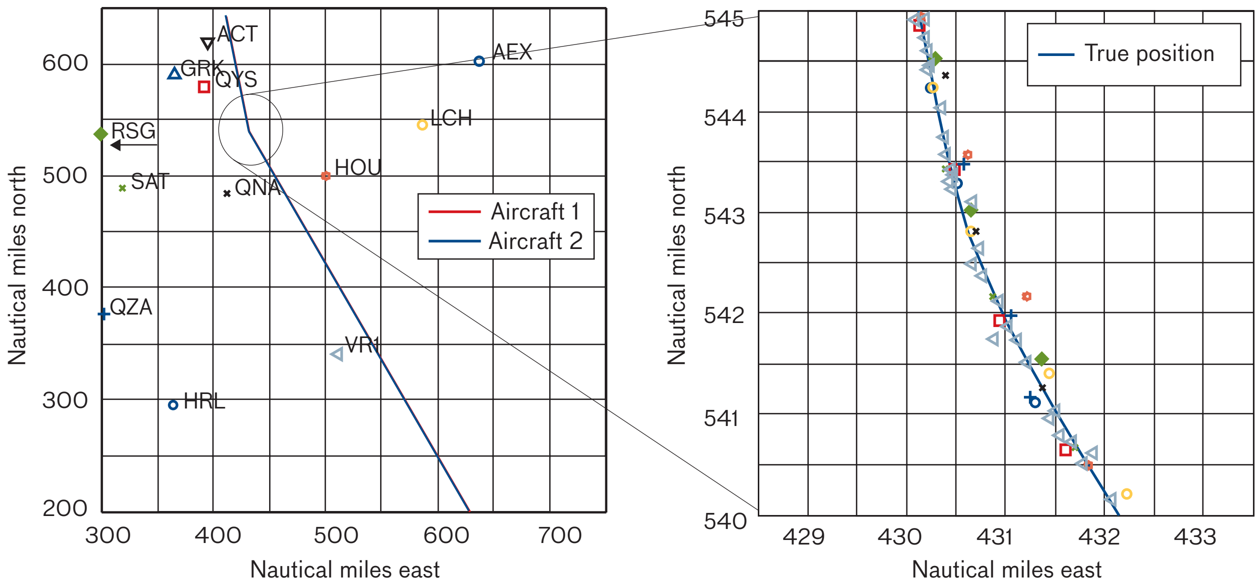

FIGURE 9. The aircraft may be tracked by multiple sensors throughout their simulated flights through GoMex. Here the aircraft are flying in-trail radially from near the Gulf coast (top of figures) toward the open waters of GoMex. The markers in the right image correspond to the radar that was tracking the aircraft at that point in their flights. The light gray triangles that dominate the markers are the raw inputs from the ADS–B before conversion to virtual-radar reports.

encoded in CD2 format, and merged with the regular radar reports. If ADS–B extrapolation is turned on, the last report is extrapolated to the virtual-radar sweep by using $NAC_v = 1$, which corresponds to an accuracy of better than 10 m/s 95% of the time.

The modeled estimated position reports as displayed to the controller are then compared to the modeled true position of the aircraft, and statistics are generated that measure performance over the simulation run. Output from the simulation includes measurements of the position accuracy and errors in measured separation. Errors in measured separation are important to correctly account for bias errors and asynchronous measurements when different sensors are tracking the two aircraft.

Each simulation run produces a plot showing the aircraft track relative to the sensors (Figure 9) and a plot showing which sensor reports were chosen by the automation to be displayed to the controller (Figure 10)—i.e., of all the sensors making measurements, which sensor was tracking the aircraft when it was displayed to the controller. Also produced is a scatter plot of position report errors made for the two aircraft during the run. Histograms of position errors and update-interval times are produced. Another plot shows the probability distribution function of the errors in measured separation, randomly sampled in time. In other words, at any random time during the simulation, what is the probability of the error between the true separation of aircraft and the separation displayed to the controller? These errors can result from position-measurement errors or errors due to asynchronous updates and changes in separation between update measurements.

For the virtual radar analysis it is assumed that an ADS–B report is sent by the aircraft twice a second. Rotation rates are randomly selected within the assigned limits (4 to 5 s for short-range radars and 10 to 12 s for long-range radars). Figure 11 shows the effect of the rotation rate and unsynchronized sweep on update times. The update time may be very short as the aircraft moves from one radar that just updated into a new radar region that is just about to sweep its location. If the opposite occurs, the update time may be considerably longer. Figure 12 shows the updated separation distance between two aircraft as a function of time while the aircraft are moving through several radar regions. Aircraft separations group farther from the true separation-mark measurements when one aircraft is updated before the other. Which aircraft is updated first, the leading or trailing aircraft, determines if the estimated separation is greater than or less than the true separation.

The probability of reception for each ADS–B report was set at 0.393, which corresponds to a 95% chance of

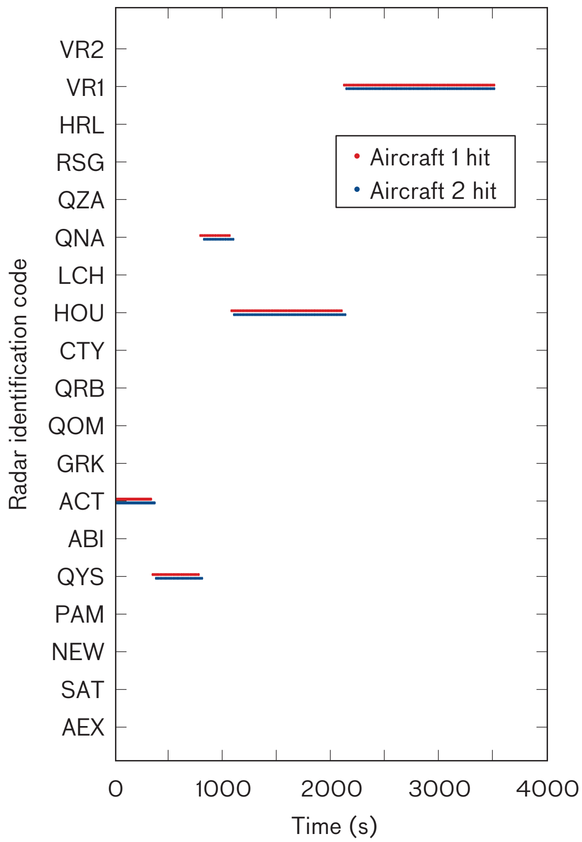

FIGURE 10. The horizontal lines are composed of individual points of position reports by a radar or virtual radar as a function of time. Note that the leading aircraft (red) always shifts to a new sensor prior to the trailing aircraft (blue). In this case, the aircraft move from ACT-Waco to QYS-Rogers to QNA-Morales to HOU-Houston (Ellington) to VR1-virtual radar 1.

having a reception within 5 s. The nearest virtual radar tracking the ADS–B aircraft sweeps with an update rate randomly chosen between 10 and 12 s (the same as for a long-range MSSR) until hitting, or updating, the ADS–B aircraft on the basis of the aircraft's true position. The last ADS–B position report is extrapolated and converted to ρ, θ radar output in CD-2 format and then converted, as with other radar reports, to the coordinates in the SP. The GPS error in position report was assumed to be Gaussian with a standard deviation, depending on the NAC_p specified. The simulation model samples all bias errors once for each run—e.g., θ and range bias, site-location errors for each radar, and transponder range bias for each aircraft.

Figure 13 illustrates a scatter plot for all aircraft position-error measurements during the entire simulation. Because ADS–B virtual-radar position errors tend to be in the direction behind the aircraft, the pattern will depend on the flight plan. When aircraft are near the radar, errors tend to be random about the radar bias. At far ranges, radar errors are dominated by azimuth errors. In this case, the errors are relatively random because the data are for the entire flight, with five different radars at various ranges and geometries. Figure 14 shows the error distribution for measured separation of two aircraft at random times during a test run. The statistical data obtained from this figure (for each simulation) form the basis for the results shown in Table 1.

The overall performance of the radars for the simulation is measured by sampling the errors in measured separation during the flight. At any given instant, there is a true separation between the two aircraft, defined as the distance between the two true positions of the aircraft. The measured separation at that instant is the difference between the last updated position estimates of the two aircraft. This measurement may or may not be from the same radar for the two aircraft because the radar used to report the position is the radar closest to the air-

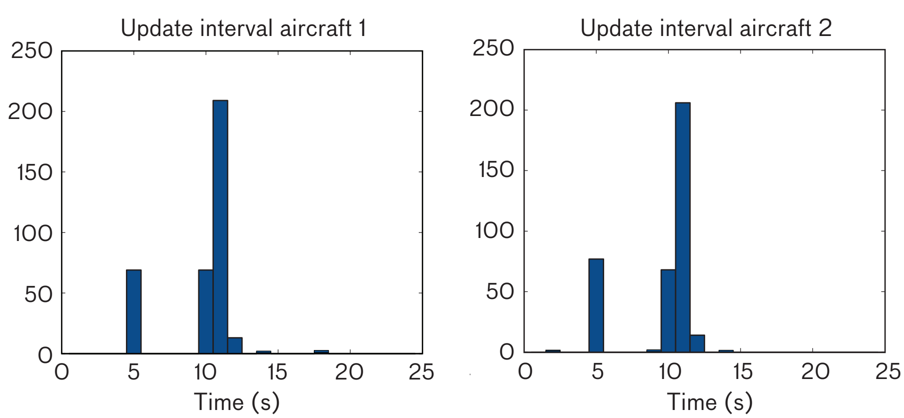

FIGURE 11. The update intervals for the aircraft are centered around 5 s (short-range radar) and 10 to 12 s (long-range radar), but shorter times (2 s for aircraft 2) and longer times (18 s for aircraft 1) occur. These variations from the norms are due to the aircraft's transition from one radar to another. The vertical scale is number of update points recorded at each time interval.

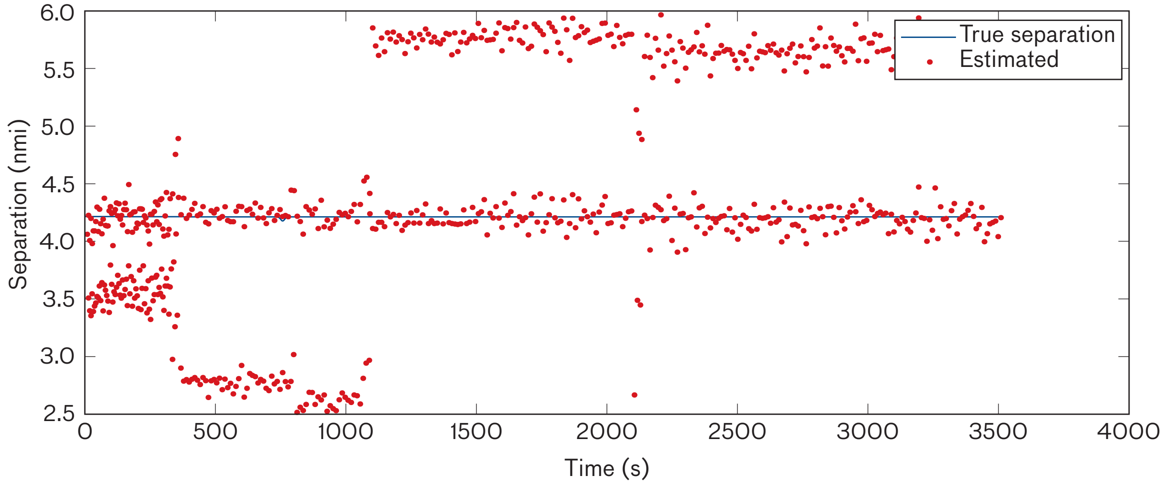

FIGURE 12. Because of the variations in update times shown in Figure 11, the separation distance shows apparent but not real shifts. Depending on which aircraft is sensed first and how much time there is between one aircraft being updated and the second update, the estimated separation is affected by the aircraft's motion. The apparent shift of approximately 1.5 miles is the distance traveled by an aircraft travelling at 500 mph for a duration of the longer update time of 10 to 12 s.

craft. Thus the error in measured separation at any given instant will depend on the errors in the position estimates and the movement of the aircraft since their last respective position estimate.

There are really two cases to be considered in the Gulf. In one, both aircraft are transponder and ADS–B equipped and are tracked by the same sensors. In the second case, one aircraft is transponder and ADS–B equipped but the other aircraft is only transponder equipped; additionally, the two aircraft are in a region of airspace where the transponder-only aircraft is tracked by a radar and the aircraft with transponder and ADS–B equipment is tracked by the virtual radar. Results of the simulation runs showed that separation errors between ADS–B-equipped aircraft and non-ADS–B-equipped aircraft were larger than if MSSRs were at the virtual-radar locations and tracking both aircraft. As a result, it was recommended that Houston ARTCC make the vir-

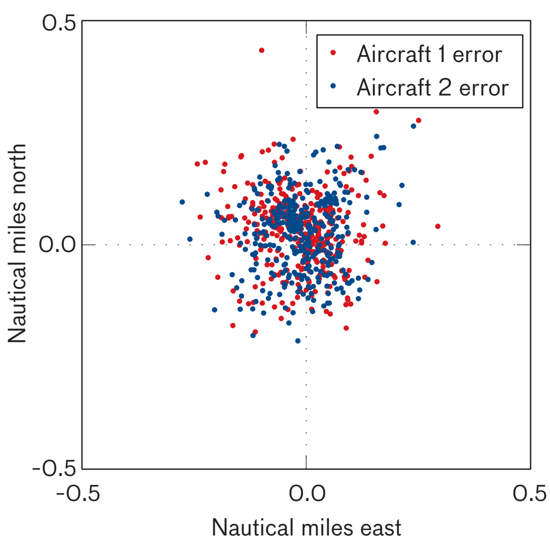

FIGURE 13. Because the flight paths and relative geometry to the radars varied during the flight, the bias and latency errors are not apparent. Thus the scatter plot of position errors for both aircraft over the entire flight appears random.

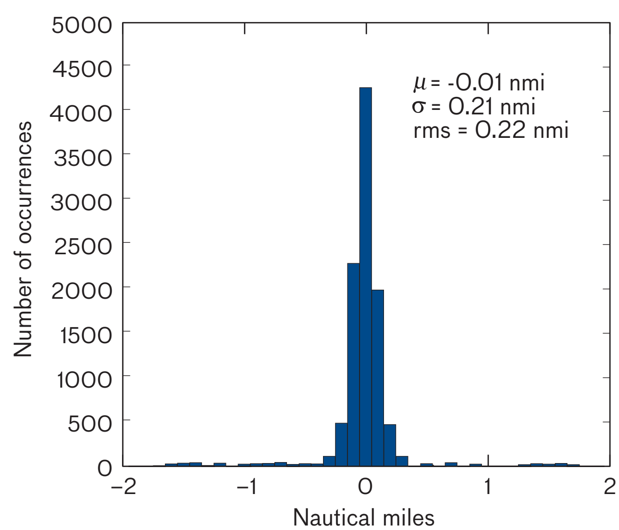

FIGURE 14. The histogram is a random sampling (in time) of the errors in measured separation. The outliers are due, in part, to asynchronous radar updates.

tual radar the preferred sensor only in sort boxes that did not currently have a radar assigned as the preferred sensor, that is, only in airspace where there was no radar coverage. This procedure would eliminate the cases in which one aircraft was tracked by radar and one by the virtual radar when both are covered by radar. Non-ADS–B-equipped aircraft would not be separated from ADS–B aircraft by surveillance in the airspace not covered by radar. The results also showed that it was necessary to extrapolate the ADS–B position reports to the virtual-radar sweep; too much position error was introduced if the virtual radar simply reported the last received ADS–B report.

The results of the simulations using the Lincoln Laboratory Monte Carlo model are summarized in Table 1 for the various scenarios. The results show that the ADS–B virtual radars will provide equivalent performance if they are the preferred sensor in sort boxes not currently covered by radar and if extrapolation is employed. This preliminary analysis based on simulations concludes that the virtual-radar concept can work in GoMex and offers the potential for increased efficiency that will be an incentive for aircraft crossing the Gulf to equip with ADS–B. The next step is to validate the findings with flight tests.

The performance of radar versus radar and radar versus ADS–B depends greatly on the relative orientation of the aircraft to each other and to the radar. The ADS–B versus ADS–B performance also depends on the relative geometries of the flight paths of the two aircraft. Therefore, comparisons of the performances depend on the operational scenario.

Positional accuracy is not an issue for ADS–B. The problem in ADS–B versus radar is synchronization of the reports. An additional problem for ADS–B versus radar is the radar bias errors that are not reflected in separation errors for radar versus radar but do add to the separation errors for ADS–B versus radar. In some cases, MSSR outperforms ADS–B (in-trail radial), and although the range errors are small and still acceptable, the ADS–B results will improve if the updates are synchronized.

ADS–B performance in a non-radar environment is as good as or better than radar. The performance of mixed ADS–B and radar separation is similar to the performance between two separate MSSRs that include uncorrelated bias errors and asynchronous updates. It is important to consider the configuration of the sort boxes in analyzing performance. One method is to have radar as the preferred sensor in radar coverage areas and ADS–B as the preferred sensor in non-radar coverage areas. Then the transition between radar and ADS–B coverage would be like the transition between sort boxes with different preferred radars.

Table 1. GoMex Operational Scenarios

	MSSR		ADS–B virtual radar		Mixed ADS–B and radar	
	Mean μ (nmi)	Standard deviation σ (nmi)	Mean μ (nmi)	Standard deviation σ (nmi)	Mean μ (nmi)	Standard deviation σ (nmi)
Typical crossing of the Gulf in-trail, 5 nmi separation	0.00	0.27	–0.01	0.24	n/a	n/a
Radial in-trail, 5 nmi separation	0.01	0.16	0.03	0.18	0.00	0.63
Radial parallel, 5 nmi separation	0.00	0.15	0.00	0.22	0.1	0.61
Nearing and passing a holding aircraft	–0.49	0.95	–0.46	0.90	–0.27	0.73
Orbiting in-trail, 5 nmi separation, 60 nmi from radar	0.02	0.23	0.01	0.21	0.08	0.69
Orbiting in-trail, 5 nmi separation, 100 nmi from radar	–0.01	0.18	0.01	0.19	0.11	0.82

The large number of summary results tables for GoMex, combined with our preliminary work in terminal and en route simulations, can be summarized as follows:

- ADS–B positional accuracy is not an issue.
- ADS–B reports must be synchronized and extrapolated.
- Performance in a mixed radar environment, where some aircraft are tracked by ADS–B and some by radar, is not as good as the current single radar environment. However, if radar is the preferred sensor in radar coverage areas and ADS–B is the preferred sensor in non-radar coverage areas, the performance is like that observed when different radars are tracking the two aircraft across sort-box boundaries.

Future Work

The next steps will be to model performance in Juneau and the other key sites. This model will be expanded to cover the other ADS–B data link, known as Universal Access Transceiver. On the basis of the preliminary modeling presented by the Separations Standards Working Group, the FAA's Surveillance and Broadcast Services Program and the Flight Standards Group have decided to proceed to the next step of the flight test measurements at the four key sites. The modeled performance of ADS–B (and ADS–B in a mixed radar environment) will be validated by using targets of opportunity that are equipped with ADS–B and flight tests by using instrumented flight test aircraft.

The modeling will also be extended to study the performance of proposed fusion trackers—that is, systems that use all available radar and ADS–B data to form tracks. Finally, the performance of a proposed backup system to ADS–B, Wide Area Multilateration (WAM), will be analyzed. WAM uses a grid of ground receivers to record ADS–B reports such as the 1090 MHz Extended Squitter and to perform a time-difference-of-arrival analysis to estimate the aircraft position. This analysis could be used when the GPS signal is not available. ■

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