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Subject: White Paper on SA01 Near Mid-Air Collision Risk Modeling

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Approved by: _____

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Background

SA01a events occur when two TCAS-equipped aircraft are involved in a coordinated Resolution Advisory situation, one aircraft acts opposite to its RA sense, and the RA fails to reverse sense in a timely manner. The result could lead to a near mid-air collision (NMAC) or mid-air collision (MAC). SA01b events are similar but involve one TCAS-equipped aircraft against an intruder without TCAS that maneuvers in the same direction as the RA sense. Of interest is what fraction of SA01 events (either SA01a or SA01b) might result in NMACs, and ultimately, in MACs.

A Eurocontrol document (Reference 1) describes observations, modeling, and analysis of SA01 events that occurred between approximately 2001 and 2005. A total of eight events were assessed in more detail (including the Überlingen mid-air collision in 2002) with estimated horizontal and vertical miss distances shown in Figure 1. Average horizontal miss distance of SA01s was stated to be 0.8 NM (4860 ft); average vertical miss distance was 223 ft. The average horizontal and vertical miss distances are shown as forming a black-lined rectangle in Figure 1. Also shown for reference in red in Figure 1 is the generally-accepted size of an NMAC box: 100 ft vertically x 500 ft (0.082 NM) horizontally.

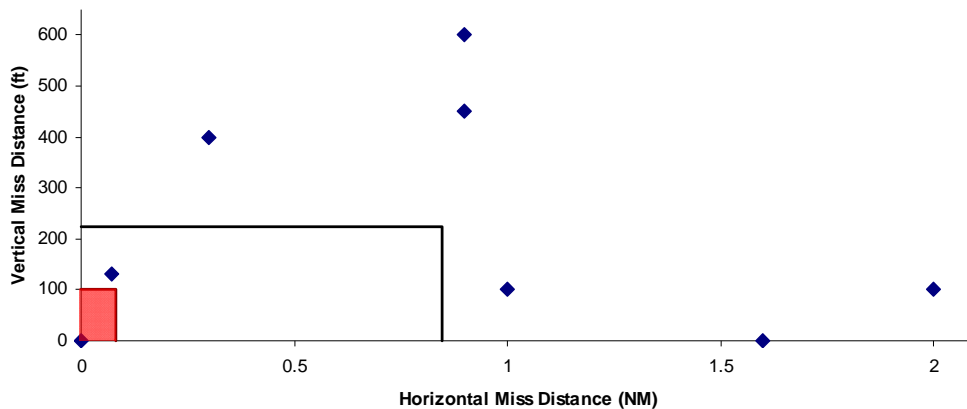


Figure 1: SA01 Event Estimated Horizontal and Vertical Miss Distances (2001-2005)

Black rectangle: average SA01 miss distances

Red rectangle: Near Mid-Air Collision Criteria

Appendix A of Reference 1 describes Eurocontrol analysis to estimate the probability of NMAC given that an SA01 event has occurred. A key assumption in this analysis is that the horizontal and vertical miss distances of SA01 events can be described by independent uniform probability distributions. That is, once an SA01 event occurs, the miss distance that results is equally-likely to occur anywhere within some region in Figure 1. Eurocontrol set the size of this region to be a rectangle equal to the average SA01 miss distances, namely 223 ft vertically and 4860 ft horizontally, as shown by the black lines in Figure 1. Under these assumptions, the probability that an SA01 event leads to an NMAC was computed as the ratio of areas of the NMAC rectangle (100 x 500) to the SA01 rectangle (223 x 4860):

$$P(\text{NMAC} \mid \text{SA01}) = (100 \times 500) / (223 \times 4860) = 0.046$$

Alternate Analysis

This white paper describes analysis performed by Lincoln Laboratory to provide an alternate estimate of the probability of NMAC given that an SA01 event has occurred.

There are two concerns with the Eurocontrol analysis. First, even given as fact the assumption of uniformity, the Eurocontrol computation of $P(\text{NMAC} \mid \text{SA01})$ is overly conservative due to their choice of the SA01 rectangle dimensions. Second, based on close encounter events observed from two different volumes of radar data in the US, the assumption of uniformity does not appear to be warranted and leads to additional conservatism. Each of these concerns is described below.

1. $P(\text{NMAC} \mid \text{SA01})$ given a uniform distribution of SA01 events.

Assume SA01 events do indeed result in uniformly-distributed miss distances. Based on the SA01 rectangle defined by Eurocontrol (223 ft vertically x 4860 ft horizontally), one would expect that the average of many random SA01 miss distances would then be in the center of that rectangle, which corresponds to 111 ft vertically and 2430 ft horizontally. But this is half of the average miss distances that were cited as occurring in the observed SA01 events. Accordingly, the rectangle that was used by Eurocontrol artificially compressed the miss distances of SA01 events such that their average miss distances were half of what was observed.

To perform this analysis properly, the SA01 rectangle should have twice the dimensions that were used. This is shown as the shaded rectangle in Figure 2. If SA01 miss distances were uniformly distributed in the shaded rectangle shown in Figure 2, then they would have the desired average vertical and horizontal miss distances (at the center of the shaded rectangle).

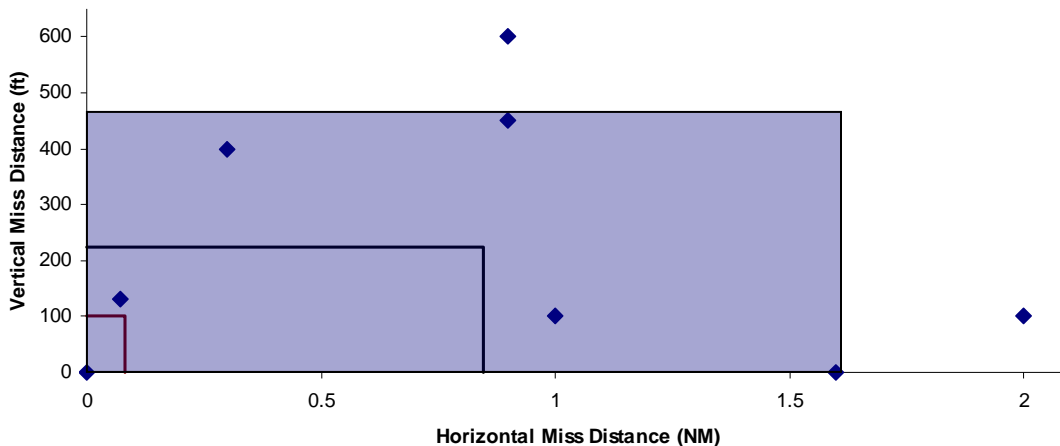


Figure 2: Shaded rectangle within which uniform SA01 events provide desired average miss distances

Now, using the shaded rectangle, the probability of having an NMAC would be given by the area of the NMAC rectangle relative to the area of the shaded rectangle:

$$P(\text{NMAC} \mid \text{SA01}) = (100 \times 500) / (446 \times 9720) = 0.012$$

This leads to a result that is one-quarter of what was computed by Eurocontrol. By reducing the SA01 rectangle to have dimensions equal to the average miss distance, the Eurocontrol analysis artificially compressed SA01 miss distances and quadrupled the NMAC risk that should apply.

An alternate interpretation could be posed in which the Eurocontrol SA01 rectangle defines the range of vertical and horizontal miss distances that would be required to be considered an SA01 event. In this case, the Eurocontrol computation of $P(\text{NMAC} \mid \text{SA01})$ would be correct, but only 2 of the 8 identified events in Figure 1 would then qualify as SA01 events (the two within the black rectangle). This might lead to a corresponding decrease in the estimated rate of SA01 events per flight-hour by a factor of 4, resulting in the same factor-of-4 reduction in SA01 NMAC risk.

2. Assumption of Uniformity.

The second concern is the assumption that SA01 miss distances are uniformly-distributed. This is a more difficult assumption to test, especially with regard to vertical motion due to the potential effects and interactions of TCAS RAs during SA01 events. However, as an indicator, the assumption of uniformity can still be tested in the horizontal plane, which is less sensitive to TCAS effects.

To perform this analysis, Lincoln Laboratory examined two sets of radar data from events in the US. The first set included 133 close encounters between two aircraft in which an RA had been issued, covering Boston (approximately 2 years), New York (approximately 2 months), and Philadelphia (approximately 51 days). The second set included 21,615 close encounters (with and without TCAS, but including at least one discrete-code aircraft) observed between 1 December 2007 and 31 August 2008 using approximately 130 radars across the US. The Lincoln datasets excluded parallel runway operations, formation flight, operations in Special Use Airspace, and events in which vertical miss distance was greater than 223 ft.

Note that the Lincoln datasets were not filtered to identify or extract SA01 events, and so they represent a significantly different population than the eight known-SA01 cases used in the Eurocontrol analysis. The Lincoln data were used under the assumption that the presence or lack of TCAS or SA01 events would not significantly affect the distribution of horizontal miss distances. Due to the lack of observability into SA01 events and the resultant uncertainty in what occurs vertically, the Lincoln data were not used to estimate vertical miss distance distributions.

Figure 3 shows the distribution of horizontal miss distances from the first dataset involving TCAS RAs. Figure 4 shows the corresponding distribution of horizontal miss distances from the second dataset, involving at least one discrete-code aircraft but in which TCAS may or may not have been present or issued an RA.

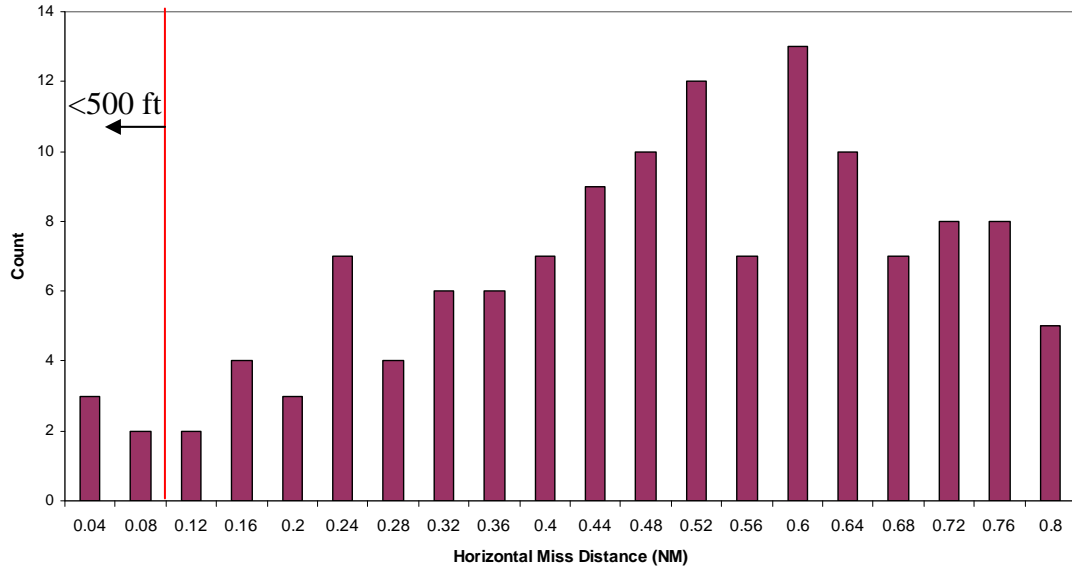


Figure 3: Distribution of minimum horizontal separation (0 – 0.8 NM)
133 close encounters with TCAS RAs in Boston, New York, and Philadelphia

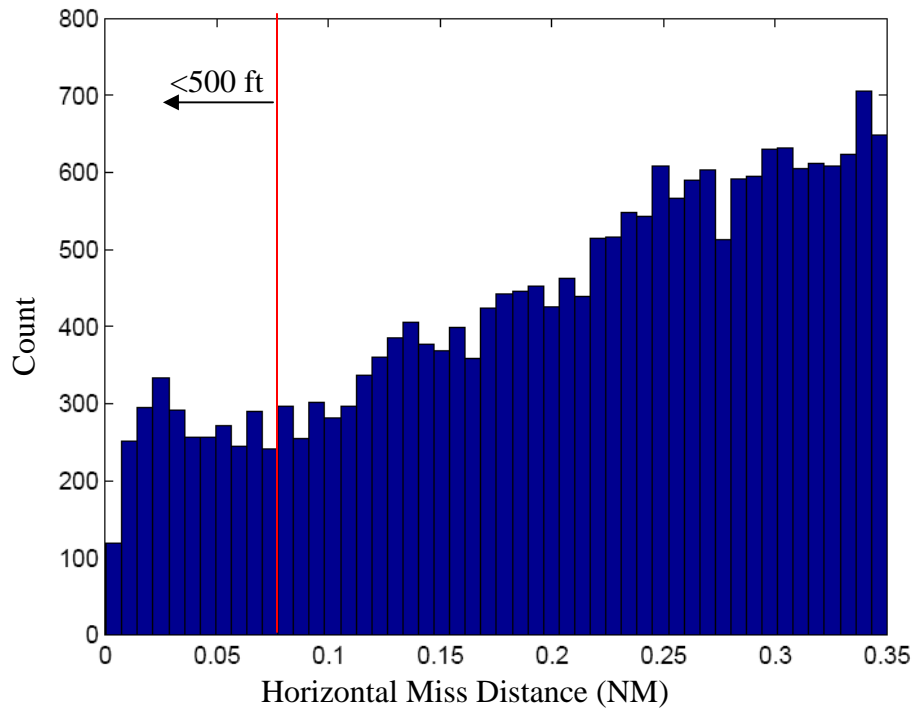


Figure 4: Distribution of minimum horizontal separation (0 – 0.35 NM)
21,615 close encounters across the US between 1 November 2007 – 31 August 2008

Each dataset shows an increasing likelihood as horizontal miss distance increases, out to or beyond approximately 0.35 NM.

In the first dataset (involving actual TCAS RAs), 5 out of 133 encounters result in less than 500 ft horizontal miss distance (3.8% of the encounters). If the 133 encounters had instead been uniformly-distributed in horizontal miss distance, the probability of NMAC would have been $(0.082 \text{ NM} / 0.8 \text{ NM}) = 10.3\%$. Thus, an assumption of a uniform horizontal miss distance distribution would overestimate P(NMAC) by approximately a factor of 2.7 ($10.3 / 3.8 = 2.7$).

The second dataset covers a different range of horizontal miss distances (0.35 NM, compared to 0.8 NM for the first dataset), but the general trend appears to be similar. In the second dataset, 3072 encounters achieved less than 500 ft horizontal separation (14.2%). If instead the miss distances were uniformly distributed, one would expect 23.4% of the encounters to result in less than 500' horizontal separation ($0.082 \text{ NM} / 0.35 \text{ NM} = 0.234$). Thus, for the second data set, an assumption of uniformity would result in overstating the probability of NMAC by a factor of 1.6 ($23.4 / 14.2 = 1.6$).

Because the European P(NMAC) estimate was computed using an interval for horizontal miss distance out to 0.8 NM, it is worth considering how the distribution in Figure 4 might behave beyond the 0.35 NM where data were actually collected. If the miss distance distribution trend in Figure 4 continued out to 0.8 NM in a linear fashion as shown in Figure 5(a) (which is speculation at this point), the observed fraction of cases that resulted in NMACs would have been 3.7% compared to 10.3% assuming a uniform distribution (uniform overestimates by a factor of 2.8). Note that this is very similar to what was observed in the first dataset. Even if the distribution continued in a uniform manner beyond 0.35 NM (Figure 5(b)), then 4.8% of the observed events would result in NMACs compared to 10.3% assuming a completely uniform distribution (uniform overestimates by a factor of 2.1).

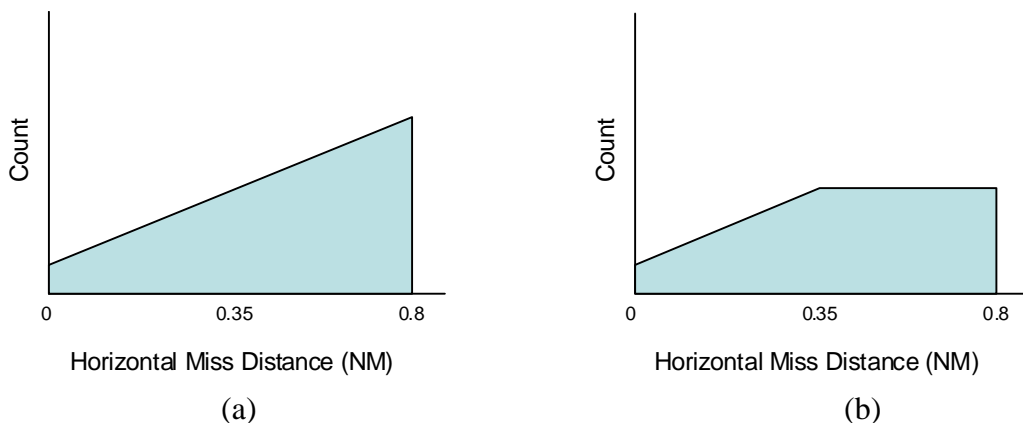


Figure 5: Hypothetical Miss Distance Distributions Beyond 0.35 NM

Accordingly, based on using a horizontal miss distance interval out to 0.8 NM from two different datasets, the Lincoln airspace data predict an NMAC fraction that is from 2.1 to 2.8 times less than was computed by the Eurocontrol analysis under the assumption of uniformity. Further investigation into the vertical miss distance distribution for SA01 events would also be warranted to confirm whether the assumption of uniform vertical miss distances is appropriate.

Summary

This white paper revisits two assumptions made in a recent Eurocontrol document describing the risk of collision due to SA01 events (Reference 1).

1. The method used by Eurocontrol to estimate the fraction of SA01 events that would lead to NMACs was found to artificially compress SA01 miss distances. The result is a quadrupling (x 4) of the probability of NMAC compared to what would normally be expected. This finding is independent of any assumptions about the uniformity of miss distance distributions and will not change as additional data become available.
2. A second Eurocontrol assumption (uniform distribution of miss distances), was found to not accurately represent miss distances between aircraft observed from radar data in the US, at least in terms of horizontal miss distances less than 0.35 NM. This resulted in an estimated two-fold (x 2) increase in probability of NMAC given SA01. Because similar non-uniform horizontal miss distance distributions were observed in a TCAS RA dataset and in a second miss distance dataset that included many non-RA encounters, this finding is expected to be independent of TCAS effects and so would hold equally well for SA01 encounters. However, the horizontal miss distance distribution will be further refined as additional TCAS RA monitoring data become available specifically for SA01 events.

The effects of the above two issues combine in a multiplicative manner, so the Eurocontrol NMAC risk estimates are felt to be at least 8 times larger than the US airspace data imply. There are parallel concerns with the assumptions made in Appendix B of Reference 1 addressing $P(\text{NMAC} \mid \text{SA-AVSA})$ due to Adjust Vertical Speed, Adjust (AVSA) issues.

It should be noted that in the absence of better information, an assumption of uniformity is often made and is often reasonable. It is only because Lincoln is fortunate to have access to a large set of radar observations that it is possible to test that assumption for horizontal miss distance. Both analyses assumed a uniform vertical miss distance distribution. If SA01 events tended to drive aircraft closer together vertically than would be expected from a uniform distribution, then the factor-of-8 level of conservatism in the Eurocontrol model would be reduced.

It is anticipated that the analysis described in this memo will be updated as additional data on SA01 miss distances become available through the FAA TCAS Operational Performance Assessment (TOPA) program. TOPA involves monitoring TCAS RAs across the US and performing analysis to identify SA01 events. When sufficient numbers of SA01 events have been evaluated, it may be possible to re-evaluate the horizontal and vertical miss distance distribution assumptions used in the Eurocontrol and Lincoln analyses.

One of the limitations of the Lincoln analysis relative to the Eurocontrol analysis is that the former is not based on SA01 events, but rather uses a much broader set of close encounter situations to infer SA01 risk. However, it is considered a reasonable assumption that SA01 behavior would not significantly affect horizontal miss distances, and so the focus of this analysis has been on the horizontal distribution. It should also be noted that the Lincoln analysis is based on US airspace data whereas the Eurocontrol analysis was based on events that occurred outside US airspace.

Further investigations will focus on using observed SA01 miss distance distributions from US airspace data via TOPA and also re-evaluating the assumption that $P(\text{MAC} | \text{NMAC}) = 0.1$, each of which may result in additional adjustments to the estimate of overall collision risk.

While both the SA01 and SA-AVSA issues are certainly of significant concern, it appears that based on US airspace data, estimates of mid-air collision risk for each have been computed in an overly-conservative manner. Despite the conservatism of the Eurocontrol document, this white paper is not intended to dispute the potentially catastrophic safety impact of SA01 or SA-AVSA events when they occur, but is intended to provide an alternate viewpoint on the likelihood that such events may lead to NMACs.

Reference

1. Chabert and Drevillon, "Decision Criteria for Regulatory Measures on TCAS II Version 7.1", Eurocontrol Mode S Programme, SIRE+/WP7/69/D, 25 July, 2008.