

# Characterization and Analysis of Traffic Alert and Collision Avoidance Resolution Advisories Resulting from 500' and 1,000' Vertical Separation

## FAA TCAS Monitoring in the U.S. National Airspace System

Jessica E. Olszta & Wesley A. Olson

Homeland Protection and Air Traffic Control  
Surveillance Systems

MIT Lincoln Laboratory

Lexington, Massachusetts, U.S.A.

jessica.olszta@ll.mit.edu, wes.olson@ll.mit.edu

**Abstract**— Some U.S. and international aviation organizations have expressed a desire to reduce the existing Traffic alert and Collision Avoidance (TCAS) Resolution Advisory (RA) rate, especially in those cases where the alerts are perceived unnecessary, such as where TCAS alerting criteria is incompatible with normal and safe ATC vertical separation. The first step in pursuing this goal is a comprehensive examination of data to quantify and characterize actual TCAS RA experiences and identify: 1) if nuisance RAs exist, and 2) the impact on airspace efficiency and workload. In this study, data on 36,689 TCAS RAs from five terminal areas collected under the Federal Aviation Administration's (FAA) TCAS Operational Performance Assessment (TOPA) program were analyzed to determine the relationship between vertical separation and TCAS RA experiences. The results show that most RAs are likely due to interactions between TCAS aircraft operating under Instrument Flight Rules (IFR) and other aircraft operating under Visual Flight Rules (VFR). Normal, legal, 500' foot vertical separation between IFR and VFR traffic in Visual Meteorological Conditions (VMC) contributed to ~65% of the RAs observed in terminal airspace. Additionally, RA encounters occurring when IFR aircraft intentionally level-off in close horizontal proximity to other aircraft 1,000' above or below contributed to approximately 7% of all the terminal RAs studied. In order to better understand the impact of these RAs on pilot workload and airspace efficiency, this study also examined other facets of TCAS performance including: the types of RAs issued, relevant encounter features such as the vertical geometry, operating rules of the aircraft involved, and locations relative to navigational fixes. These analyses found that TCAS is operating as intended in most cases by providing alerts that enhance situational awareness on the flight deck but should not increase pilot workload or cause disturbances in the National Airspace System (NAS).

*Keywords; TCAS; collision avoidance; aviation safety*

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### I. INTRODUCTION: 500' & 1,000' VERTICAL SPACING IN THE U.S. NAS

#### A. Description of Operation

Analyses of U.S. TCAS monitoring data suggest that RAs may often result from normal interactions between TCAS aircraft operating under Instrument Flight Rules (IFR) and other aircraft operating under Visual Flight Rules (VFR) or also operating under IFR [1], [2]. In the U.S. National Airspace System (NAS), aircraft operating under IFR are provided 1,000' vertical separation from other IFR aircraft and 500' vertical separation from aircraft operating under VFR. This vertical separation is the result of the hemispheric rule for IFR and VFR cruise altitudes [3]. When flying westerly courses (magnetic courses 180 – 359 degrees), IFR altitudes are even thousands (i.e. 4,000', 6,000') and VFR altitudes are even thousands plus five hundred feet (i.e. 3,500', 5'500'). For easterly courses (360 – 179 degrees), the rule is applied as above with odd thousands. For most structured IFR and VFR operations, these recommended altitudes and the resulting 500' and 1,000' vertical separation between the aircraft operations result in safe and efficient flight operations.

#### B. TCAS RA Monitoring and Data

In 2008, the FAA's TCAS Program Office initiated the development of a nationwide TCAS Operational Performance Assessment (TOPA) monitoring network with 21 planned monitoring locations across 18 terminal areas in the U.S. with all monitoring locations to be operational by the end of 2011[1]. The primary data collected by the TOPA program is RA downlink information transmitted by a TCAS aircraft's transponder upon interrogation from a Mode S radar whenever the aircraft has an active TCAS RA. RA downlinks are only transmitted in response to interrogations by Mode S radar. Therefore, RA downlink reports occur approximately every 4.6 seconds for short range radars which provide information on all activity within 60nm of the sensor. The TOPA program collects TCAS RA downlink information via data extraction

from existing FAA radars to gather RA downlink contents and associated surveillance information.

Data are sent to MIT Lincoln Laboratory for processing and storage. During processing, the RA downlinks are de-identified by removing the Mode S address and the day of the month in order to protect privacy of pilots, controllers, and aircraft owners/operators. During processing, the surveillance data is correlated with the RA downlink information; the surveillance tracks are interpolated to one second increments and information regarding each RA encounter is permanently stored to facilitate further analysis. The database includes information on RA type, location, aircraft involved and encounter parameters such as velocities and separation. The analysis reported here is drawn from 36,689 RA encounters recorded in the Boston, Philadelphia, New York, Southern California and Dallas terminal areas in 2008 and 2009.

### C. 500' & 1,000' Vertical Separation RAs

In order to better understand typical vertical miss distances and to estimate the impact of 500' and 1,000' vertical separation on TCAS RA experiences, 36,689 TCAS RA encounters from the TOPA database were examined to understand resulting horizontal and vertical miss distances at the time of closest approach. As shown in Fig. 1, significant clustering at vertical miss distances of approximately 500' and 1,000' is observed across the range of horizontal miss distances. This indicates that a substantial number of TCAS RAs were likely related to the standard spacing used between IFR aircraft and other IFR (1,000') or VFR (500') aircraft.

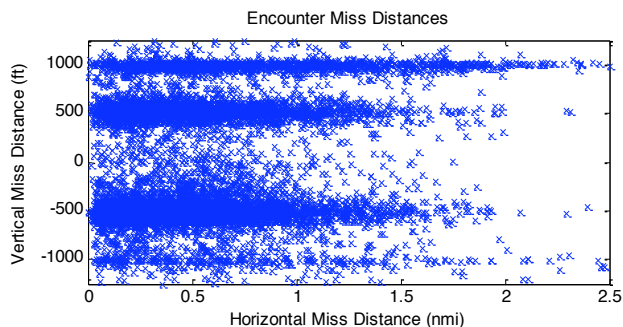


Figure 1. RA Vertical and Horizontal Separation<sup>1</sup>

RAs often result from 500' spacing because the TCAS vertical alerting threshold (ZTHR) is a minimum of 600', thus all encounters between aircraft with 500' vertical separation where the projected horizontal miss distance is within TCAS alerting criteria will generate an alert. In addition to 500' spacing between IFR and VFR traffic, previous studies and operational experiences have shown that RA encounters often occur when aircraft level-off in close horizontal proximity to other aircraft 1,000' above or below. U.S and European monitoring studies alike have observed RAs that were likely related to the level-offs of aircraft at 1,000' vertical separation operating under IFR [4], [5]. These RAs tend to occur when

<sup>1</sup> Negative vertical separation indicates the TCAS aircraft was below the threat aircraft, positive vertical implies the intruder was below.

two aircraft are navigating to the same fix and either one or both have vertical rates toward each other. In these instances, TCAS does not have information regarding flight crew intentions to level off and thus issues alerts based on projections of their continued flight paths.

## II. ASSESSMENT

### A. Geometry Classifications

Given that most of these encounters with 500' or 1,000' separation likely represent cases where normal and safe air traffic procedures are in use, yet fall within TCAS alerting criteria, these RAs may be considered “nuisance” or “unnecessary” RAs. The International Civil Aviation Organization (ICAO) defines the term “unnecessary RA” as ... “an advisory in accordance with its technical specifications in a situation where there was not or would not have been a risk of collision between the aircraft.”[6] While reduction of nuisance or unnecessary RAs is a laudable goal, detailed analysis is required to better understand the specific factors present in these encounters in order to present informed mitigation strategies and execute the appropriate safety studies that will be required prior to implementing any changes to the TCAS logic or surveillance.

In order to achieve the goals of this analysis, RA encounters were assessed to determine the vertical geometry represented by the encounter. Three categories of vertical encounter geometries were considered: 1) Level/Level, 2) Level-off/Level, and 3) Level-off/Level-off. These descriptors correlate to the vertical geometry of each TCAS and intruder aircraft trajectory. Note that in all cases, the defined “intruder” aircraft may also be equipped with TCAS. No restrictions on the horizontal geometries were imposed. A Level/Level encounter occurs if both aircraft are flying level when the RA is issued (Fig. 2).

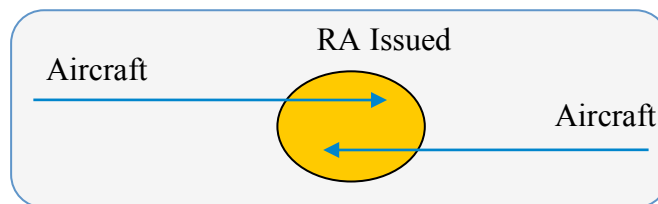


Figure 2. Level/Level Encounter Geometry

A Level-off/Level encounter occurs when one of the aircraft is level while the other aircraft changes trajectory from descending or climbing to a level path during or just after the RA is issued as depicted in Fig 3.

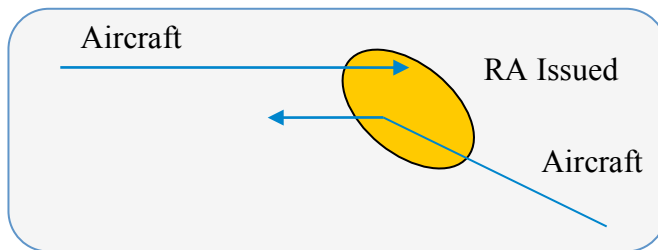


Figure 3. Level-off/Level Encounter Geometry

Finally, Level-off/Level-off encounters occur when both airplanes are climbing or descending and then transition to level flight immediately after or while the RA is issued as pictured in Fig. 4.

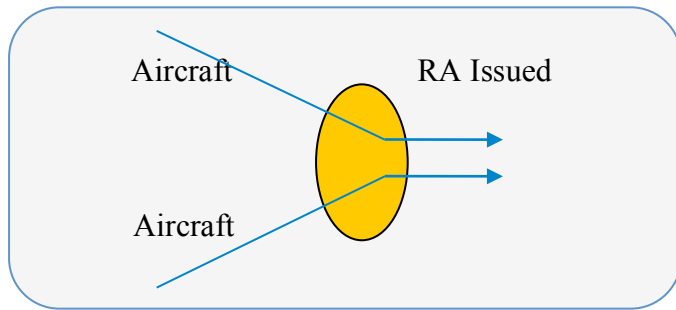


Figure 4. Level-off/Level-off Encounter Geometry

Once the overall population of encounters was separated into the described geometry categories, the remaining encounters were classified as “Other”. These specific encounters groupings were further classified by vertical separation and examined in more detail.

Automated classification of these geometries was essential given the large population of encounters which made manual examination of the size dataset impractical. An automated Matlab filter was created to examine encounters, categorize them according to the three vertical geometry categories illustrated and described above, and calculate vertical and horizontal separation. Additionally, encounter parameters such as RA type, airspace, aircraft involved were also analyzed to better understand the nature and impact of RAs related to each encounter geometry.

### III. RESULTS

According to the automated categorization and across all vertical separation levels, the majority (57%) of encounters were classified as Level/Level, 23% were Level-off/Level, 3% Level-off/Level-off, and the remaining 17% (other) were not classified (Fig. 5).

#### Overall Geometry Classifications

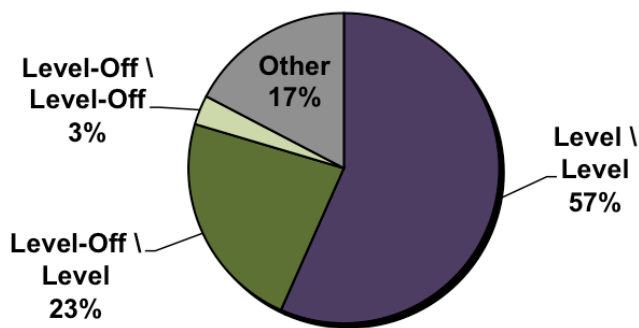


Figure 5. Encounter classification Overall

Within each encounter geometry category, vertical separation at time of closest approach was determined and

encounters were categorized based on IFR/VFR and IFR/IFR separation criteria: 1) 500’ vertical separation, which is typical IFR/VFR separation in visual conditions and 2) 1,000’, which is typical IFR/IFR separation in all airspace classifications. These results are depicted in Fig. 6 and Table 1. Fig. 6 indicates the proportion of 500’ and 1,000’ vertical separation for each geometry category. Recall that most encounters are Level/Level (57%) and very few (3%) are Level-off/Level-off. To provide information on overall frequency, Table 1 depicts the percentage of each encounter geometry and vertical separation level relative to the entire population of 36,689 RAs.

#### Geometry by Vertical Separation

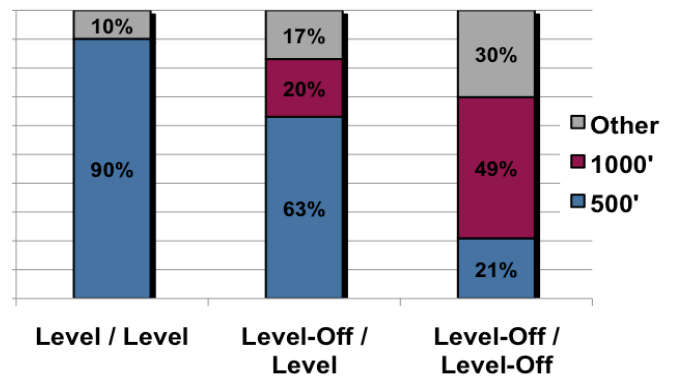


Figure 6. Geometry and Vertical Separation

TABLE I. TABULAR DATA FROM FIG. 6

Vertical Geometry	500'	1000'
Level-Level	51%	0%
Level-off/Level	14%	5%
Level-off/Level-off	1%	2%
<b>Total of Encounters</b>	<b>66%</b>	<b>7%</b>

The results show that 500’ vertical separation, commonly used between IFR and VFR traffic in the U.S. contributed to approximately two thirds of all RAs while 1,000’ vertical separation contributed to approximately 7% of all RAs. Taken together, these findings suggest that approximately three quarters of all RAs may be related to the separation associated with normal and safe airspace procedures. Each geometry category shows specific patterns related to 500’ and 1,000’ vertical separation.

Most Level/Level RAs (90%) were associated with 500’ vertical separation. The remaining 10% of Level/Level encounters generally reflect encounters with less than 500’ vertical separation. No 1,000’ vertical separation encounters were observed in the Level/Level geometry as expected since the TCAS vertical alerting threshold (ZTHR) is 600’ up to FL200<sup>2</sup> and 700’ between FL200 and FL420. Thus, aircraft that are in level geometries with at least 1,000’ vertical separation should not trigger a TCAS RA. Fig 6 shows that 51% of all

<sup>2</sup> Class A pressure altitudes are described by flight levels (i.e. FL200 = 20,000’ above a standard datum plane which is based on 29.92” Hg)

RAs are Level/Level classified encounters with 500' vertical separation.

The Level-off/Level geometry classification shows a mix of 500' and 1,000' vertical separation with the majority ( 63%) due to 500' vertical separation. This is not unexpected since TCAS may issue RAs when a moderate or high vertical rate of climb or descent is maintained close to the intended level-off altitude when a level aircraft is either above or below. 500' and 1,000' vertical separation contributed to 63% and 20% respectively, of level-off/level RAs. When considering the overall population of RA encounters, Fig 6 shows that 14% of all RAs were Level-off/Level RAs with 500' separation and 5% were due to 1,000' separation.

The last encounter geometry examined, Level-off/Level-off, showed a preponderance of 1,000' vertical separation with 49% of the Level-off/Level-off RAs attributed to 1,000' vertical separation and only 21% from 500' spacing. These results correlate with the common air traffic procedures for IFR traffic where climbing and descending aircraft are both leveling to a cleared altitude 1,000' apart at the same navigation fix. While it is noteworthy that the 1,000' Level-off/Level-off RAs are likely due to normal procedures, the frequency of occurrence is relatively low and only accounts for approximately 2% of all the RAs included in the study. The 500' Level-off/Level-off are even more infrequent since IFR and VFR traffic may be less likely to level-off near the same navigation fix. 500' Level-off/Level-off encounters account for only 1% of all RAs. Taken together, 500' vertical spacing between IFR/VFR aircraft contributes to 66% of the 36,689 RAs studied and 1,000' spacing between IFR traffic accounts for approximately 7%.

#### A. RA Types

The general quantification provided in the previous section does not provide the detail required to assess TCAS performance or fully understand the operational impact these RAs have on the pilots or air traffic system, therefore, the type of RAs<sup>3</sup> issued is an important factor. TCAS may issue RAs in situations where the projected vertical miss distance at the closest point of approach is anticipated to be below the established threshold. There are two categories of RAs, corrective and preventive. Corrective RAs advise a pilot to achieve a vertical rate that differs from their current state while preventive RAs simply advise a pilot to maintain their current vertical rate state to satisfy the vertical miss distance requirements. Within corrective RAs, Climb and Descend RAs generally command a greater change in vertical rate than Adjust Vertical Speed, Adjust (AVSA) RAs which require only a slight modification (reduction) in their vertical rate. TCAS Version 7.0 RAs are described in more detail in Table 2. Monitoring studies indicate that approximately 40 - 45% of RAs are preventive MVS RAs with the remainder corrective AVSA (~20%) or Climb/Descend RAs (~35%) [1].

TABLE 2. VERSION 7.0 RA TYPES

Version 7.0 RA	Type	Pilot Response
Climb & Increase Climb	Corrective	Requires change in vertical rate from current state (i.e. climb from level)
Descend & Increase Descend	Corrective	Requires change in vertical rate from current state (i.e. descend from level)
Adjust Vertical Speed (AVSA)	Corrective	Requires minimal change from current vertical rate (i.e. reduce climb/descent rate)
Monitor Vertical Speed (MVS)	Preventive	Does not require any change in current vertical rate (i.e. remain level)
*Reversal, Multi-threat	* Special case and infrequent RAs, not evaluated in this study	

From the perspective of the flight crew and ATC, the corrective Climb and Descend RAs would likely be the most disruptive to airspace efficiency given that they generally require pilots to deviate from their current path and achieve at least a 1,500 fpm vertical rate in the appropriate direction. If a corrective Climb or Descend RA strengthens, an increase in vertical rate from 1,500 fpm to at least 2,500 fpm is required. Note that in some cases, a preventive "Maintain Climb" or "Maintain Descend" RA can be issued when the pilot is currently climbing or descending in excess of 2,500 fpm in the same vertical direction and in these cases, the RA serves to advise the pilots to continue but maintain at least the current vertical rate. The AVSA RAs are generally less disruptive than Climb and Descend RAs even though they also are considered corrective. AVSA RAs will advise the pilots to reduce their current climb or descent rates and will provide guidance regarding maximum allowable vertical rate that should be maintained. AVSA RAs typically occur when a pilot is climbing or descending toward their altitude clearance while another aircraft is level or leveling just above/below their projected path. These RAs command a reduced vertical rate in situations where TCAS projects a potential conflict based on a straight projection of the current vertical profile. If a pilot is climbing or descending toward a cleared level-off altitude, the AVSA guidance is in line with their intentions.

Finally, preventive Monitor Vertical Speed (MVS) RAs do not require pilots to change their flight path. They serve as a time-critical alert advising pilots not to deviate from their current vertical profile to avoid a potential conflict with an aircraft that is above or below. During initial development of the TCAS logic, alerting thresholds were intentionally designed to provide an MVS RA in situations where level aircraft are vertically separated by 500'. Given the potentially short alert time available in this situation in the event of a sudden vertical maneuver, the MVS RA was intended to supplement the TA by reinforcing the potential threat posed by nearby traffic 500' above/below and the necessity to avoid altering the existing vertical rate. Since MVS RAs require no change to the current flight path, they were expected to have minimal negative effect on pilot workload or airspace efficiency.

In order to determine whether existing TCAS logic is functioning as intended, RA types were examined within each encounter geometry category. Based on intended TCAS design,

<sup>3</sup> TCAS provides vertical guidance only when issuing RAs, horizontal maneuvering is not commanded nor is it authorized without ATC approval

it was expected that Level-Level encounters would primarily lead to MVS RAs while Level-off RAs would be predominately AVSA or MVS RAs. The encounter geometry by vertical separation of 500' and 1,000' are shown in Fig. 7.

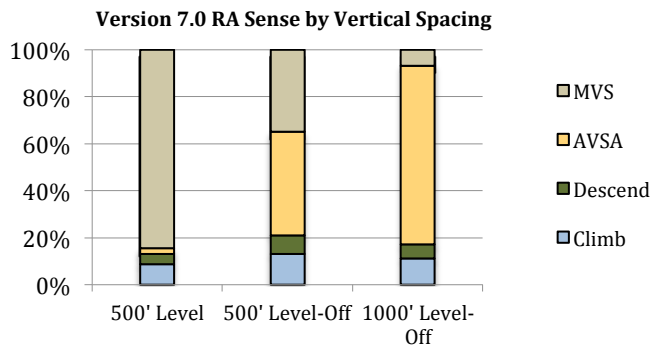


Figure 7. RA Sense by Geometry and Vertical Separation

Fig. 7 shows TCAS generally alerts as intended in the Level/Level or Level-off geometries by primarily issuing AVSA and MVS RAs in ~80% of encounters. By design, AVSA and MVS RAs require little or no pilot response, thus the workload and operational impact on airspace operations is likely minimal while maintaining a safety benefit through improved situational awareness to the flight crews.

In order to further minimize airspace impact, TCAS design intends RAs are primarily issued to the leveling aircraft in level-off/level coordinated encounters where both aircraft are TCAS equipped. In these cases, TCAS logic prioritizes RA issuance to the aircraft that has a vertical rate while the level aircraft is less likely to receive an RA. Fig. 8 shows that of the coordinated 1,000' level-off encounters analyzed; only the leveling aircraft received an RA in 97% of the encounters.

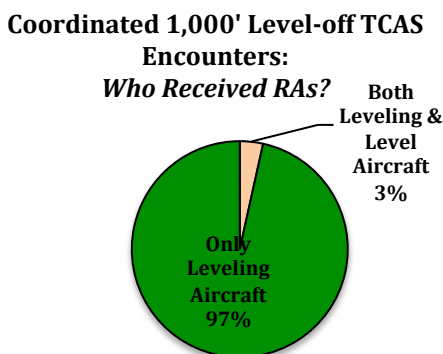


Figure 8. Coordinated 1,000' Level-off RA Prioritization

Taken together, these findings show that of the classified encounters for 500' and 1,000' vertical spacing geometries, **TCAS is issuing RAs as expected according to the intended design by issuing AVSA or MVS RAs in 85% of Level/Level and Level-off encounters.**

**B. Airspace**

The preceding analyses regarding geometry and vertical separation clearly show that most RAs are related to 500' vertical separation, which is a common separation standard for

IFR and known VFR traffic. Airspace class has a significant impact on the interaction between IFR and VFR traffic and provided vertical separation. For example, VFR traffic is not allowed in Class A airspace and is restricted in Class B airspace. Additionally, since all air traffic in Class A airspace is IFR and participation in ATC separation services is mandatory, relatively few RAs should be due to co-altitude encounters and level-off RAs may be more common. The following section describes RA experiences within each airspace class.

Class A Encounters

Class A airspace is the most strictly controlled airspace with the requirement that all aircraft operate under IFR and adhere to ATC clearances and separation is provided to all aircraft. In the U.S. NAS, Class A airspace is defined as all non-special use airspace above 18,000' pressure altitude up to FL600. Separation requirements are nominally 1,000' vertical and 5 nmi lateral. Relatively few RAs occur in this airspace as the required separation is almost always outside of TCAS alerting criteria, however, the 1,000' spacing can lead to Level-off RAs when aircraft climb/descend at relatively high vertical rates toward their assigned altitude with another aircraft 1,000' above or below. Fig. 9 and the corresponding data table show the relative percentage of 500' and 1,000' spacing and the other remaining RAs by airspace class.

No 500' RAs were observed in Class A airspace since VFR separation is not permitted. 71% of the RAs occurring in Class A airspace are attributed to the 1,000' level-off geometries while the remaining 29% fell in the "other" category.

Class B Encounters

Class B airspace has a mix of IFR and VFR traffic, but all traffic is controlled and operating on an ATC clearance. The occurrence of 1,000' vertical spacing RAs (10%) is not entirely unexpected and is likely due to the vertical rates achieved by high-performance aircraft flying into large commercial airports, especially if they maintain these rates until just prior to leveling off. However, the high percentage of 500' RAs (67%) is more surprising since limitations on VFR traffic in the Class B airspace might be expected to reduce the prevalence of 500' vertical spacing. However, while many pilots operating under VFR choose to avoid Class B airspace if possible, there are still numerous VFR users of this airspace. The VFR flights transiting Class B are typically provided 500' vertical spacing between other IFR traffic when visual acquisition exists. VFR flights in Class B typically include operations such as traffic reporting, medical flights and law enforcement, and many receive 500' separation from IFR operations. Remember, however, that while 500' vertical separation may seem low, all the encounters involve aircraft that are operating on a clearance, cooperating with air traffic control for separation and sequencing, and are flying in VMC using see and avoid separation procedures.

## RA by Airspace

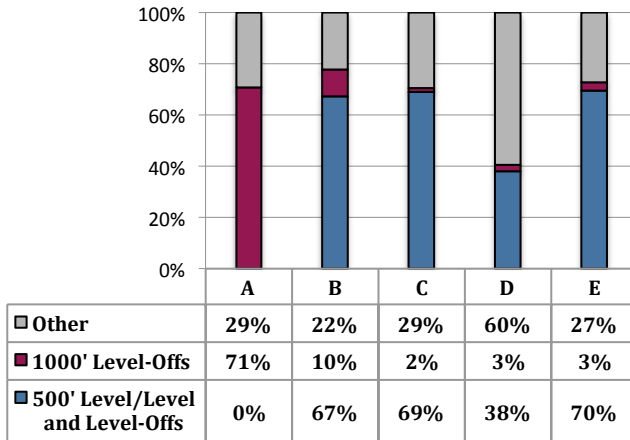


Figure 9. RAs by Airspace & Vertical Separation

The remaining 22% of RAs occurring in Class B are not comprised of the 500' and 1,000' geometry categories, however, TOPA monitoring data indicates that approximately 16% of all Class B RAs occur during approach to closely-spaced parallel runways thus it is estimated that the combination intentional 500'/1,000' vertical spacing and parallel approach RAs account for 93% of RAs in Class B airspace. The remainder (7%) have been noted in many cases to be scenarios where TCAS aircraft receive RAs from intruders just under or outside the vertical and lateral limits of the Class B or occur when visual procedures and separation are used such as visual climb and descents at the discretion of the pilots, or interaction with helicopters operating in close vicinity of the airport of intended landing or departure.

### Class C RAs

Class C airspace is similar to Class B since all IFR and VFR traffic must cooperate with ATC, and 500' vertical spacing between IFR and VFR aircraft is also used for separation. Approximately 69% of all Class C RAs are attributed to the use of 500' vertical spacing. Very few 1,000' vertical spacing RAs were observed (only 2%) and 29% of the remaining RAs were of the "Other" classification.

### Class D RAs

Class D is typically the volume of airspace within 4 nmi and 2,500 ft around tower controlled airports. While most users in Class D airspace are general aviation aircraft, some airports within Class D airspace also support commercial air carrier operations. This airspace is primarily intended to restrict traffic to only those landing or departing the airfield. ATC provides sequencing instructions and traffic advisories to these aircraft but structured separation is not necessarily guaranteed. When weather permits, most operations are VFR with visual separation and most RAs are expected to occur during descents to or climb-outs from the airfield, as well as in the traffic pattern. Fig. 9 shows that in contrast to Class A, B, C, and E airspace, Class D airspace has the highest percentage of RAs attributed to the "Other" classification (60%). Only 2% of RAs are related to 1,000' level-offs that may simply be IFR traffic

passing above the airspace ceiling. The remaining 38% are classified as 500' level/level or level-off encounters. Since there is no structured separation by ATC between IFR and VFR traffic in Class D and the hemispheric rule for altitudes to fly does not apply below 3,000' AGL, the relatively high percentage of 500' vertical spacing RAs is initially surprising. However, the main explanation is that traffic pattern altitudes between turbine aircraft such as business jets equipped with TCAS and the lower-performance, piston aircraft typically differ by 500' vertically and most airports within Class D publish traffic pattern altitudes for piston aircraft at 1,000' above ground level (AGL) with jet traffic at 1,500' AGL. This keeps the aircraft of significantly different speeds from interacting at the same altitude while sequencing to land, however, the 500' vertical separation coupled with low horizontal separation due to visual separation procedures will often be within TCAS alerting criteria, especially if one or both of the aircraft are maneuvering vertically towards each other.

### Class E RAs

Class E is considered controlled airspace since it is designated for use by IFR traffic where ATC provides separation to all IFR aircraft. However, Class E airspace also has VFR traffic that freely uses it along with the IFR traffic. Some VFR aircraft are operating on discrete codes and are receiving traffic advisories and are cooperating with ATC while others are strictly VFR on 1200 codes (if transponder equipped) and are not communicating with any controlling agency. Air Traffic Control will utilize 500' spacing between IFR aircraft and VFR aircraft (both on discrete and 1200 codes) in visual conditions to increase airspace efficiency. Also, flight altitudes based on the hemispheric rule put VFR aircraft in level flight 500' above or below those level IFR altitudes [3]. The use of 500' vertical separation is a visual separation procedure and is not employed between IFR only aircraft unless in special circumstances the pilots have requested/accepted visual separation. Fig. 9 shows that Class E airspace has the highest prevalence of 500' vertical spacing RAs (70%) while 1,000' level-offs account for only 3% of RAs observed, and the remaining 27% are "Other" geometries and vertical separation.

### C. 1,000' RA Locations

As indicated by in the previous section, approximately 22% of the RAs in the TOPA database were attributed to Level-off geometries and of that total, one third are related to 1,000' IFR/IFR separation. Level-off RAs may occur when TCAS aircraft are climbing or descending toward their assigned altitude and receive a TCAS RA based on another aircraft that is level or also leveling off above or below their assigned altitude. A geographic analysis of these RAs indicated that these RAs often occur at specific locations (navigational fixes) used for arrival/departure routes where IFR traffic is operating under ATC clearance and control. Fig. 7 provides an example of these locations or "hot-spots" of level-off RA locations resulting from the interaction of TCAS aircraft on Standard Terminal Arrival procedures (STARs) and Departure Procedures (DPs) at Los Angeles International

Airport (LAX) as well as at Dallas Fort/Worth International Airport (DFW).

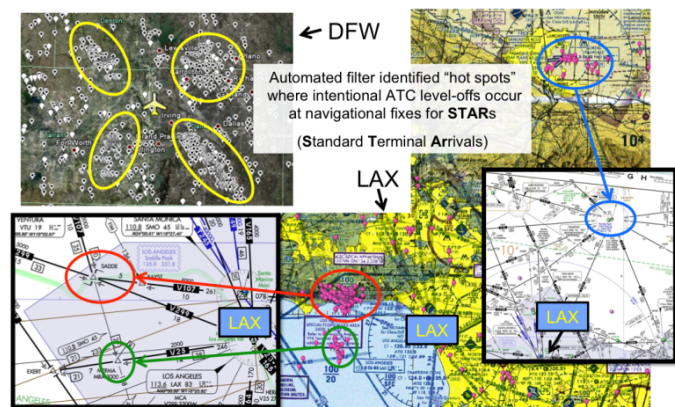


Figure 7. Level-off RA "Hot-Spots" Examples

Fig. 7 depicts several locations where RA clusters exist along with the corresponding navigational fixes from the aeronautical charts. These locations are typically included in the IFR arrival and departure procedures for aircraft operating out of the associated airports and often correspond with published altitude restrictions. Depending on the airport configuration in use and corresponding TRACON sequencing, the departing IFR aircraft may be climbing toward these fixes at the same time that arrivals are descending to or level at the same fix. The vertical separation is at typically 1,000' between these operations and TCAS may issue RAs if the vertical rates and projected vertical miss distance along with the horizontal miss distance projections are within TCAS alerting criteria. While the examples above show fixes relevant to DFW and LAX airports, there are other locations in other terminal areas as well that have similar characteristics.

#### D. Flight Operation

A previous TOPA study examining the TCAS RA experiences of air carriers compared to business jets found the percentage of RAs received by business jets and air carriers was similar. However, business jets had higher RA rates, mostly likely resulting from the higher proportion of low altitude flight to airports that lie outside of Class B airspace [2]. Business jets fly predominately in Class E airspace where interaction with VFR intruders is more frequent and less structured than the experiences of air carriers that typically operate in Class B airspace when at low altitudes (<10,000'). Therefore, it was anticipated that business jets should have more TCAS RAs resulting from 500' vertical separation when compared to air carrier operations. Additionally, since 1,000' spacing is typically associated with interaction between IFR aircraft and may be a consequence of interactions between arrival/departure procedures for busy Class B airports, it was expected that air carriers may have higher incidence of 1,000' RA encounters than business jets since they typically operate into airports outside the Class B airspace.

### 500' RAs by Aircraft Type

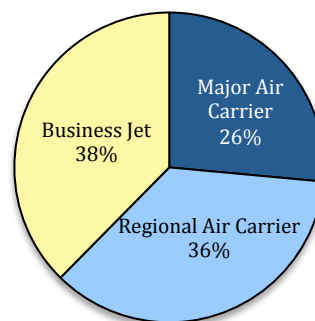


Figure 8. 500' RAs by Aircraft Type

### 1000' RAs by Aircraft Type

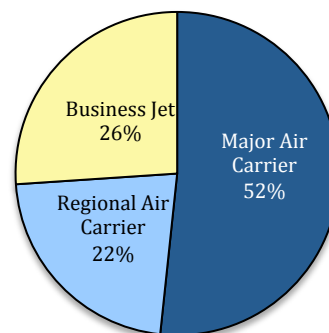


Figure 9. 1,000' RAs by Aircraft Type

Fig. 8 and Fig. 9 show the distribution of 500' (Level/Level, and Level-off) and 1,000' level-off RAs broken out by category of operation. Unlike the relatively equal distribution of overall RAs across categories, business jets had the most RAs with 500' vertical spacing category (38%), regional air carriers had slightly fewer with 36%, and major air carriers had the least with just slightly more than a quarter of the RAs (26%). This analysis corroborates the findings from the comparative study referenced earlier which indicated business jets have more interaction with VFR intruders and as a result have a higher RA rate since visual see and avoid separation, as well as 500' vertical spacing, may often fall within TCAS alerting criteria.

In contrast, major air carriers have the majority of the 1,000' RAs (52%). These RAs are predominantly a result of interaction between IFR aircraft, often between aircraft on published arrival and departure procedures for busy Class B airports. Business jets and regional air carriers have similar proportions with 26% and 22% respectively. These findings corroborate previous studies that indicate differences in RA experiences between aircraft types are driven by airspace factors related to interaction between IFR and VFR traffic. Specifically, major air carriers have the least RAs with VFR intruders resulting from 500' spacing while business jets have

the most. Also, major air carriers have the most RAs resulting from structured, ATC controlled, 1,000' level-offs.

#### IV. SUMMARY AND CONCLUSION

The goal of this study was to define and classify TCAS RA encounters related to 500' and 1,000' vertical separation, provide data regarding the frequency and rates of these occurrences, identify the contributing factors, and finally, assess whether TCAS is operating as designed. Analyses conducted on the large data set of 36,689 RAs were based on automatic classification of encounter vertical geometry. Vertical separation was calculated between the TCAS-equipped aircraft and the likely intruder, which in some cases was also TCAS-equipped. The analyses included: overall encounter geometries and associated vertical separation (500' and 1,000') within those classifications, RA types, airspace-specific factors and hot spot locations.

The results show that 500' vertical spacing for Level/Level or Level-off geometries contributed to approximately 66% of all the RAs in the dataset. This is due to an incompatibility between 500' IFR/VFR separation criteria and the TCAS vertical alerting criteria, ZTHR, which is a minimum of 600'. While the 1,000' separation provided IFR aircraft is outside of ZTHR, it can also lead to TCAS RAs when aircraft maintain a moderate to high vertical rate during level-offs above or below level or other leveling aircraft. These types of encounters represented approximately 7% of all RAs studied.

While a substantial number of RAs do result from standard separation procedures, examination of the types of RAs issued in these encounters indicates that, in general, TCAS is operating as designed. In both 500' and 1,000' encounters, the data on RA type indicates TCAS is generally performing as intended by issuing MVS or AVSA RAs. Specifically, in 90% of the level/level encounters with 500' vertical spacing, TCAS issued only preventive MVS RAs. Additionally, in 85% of 1,000' vertical separation encounters, TCAS alerted as designed by issuing MVS or AVSA RAs which should have a minimal adverse impact on flight crew workload and airspace efficiency and safety. Both MVS and AVSA RAs were generally given to the leveling aircraft and require little change to pilot vertical profile, thus they should not increase workload or adversely impact airspace efficiency.

Only a small portion (15%) of RAs from 500'/1,000' spacing were corrective Climb or Descend RAs requiring more substantial pilot deviation from the original flight path. In some cases, these were appropriate given maneuvering by either the TCAS aircraft or intruder was projected to increase the severity of the conflict. However, in some encounters, corrective RAs may be due to imperfect surveillance or vertical tracking issues related to noisy 100' altitude quantization. The data indicate that most intruders in 500' and 1,000' spacing encounters report altitude in 100' increments. Additionally, an examination of horizontal miss distances indicates that vertical separation at CPA was greater than DMOD in a majority of encounters. These findings suggest that implementation of improved TCAS tracking and/or surveillance data may lead to a reduction in RA rates.

Airspace class and procedures are related to the nature, prevalence, and locations of RAs related to 500' and 1,000' vertical separation. Analysis of RA experience by airspace class shows that RAs associated with 500' spacing are prevalent in all airspaces except for Class A where 500' separation is not allowed. 70% of the Class E RAs are attributed to 500' spacing which is not unexpected since it has the least restrictions imposed on VFR flights and considerable IFR traffic exists. 69% of Class C and 38% of D airspace RAs are 500' spacing. The RAs in Class C are mostly VFR aircraft cooperating with ATC and are being separated from IFR aircraft at 500' vertical spacing. While there is no standard vertical separation provided by ATC between IFR and VFR aircraft within Class D, the 500' RAs observed are likely a result of the difference in traffic pattern altitudes, typically 500' vertically, between turbine aircraft such as business jets equipped with TCAS and the lower-performance, piston aircraft. Class B airspace, in which all operations are strictly controlled, has a surprising number of 500' spacing RAs (67%). However, these RAs typically reflect controlled interactions between IFR traffic and common cooperative VFR airspace users such as traffic reporting, helicopter operations, medical flights, and law enforcement. Since visual acquisition and see and avoid procedures are necessary for 500' separation, these encounters likely reflect safe operations that increase efficiency, yet fall within TCAS alerting criteria. Additionally, since TCAS generally issues preventive RAs in these situations, the impact on flight crews and airspace efficiency is likely minimal, yet the increased situational awareness may be a safety benefit. Examination of 1,000' separation RAs by airspace showed that Class A airspace, where 500' separation is not used, had the highest percentage of RAs related to 1,000' separation (71%). In contrast, 1,000' vertical separation is not common in Class D and C and very low percentages of 1,000' encounters were observed. Airspace procedures also contributed to 1,000' separation encounters. An analysis of the geographic location of 1,000' encounters revealed hot spot locations at navigational fixes and common level-off points for IFR arrival and departure procedures.

This study indicates that 500' vertical spacing contributes to a significant proportion of RAs in the U.S. NAS. While some might consider these RAs to be "unnecessary", the MVS RAs that are predominantly issued in these encounters are intended by TCAS design to provide adequate alerting and situation awareness to allow prompt pilot action in the event vertical separation decreases further. When aircraft are separated vertically by 500', very little time may be available to react in the event that a converging vertical closure rate develops between aircraft. Therefore, any proposed design changes intended to reduce RAs issued in the case of 500' or even 1,000' separation must consider the corresponding impact on safety.



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## AUTHOR BIOGRAPHIES

**Jessica E. Olszta** was born in Nashua, New Hampshire. She received two Bachelor of Science degrees in aeronautical engineering and aviation flight operations from Daniel Webster College in 2008. She is an instrument-rated, single and multi-engine commercial pilot and flight instructor as well as a NH

Certified Engineer in Training. She is currently an associate staff member at MIT Lincoln Laboratory in Lexington, MA where her work encompasses two aviation safety systems that help prevent airborne and surface aircraft collisions. Additionally, Ms. Olszta participates in numerous educational outreach programs to encourage interest in science, technology, engineering, math, and aviation.

**Wesley A. Olson** received his Ph.D. (1999) in Engineering Psychology from the University of Illinois at Urbana-Champaign. He holds an FAA Air Transport Pilot rating and served in the U.S. Air Force for 22 years as a pilot flying the C-5, C-21 and TG-7 aircraft. Dr. Olson is employed by MIT Lincoln Laboratory in Lexington, MA as a Technical Staff member in the Surveillance Systems Group. He is the Lincoln program lead for support to the FAA's TCAS program office and also works with the FAA Human Factors office on the NextGen flight deck human factors research plan.