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STCA, TCAS, Airproxes and Collision Risk

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The focus here is on the performance of and interaction between the Traffic Alert and Collision Avoidance System (TCAS) and the controller's short-term conflict alert (STCA) system. The data source used is UK Airprox Board Reports of close encounters between aircraft, and the focus is on commercial air transport aircraft using UK controlled airspace with a radar service. Do the systems work well together? Are controllers surprised when they find out that a pilot has received a TCAS resolution advisory? What do TCAS and STCA events say about collision risk? Generally, the systems seem to work together well. On most occasions, controllers are not surprised by TCAS advisories: either they have detected the problem themselves or STCA has alerted them to it. The statistically expected rate of future mid-air collisions is estimated by extrapolation of Airprox closest encounter distances.

KEY WORDS

1. Collision Avoidance. 2. Mid-air collision. 3. ATM. 4. ATC.

1. INTRODUCTION. Aviation is a highly safety conscious industry. Tragedies provoke strong responses. The official report into the Überlingen mid-air collision tragedy (BFU, 2004) has already stimulated specific actions and proposals about what else should be done. Everyone says 'this should never happen again'. But then the question is 'what should be done to prevent this *kind* of accident?' What actually must be done? Should the focus be on improvements to existing systems – attention to specific operational practices, better-focused training programmes, etc? Or should the solution be changes to the system – fixes to technical problems, new system features, extra displayed information, etc?

Economists have a useful phrase: 'Pareto efficiency'. This is a situation in which no change can make at least one individual better off, without making any other individual worse off. There are probably very few operational safety changes of this kind. Changes can often improve safety for most potentially hazardous situations, but then have negative consequences for a few of them. In some cases, a new piece of technology can – in a very few circumstances – induce new accident types. Decisions have to be made. This makes it vital to have a full understanding of the safety consequences of changes. This understanding has to be firmly anchored in the real, current world. The safety picture has to be factually based and up-to-date. These are necessary steps in the decision-making process.

The focus here is on the performance of and interaction between the Traffic Alert and Collision Avoidance System (TCAS) and the controller's short-term conflict alert (STCA) system. Do the systems work well together? Are controllers surprised when they find out that a pilot has received a TCAS resolution advisory – or did they anticipate it happening? What are the lessons that can be learned from any incidents in which either TCAS or STCA did not function perfectly? What do TCAS and STCA events say about the degree to which potentially hazardous situations are 'under control', with the controller being situationally aware? What do TCAS and STCA events say about collision risk?

The data source used to investigate these questions is the UK Airprox Board Reports (UKAB, 1999-). Before the analysis of this data, some background is given on TCAS, STCA and Airproxes, with a strong emphasis on recent development work.

2. BACKGROUND

2.1. *Short Term Conflict Alert*. In the UK's National Air Traffic Services (NATS) version of STCA, a computer system continually monitors secondary surveillance radar (SSR) data and alerts air traffic controllers if it detects a situation where two aircraft are in danger of approaching too close to one other. Thus STCA is concerned with potential conflicts in projected flight paths. The goal is to provide a warning – with special symbols on the controller's radar display – around 90 to 120 seconds before the Closest Point of Approach (CPA) of the two aircraft. This gives them time to redirect the aircraft if they judge it necessary. STCA alerts do not imply specific mandatory action by the controller. He or she is presented with the extra information as part of the normal air traffic control (ATC) task. Similar STCA systems are in operation in many European countries and elsewhere. STCA alerts generally occur many tens of seconds *before* separation minima are breached. They are not intended to tell the controller or operational supervisors about separation minimum infringements.

The NATS STCA system became operational for parts of UK en route airspace in 1988 (Hale and Law, 1989). An essential ingredient for its introduction was a new generation of secondary surveillance radars with much better accuracy and performance. STCA versions capable of coping with complex terminal area airspaces have been in operation since the mid 1990s. The algorithms in the STCA computer software, which is under continuous development, are specifically tailored for the varieties of airspace and separation rules used in the different parts of UK. The STCA software contains a large number of parameters, whose values have to be fixed by extensive safety testing. Formal search techniques have been used in recent years. A modern heuristic technique, 'tabu search', has recently been used (Beasley et al, 2002).

One problem is that, because it uses SSR data as its basic source, STCA does not 'know' the intentions of the pilots or air traffic controllers; who may be aware of a potential conflict and already be taking measures to avoid it. As STCA must make cautious predictions, there are necessarily nuisance alerts as well as genuine alerts. There is a trade-off between genuine and nuisance alerts: if the software eliminated all the nuisance alerts, then it would also fail to identify many genuine alerts. But if there were too many nuisance alerts it would be difficult to maintain the controllers' confidence in STCA (Endsley et al, 2003). Formal analytical techniques have been applied to get the right balance (Fieldsend and Everson, 2004; see Swets et al (2000) for background).

2.2. *Traffic Alert and Collision Avoidance System.* The abbreviation TCAS is used here to mean what is more formally known as TCAS II. There is a substantial literature on the development of TCAS. The nature and history of TCAS is briefly described in FAA (2000), while Dean and Baldwin (2004) describe its current operational use in Europe. The description here is considerably simplified.

TCAS is a commercially available version of what are generically known as Airborne Collision Avoidance Systems (ACAS). These are aircraft systems using SSR transponder signals to provide advice to the pilot on potential conflicting aircraft that are equipped with SSR transponders, either Mode C or Mode S. ACAS operates independently of ground-based equipment. ACAS II is an ACAS that provides vertical Resolution Advisories (RAs) in addition to Traffic Alerts (TAs). TCAS II is a commercially available version of ACAS II. Based on the horizontal and vertical closing rates, TCAS calculates dynamic protective volumes around its aircraft. If the closing intruder is assessed as a threat, then a TCAS II system proposes an RA to the pilot as a Vertical Avoidance Manoeuvre. The system can coordinate its RA with the intruder aircraft, if it can generate an RA, so that the manoeuvres are complementary. Corrective RAs require the pilot to change the flight path of the aircraft; preventive RAs require the pilot to keep the aircraft on that flight path.

The current version of TCAS II is Version 7. From late 1999 onwards, the new version of TCAS II progressively replaced the previous Version 6.04A in all aircraft. Version 7 has many operational and technical improvements and it generates fewer false alerts:

- A horizontal miss distance filter reduces the number of occasions when an RA is triggered even though the aircraft will miss each other by a large horizontal distance.
- The thresholds for triggering an RA in the case of level off manoeuvres (where the majority of spurious RAs occur) have been changed.

TCAS II has been mandatory in US airspace since 1991. ACAS II became mandatory in Europe on the 1 January 2000, with some transitional arrangements extended until 30 September 2001. ACAS II has a worldwide ICAO mandate from 1 January 2003.

TCAS's RAs are generated much nearer to the predicted CPA than are STCA alerts. Typical threshold times are between 15 and 35 seconds before predicted CPA. This depends on the flight level of the aircraft: details are set out in FAA (2000). The TCAS RA logic requires a climb/descent to resolve the conflict. It assumes that a pilot reacts within 5 seconds of receiving the RA and then accelerates at 0·25 g to a vertical speed of ± 1500 feet/minute. Again, this is a simplification, but it does show that the total time from receipt of the RA to resolution is ~ 10 seconds.

2.3. *Airproxes.* A vital tool in learning about ATC safety is data from Airproxes. An Airprox is formally defined as a situation in which, in the opinion of a pilot or a controller, the distance between aircraft as well as their relative positions and speed have been such that the safety of the aircraft involved was or may have been compromised. The Civil Aviation Authority (CAA) and the Ministry of Defence are responsible for the joint UK Airprox Board (UKAB), which deals with all Airproxes reported in UK airspace. The UKAB's independent expert members assess every reported Airprox incident in order to determine why the events started, i.e. the causal factors, and what lessons should be learnt.

There are four Risk Level categories used by the UKAB, agreed at international level:

A. Risk of Collision: *an actual risk of collision existed*
B. Safety not assured: *the safety of the aircraft was compromised*
C. No risk of collision: *no risk of collision existed*
D. Risk not determined: *insufficient information was available to determine the risk involved, or inconclusive or conflicting evidence precluded such determination*

The extensiveness of information gathering and thoroughness of the incident assessment are of high quality. Radar tape recordings are called forward for inspection and radio-telephony (RT) transcripts are produced. Reports are collected from each of the pilots and/or controllers involved allowing them to say what they think happened. The UKAB's final report sets out what happened and why. The names of companies and individuals are removed to preserve anonymity; all language of blame is avoided to encourage open and honest reporting. UKAB risk level assessments are based on what actually took place, and not on what may or may not have happened.

3. WHAT ARE THE STCA/TCAS PROBLEMS? The official report into the Überlingen mid-air collision tragedy (BFU, 2004 [BFU's English version]) concluded that:

- "The integration of ACAS/TCAS II into the system aviation was insufficient and did not correspond in all points with the system philosophy. The regulations concerning ACAS/TCAS published by ICAO and as a result the regulations of national aviation authorities, operations and procedural instructions of the TCAS manufacturer and the operators were not standardised, incomplete and partially contradictory.
- Management and quality assurance of the air navigation service company did not ensure that during the night all open workstations were continuously staffed by controllers.
- Management and quality assurance of the air navigation service company tolerated for years that during times of low traffic at night only one controller worked and the other one retired to rest."

All of these issues have generated actions. In particular, the 'non-standard' use of TCAS has been vigorously addressed by Eurocontrol guidance, emphasizing that the pilot should disregard controller instructions when following an RA (e.g. Eurocontrol, 2002). It is worth noting (Dean and Baldwin, 2004) that 97% of pilots in TCAS European monitoring obeyed the RA – an increase of 2% on the previous year. Several specific actions and proposals have been made about what else needs be done. For example, it has been suggested that information should be automatically down-linked to the display of the controller handling the aircraft involved in a TCAS RA (e.g. see Eurocontrol (2003), Drozdowski (2004), Brooker (2004b)). Recent analyses of the Überlingen mid-air collision tragedy are by Bennett (2004), and by Nunes and Laursen (2004). Bennett reflects on safety culture and international regulation – it is not difficult to see from the BFU Report that both were deficient.

Nunes and Laursen's approach is to establish a causal chain for the accident. Their list of 'Contributing Factors' in the Überlingen accident is:

- Single Man Operations
- Downgraded Radar [STCA]
- Dual Frequency Responsibility
- Phone System
- TCAS
- Corporate Culture

The second and fifth of these – the operation of the ground and air safety nets – are of most interest here. Nunes and Laursen comment [NB: précised text]:

> STCA: "On that night, maintenance work was being done on the main radar system, which placed radar services in their fallback-mode … meant that the STCA was not available … Unit procedures specifically mandated that the STCA be available when Single Man Operation were taking place: but it was not … Had radar service not been downgraded … the STCA system would have provided the controller with over a two-minute visual warning of the collision instead of the 32-second auditory alarm that he received."

> TCAS: " … a possible design flaw in the TCAS system, which does not provide the controller with sufficient information about aircraft manoeuvre recommendations, leaving the controller 'out-of-the-loop' in terms of knowing the pilot's perceived manoeuvre choices. Similar design 'flaws' also led to the TCAS's system's inability to account for non-compliance on the part of one user, evident when it continued to instruct the B757 aircraft to increase its descent rate even after the T-154 had begun to execute the same manoeuvre, putting both aircraft on a collision course … Finally, cultural differences led the crew of one aircraft to following TCAS recommendations and another to ignore it, under high temporal pressure."

The comments about TCAS here are the kind of thinking that has led to the work on RA Downlink noted above. This poses the kind of question noted in the Introduction: "What is the best thing to do?" Thus, when a pilot does not follow a TCAS RA, is the answer to 'repair' TCAS by down-linking information to the controller? Or should the focus be on regulatory guidance and pilot training, to increase the probability that they will indeed follow the RA, and not be distracted either by controller instructions or visual acquisition of (possible?) intruders? These kinds of questions must be rationally analysed without inserting opinions or entering into some kind of 'blame-game' against particular individuals or ATC bodies.

The aim here is to focus on one aspect of these questions: "To what extent can good estimates of system risks be made by extrapolating from 'normal' hazardous occurrences?" This is distinct from risks caused by system 'abnormalities', such as defective regulation or safety culture. These abnormalities are real risks, but they overlay the proper functioning of the 'designed ATC safety system'. Thus, the key data must be factual statistical and operational information about what is actually happening in the UK ATC system. The methodology here is to analyse rationally, focusing on what the data actually says and with as few assumptions as possible, how properly-functioning TCAS and STCA work together in practice in ordinary controlled airspace in normal operation, by examining hazardous incidents carefully. People's views about this tend to be 'folk memory' of past performance, largely deriving from much earlier work, i.e. before much of the development of TCAS and

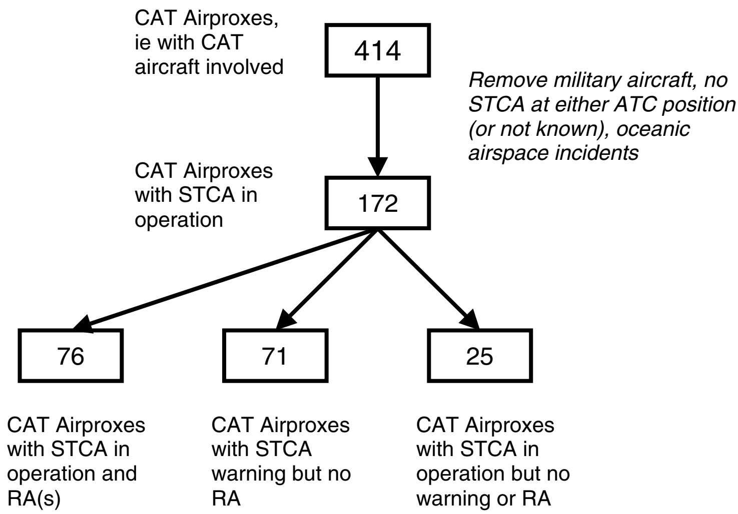

Figure 1. Extraction of TCAS and STCA related Airproxes.

STCA described briefly in the previous section, had been carried out. Hale and Law (1989) is a key reference from which the main conclusions (terminology updated) are:

Results from computer modelling of STCA and TCAS for en route UK encounters:

- Some 60% of encounters likely to result in a TCAS RA would be alerted to the controller by STCA alerts in good time to anticipate the RA.
- Of all the TCAS RAs generated, some 65% advised some manoeuvre which would be noticeable to ATC. STCA alerts would 'pre-empt' some 58% of these unanticipated manoeuvres by more than 30 seconds.

Note that these quotes from Hale and Law refer to en route encounters rather than in the airspace immediately adjacent to airports – a point examined in more detail later.

4. ANALYSIS OF AIRPROX STATISTICS. The UKAB publish full reports of their work twice a year. Each Airprox is described and assessed in between two and four A4 pages. Key data from these reports is processed by the UKAB into a computer database. The following analyses use extracts from this database, kindly provided by the UKAB in Microsoft Excel form, which in some cases have been supplemented by scrutiny of the detailed Airprox reports. The focus here is on Airproxes involving Commercial Air Transport (CAT). These are scheduled and non-scheduled passenger flights in airliners and helicopters, plus cargo flights. For the five-year period examined, 1999 to 2003 inclusive, there were 414 Airproxes involving CAT aircraft (see Figure 1).

It is worth noting that 10 of these Airproxes were assessed as Category A. Six of these were with military aircraft, mainly in Class F/G or non-rule 21 airspace (CAA, 2004c). Military aircraft are not covered by the TCAS/ACAS mandate. Three involved civil, but not CAT, aircraft, for airspace in which STCA was not in operation. Two CAT aircraft produced a RA but not an STCA alert in just one incident – the

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Table 1. Frequency of airspace types in the STCA/TCAS set.

Airspace Type	No.	%
A – Airways	10	13
A – Terminal Control Areas (Rule 21)	55	72
B – Upper Information Region FL245 -	3	4
B – Upper ATS Route	5	7
D – Control Zones and Areas (Non Rule 21)	3	4
Total	76	

Airprox happened in Oceanic airspace. The Airproxes have to be filtered down in order to concentrate on those in which TCAS and STCA can potentially interact. The first filter is to take out all those in Oceanic airspace (a discussion of safety in North Atlantic airspace is set out in Brooker, 2004a). The second filter is to take out all those involving military aircraft (a discussion of safety in UK Class F/G airspace – in which both military aircraft and some commercial aircraft operate, and where ATC *may* supply an information or advisory service – is set out in Brooker, 2003). These two filters take the number of incidents down to 267.

The next filter now focuses in on TCAS and STCA. Only incidents in which at least one aircraft received an RA are counted. Did the controllers have STCA available to them? If neither of them did, then these too are eliminated – producing 76 remaining: the 'STCA/TCAS set'. None of these 76 is identified as Category A by the UKAB. 19 of the 76 pairs of aircraft involved a non-CAT aircraft, the rest were both CAT aircraft.

For comparison, there were 71 CAT Airproxes in which there was an STCA alert but not a TCAS RA (again not counting in those involving the military, unknown data, etc). There was a variety of reasons for this: the alert was a cautious 'nuisance' type; the aircraft flight paths quickly went out of conflict; the controller resolved a conflict before TCAS came into operation; aircraft did not have TCAS fitted; etc. Note that STCA alerts in which the controller did not judge there to have been any risk of collision would not be reported to the UKAB. Thus, there were $76+71=147$ incidents in which there was either or both a TCAS RA or a STCA alert.

Interestingly, there were three of these 71 incidents categorised as 'B' risk level by the UKAB. Two of them had neither aircraft fitted with TCAS. The miss distances at the CPA, as recorded by the radar system, were: incident 51 in 2000 – 0·6 nm horizontal, zero vertical; incident 199 in 2000 – 0·2 nm horizontal, 200 feet vertical. The third incident, number 136 of 1999, involved one aircraft carrying TCAS, which had a TA but not an RA – and TCAS worked properly. The miss distance at CPA was 1 nm and 600 feet. The reason that the UKAB rated this incident as a 'B' was that there were RT difficulties, including transmissions blocked by another aircraft. The UKAB noted that: "TCAS again proved its worth."

Table 1 shows the airspace breakdown of the STCA/TCAS set. The UK airspace classes are A to G. Class A is the highest status, B, D, and E are other controlled airspace. Class C is not currently allocated. In simplified terms: Class A is Airways, except where they pass through a Terminal Control Area (TMA) or control zone of a lower status; Class B is upper airspace – above FL245; Class D/E is mostly control zones/areas. Classes F and G are uncontrolled airspace. Rule 21 of the 'Rules of the

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Table 2. STCA incident types in the STCA/TCAS set.

STCA Incident Type	Cat	No.	%
Controller action before warning	1	20	26
Warned and acted on	2	39	51
Seen by another controller	3	3	4
Warned but not actioned	4	6	8
Outside [STCA] parameters	5	7	9
Garbled	6	1	1
Total		76	

Table 3. Airproxes 'Seen by another controller'.

Airprox number	Summary	H nm	V feet
2001098	Penetration of controlled airspace. STCA-equipped colleague contacted non-equipped controller by telephone.	0·7	500
2002089	Controller descended a/c1 into conflict with a/c2. He could not recall STCA alert, but another controller noticed it.	0·9	600
2003131	Controller descended a/c1 into conflict with a/c2. Controller alerted by adjacent colleague, at just about the time that STCA activated.	0·15	600

Air' restricts parts of controlled airspace to pilots holding valid IFR (Instrument Flight Rules) rating and in aircraft equipped to fly IFR. The most noticeable feature in Table 1 is the large proportion of incidents – more than two thirds – occurring in TMAs. Note, for later reference, that the radar separation (horizontal) minimum in this airspace is 3 nm and the vertical minimum is 1000 feet (N.B. 1000 feet would be in use outside TMAs post early 2001, prior to that 2000 feet was in use).

Table 2 shows the STCA/TCAS set broken down into the UKAB database categorisations ('Cat') for ATC reaction to an STCA alert. The Cat values in Table 2 are a rough indication of the effectiveness of the ATC system in dealing with the incident. Table 2 is a slightly simplified version of the full statistical picture. There can be two controllers involved in a particular incident – indeed, on occasion, the two aircraft are in different pieces of airspace. The Cat Value in Table 2 is the 'higher value' of the two, e.g. if one controller is in Cat 1 and the other does not act, i.e. Cat 4, then the incident is allocated to the higher known category: there are 14 of these.

Categories 1 and 2 are obvious in Table 2 (but note in passing that controller action in these categories will have changed corrective RAs into preventive RAs). A read of the Airprox reports shows that STCA and TCAS generally operate as would be expected, in terms of flight path geometries, warning times and controller/pilot actions. But what can be learned from the 'exceptional' Categories 3 to 6? Rather than analysing these other categories abstractly, it is easiest to summarise the incidents concerned in Categories 3 to 6 in Tables 3 to 6 respectively. Note that these are the author's selections and interpretations from the UKAB text. This serves to highlight the kinds of safety issues involved. The first four digits of the Airprox number indicate the year; H (nm) and V (feet) are the miss distances at the CPA as recorded by the radar system; a/c1 is aircraft 1 in the database, etc.

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Table 4. Airproxes 'Warned but not actioned'.

Airprox number	Summary	H nm	V feet
1999221	Mentor did not detect that instruction by trainee put both a/c at same level without standard separation. Mentor issued avoiding action at time when pilots were responding to RAs.	1	700
2002112	The control team did not ensure that a/c1 was coordinated with the neighbouring Control Centre. STCA was dismissed as a 'nuisance warning' – a/c2 was assumed to be climbing to a level 1000ft below a/c1.	1·6	400
2003075	Controller dispensed with vertical separation without ensuring lateral separation. Controller had seen the STCA alert but did not consider it a problem, as he believed that a/c1 would safely descend through the level of a/c2.	1·4	700
2003164	a/c1 crew descended below their cleared level into conflict with a/c2. STCA alerted after a/c1 had received a TCAS RA.	3·7	500
2003169	A sighting report, given that a/c1 was in TMA airspace and the other in Class G airspace – deemed separated (according to the CAA 2004a regulations) when STCA activated.	0·6	500
2003184	The a/c2 crew read back the wrong heading and level instructions, which went undetected by the controller. The controller said he had no reason to doubt that the a/c would not comply with the issued clearance. STCA activated and shortly afterwards a TCAS RA climb was issued.	3·4	600

Table 3 largely speaks for itself. The key point is that the 'ATC Team' was functioning.

The Airproxes shown in Table 4 are a disparate group – there is no simple dominating feature. There is a mixture of problems caused by aircrew and controller errors. Note the Level Bust by the pilot in 2003164. There were no instances where an STCA alert misled the controller.

Table 5 contrasts with Table 4 in that the most noticeable immediate causes of most of these incidents were incorrect climb/descent actions – four in Table 5 plus one more (2003164) in Table 4. Note especially that in these incidents the STCA safety defensive layers could not provide protection. The technical problems of incident 2000055 are now of historical interest.

There is only one Airprox shown in Table 6, but it is obviously a potentially very serious incident. The UKAB made recommendations to NATS about changing displays so that this kind of incident does not reoccur.

Of incidents producing RAs, Tables 1 to 6 indicate that ATC was aware of a potential conflict in about 90% of occasions – the exact percentage depends on interpretation of the Airprox reports.

5. CLOSE PROXIMITY AND COLLISION RISK.

What do TCAS and STCA Airproxes with RAs tell us about the collision risk for such events? (The collision risks associated with events with aircraft fitted with TCAS, but not generating RAs, are taken as negligible.) To start with, Table 7 shows the trend in TCAS/STCA Airproxes over the five-year period. The second column is the Annual Total Air Transport Movements at UK airports (CAA, 2004b): this is a rough indicator of total flying hours (i.e. it will not cover overflight contributions). The Ratio

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Table 5. Airproxes 'Outside [STCA] parameters'.

Airprox number	Summary	H nm	V feet
1999127	Controller had issued a descent clearance that would have led a/c1 to descend through the level of a/c2, which he had inadvertently not taken into account.	0	1100
1999200	Controller did not take a/c1 into account when he descended a/c2.	4·5	400
2000018	Aircraft were being vectored from N and S to line up on the Heathrow ILS. Controller did not ensure standard separation.	1·2	300
2000032	Controller gave 'erroneously and essentially unforced descent instruction' to a/c2.	2	700
2000055	Apparently anomalous RA [NB: Version 7·0 not in use]. Might have been TCAS malfunction or misheard aural warning ('reduce climb' for 'climb'?).	2·5	500
2000126	Controller did not ensure standard separation between the two aircraft. STCA did not alert because of geometry of the situation.	1·1	700
2001069	Controller allowed a/c1 to climb to the level that he had cleared a/c2 to fly at, without coordination.	2·8	700

Table 6. 'Garbled' Airprox.

Airprox number	Summary	H nm	V feet
2002222	Controller confused relative positions of a/c1 and a/c2 and descended a/c1 into conflict with a/c2. Confusing display of overlapping track data blocks and aircraft symbols.	1·5	600

Table 7. TCAS/STCA Airproxes and traffic over the five-year period.

Year	ATMs	Airprox	Ratio
1999	1899017	13	6·85
2000	1985734	19	9·57
2001	2030062	16	7·88
2002	2023093	19	9·39
2003	2088289	9	4·31
		76	

in the final column suggests that 2003 was markedly better than the earlier years, but this is not a strong statistical conclusion. In the following, it will be assumed that the average number of these incidents per year is constant.

The next aspect of interest when trying to understand potential collision risk is the recorded distances between aircraft at their recorded CPA. Figure 2 shows a scatter plot of H and V values for the STCA/TCAS set (N.B. One data point is for estimated H/V distances).

There is little apparent relationship between the H and V values (should this have been expected?). In fact, the correlation coefficient between H and V is −0·05, which is not statistically significant at even the 10% level. In other words, H and V appear to

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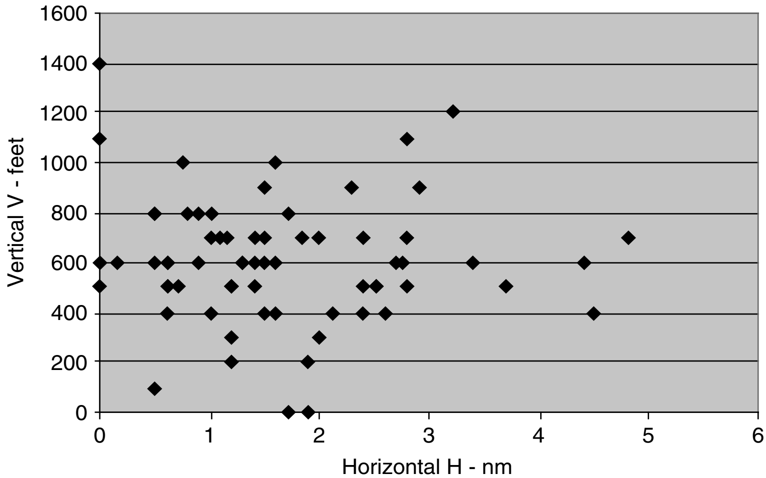

Figure 2. Scatter plot of H and V values.

be statistically independent variables: high values of one are not associated with either high or low values of the other. This offers the opportunity of combining the H and V values in some way – a single indicator of close proximity is easier to deal with than a two-dimensional array. The key question is what should be the relative weightings in such a combination. It is not adequate just to add H and V together because this would just swamp the V contribution. The two parameters need to be re-scaled, possibly relative to the corresponding velocity components? As already noted, an RA climb/descent manoeuvre takes the aircraft to a vertical speed of 1500 feet/minute, whereas an aircraft might be travelling at 240 knots in a terminal area and 480 knots in en route airspace.

The simplest thing is to assume that the weighting should be based on the proportional deviation from the separation minimum, and to use terminal airspace criteria (because the great majority of these Airproxes occur in TMAs). Thus, as the horizontal minimum is 3 nm and the vertical minimum is 1000 feet, the 1 nm horizontal CPA can be taken to be equivalent to 333 feet CPA. The simplest combination of the weighted H and V is just to add then together, i.e.

$$\mathrm{CPI} = 333 \times \mathrm{H} + \mathrm{V}$$

Here CPI stands for Close Proximity Indicator. It would also have been possible to use a kind of slant range estimate (compare Hale and Law, 1989).

Is there a trend in CPI values over time? Figure 3 shows a moving average for the sequence of Airproxes (which are rounded down to the nearest 100 feet in the following, apart from the smallest, which is rounded down to 250 feet from 267 feet). There is a slight negative trend, a correlation coefficient of –0·09, but this is not statistically significant at even the 10% level. This means that is reasonable to assume that the Airproxes come from the same statistical population, i.e. that the variations in CPI values are much the same from year to year.

The cumulative distribution of CPI values is shown in Figure 4. This is probably an appropriate point to note that some possible Airproxes may not be reported. But the

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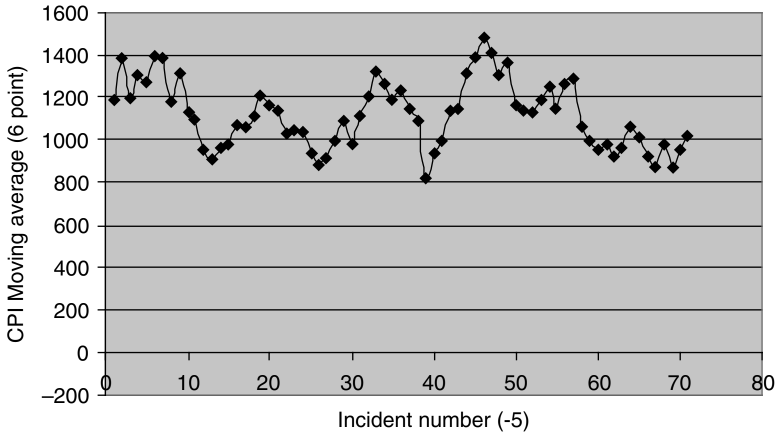

Figure 3. Moving average of CPI values.

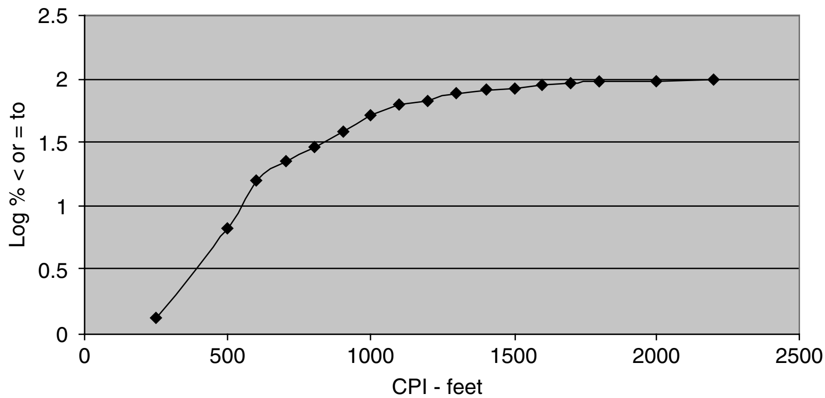

Figure 4. Distribution of CPI values.

likelihood is that the degree of any under-reporting is small for incidents involving TCAS/STCA alerts.

It was noted earlier that the UKAB assesses incidents based on what happened rather than what might potentially happen with similar incidents in future. The kinds of questions posed here are concerned with future risks, and try to use the evidence from Airproxes to say something about mid-air collision risk:

- What systems providing ATM safety actually functioned effectively?
- Was ATM 'system control' lost?
- What incident parameters prevented a mid-air collision?
- How much would these parameters have to be varied for there to be a collision?
- What is the most likely cause of a mid-air collision?

This is where the Airproxes with small CPI values are crucially important. If an Airprox has a CPI of 300 or 500 feet, then one can ask what would prevent a future occurrence with 200 feet, or 100 feet, or zero – which would be a mid-air collision. If the universe and fate are indifferent to human activity, then the frequency of these smaller CPI values will be just an extrapolation of the existing curve.

Table 8. Airproxes with small CPI values.

Airprox number	CPI feet	Report text re separation
1999172	500	ATC climbed a/c1 into conflict with a/c2. a/c1 followed TCAS RA descent and then turned L to avoid a/c2 visually sighted.
2001052	250	a/c1 took wrong instruction to descend; undetected by ATC because of simultaneous transmissions. a/c1 crew ignored RA and used 'visual' avoidance action.
2001129	500	ATC did not control adequately the flight paths of a/c1 and a/c2. a/c2 pilot had been monitoring a/c1 visually for several minutes before it was vectored away – the TCAS RA ceased after a few seconds.
2001180	600	In turbulent conditions, the a/c2 autopilot disconnected and the crew allowed their a/c to descend below its cleared level into confliction with a/c1. a/c1 pilot received a TCAS RA and followed it. The aircrews knew of the other a/c from their TCAS displays.
2002208	600	Mentor allowed trainee to descend a/c1 into conflict with a/c2. Following STCA alert, ATC instructed a/c1 to maintain altitude; TCAS RA then gave 'adjust vertical speed' RA, ie indicating need to increase climb rate. Neither aircrew is noted as seeing the other aircraft.
2003120	600	a/c1 crew did not comply with the SID but left controlled airspace and flew into conflict with a/c2. a/c1 crew did not see a/c2. ATC issued a turn to a/c1 simultaneous with the TCAS RA. Descending in response to the RA produced a Ground Proximity Warning System warning.
2003130	600	ATC descended a/c1 into conflict with a/c2. a/c2 crew received TCAS RA, saw a/c1 on TCAS display but not visually.

Extrapolating the curve roughly produces an intercept on the y-axis of $-0{\cdot}5$. The y value for 50 feet, i.e. roughly the size of an aircraft, would be about $-0{\cdot}5$. This is the logarithm of the percentage value – which is roughly 0·32, about 1 in 300. At a constant rate of (say) 15 STCA/TCAS Airproxes a year – i.e. assuming the recent average rate is continued into the future, with neither technological/system improvement nor any worsening because of increased traffic – this would correspond to a mid-air collision rate of around 1 in 20 years. If traffic grows at 4% a year (roughly the historical rate in the UK) then the yearly Airprox numbers would increase at a rate of around 8% annually – simply because the number of potential pair encounters would increase at this rate. This rate of traffic increase produces a doubling of annual Airproxes every decade: the statistically expected rate of mid-air collisions would be 1 in the next 13 years (i.e., in Airprox terms, there would be 20 years' worth of current traffic in about 13 years).

But are these kinds of numbers realistic? The degree of extrapolation with a logarithmic scale is obviously a major problem, but there is no obvious way of refining the estimate. It is possible to analyse horizontal and vertical distances independently, but this requires assumptions to be made about their statistical distributions. One further mitigating factor would be the use of visual avoidance after the TCAS RA. This would be a last-minute avoidance/manoeuvre *if* the pilot judged that the RA advice was not resolving the conflict. (But note also that the guidance on TCAS warns the pilot that 'visually acquired traffic may not be the same traffic causing an RA' (CAA, 2002).) Table 8 presents some information on the Airproxes with the smallest CPIs.

Monitoring of the TCAS display and visual avoidance/sighting were elements in about two thirds of the incidents shown in Table 8 (re visual sighting, note Moore (1998) and BASI (1991)). Visual acquisition does not necessarily imply that the mid-air collision would be avoided. But, suppose it did, and that the two-thirds figure were to be representative of the long-run picture. Using the same kind of argument as in the earlier calculation, the statistically expected number of mid-air collisions reduces to about 1 in the next 25 years or to 1 in 60 years, depending on the extent to which the effects of traffic growth can be fully mitigated. However, for aircraft flying in controlled airspace under IFR, should safety be at all reliant on visual, non-instrument, means for any part of the protection against catastrophic system failures?

These are probably the simplest direct calculations that can produce an estimate of collision risk for these circumstances. Would additional, more complex, calculations produce a more rigorous or a more precise answer? It is difficult to see how it could be proved that they would. Any statement about future accident risk has to extrapolate from present data or use models based on present data. Modelling, for example, the different orientations of aircraft flight paths and/or pilot/controller behaviours would require estimates to be made of their statistical frequencies. If the model has more complexity, then the more complex will be the extrapolation elements, with increased statistical uncertainties. Complexity does not add precision unless there is appropriate data available to support all the important elements of the modelling process.

6. CONCLUSIONS.

The conclusions here are appropriate for commercial air transport aircraft using UK controlled airspace with a radar service, in which TCAS and STCA are functioning properly. Two basic assumptions are that Airprox events over the last five years are typical of what might be expected in the future, and that the collision risks associated with events in which TCAS-fitted aircraft do not generate RAs are negligible. These results do *not* apply when there are system safety failures at a higher level, e.g. system 'abnormalities' such as defective regulation or safety culture, so the risks from such causal factors are additional to the figures here.

What has been learned? The following picks up questions posed earlier:

- *Do the systems work well together?* Generally, from the Airprox texts, they seem to work together well. STCA appears to prevent many encounters from producing TCAS RAs.
- *Are controllers surprised when they find out that a pilot has received a TCAS resolution advisory or did they anticipate it happening?* On most occasions, controllers are not surprised: either they have detected the problem themselves or STCA has alerted them to it. Of incidents producing RAs, the controller(s) are already aware of a potential conflict in about 90% of occasions.
- *What are the lessons that can be learned from any incidents in which TCAS and STCA do not function perfectly?* STCA cannot protect against sudden erroneous climbs/descents. On occasion, controllers can misjudge the likely nature of conflicts.
- *What do TCAS and STCA events say about collision risk?* The rate of mid-air collisions is estimated by a simple and direct extrapolation of Airprox closest encounter distances as about 1 in the next 25 years or to 1 in 60 years, depending on whether the effects of traffic growth can be fully mitigated by safety

improvements. This includes an assumption that visual acquisition would prevent about two-thirds of the accidents. Thus, the challenge is to continue improving the ATC system: first to ensure that the traffic growth effects can indeed be mitigated; and second to do better than that.

- *What is the most likely cause of a mid-air collision?* If the Airproxes here were typical of the most extreme events, then the most likely cause would seem to be ATC or the pilot descending/climbing an aircraft into another's path. In these circumstances, STCA would probably not alert before the TCAS RA, i.e. the STCA safety defensive layer would not operate. Five cases are identified (Tables 4 and 5) – about 7% of the total RAs. The effectiveness of TCAS would depend on the chance geometry of the two aircraft. Bad visibility and relative geometry would be important contributory factors.

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