Free-Flight in Europe, Problems and Solutions

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Earlier papers, based on a computer model of European air traffic, deal with the probability of *conflicts* arising between pairs of aircraft operating under *free-flight* rules. This paper discusses the problems of resolving these *conflicts*. When a potential collision takes place in the neighbourhood of other *intruding* aircraft, these must be taken into account when choosing an escape manoeuvre. A suggestion is made that may ease the problem.

KEY WORDS

1. Air Traffic Control. 2. Safety. 3. Modelling.

1. INTRODUCTION. *Free-flight* (RTCA, 1995) aims to allow airspace users the freedom to choose their own route and height for a given flight. The concept recognises that there may still remain some flow management restrictions on timing of flights in congested airspace. After takeoff, ATC, where available, may have the sole task of intervening to resolve dangerous encounters.

The airways system, which *free-flight* is intended to replace, has been shown (Ratcliffe and Ford, 1982), in the absence of ATC planning, to result in more potential collisions than would arise in *free-flight*. However, in the airways system, most of these potential collisions are eliminated, usually by the creation of one-way routes and by requiring aircraft on intersecting paths to go through the intersection at safely separated heights. In the EUROCONTROL area, the principal subject of the present paper, there are about 1000 such intersections. Analysis of a one-day sample of EUROCONTROL traffic showed that, if all aircraft travelled on rhumb-line routes from origin to destination, there would be at least 62 000 intersections where collisions were possible. Even if the *free-flight* concept did not rule out the possibility, any attempt, before take-off, at planning-out even the majority of the risks seems doomed to fail, if only because of uncertainty in predicting departure times. We are therefore left with the task of finding on-line solutions to many complex problems that may arise.

Internationally agreed *separation standards* set lower bounds to the separation that ATC should maintain between any pair of aircraft within their jurisdiction. In European radar-controlled airspace, the separation standards usually define a right-circular cylinder of 3 or 5 nm radius, and a relative height of at least plus or minus 1000 ft. At higher levels, the vertical separation is 2000 ft, but the model anticipates a change to 1000 ft at all levels (Benoist, 1999). The standard dimensions are intended to allow for errors in the sources of information, the aneroid barometer for aircraft height, and the radar network for position in plan. Reich (1966) is the seminal paper on the means by which standard separations should be derived.

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The above standards require ATC to achieve, at closest approach, an adequate separation in the vertical or horizontal plane. Morrel (1958) proposed that the criterion by which collision risk should be assessed should be the time to closest approach, predicted from the ratio of present separation to the rate of closure, measured in seconds. This ratio, termed *Tau*, is the basis, after some slight modifications, of the alarm threshold for the TCAS airborne collision warning system. TCAS is primarily intended to provide a last-ditch defence against failures in other systems that guard against collision. If it saves only half such collisions, it will be a very valuable device, but an inadequate substitute for ATC.

The discussion that follows will centre on the *conflict* problems predicted for *free-flight* in Western Europe (Ratcliffe, 1999). For this purpose, a *conflict* will be said to arise when it is not possible to guarantee that the separation standard will be satisfied. *Conflict* prediction was based on a computer model and a traffic sample collected on a busy day in 1997. It was assumed that flights between 9725 pairs of airports take place at uniformly random times in a 15 hr day and follow rhumb-line courses from origin to destination. Any possible automatic alarm system, for pilots or controllers, tests for *conflict* on the basis of a mathematical algorithm. In the present study, a *conflict* is declared if two routes intersect at a point where the flight levels will differ by plus or minus 1000 ft or less and if the times of arrival of aircraft at the intersection differ by less than 30 seconds, the *time window*. The contribution of each intersection to the overall *conflict* count will take account of the traffic levels on the intersecting tracks. Given the assumptions made in the model, results are easily scaled to allow for other *time windows*.

The model is based on data kindly supplied by the EUROCONTROL Route Charges office. This covers only flights passing through EUROCONTROL airspace. For this and other reasons, it cannot take account of all possible *conflicts*, and hence underestimates the total *conflict* count. However, despite this, the predicted *conflict* probability is high enough to cast serious doubts on the feasibility of *free-flight* in Europe. It is with the problems of resolving these *conflicts* that the present paper is concerned.

The EUROCONTROL data did not give the cruising level followed by each flight, hence the need for some arbitrary assumptions. Any aircraft in flight between the TMA boundary and cruise level is assumed to climb at a uniform rate (ft/nm), the same for all aircraft. The assumptions also apply to aircraft in descent, but climb and descent rates differ. The model then computes from the length of flight the highest level that each aircraft could attain, rounded down to a multiple of 1000 ft and then assigns, rather arbitrarily, cruising levels within the aircraft capability which were odd or even multiples of FL 100 (1000 ft) on the basis of the direction of flight. We then have a system that offers aircraft freedom to choose their routes, but a choice from a limited set of cruising levels appropriate to the route chosen. These rules are against the *free-flight* philosophy. Many airlines might choose to fly a cruise-climb trajectory, increasing cruise level with diminishing weight of fuel.

2. RESOLUTION OF THREATENED CONFLICTS.

Assuming a traffic density of 20000 movements per day (little greater than the peak day in 1997), the daily *conflict* rate predicted by the model is 863, and the expectation of a crossing encounter for an aircraft spending 15 hrs on a given route is 11%. *Conflicts* will increase as traffic level squared, but crossing expectancy increases only directly as

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Table 1. *Conflicts* by category.

Phase of flight	Percentage of *conflicts*
Both a/c in climb	0·39
Both a/c level	82·48
Both a/c in descent	1·39
One climb, one level	3·67
One descent, one climb	4·59
One level, one descent	7·48

traffic level. (The increased *conflicts* will be shared amongst the increased number of flights.)

The model has been used more recently to break down the *conflict* total into various categories. Table 1 shows the *conflicts* categorised by the phase of flight of each aircraft involved. Results are given as a percentage of the total conflicts.

60% of all *conflicts* involve pairs of aircraft at FL 280 or above. The present paper will confine itself to a discussion of *conflict* problems at or above this level. Failing a demonstration that these problems can satisfactorily be resolved, a more general study can hardly be necessary.

In a *free-flight* system, the problem of resolving a *conflict* threat is, not infrequently, compounded by the presence of other aircraft, here termed *intruders*, in the vicinity. An intrusion is defined, quite arbitrarily, as the presence of another aircraft within 10 nm of the site of a predicted collision, with a vertical separation less than 2000 ft at the point of the intersection, and a Time of Closest Approach within plus or minus one minute of the predicted time of collision. In busy airspace, the possibility of the simultaneous presence of several *intruders* adds considerably to the problem-solving task.

The author has, more recently, had doubts about the validity of the 'Poisson process' assumption used in (Ratcliffe, 1999) to derive estimates of the probability of multiple intrusions. Table 2 gives, for aircraft cruising at levels between FL280 and FL380, the probability that aircraft involved in the least fortunate *conflict* arising in the model will experience 1, 2, 3 or 4 intrusions. A brute-force enumeration of all possible combinations of circumstances leading to an intrusion was used to derive the percentage probability of one or more intrusions on the worst-case *conflict*.

Table 2. Worst-case probability of intrusion on the site of possible collision.

Number of intruders	1	2	3	4
Probability of event (%)	0·164	0·0048	0·000073	0·0000006

If there are M movements on a given route which passes close to a given *conflict*, the probability of an aircraft on that route *intruding* on the *conflict* is given by the product of M and the ratio of the time window in which an *intruder* must fall (2 min) to the period (900 min) over which arrival times are assumed to be evenly distributed. The probability of coincidental arrival of, for example, four such *intruders* on different routes is given by the product of four individual probabilities,

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so that doubling the overall traffic will increase the quadruple intrusion rate by a factor of sixteen.

It is not easy to translate probabilities arrived at in the simulation into fatal accident rates. Firstly, there are limitations on the data available. This provides justification for the adoption of broad assumptions that lead to relatively simple computer logic. Virtually all the shortcomings of the simulation are likely to result in underestimates of the risks involved. Any solution to the problems sketched in this paper is a necessary, but by no means adequate, guarantee of safety. Given that the ICAO Target Level of Safety is five fatal accidents in one thousand million flying hours, the probability of a quadruple intrusion, quoted in Table 2, is unlikely to be negligible.

3. CHOOSING AN ESCAPE MANOEUVRE.

3.1. *Airliner Limitations.* There are two main boundaries to the speed of an airliner in cruising flight. Firstly, the low-speed stall: at a speed that increases as air density falls with flight level. It also varies with the weight of fuel currently being carried. The second limitation is the upper speed boundary that is set by a shock wave causing the airflow to separate, giving a large increase in drag and, in many cases, severe buffeting. The upper speed boundary is defined by the Mach Number, the ratio of the airspeed to the speed of sound. This latter falls with air temperature which, below FL360, falls with increasing flight level, as must the airspeed if the critical Mach Number is not to be exceeded.

These two limits therefore converge as flight level increases. Aircraft will normally aim to fly at or near their thrust-limited altitudes, where engines are at their most fuel-efficient and the aircraft can cover the ground with minimum fuel consumption. This speed is chosen to allow for possible sudden wind gusts that may temporarily reduce or increase airspeed, carrying the aircraft towards one or other of the dangerous boundaries. It can be seen, therefore, that change of speed offers little help when avoiding collision. We are left with changes of heading or height. The airliner's capability to manoeuvre within the above limitations will be highly relevant to escape decisions.

3.2. *Horizontal Manoeuvre Capability.* Consider first the airliner in a turn. It is an airworthiness requirement that, under cruise conditions, the airliner lift can be increased by 30% to give a manoeuvre capability of 1·3 g without incurring buffet. At 500 knots, this corresponds to a bank angle of 40 degrees and a turning radius of 4·3 nm. Such a sudden increase in gravity may lead to injury to cabin crew or passengers, and will almost certainly alarm many of the latter. A more prudent assumption would be that evasive turns are made at a 20 degree bank angle. At 5000 knots, this gives a turning circle of 10 nm radius and an acceleration, on aircraft and passengers, of 1·06 g. In what follows, this radius will be assumed for purposes of illustration.

3.3. *Vertical Manoeuvre Capability.* As explained earlier, a ruthless exploitation of the cruise-climb strategy, in pursuit of fuel economy, would create a situation in which climbing to avoid collision was impossible. If both aircraft in a potential collision are in this condition, the only available vertical manoeuvre will require one aircraft to dive. It may be reasonable to assume a maximum rate of descent of 1000 ft per min. Some legislation may be desirable to retain the ability to escape conflict by climbing.

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3.4. *Collision Avoidance Logic*. The solution to any conflict must ensure that any evasive actions by neighbouring aircraft are mutually compatible, and that any new *conflicts* resulting from the 'solution' are also dealt with. Other aircraft must be confident that an adequate solution is being implemented.

For simplicity in what follows, assume that two aircraft are in risk of collision, but that there are no other aircraft in the vicinity. Turning manoeuvres should allow aircraft not merely to escape collision but also ensure that at no point does the predicted separation fall below some agreed standard. For aircraft on converging tracks, it may be a simple matter to avoid collision by a 'turn-away' manoeuvre, putting the aircraft on to parallel courses, but the problem is only resolved when aircraft have safely passed each other and can resume their desired tracks. This may be achieved by temporarily moving one aircraft to a lower flight level or by some time-wasting manoeuvre, preferably without generating further conflicts.

There are two alternative horizontal escape manoeuvres based on a turn by one or both aircraft; 'turn away' or 'turn towards'. Consider first the turn-away manoeuvre shown in Figure 1, which illustrates a potential collision situation involving two

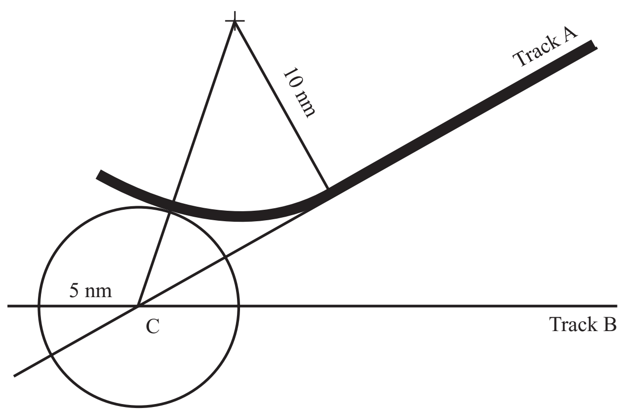

Figure 1. Collision Avoidance Manoeuvre, 'Turn Away'.

aircraft, A and B, in level flight at nearly the same height and approximately the same speed. The two tracks intersect at C, where A and B are due to arrive at approximately the same time. The last-ditch escape path, shown as a thick line, is simply part of the aircraft turning circle tangential to A's original course and to the circle centred at C. The diagram is applicable to any 'turn away' manoeuvre. The problem is not merely to avoid collision at C, but also to maintain a five-mile separation at all times. When the tracks are nearly perpendicular, the escape manoeuvre must be initiated at a much greater spacing than Figure 1 suggests. After escaping collision, it may remain necessary for aircraft A and B to cross each other's track and vortex wake. This problem may be solved by creating a difference in flight levels or by some time-wasting manoeuvre which allows one aircraft safely to pass behind the other, preferably without creating further conflicts.

Figure 2, to the same scale as Figure 1, illustrates aircraft A taking action to avoid a similar collision threat. This time, A uses a 'turn towards' manoeuvre. As before, the thick line shows the escape path to be followed. The 'turn towards' is initiated at A′ on the diagram. B′ (at the same distance from C) shows the position of aircraft B

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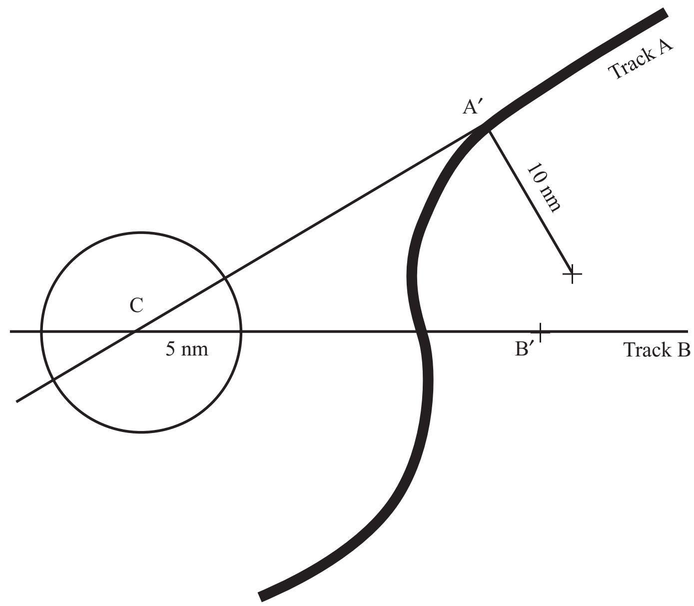

Figure 2. Collision Avoidance Manoeuvre, ‘Turn Towards’.

at the same time. To avoid the risk of collision when A crosses track B, the turn has to be initiated much earlier. (It can be shown that, in Figure 2, when A crosses B’s track, B will have reached a position about five miles nearer C). The advantage of the ‘turn towards’ is that it solves the problem of getting A safely across B’s track. The manoeuvre shown in Figure 1 can safely be used by both aircraft. This cannot be said of Figure 2. Given tracks intersecting at a different angle, the problems may be different. A more general discussion of multi-aircraft escape manoeuvres would add considerably to the length of this paper.

Vertical manoeuvre to escape possible collision has, despite limitations on rate of climb when in cruise at high levels, the considerable advantage that the end product of a climb or descent is well defined. The consequence of the turn may not be entirely clear, even to the pilot of A in the Figures. Pilot B, who has an equal interest in the outcome, may have an even poorer grasp of the consequences. If both aircraft are manoeuvring, the situation may be even less comprehensible.

The choice of escape manoeuvre is probably best made by some central, and presumably ground-based, organisation, which considers the problem as a whole. This may be felt to be against the *free-flight* philosophy, and has the weakness that the pilot of any aircraft is almost certainly more familiar with the limitations on the aircraft capability than is some outside authority. However, a group of pilots might have great difficulty, in a limited time, in agreeing manoeuvres for aircraft in or near a conflict.

3.5. *Intruders*. In a *free-flight* system, resolution of a threat may be more difficult if there are intruding aircraft in the vicinity. As shown earlier, the probability of multiple intrusions will increase rapidly with the traffic level. A wide variety of situations may arise. Ashby (1956) points to the need for a control system having a library of solutions that adequately cover the variety of problems. This task can be broken down into two phases, to demonstrate that adequate solutions exist, and to

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devise a means of allocating solutions to problems. The present paper has by no means overcome even the first of these hurdles. Given the safety standards set for civil aviation, it is doubtful whether any formal abstract logic, or a process of necessarily very limited trial and error, can demonstrate, to an adequate confidence level, that *free-flight* in Europe can meet Ashby's target.

3.6. *A Maritime Analogy*. It is interesting to look at the maritime equivalent of what is, in many respects, the same problem. Even given radio and primary radar, coordination between two vessels threatened with collision is generally based on regulations that assign to one vessel responsibility for evasive action whilst the other maintains course and speed. In regions of high traffic density, multi-vessel encounters require a considerable variety of solutions. One approach to the problem, in the Dover Straits, for example, has involved the adoption of a route structure resembling a two-dimensional airway. It is interesting to see mariners and airmen, faced with high traffic densities, apparently evolving in diametrically opposite directions.

Taylor (1998) discussing the International Regulations for Preventing Collisions at Sea (IRPCS), draws the distinction between 'regulations' that contain all their meaning within the text, and 'rules' that are socially defined and depend on a mutual agreement, explicit or otherwise, between those concerned. Rules depend for their meaning on a knowledge of the system to which they refer, and cannot be understood by reference to the text alone. The IRPCS regulations often fall within Taylor's definition of 'rules'. For example, 'as the circumstances of the case permit' is a phrase with the flexibility and apparent simplicity to allow scope for mutual agreements. A programmer attempting to devise software that can detect and resolve potential collisions would find such words less than helpful.

4. CONCLUSION.

In the USA, it has apparently been accepted that many problems of airspace capacity and access could be dealt with by abolishing the existing route structure together with the right of ATC to dictate to airspace users their choice of route and height (Hopkin, 1999). Given that *free-flight* is put forward as the solution to existing traffic problems, there is a remarkable absence of quantitative evidence, in the public domain, to justify this conclusion.

This present study has been restricted to a discussion of the collision avoidance problems facing jet aircraft at or near cruising level, perhaps 60% of all *conflicts* predicted in the model. This sample includes, perhaps, some of the more difficult problems that arise. Almost all the many simplifications in the model are likely to result in underestimates of the difficulties. Having failed to show that there is a plausible solution to even this subset of the problem, the feasibility of the concept remains in considerable doubt.

Hopkin (1999) points out the transition problems when controllers must provide, in the same airspace, services for aircraft in *free-flight*, assorted military activities and aircraft still flying along traditional routes. The variety of these problems is probably much more extensive than those discussed in this paper, which is confined to the situation that would follow universal adoption of *free-flight* in Europe.

In an attempt to lighten the 'doom and gloom' atmosphere of this paper, a constructive proposal is made. It was pointed out, earlier in the paper, that escape plans based on vertical manoeuvre probably have consequences that are easier to envisage than are the consequences of horizontal turns, whose complexities were perhaps hinted at in Figures 1 and 2. Automatic solutions might be provided to

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resolve the majority of conflicts if vertical manoeuvre was available and implemented without departing from a straight-line course. Aircraft in conflict or intruding are then, at most, faced with three options; *up*, *down* and *do nothing*. It would not be beyond the capability of a computer to chose a *best* solution, however defined. The definition of *best* should preferably set an upper bound to the number of aircraft required to change trajectory, thus preventing a chain reaction. Failing an adequate solution, one or more horizontal manoeuvres will be called for, and an automated solution might present great problems until a computer system can be devised that can invent solutions to situations not previously envisaged.

Attention was drawn, earlier in this paper, to the way in which multiple *intruders* would proliferate with rising traffic levels. If vertical separation standards could be lowered to 500 ft, the traffic in the computer model could be shared between twice the number of flight levels. The probability of *conflict* would fall by a factor of roughly four, and the probability of a fourfold intrusion on a single *conflict* by a factor of sixteen. Conversely, the system could handle a traffic level twice that in the EUROCONTROL 1997 data, with a simulated performance no worse than that shown earlier. An additional advantage is the increased likelihood of aircraft being able more rapidly to achieve a change in flight level adequate for collision avoidance.

It has been argued that GPS can provide an adequate replacement for many of the various aids to aircraft navigation. Opinion in Europe seems to be strongly opposed to any such 'sole means' navigational system on the grounds that such a system is inherently fragile, even when the aircraft has duplicate equipment. Navigation in the vertical plane, however, is today solely based on one or more aneroid barometers. Ground-derived measurements of flight level of aircraft on certain busy routes have, at considerable expense, collected enough data to convince ICAO that there are grounds for reducing the vertical separation standard at high levels from 2000 ft to 1000 ft. Moek *et al*. (1993), discussing the case for this reduction of vertical separation, give an interesting account of some of the circumstances under which significant height-keeping errors may arise. Some sources of altimeter error may easily pass undetected for long periods.

Ratcliffe (1992) has earlier pointed out the possibility of using satellite navigation data to supplement that from barometers. It is reasonable to suppose that, over a suitably small volume of sky and period of time, the difference between height derived from a satellite system and that derived from a barometer should be reasonably constant. If the difference was made available from sufficient aircraft, to some central agency, by SSR or other automatic dependent surveillance means, it should now be possible to detect 'rogue' altimeter systems in any equipped aircraft. This process might make possible a healthy reduction in collision risk, and therefore of the vertical separation standard, even if the monitoring system did not have universal full-time coverage. This, in turn, might improve the prospects for the introduction of *free-flight*.

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