TCAS: Maneuvering Aircraft in the Horizontal Plane

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■ The Traffic Alert and Collision Avoidance System (TCAS II) is now operating in all commercial airline aircraft to reduce the risk of midair collisions. TCAS II determines the relative positions of nearby aircraft, called intruders, by interrogating their transponders and receiving their replies. An intruder deemed a potential threat will trigger a resolution advisory (RA) that consists of an audible alert and directive that instructs the pilot to execute a vertical avoidance maneuver.

Lincoln Laboratory has investigated the possibility of increasing the capability of TCAS II by incorporating the horizontal maneuvering of aircraft. Horizontal RAs can be computed if the intruder horizontal miss distances at closest approach are known. Horizontal miss distances can be estimated with range and bearing measurements of intruders. With this method, however, large errors in estimating the bearing rates will result in large errors in calculating the horizontal miss distances. An improved method of determining the horizontal miss distances may be to use the Mode S data link to obtain state data (position, velocity, and acceleration) from intruder aircraft.

Driving down a dark country road without headlights would be a terrifying experience. By emitting a beam of light, a car's headlights informs the driver about what lies ahead, while at the same time communicating the car's approach to oncoming traffic. Similarly, the Traffic Alert and Collision Avoidance System (TCAS), an airborne collision warning system for aircraft, emits radio waves to ascertain the location of other planes, referred to as *intruders*, that are within the host aircraft's proximity. In a car, the driver surveys and detects an approaching beam of light, determines its origin, and predicts the course of the approaching vehicle. In an aircraft, TCAS performs surveillance and detection of nearby intruder aircraft, determines their location, and predicts their future courses. In lieu of headlights, TCAS communicates with intruder aircraft by means of radar beacon transponders carried by most aircraft for ground air traffic control (ATC) purposes.

By predicting the course of a nearby car, the driver of a vehicle can assess whether or not a possible collision may occur. The driver can then decide either to slow down or to make a turn. For aircraft equipped with TCAS, the system uses the aircraft cockpit displays and auditory alarms to make a recommendation to the pilot to climb, descend, or remain on the host plane's present course. The main difference between cars and TCAS-equipped aircraft is that, if an approaching car does not have headlights, the vehicle may still be detected by surrounding cars that do have headlights, whereas, for an aircraft to be detected by TCAS, the vehicle must be equipped with a radar beacon transponder.

As mandated by the U.S. Congress in 1987 [1], TCAS II—the current operational version of TCAS that resolves potential conflicts by issuing directives for vertical maneuvers—has been implemented nationwide in all aircraft with more than thirty seats. Lincoln Laboratory is currently developing the surveillance function for the next generation of TCAS, which will issue escape directives in the horizontal as well as the vertical direction to take advantage of the three-dimensional airspace.

Horizontal maneuvering is a highly desirable feature. According to ATC separation standards within airways, aircraft should be at least 1000 ft apart from each other vertically and 3 nmi apart horizontally. Vertical maneuvering directed by TCAS can cause noticeable disruption in the ATC flow because aircraft may be closely spaced vertically. Horizontal maneuvering would usually be less disruptive under similar circumstances. Additionally, a pilot performing a horizontal maneuver can usually maintain visual contact with an approaching threat, whereas vertical maneuvering generally causes pilots to lose sight of the threat.

This article begins with a description of TCAS II, the current implementation of TCAS. Next, details of Lincoln Laboratory's research for TCAS III—an improved version of TCAS that uses bearing measurements to calculate the relative position between aircraft in the horizontal plane—are presented. A description is then given of the field measurements that were taken to validate this new TCAS design, followed by details and results of the simulation used to model and evaluate aircraft encounters. Finally, this article discusses TCAS IV, which uses new technologies made possible by advanced avionics and the Mode S data link to provide a better solution for resolving encounter conflicts in the horizontal plane.

TCAS II

TCAS II is completely independent of the ground ATC system and is considered a backup solution to reducing the risk of midair collisions between aircraft. When an intruder aircraft is considered to be a serious threat to a host aircraft, TCAS II issues a directive maneuver, known as a *resolution advisory* (RA), instructing the host aircraft to climb, descend, or maintain its present course.

Using TCAS II to interrogate other aircraft, a host aircraft can survey the local airspace by measuring the range, altitude, and relative bearing of all potentially threatening aircraft. (Note: The relative bearing is the angle formed between the nose of the host aircraft and the direction to another aircraft.) In the horizontal plane, the variable *tau* is defined as the time to collision if both the host and an intruder aircraft are traveling on a collision course at constant velocity. The value of tau can be calculated with

$$\tau = -\frac{r}{\dot{r}},$$

where r is the measured range, i.e., the radial distance from the host aircraft to the intruder aircraft, and $\dot{r}$ is the estimate of the range rate, i.e., the rate of change of r. The range, altitude, and relative bearing of intruder aircraft are shown in a cockpit display in the host aircraft to aid the pilot in visually locating intruders.

To determine potential conflicts, TCAS II constructs a volume of protection surrounding the host aircraft that, when penetrated by an intruder, produces an RA. This volume of protection is called the *threat boundary*. The threshold value of tau that is used to construct the boundary is between 15 and 35 sec, depending on the altitude of the potential conflict.

To account for possible aircraft accelerations and inaccuracies in the estimate of $\dot{r}$, the calculation of tau is modified slightly with a criterion developed by the U.K. [2]:

$$\tau = -\frac{r - \left(\dfrac{\mathrm{DMOD}^2}{r}\right)}{\dot{r}},$$

where the incremental distance modifier (DMOD) value is between 0.2 and 1.1 nmi, depending on the altitude of the potential conflict.

TCAS II generates a vertical RA when an intruder penetrates the threat boundary and is within the relative altitude limits of the host aircraft. Although TCAS II is very effective for resolving conflicts between aircraft, the system does have its limitations. One limitation is the inability to resolve potential conflicts by instructing aircraft to turn. For some situations, horizontal maneuvers may be a safer alternative, but it is not an available option in TCAS II. Another disadvantage is that unnecessary alerts are issued regularly; that is, certain encounters (typically having high relative speed) result in the issuance of RAs even though they present no serious danger. Figure 1 illustrates a common nuisance RA. The intruder

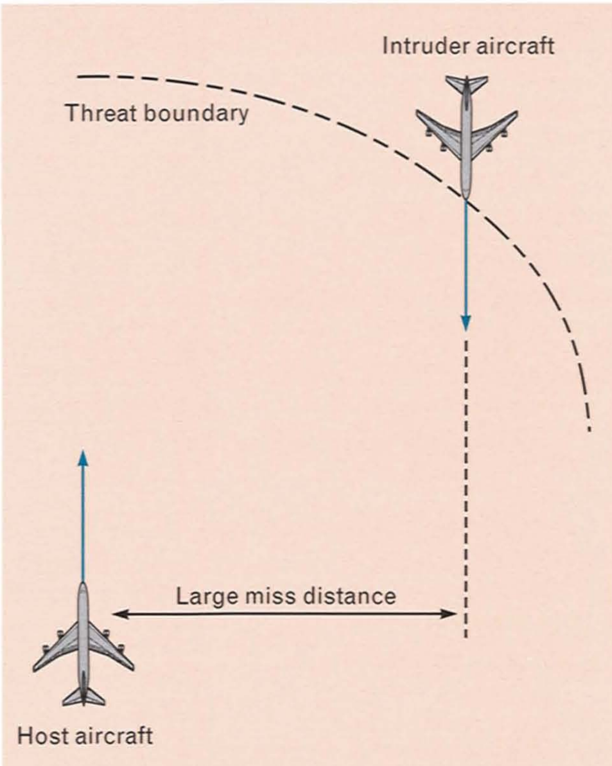

FIGURE 1. Example of a nuisance resolution advisory (RA). The intruder aircraft crosses the threat boundary, thus causing TCAS II to issue an RA to the host aircraft even though the two aircraft will miss each other by a large distance.

penetrates the threat boundary, causing issuance of an RA, but in fact the intruder will pass at a safe distance from the host aircraft.

TCAS III Principles

Pilots in particular view TCAS II as an interim step to a complete system that will augment vertical maneuvers with a horizontal RA capability. Such capability is provided in TCAS III, the next generation of TCAS. In addition, TCAS III improves on TCAS II by decreasing the number of nuisance RAs issued by the system. These improvements have been made possible through the use of estimates of the *miss distance,* i.e., the distance in the horizontal plane between an intruder and host aircraft at the time of closest approach.

The miss-distance estimate is a very important parameter for describing the encounter geometry in the horizontal plane. An accurate estimate of an intruder's miss distance offers the capability to issue a horizontal RA, which instructs the host aircraft to turn in the horizontal plane to escape a possible collision. Or, for intruders with large horizontal miss distances, the RA can be eliminated altogether—a process known as *miss-distance filtering* (MDF). MDF is a very desirable feature because it reduces the overall number of nuisance RAs, thereby increasing confidence in the system while decreasing unnecessary TCAS maneuvers that could result in a TCAS-induced collision. These two horizontal functions—namely, horizontal RAs and MDF—are enabled by accurate estimates of the miss distance.

Depending on the method chosen to calculate the miss distance, five parameters must be known. For the TCAS III method, the five parameters are the range, range rate, bearing, and bearing rate of the intruder, and the speed of the host aircraft. With these parameters, the miss distance m can be calculated as

$$m = \frac{r^2\omega}{v},$$

where r is the measured relative range between the host and intruder aircraft, ω is the estimated intruder bearing rate, and v is the magnitude of the relative velocity between the two aircraft. (Note: a detailed description of the solution method used by TCAS III to estimate the miss distance is given in the box, entitled "Calculation of the Miss Distance between Two Aircraft in a Horizontal Plane," on page 305.)

Once the miss-distance estimate has been calculated, its quality or associated error must also be determined because the miss-distance error will dictate whether the miss-distance estimate has the necessary accuracy for TCAS III to perform its horizontal functions. The accuracy of the estimated miss distance for a particular encounter depends on three factors: the encounter geometry, the particular method used for computing the miss, and the accuracy of the input measurements.

The miss-distance estimation error is highly dependent on the bearing-rate error:

$$\sigma_m = \frac{r^2\sigma_\omega}{v},$$

where σ_m and σ_ω are the standard deviations of the

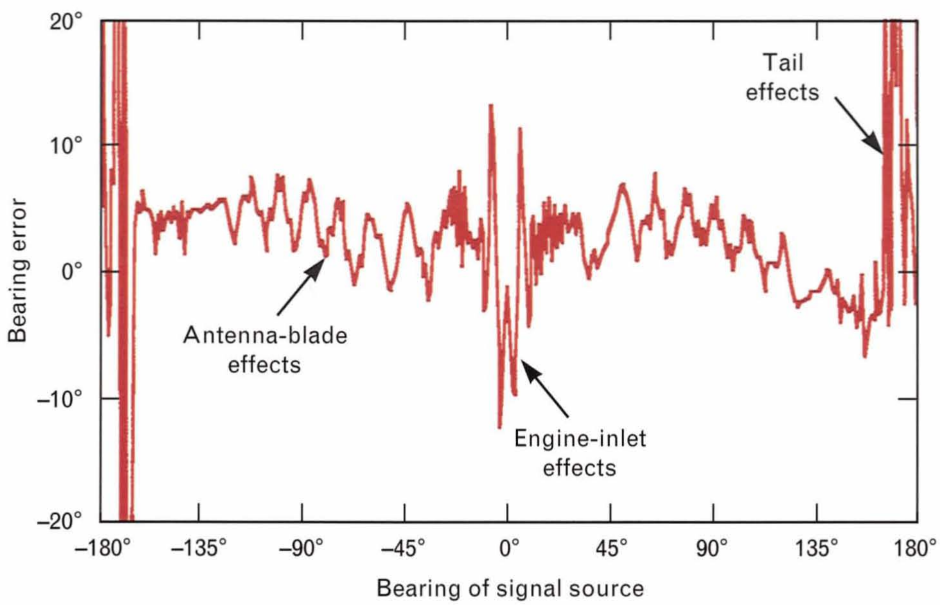

FIGURE 2. Bearing error in TCAS measurements for the Boeing 727. Note the oscillatory effects and deviations that result from various structural entities such as the engine inlet and tail. For example, the tail of the aircraft will cause errors in the bearing measurements exceeding 20° for a signal source with a bearing of 180°. This figure is for the TCAS antenna mounted in the optimal location: on top of the B727 fuselage, back from the forward slope of the cockpit section but in front of the tail engine inlet.

miss-distance error and bearing-rate error, respectively. Because ω is not measured directly but estimated by differentiating bearing measurements, the error characteristics of ω depend on the errors in the bearing measurements and the particular filter characteristics used for the differentiation process. Consequently, Lincoln Laboratory has performed field measurements and computer modeling to determine the error characteristics of the bearing measurements.

TCAS III Antenna

TCAS III uses a simple direction-finding antenna to determine the relative bearing of intruder aircraft. Measurements of the bearing accuracy of the TCAS III antenna system show that the system performs quite well in ideal conditions, on the order of 1°-to-2° accuracy. The bearing performance degrades significantly, however, when the antenna is installed on an airplane fuselage in the vicinity of large reflecting structures such as the wings and tail and in close proximity to other antennas.

Because the miss-distance estimate that is used for MDF and horizontal RAs depends on the bearing-rate error, we need to understand the impact of the bearing error on the accuracy of the bearing-rate estimate. To do so, we must first determine the expected magnitude of the bearing error of an installed antenna.

TCAS Bearing-Error Sources

The reply signal that is used to determine an intruder's relative bearing is corrupted by a variety of sources that result in errors in the bearing measurement. Some sources contribute relatively small, insignificant errors and are independent of the installed TCAS configuration; others add significant biases that differ from aircraft to aircraft. Some sources are associated with the TCAS receiver components and digital signal processing, and others with the physical characteristics associated with an aircraft installation.

The error sources can be separated into two categories. The first category includes sources that produce random bearing errors, uncorrelated with any aspect of the measurement. These error sources are generally associated with the random movement of electrons within the receiver and analog-to-digital (A/D) components.

The second category of error sources are fixed biases that depend on the bearing and elevation angle of the measurement. These types of errors, referred to as systematic errors [3], are often correlated tightly with the configuration of the TCAS antenna installation mainly because of the surrounding reflection environment of the airframe structure and objects mounted on the structure.

To determine the extent of the systematic errors that result from the reflection environment of the airframe structure and nearby objects, we undertook a study that included actual antenna measurements as well as detailed analytical modeling of the prominent features of the aircraft structure.

Bearing Errors Caused by the Airframe

Reflections and electromagnetic scattering off an aircraft's frame, wings, tail, and engine housings are a primary source of antenna interference. Although in most cases these structures are not nearby the TCAS antenna, their sheer size causes large reflections that affect the antenna's ability to measure the bearing of a signal source.

The large size of these structures prohibits measuring their interference effects because most antenna ranges cannot support a large commercial aircraft. Thus the effects of the airframe must be modeled and simulated on a computer. Accordingly, the Ohio State University (OSU) ElectroScience Laboratory was contracted to perform an analytical study of the effects of airframe scattering on the TCAS bearing performance by using the laboratory's computer-based geometric diffraction model.

The first aspect of the OSU study entailed modeling the TCAS antenna and three representative airframe types: the Boeing 727, Boeing 737, and Boeing 747. The three aircraft types were chosen because each has prominent features that are typical of other aircraft found in the industry.

The results of the OSU analysis [4] show several apparent trends. The optimal location for a top-mounted antenna occurs on the flattest portion of the fuselage: back from the forward slope of the cockpit section and in the shadow region of wing-mounted engines. For cases in which the tail engine inlet is visible to the antenna (such as with the B727), the optimal location is a compromise between being forward

FIGURE 3. TCAS antenna measurements at the Lincoln Laboratory Antenna Test Range (ATR). In the foreground, the TCAS antenna and VHF blade antenna are mounted on a mock-up of a Boeing 727 fuselage. During the experiments, the fuselage was mounted in an anechoic chamber (Figure 4). At the far end of the range is the dish antenna that provides the signal source used for the bearing-error measurements.

of the engine inlet and back from the forward fuselage. Figure 2 shows the bearing-error curve for the B727 airframe for the antenna mounted at the optimal location. Note the oscillatory effects and deviations that result from various structural entities such as the engine inlet and tail. Another trend was that the effects of other antennas located at moderate spacing from the TCAS antenna generally overshadowed the effect of airframe scattering regardless of the airframe type. This result led to the conclusion that, for close to moderate spacing of nearby objects, the TCAS bearing-error transfer function was relatively insensitive to different airframe types.

Bearing Errors Caused by Nearby Objects

We conducted measurements of the TCAS antenna at the Lincoln Laboratory Antenna Test Range (ATR),

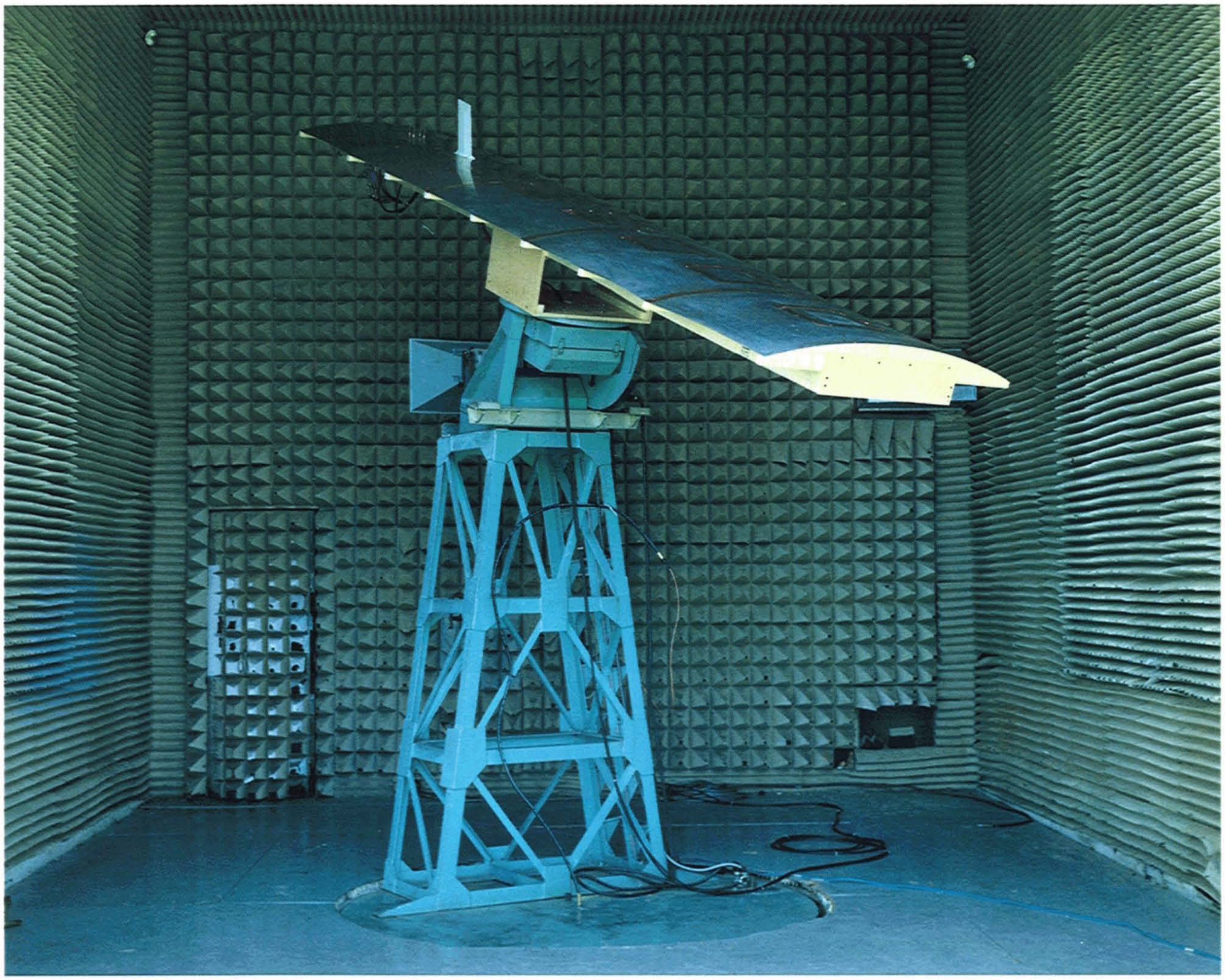

FIGURE 4. The fuselage mock-up mounted on a pedestal in an anechoic chamber. In the photograph in Figure 3, the chamber is located at the near end of the ATR. As the pedestal rotates, RF signals emanating directly from the transmit antenna (at the far end of the ATR in Figure 3) as well as those reflected off the nearby object (in this case, the VHF blade antenna) are received by the TCAS antenna. The received signals are transformed to bearing measurements and compared to the actual azimuth of the pedestal; the difference is denoted as the error in the bearing measurement. Anechoic material on the walls is used to minimize reflections within the chamber.

as shown in Figures 3 and 4. In the experiments, we used various objects with locations relative to the TCAS antenna that are typical of actual operational installations. The objects, which are shown in Figure 5, included antennas used for communication and navigation both in and out of the TCAS frequency band.

The ATR measurement process consisted of locating an object (such as an ATC transponder antenna) in close proximity (2 to 10 ft) to the TCAS antenna, and illuminating the TCAS antenna with radio frequency (RF) energy. Figure 4 shows the measurement setup when the VHF blade antenna was used as the nearby object. The received signals at the TCAS antenna were used to measure the bearing of the source of the incoming signal. The measured bearing was then compared to the true rotation angle, and the difference (i.e., the error) in the bearing measurement was attributed to reflections caused by the nearby object. As suspected, the error in bearing measurements was related to the size and relative location of the object.

Figure 6 illustrates the effect of a nearby VHF communication antenna on the bearing performance

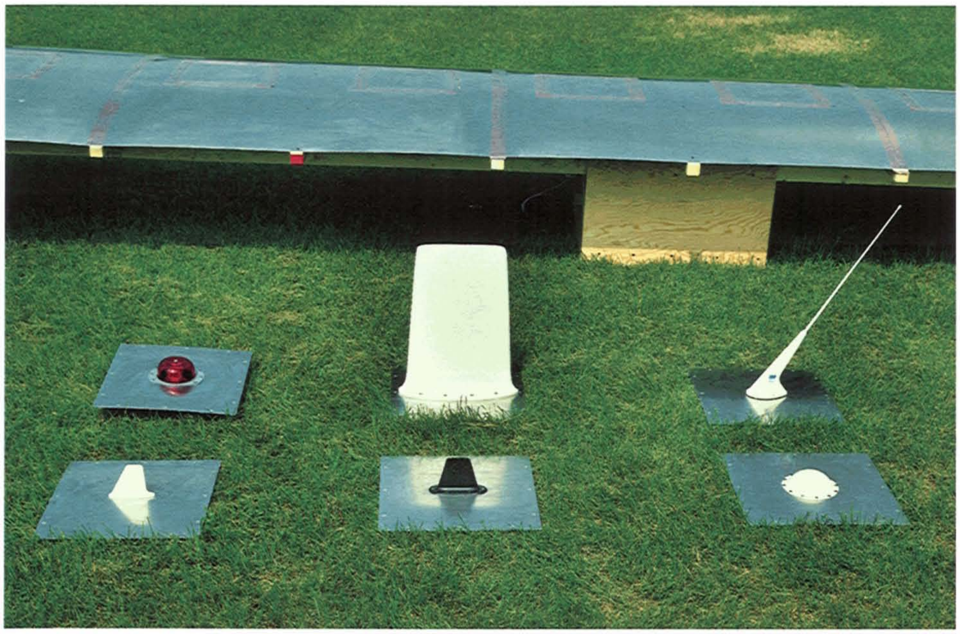

FIGURE 5. Close-up of mock-up Boeing 727 fuselage and the six interfering objects used during the TCAS antenna measurements. Clockwise from the red anti-collision light, the objects are the UHF blade antenna, VHF rod antenna, GPS antenna, ATC transponder blade antenna, and Distance Measuring Equipment (DME) antenna. Not shown is the VHF blade antenna that was also used in the measurements.

of the TCAS antenna. The three figures represent different spacings between the VHF and TCAS antennas. There are some interesting characteristics that are evident in the bearing-error curves. The first is that the peak magnitude, or *amplitude,* of the bearing error decreases as the spacing increases because of the decrease in signal strength of the energy reflected off the VHF antenna. The second interesting characteristic is that the *frequency* of the sinusoidal behavior of the error curve increases as the antenna spacing increases; i.e., the increased path difference between the VHF and TCAS antennas results in more cycles in the error curve.

Intuitively, we would expect that larger objects would produce larger errors for the same relative spacing. This statement is true for most cases. However, as the height of an object approaches ¼ wavelength at the TCAS operating frequency, other electromagnetic phenomena begin to emerge as the predominant contributors. Effectively, an object at that particular height (approximately 2.5 in) looks larger than its physical size in terms of its effect on the TCAS bearing performance. Figure 7 shows the relationship between the measured peak bearing error and the physical height of an object for objects at a fixed spacing of 2 ft. Note that the ATC transponder and Distance Measuring Equipment (DME) blade antennas at a height of ¼ wavelength perturb the bearing performance more than their physical height would suggest. For the VHF rod antenna, the peak bearing error is far less than expected, given the object's height. The interference effects of that antenna were mitigated primarily by the thinness of the antenna for most of its height (Figure 5).

In summary, the bearing error caused by a nearby object can generally be described by a sinusoidal function whose *amplitude* is related both to the object's *height* and the *relative spacing* between the object and the TCAS antenna, and whose *frequency* is also related to the *relative spacing.*

TCAS III Simulation

Thus far we have shown how the bearing-rate estimation errors equate to miss-distance estimation errors, and we have examined the expected magnitude of the bearing-error measurements. What remains is to ex-

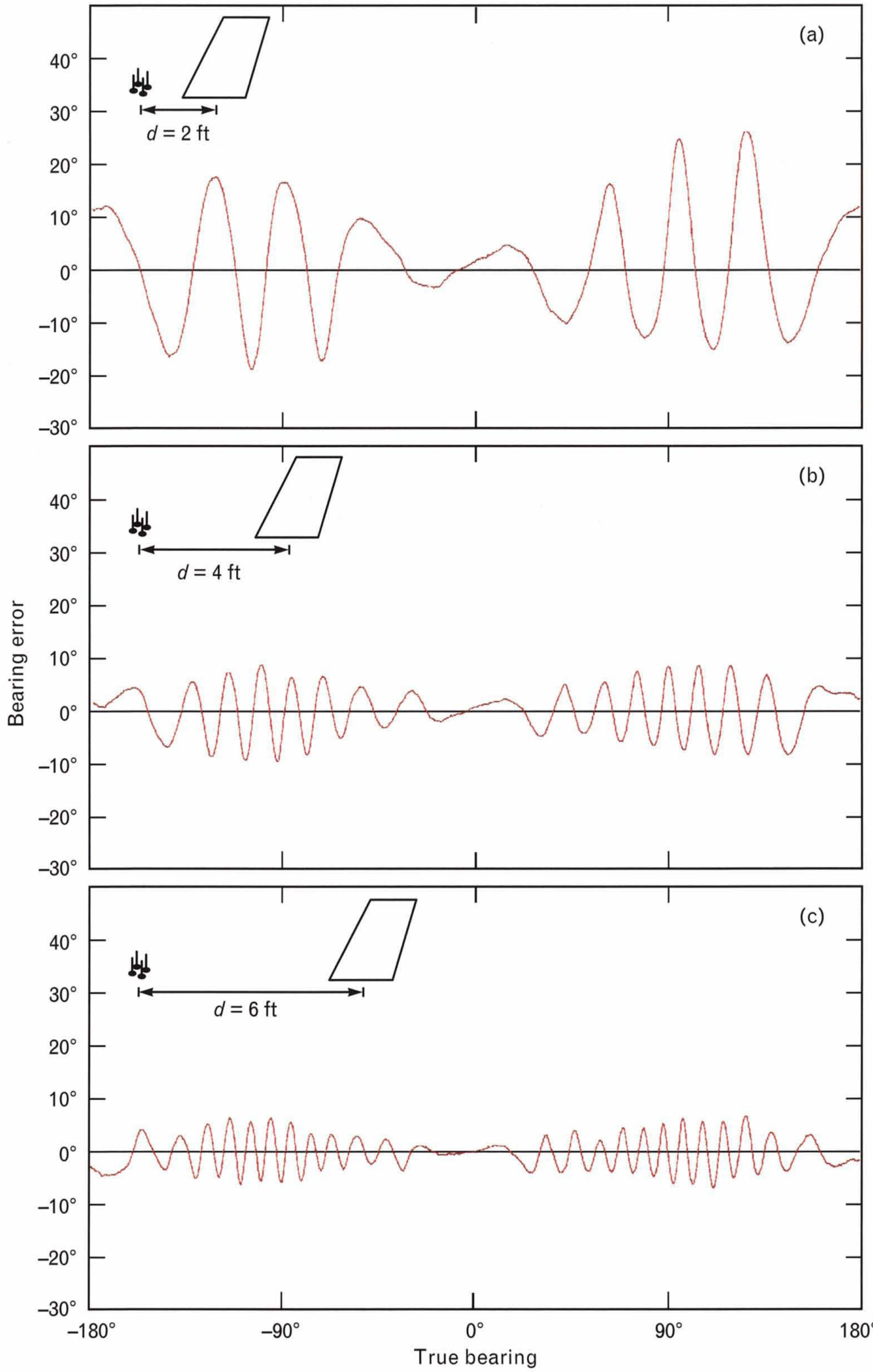

FIGURE 6. VHF antenna effects for different spacings between the VHF blade and TCAS antennas: (a) 2 ft, (b) 4 ft, and (c) 6 ft. Note that the error magnitude in the bearing measurements made by the TCAS antenna decreases as the VHF antenna is located farther from the TCAS antenna.

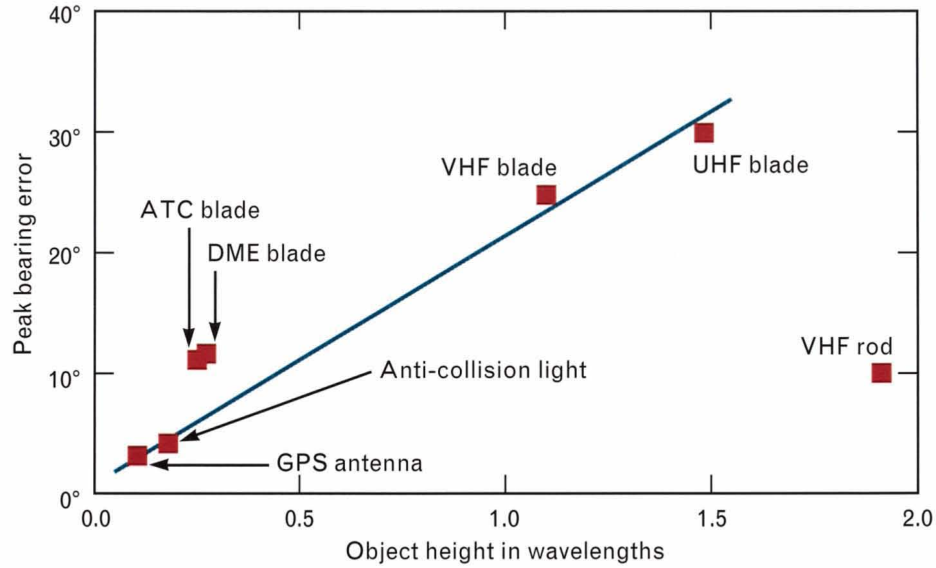

FIGURE 7. Peak bearing error versus object height for different objects spaced 2 ft from the TCAS antenna. Note that the ATC transponder and DME blade antennas at a height of 1/4 wavelength of the TCAS operating frequency perturb the bearing performance more than the physical height of the antennas would suggest. This result can be explained by the fact that, as the height of an object approaches 1/4 wavelength, other electromagnetic phenomena begin to emerge as the dominant contributor. For the VHF rod antenna, the peak bearing error is far less than expected, given the object's height. The interference effects of that antenna were mitigated primarily by the thinness of the antenna for most of its height (Figure 5).

amine the translation of bearing errors into miss-distance errors and to determine how these errors affect the performance of the TCAS III horizontal functions.

The analysis of the effects of bearing measurement errors on the TCAS III horizontal performance is not a trivial task. First, the estimation of the bearing rate from the bearing measurements depends on the TCAS installation environment and the characteristics of the differentiating filter—algorithms that estimate the bearing rate from the bearing measurements. Next, the estimation of the miss distance depends on the geometry of the particular encounter. Lastly, the miss-distance estimate is just one of many parameters used in the decision process by the collision-avoidance system (CAS) logic in TCAS. Because of these factors, the analysis is better suited to computer simulation, in which many different encounters and TCAS antenna configurations can be varied to study their effects on TCAS performance.

There are four major steps required of this simulation, as shown in Figure 8. First, encounters must be generated that span the expected domain of real-life encounters, including aircraft approaching each other at velocities that are typical of real airspace. Second, a means for introducing the anticipated surveillance measurement errors to the surveillance data must be invoked. Third, transformation of the relative measurements into miss-distance estimates by means of a differentiating filter must be performed. Finally, a suitable representation of the CAS-logic horizontal functions, which use miss-distance estimates to assess and resolve threatening encounters, is required to understand the relationship between measurement errors and TCAS performance. We now describe each of the four steps in greater detail.

The simulation generates co-altitude encounters between two aircraft with varying miss distances and relative velocities. The initial conditions are varied in Monte Carlo fashion, but the encounters are structured at the start such that penetration of the threat boundary is assured. One aircraft, designated as the host aircraft, is started at the center of an arbitrary coordinate system; the other aircraft, designated as

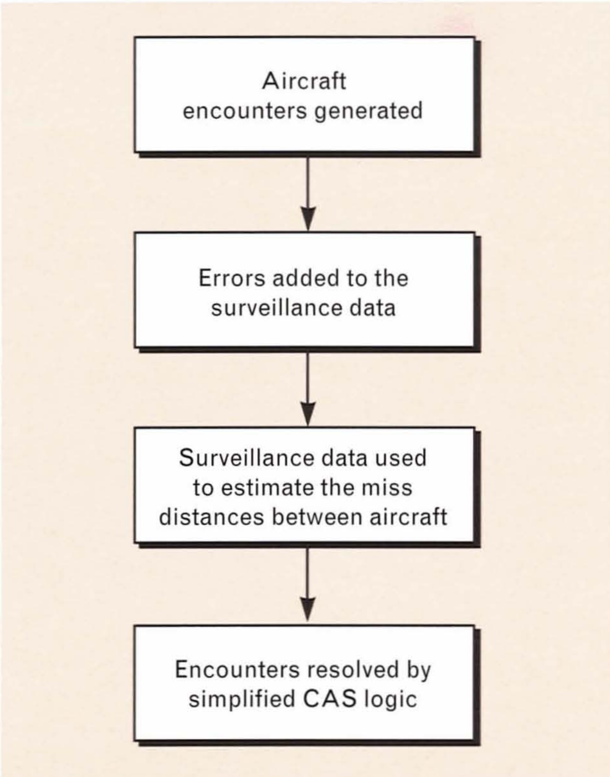

FIGURE 8. Steps used in the simulation of the TCAS III surveillance subsystem. The simulation first generates co-altitude encounters between aircraft approaching each other at velocities that are typical of real airspace. Errors are then introduced into the range and bearing surveillance measurements of the intruder aircraft. With these surveillance data, which now include contributions from various error sources, estimates of the miss distances between the host and intruder aircraft can be calculated. The simplified CAS logic can then determine if an RA is necessary for a particular encounter and, if so, the type of RA that would best resolve the encounter.

the intruder, is started well in advance of the threat boundary. The encounter is progressed according to aircraft linear motion equations. By varying the initial conditions of an encounter, we can run the simulation repeatedly, producing an unlimited range of scenarios.

Once the encounters have been generated, errors are introduced into the range and bearing measurements of the intruder aircraft. As discussed previously, these error sources are both uncorrelated and systematic contributors. The uncorrelated errors are relatively small and insignificant and are independent of the TCAS configuration, whereas the systematic errors are coupled tightly with the TCAS antenna installation configuration. In the simulation, the uncorrelated error characteristics are described statistically with known probability distributions. The systematic error characteristics are taken directly from the OSU study and the ATR measurements.

Next, a differentiating filter—a recursive alpha-beta tracking filter [5]—transforms the bearing measurements into estimates of the bearing rate. Using the bearing-rate estimates, the simulation can then calculate miss-distance estimates for the encounters.

For the simulation results to be meaningful, the simplified CAS logic must be similar in its decision-making process to the TCAS III CAS logic [6]. Thus the simplified CAS logic must contain the pertinent equations and parameters proposed for the TCAS III CAS logic, but without the complexity associated with real-time collision-avoidance threat logic.

TCAS III Evaluation

Earlier in this article, we described the TCAS II threat boundary, using the range and range rate. Although the threat boundary provides excellent protection against dangerous intruders, it also tends to alarm against intruders posing little or no danger. The miss-distance estimate can be used to determine more accurately whether an RA should be issued and, if so, the type of RA required, i.e., horizontal or vertical. Additionally, once an RA has been issued, the CAS logic must monitor the separation progress of the two airplanes to assess the suitability of the RA. During a vertical RA maneuver, the monitoring function watches for diverging relative altitude reports to ensure that the two airplanes are achieving separation. During a horizontal RA maneuver, the monitoring function uses the progression of the miss-distance estimates to ensure an increase in separation.

Because an accurate miss-distance estimate is vital during two phases of an encounter—at initial penetration of the threat boundary (for RA selection) and during a horizontal RA maneuver (for RA monitoring)—an examination of the horizontal functions during these two phases will provide a performance assessment of the effects of large bearing errors. Specifically, for a given set of bearing errors, there are

CALCULATION OF THE MISS DISTANCE BETWEEN TWO AIRCRAFT IN A HORIZONTAL PLANE

THE MISS DISTANCE between two aircraft in a horizontal plane can be calculated with range r and bearing B measurements. The range and bearing measurements, which a TCAS host aircraft acquires through active interrogations of intruder aircraft, can be differentiated with alpha-beta filtering to obtain estimates of the range rate $\dot{r}$ and bearing rate ω. With these estimates, the difference speed v_d, i.e., the apparent speed of the intruder as seen by the host aircraft, can be determined by using the geometry shown in Figure A:

$$v_d = \sqrt{(r\omega)^2 + \dot{r}^2}.$$

The angle θ can be expressed both in terms of the position triangle:

$$\sin\theta = \frac{\hat{m}}{r}, \qquad \text{(A)}$$

and in terms of the velocity triangle:

$$\sin\theta = \frac{r\omega}{v_d}. \qquad \text{(B)}$$

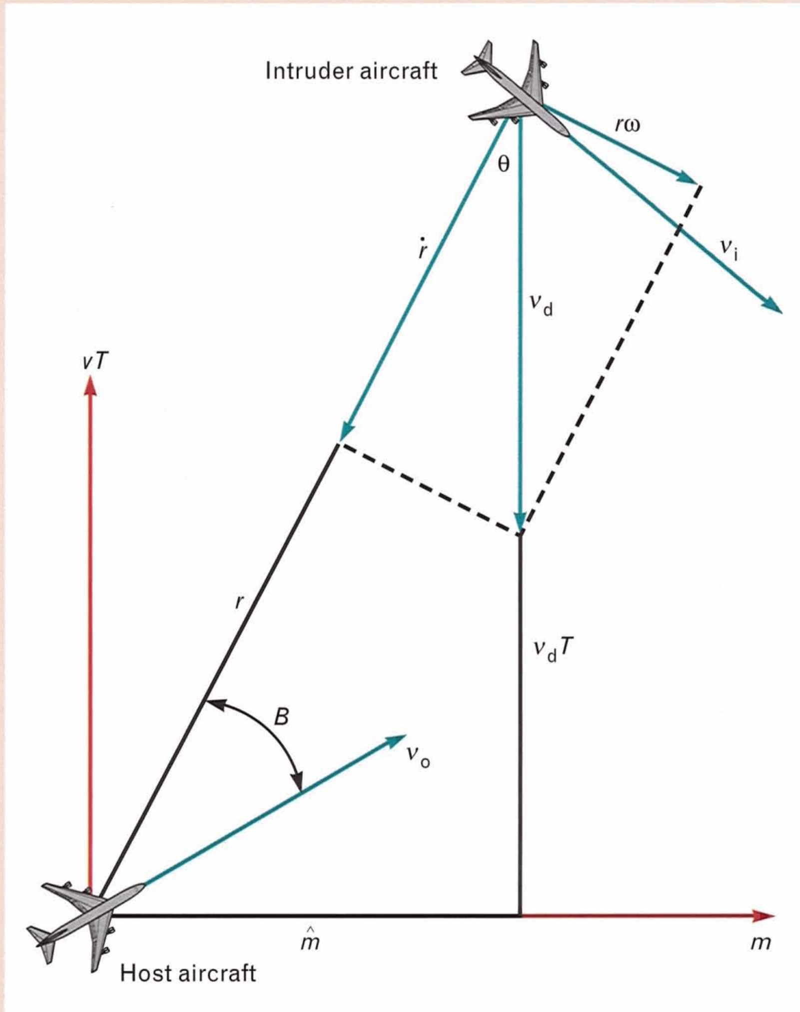

FIGURE A. Geometry of encounter between two aircraft in a horizontal plane.

Combining Equations A and B and solving for the horizontal miss distance $\hat{m}$ gives the following:

$$\hat{m} = \frac{r^2\omega}{v_d},$$

or, more appropriately,

$$\hat{m} = \frac{r^2\omega}{\sqrt{(r\omega)^2 + \dot{r}^2}}.$$

From the geometry shown in Figure A, we can solve for the quantity T, which is the time remaining until the host and intruder aircraft pass at $\hat{m}$, their closest distance:

$$T = \frac{\sqrt{r^2 - \hat{m}^2}}{v_d}.$$

Table 1. Miss-Distance Filtering (MDF) Results for Different Simulated Conditions

*Conditions**	σ_ω *(deg/sec)*	*Encounters Where RA Issued*	*Encounters Eliminated by MDF*
Error-free case	0.0	51%	49%
B727 airframe	0.24	72%	28%
B727 airframe with Mode S antenna @ 4 ft from TCAS antenna	0.51	86%	14%
B727 airframe with Mode S antenna @ 2 ft and VHF antenna @ 6 ft from TCAS antenna	0.66	92%	8%

* Each condition, consisting of 50,000 simulated encounters, represents a different degree of degradation in the bearing measurements.

Table 2. RA-Selection Results for Different Simulated Conditions

*Conditions**	σ_ω *(deg/sec)*	*Encounters Where Horizontal RA Issued*	*Encounters Where Vertical RA Issued*
Error-free case	0.0	33%	66%
B727 airframe	0.24	20%	80%
B727 airframe with Mode S antenna @ 4 ft from TCAS antenna	0.51	11%	89%
B727 airframe with Mode S antenna @ 2 ft and VHF antenna @ 6 ft from TCAS antenna	0.66	10%	90%

* Each condition, consisting of 50,000 simulated encounters, represents a different degree of degradation in the bearing measurements.

three questions that must be answered:

1. What percentage of RAs can be eliminated with miss-distance filtering (MDF)?
2. How often will a horizontal RA be selected?
3. When a horizontal RA has been issued, can TCAS determine its effectiveness?

Miss-Distance Filtering

Because an alarm results only when an intruder aircraft penetrates the threat boundary, the boundary provides an initial filtering process that eliminates the further consideration of aircraft passing by at large distances. This filtering process could be enhanced if accurate estimates of the horizontal miss distances were available.

When an intruder penetrates the threat boundary, the determination of whether an RA should be issued is performed by the MDF. The MDF compares the current miss-distance estimate to a calculated threshold value by using the following [7]:

$$\hat{m} > C_{\text{MDF}} + \sigma_m,$$

where $\hat{m}$ is the miss-distance estimate, σ_m is an estimate of the miss-distance error, and C_{MDF} is a fixed parameter that includes a buffer against the possibility of a turn by the intruder. An intruder whose current miss-distance estimate satisfies the above inequality is not considered threatening.

Table 1 shows the results of simulated encounters examined at the threat boundary with the above inequality to determine if an RA was required. These results show the percentage of encounters that MDF filtered out under four different conditions, each of which consisted of 50,000 simulations. As shown by the σ_ω values, the conditions were chosen to illustrate the effect of different degrees of degradation in the bearing rate ω. The first condition illustrates the expected outcome if the surveillance made perfect measurements, i.e., no errors in the bearing measurements. This result can be used to compare the subsequent degraded conditions, as well as to demonstrate the practical limits of the RA-elimination process. The limits are the consequence of several fixed parameters within the CAS logic. The parameters are used primarily to buffer against an unexpected acceleration by an intruder aircraft. For the error-free case, the results indicate that MDF would filter almost half of the encounters, thus significantly reducing the RA rate. For a typical installation configuration such as the B727 airframe with an ATC transponder antenna in close proximity, the RA reduction is expected to be much lower—closer to 10% to 15%.

RA Selection

Every intruder that penetrates the threat boundary will either be rejected by MDF or cause the issuance of an RA. When an RA is necessary, the selection of an appropriate escape maneuver must be performed. This selection requires several evaluation tests to determine the best RA for resolving the encounter. The CAS logic selects the appropriate RA based on a comparison of the expected increase in aircraft separation that would result from each valid RA type: climb, descend, turn left, or turn right. In our study, the decision-making logic, as illustrated in Figure 9, is comprised of three tests, namely, a Sufficient Separation Test, a Geometry Test, and a Greatest Separation Test. By the process of elimination, the appropriate RA type is selected at the completion of the tests.

The Sufficient Separation Test assures that the RA under examination will provide separation greater than a specified minimum. This test eliminates RAs that are inherently wrong for a given encounter, for example, an RA that maneuvers the host aircraft into the path of the intruder. The Geometry Test eliminates horizontal RAs for encounters in which a horizontal RA would be ineffective. In the majority of such encounters, a turn maneuver would only extend the time to collision. The Greatest Separation Test compares the expected increase in separation of the remaining available RAs and chooses the RA that provides the greatest separation.

Table 2 shows the results of simulated encounters examined at the threat boundary with the above RA-selection process. Again, the results illustrate the degradation in performance caused by a large bearing-rate error. For the case of error-free measurements, nearly a third of the encounters requiring an evasive action would be resolved with a horizontal maneuver. For actual TCAS antenna configurations, the number of horizontal RAs decreases rapidly as the bearing-rate error increases. For a typical installation, the ratio of horizontal RAs to vertical RAs is about 1:10.

RA-Monitoring Capability

Once a horizontal RA has been issued, the miss distance between the intruder and host aircraft must be

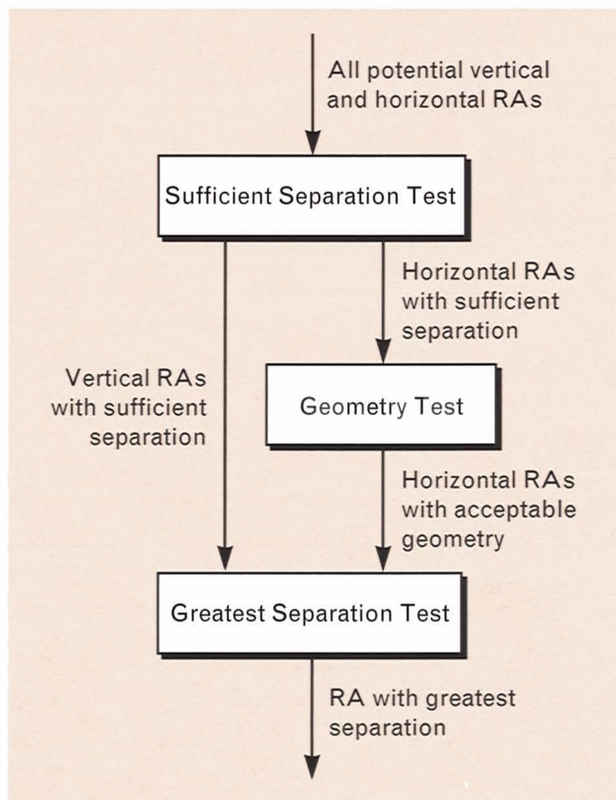

FIGURE 9. Logic used in the simulation to select the best RA.

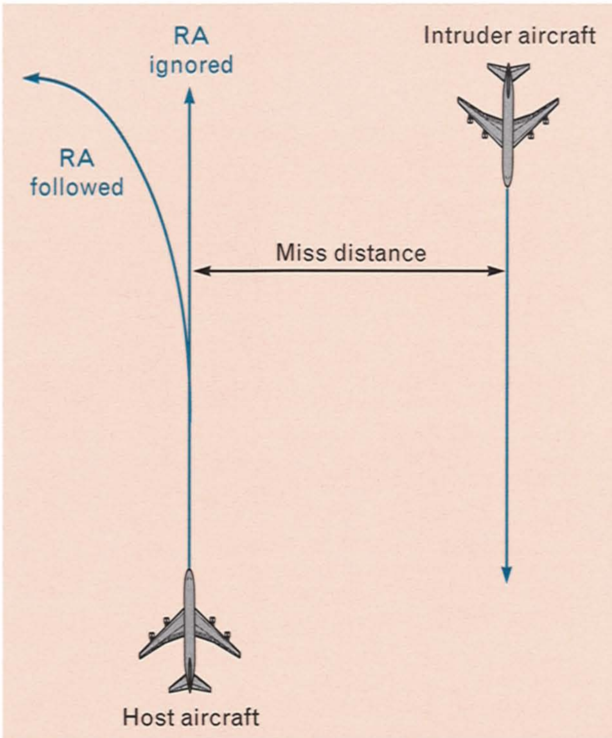

FIGURE 10. Encounter geometry used to evaluate the monitoring of horizontal RAs. Note that two scenarios have been simulated: one in which the host aircraft follows the RA and makes a turn, and the other in which the host aircraft ignores the RA.

monitored to determine the resolution of the encounter. If the issued RA does not provide the necessary spatial increase between the two aircraft, TCAS must decide if further action, such as an alternative RA, is required. Because this decision must be made early enough to avoid a possible collision, accurate miss-distance estimates are necessary to detect the encounter resolution.

To evaluate the effectiveness of RA monitoring in the presence of large systematic bearing errors, we analyzed the simulated horizontal RA encounters during the time period between RA issuance and time at closest point of approach (TCPA). During this period, the intruder remains along its original course, straight and level, with no accelerations applied. Meanwhile, the TCAS III host aircraft, in response to the RA, performs a horizontal maneuver following an initial delay comprised of 6 sec to account for pilot response time and 2.5 sec to account for the aircraft going from level to a 25° bank angle. As illustrated in Figure 10, identical sets of encounters were simulated for two scenarios: the first in which the host aircraft follows the RA and turns, and the second in which the host aircraft ignores the RA and does not turn. After issuance of the RA, the two aircraft approach closer to each other and are expected to be at their closest in approximately 30 sec, a typical value for TCPA.

The time prior to TCPA at which the miss-distance estimates clearly indicate whether or not the host aircraft has followed the RA is the earliest time that a decision can be made about an RA's progress to resolve an encounter. This decision must be made early enough to obtain adequate separation between intruder and host aircraft. If a decision to revise the initial RA is made too close to TCPA, the time delays due to pilot and aircraft response (each delay typically 3 to 7 sec long) will preclude the maneuver from obtaining additional separation.

Figure 11 shows the miss-distance estimates obtained by using the bearing-error transfer functions of the B727 airframe for two scenarios: one in which the RA is followed and the other in which the RA is ignored. For each of the 100 encounters generated, the true miss distance was set to 10,000 ft. At the time the RA was issued, the miss-distance estimates ranged roughly from 8000 to 13,000 ft. Note that the miss-distance estimates for both scenarios overlap over much of the monitoring period. This overlap illustrates the difficulty in determining an RA's progress. From Figure 11, we conclude that a positive determination of whether an RA has been followed or ignored cannot be made until 23 sec after the RA has been issued, or 7 sec prior to TCPA. As mentioned earlier, 7 sec may be too little time if a scenario requires the issuance of an additional RA to resolve a conflict.

TCAS IV

We showed that the use of bearing rate, when derived from bearing measurements, is ineffective to resolve the complex encounter geometry in the horizontal plane. For most installation configurations of the TCAS antenna, the errors were just too large to support accurate MDF and horizontal RAs. Our results, however, did not prove that horizontal functions cannot be supported by TCAS. Instead, our work simply indicated that horizontal functions cannot be supported through the use of bearing rate alone.

At the TCAS International Conference in September 1993, the FAA made a major announcement concerning the next generation of TCAS. After reviewing our above analysis, the FAA stated that it would no longer support TCAS III, a TCAS with horizontal capability based on the use of bearing rate measurements. Instead, the FAA introduced TCAS IV—a novel direction in surveillance design that uses new technologies to support an advanced collision-avoidance system. Because TCAS III has been associated over the years with the use of bearing-rate estimates, the name change to TCAS IV signifies a major step in a different direction to reach the goal of providing horizontal RA capability.

TCAS IV utilizes other available data sources to provide the degree of accuracy that is required to support all aspects of collision avoidance. Improvements include the enhancement of current TCAS II vertical functions as well as the implementation of horizontal functions. The new data sources can also be used to support new functions of TCAS in the areas of advanced applications. In one such application, pilots use TCAS to "see" other aircraft during inclement weather. In another application, TCAS functions as a visual aid for transoceanic flights where there are no ATC surveillance radars.

The cornerstone of the TCAS IV design is the use of the Mode S data link to exchange measurements about an aircraft's state (position, velocity, and acceleration). The data are derived on board from the aircraft's Global Positioning System (GPS) receivers, inertial reference sources, flight-management computers, and air data sources (e.g., the vertical-speed indicator, airspeed indicator, and barometer), and encoded into the transponder reply in much the same way as altitude data are currently provided. The real attraction of this approach is that, in addition to the improved accuracy of the aircraft state data, knowledge of an intruder aircraft's

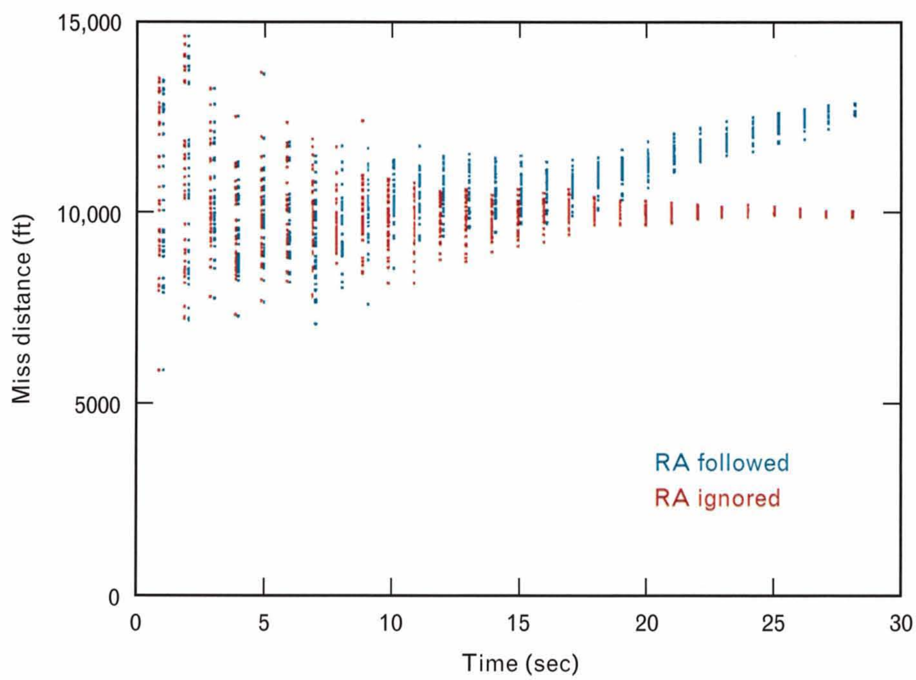

FIGURE 11. Miss-distance estimates calculated after the issuance of a horizontal RA for simulations of two scenarios: one in which the host aircraft follows the RA and the other in which the aircraft ignores the RA. At a time of 0 sec, the RA is issued. At a time of 30 sec, the two aircraft are at their closest approach to each other. Note that the miss-distance estimates for both scenarios overlap over much of the monitoring period. The data are for a B727 airframe.

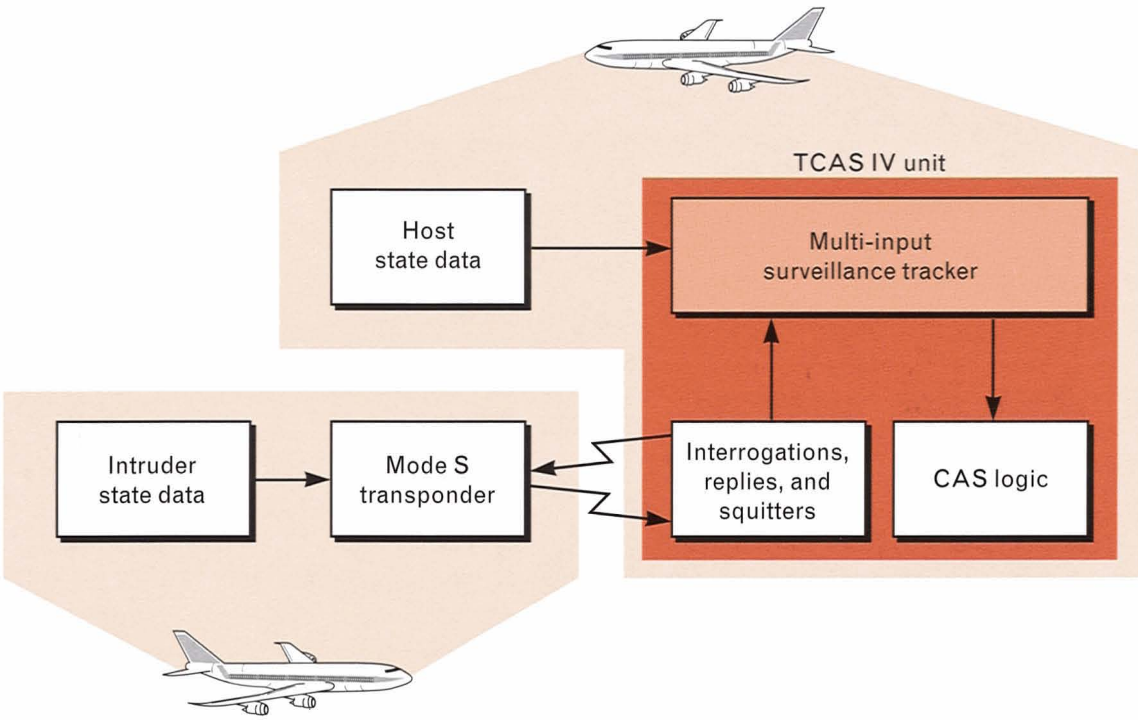

FIGURE 12. Concept for integrating on-board avionics sources into TCAS IV and the Mode S transponder.

future intentions can be relayed to a host aircraft so that the CAS logic in TCAS can more accurately ascertain the danger of the intruder.

Exchanging of Data

Numerous avionics systems continuously measure, compute, and maintain aircraft state information. Navigational systems keep track of the aircraft position, speed, and attitude; flight-management systems reduce pilot workload by assisting in flight planning and aircraft performance, guidance, and control; air-data systems monitor air-related data such as air speed and altitude; and autopilots perform air control based on prestated flight intentions. In newer aircraft, data to and from the various systems are routed via digital transmission lines. In most of these aircraft, the digital transmission lines are also connected to the on-board TCAS and Mode S transponder units.

Figure 12 shows the concept for integrating the on-board avionics sources into TCAS IV. The host aircraft data are available via the on-board digital data bus. The intruder data are loaded into the intruder's Mode S transponder and then exchanged, or cross linked, via the Mode S data link. This exchange can be performed either actively via a discrete interrogation or passively via GPS-Squitter. (See the article entitled "GPS-Squitter: System Concept, Performance, and Development Program," by V.A. Orlando et al., in this issue.)

The challenges associated with the new surveillance design focus more on algorithm development than on the hardware. The primary method of acquiring data, via the standard avionics data bus and Mode S data link, is established, well documented, and operational in a vast majority of the commercial airline fleet. In fact, in most modern aircraft, TCAS and the Mode S transponder are already receiving these aircraft state data through a connection to the avionics data bus.

New algorithms are required to integrate and sift through these data, and to choose the optimum set of measurements from the abundance of new information in order to minimize the miss-distance prediction errors. Additionally, other valuable information, not directly related to the miss-distance calculation, will require integration into the CAS logic. Information such as the intruder bank angle and heading rate, though not explicitly used in the miss-distance calculation, can be used to indicate the potential danger of an intruder. For example, if an intruder penetrates the threat boundary but the bank-angle information, crossed linked to TCAS, indicates that the intruder aircraft is turning away from the host aircraft, the RA could be suppressed. This type of surveillance design opens up possibilities for enhancing TCAS interoperability within the ATC system.

Summary

Viewing TCAS II as an interim step, pilots desire the next-generation TCAS to include the capability of issuing horizontal resolution advisories (RA) to augment vertical RAs. Horizontal RA capability is possible if estimates of the horizontal miss distance between an intruder and the host aircraft are available. Horizontal miss-distance estimates can also be used to reduce the alarm rate, a process called miss-distance filtering (MDF), by suppressing false alarms of intruders that are known to be passing by at safe distances. The effectiveness of horizontal RAs and MDF is related directly to the accuracy of the horizontal miss-distance estimates.

Previously, the development of the next-generation TCAS centered on TCAS III, a system that required accurate bearing measurements to estimate the horizontal miss distance. Unfortunately, the small antenna aperture of the system coupled with pattern perturbations caused by reflections from the airframe structure and nearby antennas degraded the miss-distance estimation performance, thus precluding effective horizontal RAs and MDF.

A new approach, TCAS IV, promises to provide the data accuracies required for horizontal functions as well as for improved vertical RA performance. The design centers on the use of the Mode S data link for exchanging aircraft state (position, velocity, and acceleration) information. Such data, which are derived on board, can be obtained through dedicated interrogations or they can be received via spontaneous transmissions known as squitters. After receiving such data from an intruder aircraft, the host aircraft can more accurately determine the state and future course of the intruder.

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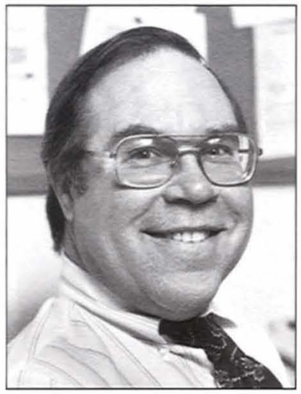

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