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Report – Assessment and Recommendations on Visual Alerts and Aural Annunciations for TCAS II

RTCA DO-299
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FOREWORD

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EXECUTIVE SUMMARY

Background and Data

Monitoring of TCAS performance has identified instances where flight crews responded in the opposite direction to that specified by TCAS when a resolution advisory (RA) was displayed and announced to the flight crews. Many of these opposite responses were observed for RAs classified as Negative RAs by the collision avoidance system (CAS) logic, and are characterized by the fact that the flight crew believed their response was correct, i.e., not opposite. A Negative RA is typically issued when a TCAS-equipped aircraft is climbing or descending towards another aircraft, and the CAS logic determines that the TCAS-desired vertical miss distance between the two aircraft can best be achieved by the TCAS aircraft reducing its vertical speed. These RAs are accompanied by an aural annunciation of 'Adjust Vertical Speed, Adjust' (AVSA). The proper response to a Negative RA is always a reduction in vertical speed, i.e., a maneuver towards level flight. When a flight crew maneuvers in the opposite direction to a Negative RA, it is almost always maneuvering towards the intruder and thus reducing rather than increasing the vertical miss distance with the other aircraft. Such an opposite response represents a safety issue.

Because opposite reactions to Negative RAs have been regularly identified since the introduction of TCAS II, and have continued since the introduction of TCAS II Version 7, RTCA Special Committee 147 (SC-147) was tasked to perform studies and analyses to investigate the display configurations and aural alerts used for Negative RAs. The purpose of these investigations was to determine whether any problems exist with the current requirements for displaying and annunciating this class of RAs. The SC-147 requested that its Operations Working Group (OWG) investigate this issue and provide a report that documents whether any problems exist in the current requirements for displaying and annunciating Negative RAs and if so, to recommend an approach to resolving the identified problem(s).

Note: The focus of the OWG's investigation has been on opposite responses to initial Negative RAs and all references to 'Negative RAs' in this Executive Summary and this Report are for initial Negative RAs.

The OWG has reviewed data from multiple sources during its investigation of this issue and has used these data to develop a number of near term and longer term recommendations. Data have been obtained from:

- Operational monitoring programs using radar data, pilot questionnaires, and controller questionnaires
- Formal investigations of some opposite responses conducted by State's accident investigation organizations
- Dedicated simulations to collect data on pilot response to Negative RAs
- On board data recordings and airline safety reporting systems

The available data have yielded the following results:

1. There have been opposite responses to Negative RAs that have resulted in the separation between the aircraft involved in the encounter becoming unacceptably small, including one event involving issue SA01 as described in DO-298.

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A. The majority of these opposite responses have occurred on aircraft where RA visual guidance is only provided on a limited analog range vertical speed indicator. Opposite responses have occurred at a significantly higher rate for Negative RAs requiring a reduction in vertical speed to 500, 1000, or 2000 feet per minute (fpm) when using these displays. Only a limited number of opposite responses to Negative RAs requiring a level off, i.e., a reduction in vertical speed to zero fpm, have been observed. The same aural annunciation is used for all Negative RAs.

B. The recorded opposite responses that have resulted in unacceptable separation between aircraft have occurred in Europe. While opposite responses to Negative RAs have been observed in U.S. airspace using radar data, there have been no events identified in over 1500 controller questionnaires received during 2005 where such a response resulted in a loss of standard air traffic control separation between aircraft. In spite of this, it is believed that additional monitoring using on board data recording will identify events where a loss of separation has occurred.

2. Three primary causes for opposite responses have been identified:

A. **Lack of suitable training**. Many training programs do not include simulations of Negative RAs nor include specific instructions on the expected response to Negative RAs. In some incidents where there was an opposite response to the RA, the pilots had never before encountered a Negative RA.

B. **Limitations in the aural annunciations**. The "Adjust Vertical Speed, Adjust" aural annunciation does not provide complete information on what a pilot has to do to comply with the RA. This is inconsistent with all other aural annunciations for corrective RAs, which explicitly state the corrective action to be taken by the flight crew.

C. **Difficulty in interpreting displays**. The large majority of misinterpretations took place with highly nonlinear vertical speed displays to provide RA guidance. Multiple display issues have been identified on one implementation, including: vertical speed needle visibility; limited analog range on some displays; and discrimination and understanding of red and green regions. Monitoring data have not identified any opposite responses to Negative RAs that require the TCAS aircraft to be leveled off, which strongly suggests that the display is a factor, since the aural annunciation is the same for all Negative RAs.

The above three primary causes appear to be interrelated, such that their combination needs to be considered in any analysis or proposed solution. At present the OWG considers that there is insufficient data to know how changing each of these factors affects the likelihood of an opposite response to a Negative RA, and therefore further research into these primary causes is recommended.

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The OWG has also identified some secondary causes that could warrant further investigation:

- *Language*. Non native English speakers have been involved in nearly all the known opposite responses to Negative RAs that resulted in unacceptable separation between aircraft. It is noted that the word "Adjust" contains no information on the sense, or direction, of the required response to the RA.
- *Procedures*. Variations in procedures (such as switching off the FD during an RA) may affect how well Negative RAs are followed
- *Visual acquisition*. Visual perception errors, in combination with the lack of directional information in the aural annunciation used for Negative RAs may lead to opposite responses.

Conclusions and Recommendations

Opposite responses to Negative RAs can result in less than desired separation from other aircraft and is thus considered to be a safety issue.

Based on the work completed to date, the OWG has reached the following conclusions and recommends that the following actions be undertaken by RTCA and the organizations supporting the work of SC-147 and the OWG.

Training

Enhanced emphasis on the expected response to Negative RAs during pilot training and providing information to pilots describing the effects of an opposite response has been demonstrated to decrease, but not eliminate, the number of opposite responses to Negative RAs. The OWG recognizes that training should not be relied on to overcome any design weaknesses in a system. However, based on demonstrated experience that increased attention to the proper response to Negative RAs will reduce the occurrence of opposite responses, the OWG is recommending that all pilots receive training on the expected response to Negative RAs during their TCAS maneuver training. Wherever possible, this training should be conducted in a flight simulator.

To support this recommendation, the report contains information that can be disseminated to operators that describe the expected response to RAs. This information should have the widest possible distribution. The report also provides updated guidelines for TCAS training and these should also be distributed as widely as possible within the next three months.

The OWG recognizes that without guidance on how to set up a scenario that consistently results in a Negative RA being issued, it is unrealistic to expect simulator instructors to train pilots on the expected response to Negative RAs. To support this, it is recommended that SC-147 perform the work necessary to provide operators and simulator instructors with guidance on generating Negative RAs during a flight. This guidance would define encounter parameters for selected weight, altitude, temperature, and aircraft state that could be entered to cause Negative RAs to be issued. This information would be required for multiple aircraft types and would require work to establish the parameters for these aircraft types. It is estimated that this information could be available for distribution within a six month period.

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As a longer term action, the OWG recommends that its future work program include a task to provide an assessment of the effectiveness of the revised training guidelines and explicit guidance on expected response to Negative RAs in reducing the frequency of opposite responses to these RAs.

Aural Annunciations

The OWG has noted that several European organizations have concluded that the lack of directional information in the aural annunciation "Adjust Vertical Speed, Adjust" contributes to opposite responses to Negative RAs. The OWG has received requests from Air France and Lufthansa to evaluate alternative aural annunciations to determine whether the use of another annunciation would improve pilot response to Negative RAs.

To be able to respond to these requests, the OWG recommends that evaluations be completed to determine whether the modification of the aural annunciations would be beneficial. These evaluations would assess pilot performance when the "Adjust Vertical Speed, Adjust" annunciation is replaced with another aural annunciation.

The evaluation of these alternative aural annunciations may include the completion of safety studies, TCAS/ATC compatibility analyses, and human factors assessments.

Displays

Opposite responses to Negative RAs are primarily seen on limited analog range vertical speed indicator implementations (vertical speed tapes and partial representations of round dial vertical speed indicators), suggesting that the display is a significant factor. In some specific scenarios these displays are more prone to allowing misinterpretation of Negative RAs. The contribution of displays to the problem may be exacerbated by the lack of sense information in the associated aural annunciation. However, the exact mechanism by which displays affect opposite responses to negative RAs is not well understood.

Assessment is needed of how displays are contributing to the observed problems. If possible, ways of reducing the effects of displays on opposite responses to RAs will be assessed. The OWG is aware that some manufacturers are updating their displays and will continue to follow this work.

Monitoring

The longer term recommendations also include several monitoring tasks. These include expanding operational monitoring to obtain additional information, especially airborne recorded data, to help identify the root cause(s) of opposite responses; monitoring work being done by airframe manufacturers to modify their display implementations; and coordinating any lessons learned from manufacturers' investigations with other manufacturers. These tasks are structured to provide additional information that will assist the OWG and SC-147 in focusing its resources on other recommended studies and tasks.

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Further Comments and Recommendations

A reduction in Negative RAs can likely be achieved if aircraft reduce their vertical speed when approaching an assigned altitude. Data collected by Lufthansa over a one year period showed that the likelihood of receiving an RA while leveling off is three times lower when the vertical speed of a climbing or descending aircraft is reduced to less than 1500 fpm within the last 1000 feet of the climb or descent. Observations made during the simulator data collection noted that approximately 65% of the pilots reduced their vertical speed when climbing or descending towards another aircraft when that aircraft was observed visually, observed on the traffic display, or after the traffic advisory (TA) was issued. Any Negative RAs issued after these reductions in vertical speed reinforced the actions taken by the pilots. The Federal Aviation Administration's Advisory Circular 120-55B currently addresses reducing vertical speed to between 500 and 1500 fpm during the last 2,000 feet of a climb or descent under 'Good Operating Practices'. The ICAO Operations Panel (OPSP) has prepared proposed amendments to Annex 6 and PANS-OPS that contain similar recommendations.

The OWG supports the OPSP recommendations to reduce the vertical speed to a value between 500 and 1500 fpm when within 1000 feet of an assigned altitude when the pilot is aware of traffic at or maneuvering to level at an adjacent altitude. The pilot can become aware of such traffic via visual acquisition of the traffic, from information shown on the traffic display, or from information provided by the controller. It is recommended that this guidance be included in pilot training programs as soon as possible. The longer term solution to this issue, as defined in the draft ICAO guidance material, is to have the autopilot or flight management system incorporate logic that automatically reduces the vertical speed when approaching an assigned altitude. The OWG fully supports this longer term solution for new aircraft and flight control system certifications. The OWG does not believe that retrofitting existing aircraft should be mandatory.

Whilst working on Negative RAs, the OWG has noted another more general issue: there are some inconsistencies in the published procedures that define the expected response to RAs. These inconsistencies exist in both high level guidance material on RA responses from ICAO and States and in detailed procedures contained in operators' training and operations manuals. Since this finding is a by-product of the OWG's work to date, whose purpose was not to review procedures, the OWG recommends that additional, detailed reviews of procedures and guidance for responding to RA, be completed to determine if there are other inconsistencies contained in Training Manuals and Flight Operations Manuals. The OWG would then develop recommendations on changes that should be made to published procedures and guidance, and define what form and type of additional guidance should be given to operators of TCAS equipped aircraft. It is estimated that the completion of this work would require approximately eight months and would require cooperation from operators and manufacturers to allow the review of their publications to be made by the OWG.

The work completed by the OWG has identified several RA display implementations that do not meet the requirements contained in DO-185A. The OWG recommends that the display implementations and the requirements of DO-185A be consistent. This can be accomplished by recommending modifications to existing display systems or if appropriate, modifying the requirements contained in DO-185A. In those cases where discrepancies are noted between implementations and DO-185A requirements, SC-147 should evaluate whether the displays deviating from the DO-185A requirements meet the technical and operational intent of the DO-185A requirements.

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If this evaluation determines that the existing implementations meet the intent of the DO-185A requirements, DO-185A should be modified to explicitly permit these implementations to be used by other manufacturers. Should the evaluation determine that the current implementation does not meet the technical and operational intent of the MOPS requirements, the appropriate certification authorities should be provided with information that documents the non-compliance with DO-185A, the concern of the OWG, and a request to review existing implementations to determine if any changes are necessary.

Even when they are understood correctly, and result in the desired action, flight crew can report the RA to the controller in a way that will mislead the controller. For example, an AVS RA to reduce the rate of climb is sometimes reported as "TCAS climb" because a rate of climb is recommended by TCAS and the aircraft is climbing. Where this RA is coordinated, the other aircraft might well have received a climb RA and the pilot of that other aircraft should report "TCAS climb". The controller then hears "TCAS climb" from both flight crew and, at best, is confused. It is recommended that problems with the phraseology for reporting AVS RAs to the controller be brought to the attention of the FAA.

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1 INTRODUCTION

1.1 Statement of purpose

Monitoring of TCAS performance has identified instances where flight crews responded in the opposite direction to that specified by TCAS when the resolution advisory (RA) was displayed to the flight crews. These opposite responses were observed for RAs classified as Negative RAs by the collision avoidance system (CAS) logic, and are characterized by the fact that the flight crew believes their response is correct, i.e., not opposite. A Negative RA is typically issued when a TCAS-equipped aircraft is climbing or descending towards another aircraft, and the CAS logic determines that the TCAS-desired vertical miss distance between the two aircraft can best be achieved by the TCAS aircraft reducing its vertical speed. Negative RAs are also referred to as Adjust Vertical Speed, Adjust (AVSA) or Vertical Speed Limit (VSL) RAs. The terms "Negative RA", "AVSA RA", and "VSL RA" are used interchangeably in this report. The focus of this report is on Negative RAs that are issued as the initial RA received during an encounter. All references to "Negative RAs" should be interpreted as referring to initial Negative RAs.

In these types of encounters, TCAS can issue RAs that call for the existing vertical speed to be reduced to a value less than 2000, 1000, 500, or to 0 feet per minute (fpm). These RAs are accompanied by an aural annunciation of "Adjust Vertical Speed, Adjust". The proper response to a Negative RA is always a reduction in vertical speed, i.e., a maneuver towards level flight. When a flight crew maneuvers in the opposite direction to a Negative RA, it is maneuvering towards the intruder and thus reducing rather than increasing the vertical miss distance with the other aircraft. Such an opposite response represents a safety issue. Although the Operations Working Group (OWG) has not developed a standard definition of an opposite response, the OWG has agreed that responses with a sustained and noticeable change in vertical speed that is opposite to the RA sense is required to classify the response as an opposite response. Different organizations supporting the OWG have defined their own criteria to complete their analyses.

If an opposite response results in continued vertical convergence between two aircraft, the TCAS logic will strengthen the initial Negative RA by issuing either a stronger Negative RA or a Climb or Descend RA, as appropriate. A Climb RA is considered an "up-sense" advisory and would be issued if the response to a Negative RA calling for a reduction in descent rate is not achieving the TCAS-desired separation. A Descend RA would be issued in cases where the initial Negative RA called for a reduction in climb rate.

Because opposite reactions to Negative RAs have been regularly identified since the introduction of TCAS II, and have continued since the introduction of TCAS II Version 7, RTCA Special Committee (SC) 147 was tasked to perform studies and analyses to investigate the display configurations and aural alerts used for Negative RAs. The purpose of these investigations was to determine whether any problems exist with the current requirements for displaying and annunciating this class of RAs. SC-147 requested that the OWG investigate this issue and provide a report that documents whether any problems exist in the current requirements for displaying and annunciating Negative RAs and if so, to recommend an approach to resolving the identified problem(s).

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This report presents the results of the OWG's initial investigations, provides a definition of factors the OWG believes contribute to the opposite responses, and presents recommendations for future work to identify items that will improve pilot response to these types of RAs.

1.2 Background

Operational monitoring conducted during the introduction of TCAS II V6.04A showed that there were sometimes errors in understanding the aural annunciations "Reduce Climb" and "Reduce Descent". Data collected during the operation of Version 6.04A determined that pilots often did not hear the first word in the annunciation and because of this did the opposite of what was required.

To improve the performance with TCAS II Version 7, the aural annunciation for Negative RAs was changed, to "Adjust Vertical Speed, Adjust" (AVSA). Although this new annunciation does not give explicit directional advice, it was selected for the purpose of alerting the pilot to the presence of an RA. The guidance is then obtained from the resolution advisory display.

Substantial numbers of aircraft started to be equipped with TCAS II Version 7 late in 2000. As with any new implementation, operational monitoring was needed. Three ICAO monitoring centers in the USA, Europe and Japan coordinated local monitoring efforts.

Europe was one of the first regions to mandate Version 7. In 2002 EUROCONTROL, CENA, Air France, the BEA, and the UK AIB detected several cases of opposite reactions to Negative RAs due to pilot misinterpretation of the RA. In each case, separation with the intruder was reduced by the pilot's reaction to the Negative RA. Simultaneously, other continuing issues with TCAS, most notably with reversals were also being observed

The issues raised were considered of sufficient concern to request the re-opening of RTCA SC-147.

1.3 Current Statement of OWG Issues

The OWG has gathered as much data as possible about opposite response to Negative RAs. During the data gathering, analysis showed that a single incident could raise more than one area of concern. After discussion, the OWG noted four categories of events associated with Negative and Preventive RAs:

1. Misinterpretation of an initial Negative RA leading to an opposite reaction (Note: The focus of this OWG work has been on opposite responses to initial Negative RAs and the remainder of this report addresses only initial RAs). A majority of the reported opposite responses to Negative RAs have occurred when the RA guidance is provided on vertical speed indicators or vertical speed tapes with a highly non linear analog scale.

2. Non reaction to a corrective Negative RA

   Note: This is not discussed further in this report.

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3. Passing through a cleared flight level whilst properly complying with a Negative RA

4. Reducing separation with the intruder whilst complying with a Preventive RA.

The OWG agreed that the first of these issues was our primary concern for data gathering and analysis because of its potential impact on safety. The other issues are noted here to help clarify the main issue and to provide additional information for training and distribution to the operational community.

1.3.1 Misinterpretation of an Initial Negative RA Leading to an Opposite Response

This issue concerns pilots increasing their vertical rate (rather than reducing it) in response to an initial negative corrective RA (i.e. the initial RA has the aural "Adjust Vertical Speed, Adjust"). Furthermore, there must be knowledge that the pilot was not deliberately going against the RA, e.g. following ATC rather than the RA, or reacting to visual information.

Figure 1-1 shows an example of misinterpreting an initial Negative RA.

The pilot of Aircraft 1 reported "exceeding the cleared level because of a TCAS RA to increase descent while visual with Aircraft 2." The descent rate of Aircraft 1 increases after the limit descent RA which required a slower rate of descent. The pilot thought he was complying with the RA.

1.3.2 Flying Through a Cleared Flight Level Whilst Complying with a Negative RA

This situation describes a level off situation where the pilot keeps the vertical speed indicator on the green arc during the RA and this results in the busting of the cleared flight level (and leveling off would have complied with the RA). Although TCAS is accurately followed, and TCAS safety parameters are respected, the case may cause disruption to ATC.

1.3.3 Reducing Separation with the Intruder Whilst Complying with a Preventive RA

A single case has been found of a misinterpretation of a pitch cue display during a Preventive RA accompanied by the aural annunciation "Monitor Vertical Speed".

Aircraft 1 was level at 6000ft and 5° pitch. Aircraft 2 was level at 5500ft. Aircraft 1 received a monitor vertical speed RA.

The pilot flying executed a descent to put the pitch marker on the horizontal line of the trapezoid. (This would be a standard procedure during a weakening RA). As a consequence the relative altitude between the two aircraft decreased. Aircraft 1 could have kept its current level and not decreased the separation between the two aircraft to 300 ft.

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