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In the development program of airborne collision avoidance, the equipment intended for installation on air carriers is designated TCAS II in the United States. A TCAS II installation may be thought of as consisting of two major subsystems: (1) air-to-air surveillance, and (2) control logic (including the logical tests that decide when another aircraft is dangerously close, algorithms that select an appropriate vertical resolution advisory, and a display of the advisory to the pilot). This paper focuses on the air-to-air surveillance subsystem. It identifies the disturbance phenomena that affect performance, presents a number of techniques that have been developed to overcome these difficulties, and presents performance measurements made through airborne testing.

A TCAS II installation carries out surveillance in both Mode S and Mode C. The former is used for all Mode S aircraft, including other TCAS II aircraft. The latter is used for all other aircraft, provided they are equipped to reply in Mode C. This paper concentrates on surveillance in Mode C, which is by far the more demanding case.

1. BASIC SURVEILLANCE TECHNIQUES

Disturbance Phenomena

A major difficulty in achieving reliable surveillance in Mode C is synchronous garble. This is the overlapping of replies from different aircraft at approximately the same range. This mutual interference is synchronous in the sense that it will repeat time after time until the relative ranges change. In Mode S, synchronous garble does not occur, because the interrogations are discretely addressed. It is for this reason that the Mode S design is relatively straightforward.

Another major disturbance is multipath, which refers to a delayed echo arising because of a reflection from the ground or the ocean. Airborne measurements (ref. 1) have shown that it is common to have multipath receptions that are within 5 to 15 dB of the desired reply. In addition to these major disturbances, the TCAS II design must be able to tolerate a high rate of asynchronous replies elicited by ground interrogators and other TCAS II equipment, which will be especially high when an omnidirectional receiving antenna is used.

Modified Mode C Interrogation

One straightforward technique to control synchronous garble is the use of a modified Mode C interrogation that does not elicit replies from Mode S aircraft. An additional pulse is included (P4, 2 μ sec after P3) for the purpose of notifying Mode S transponders to not reply. This action removes all Mode S aircraft from the Mode C synchronous garble environment. This is a growth provision that has no effect in today's environment, but may be quite useful in dealing with very high aircraft densities possible in the future.

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Whisper-shout is a special sequence of interrogations transmitted in each 1 second scan. Whisper-shout is intended to partition the replies so that fewer are received to any one interrogation. This is accomplished by a set of interrogations at different power levels, and by an added suppression just before each interrogation (other than the one at lowest power). This suppression consists of one additional pulse occurring 2 μ sec before P1 and having a power somewhat less than that of P1. This pulse acts together with P1 to suppress all transponders that detect both pulses. The mechanism is based on the differences in sensitivity of the aircraft that would otherwise be synchronously garbling. These differences in sensitivity are partly a result of differences in antenna gain. The lowest power interrogation elicits replies from a small subset of the aircraft, those having relatively high sensitivities. The next higher power interrogation is detected by a larger subset of the aircraft. But the accompanying suppression, whose power is comparable to the first interrogation, serves to suppress most of the aircraft that replied to the first. Thus only a relatively small subset of the aircraft reply to this interrogation. For the same reason only a relatively small subset of aircraft reply to each of the interrogations, and every aircraft replies to at least one. A 4-level form of whisper-shout that has been experimented with extensively has 6 dB spacing between interrogations and 3 dB overlap (that is, the suppression is 3 dB lower than the next lower interrogation). Airborne measurements using this design consistently show a major improvement compared to the use of a single high-power interrogation.

Top Antenna

It may be expected that the severity of multipath is less when using a top mounted antenna as compared with a bottom antenna, and this has been verified through airborne measurements. For this reason, the TCAS II design includes both top and bottom mounted antennas with the top being considered the primary antenna.

Dynamic Thresholding

When a strong signal is being received, even relatively weak multipath can be detected and cause errors. This can be prevented if dynamic thresholding is used, which is a circuit that raises the receiver threshold whenever a strong signal is received. If it were not for whisper-shout, dynamic thresholding would be impractical since it would be necessary to retain the normal receiver threshold at all times in order to detect relatively weak replies in the presence of stronger replies. But as whisper-shout partitions aircraft according to their sensitivities to interrogation, this action has a tendency to also group them in reply power. Dynamic thresholding in conjunction with whisper-shout has been experimented with in airborne tests and found to produce a significant improvement in performance.

Measured Performance

These basic surveillance techniques were tested in 1980 using a real-time TCAS II Experimental Unit built by Lincoln Laboratory. The unit employed a 250 watt interrogator with 4-level whisper-shout and omnidirectional top and bottom antennas. In one series of tests, a mid-air collision at San Diego (September 1978) was re-enacted. This was done in one case using a Boeing 727 equipped with the TCAS II unit and a Cessna 172 acting as the second aircraft, which were the same aircraft types as in the real accident. Tests were also conducted using a number of different aircraft combinations. In all cases the surveillance performance was found to be satisfactory to support collision avoidance.

Another test was a cross-country tour using the Boeing 727 along normal air carrier routes carrying out air-to-air surveillance on targets of opportunity. This provided experience with a large number of different aircraft as targets. The recorded results were later analyzed to determine the probability of having an aircraft in track as a function of range and aircraft density. These results are given in Figure 1 (ref. 2). Performance is seen to be quite good: above 95% throughout the most important region within 3 nmi, and degrading only gradually beyond. The region of short ranges is the most important in the sense that the great majority of encounters will occur with much less than the design maximum closing speed, and so the ranges at which tracking is required will in most cases be much less than the maximum. Cases requiring tracking at longer range will be a minority, and especially rare will be cases in which both long range and high density performance are needed simultaneously.

This test data was also analyzed for false alarms (meaning cases in which a false track, corresponding to no real aircraft, gave rise to a pilot advisory). The results showed that there were no false alarms in the entire data set of 242 flight hours.

2. ADDITIONAL TECHNIQUES

Bearing Angle

While basic surveillance includes range and altitude, it is also possible to track bearing angle by means of a simple angle-of-arrival antenna. A square array of four monopole elements, spaced 4 inches on a side, can be used to achieve an accuracy of about 10° RMS. This accuracy is sufficient to support a simple traffic display for the purpose of helping the pilot visually acquire nearby aircraft.

Non-Altitude-Reporting Targets

Some aircraft carry transponders without altitude reporting equipment. These aircraft can be tracked by the TCAS II unit, although since their altitudes are unknown, it is not possible to generate climb or dive maneuvers from these tracks. Nevertheless this mode of operation may be useful in cases where a traffic display with bearing angle is provided.

Absence of altitude makes it more difficult to associate replies with the correct tracks. This difficulty has been addressed with a carefully matched range tracking algorithm. The algorithm is based on the fact that for straight flight motions, range-squared is a quadratic function of time. For this reason, a three component "alpha-beta-gamma" tracker is used to track range-squared. After careful selection of the tracker parameters and the window sizes used to associate replies with tracks, it has been possible to achieve excellent tracking performance of non-altitude-reporting aircraft.

High Aircraft Density

As aircraft density increases, synchronous garble gradually degrades performance. The basic surveillance techniques using 4-level whisper-shout omnidirectionally are capable of reliable performance into a density of about 0.03 aircraft per nmi^2 . This density is exceeded in some of the metropolitan areas in the United States. To achieve higher density operation, whisper-shout can be extended and a technique of directional interrogation can be employed.

Airborne experiments were used to indicate the extent to which the basic 4-level whisper-shout can be extended by reducing the power step size and increasing the total number of steps. Excellent performance was achieved using a 24-level design having 1 dB steps.

Directional interrogation can serve to further partition the set of replying aircraft according to their bearing angles and thus to further reduce synchronous garble. A 4-beam directional interrogator was selected as being appropriate for achieving sufficient degarbling power, when used in conjunction with the other TCAS II surveillance techniques. To experiment with this, a 4-beam directional TCAS II unit was built by Dalmo Victor. The antenna has both directional transmission and angle-of-arrival capabilities. The protrusion above the aircraft is only about 8 inches in diameter and about 1 inch in height.

Measured Performance

To assess the performance of these high density techniques, testing was carried out in the Los Angeles Basin, which has the highest aircraft density in the United States. A Boeing 727 was equipped with two experimental TCAS II units: the 4-beam directional unit and an omnidirectional unit operated for comparison. Targets of opportunity were used in these tests.

The initial analysis was based on case studies of all encounters in a two hour period in which the minimum separation was less than 2 nmi in range and 1200 ft. in altitude. There were 19 such cases. Performance was examined in each case during the 50 seconds leading up to the point of closest approach. For the directional unit, the target was in-track continually throughout the 50 sec. period for most of the 19 cases. There were few instances of gaps or late track initiations. The overall percentage of time during which the target was in track in this data set is 97%. For the omnidirectional unit the performance was qualitatively the same, and the overall average percentage was again 97%.

A statistical study was also carried out to estimate probability of track as a function of aircraft density. The results for the omnidirectional unit are given in Figure 2. They confirm a significant improvement relative to the 4-level whisper-shout data given in Figure 1. The degradation as a function of density is not evident in this data, probably because it would take a higher aircraft density (which does not exist today) to experience a significant density-related degradation. The statistical results for the directional unit did not indicate any improvement relative to the omnidirectional unit. It was subsequently discovered that the directional antenna had suffered water damage due to a leaking gasket, and that antenna gain was much lower than nominal. This gain reduction together with insufficient aircraft density explain the absence of an evident improvement. More detailed examination of the data indicates that the interrogation was directional and that the number of replies per interrogation was consistently reduced. Thus it is believed that the directional interrogation technique is effective and would produce significant improvement in very high aircraft densities.

3. FUTURE DEVELOPMENTS

A follow-on effort is aimed at developing an "Enhanced TCAS II" (being developed by Bendix Corporation) which has a substantially higher accuracy antenna. With an angle-of-arrival accuracy of 1 to 2° RMS, this is intended to support horizontal maneuver advisories. The antenna, which has a beamwidth of about 60° and has 64 beam positions, may also be more effective in combatting synchronous garble than the 4-beam design.

References

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2. *ibid*, pp 87-102.

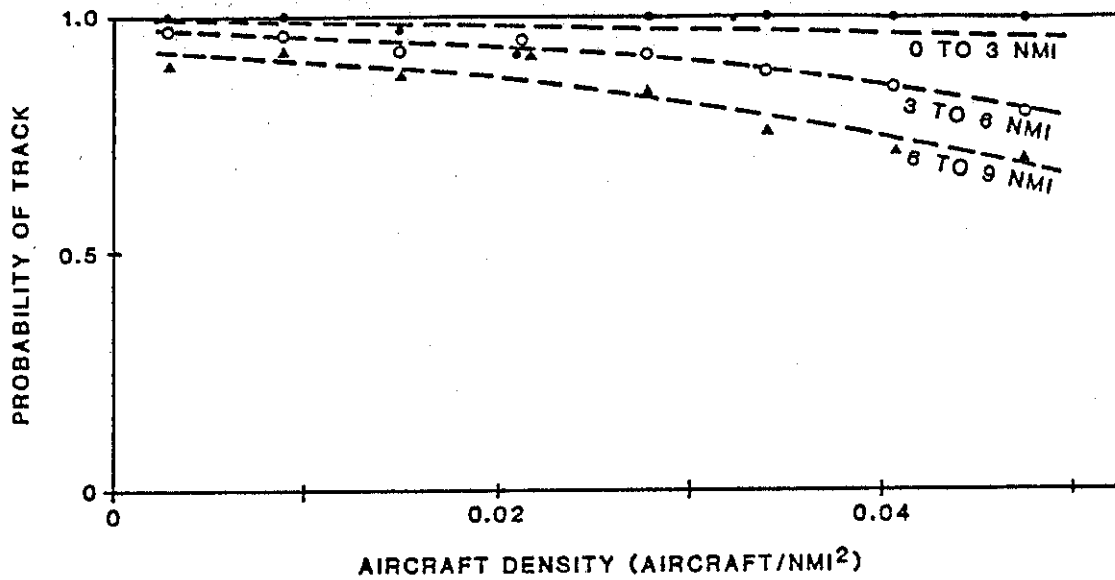


FIG. 1. MEASURED PERFORMANCE OF TCAS II -
BASIC SURVEILLANCE TECHNIQUES

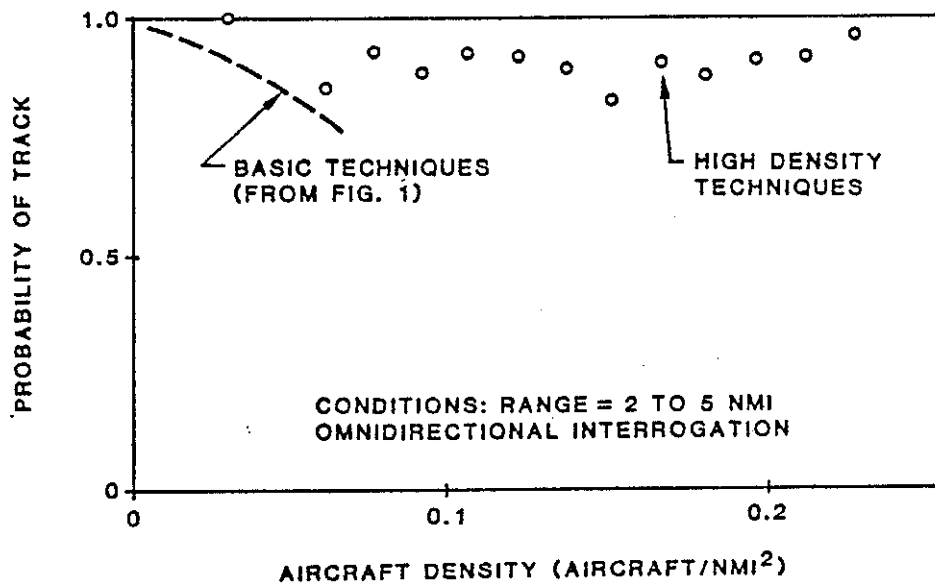


FIG. 2. MEASURED PERFORMANCE OF TCAS II -
HIGH DENSITY SURVEILLANCE TECHNIQUES