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P-RNAV, Safety Targets, Blunders And Parallel Route Spacing

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The aim is try to understand how aircraft flying on adjacent routes using precision area navigation, meeting Required Navigation Performance and under air traffic control, ought to be addressed by safety studies, given the increasing importance of blunders.

KEY WORDS

1. P-RNAV. 2. Required navigation performance.

1. INTRODUCTION. The late J. E. D Williams (Williams, 1992) observed that '*rational* navigation is *necessarily* a game of chance … there is always some – very low – acceptable probability of catastrophe; a tenet first recognised in aircraft design, but later in air navigation'. He noted that catastrophes are 'due increasingly to blunder', and that aviation could reach a state in which the reason 'a large nominal separation between aircraft is safer than a smaller one is that if separation criteria are high there are fewer obstacles for an errant aircraft to bump into'.

The present purpose is try to understand how aircraft flying on parallel-spaced routes using precision area navigation (P-RNAV) meeting Required Navigation Performance (RNP) and under air traffic control (ATC) ought to be addressed by safety studies. Figure 1 shows the track system, taken for simplicity here as just having one flight level. En route aircraft, shown as boxes, fly on adjacent parallel tracks a distance S apart. An accident can occur if an aircraft on one track has a large navigational error and deviates into the path of aircraft on the adjacent track, as shown. What should the value of S be to ensure the necessary safety? What are the legitimate sums for this simple sub-set of the 'big RNAV route system question'? P-RNAV route structures and procedures are much more complex in terminal environments, in particular because of crossing traffic – e.g. when it is possible to release an aircraft for climb/descent. But the safety issues have to be resolved for this simple case first, as a foundation and pointer to the necessary safety analysis.

The paper is organised into the following Sections:

2. Relevant background to RNP, RNAV and P-RNAV.
3. An examination of navigation performance in practice.
4. Safety cases and target levels of safety (TLS).
5. Modelling navigational performance collision risk.

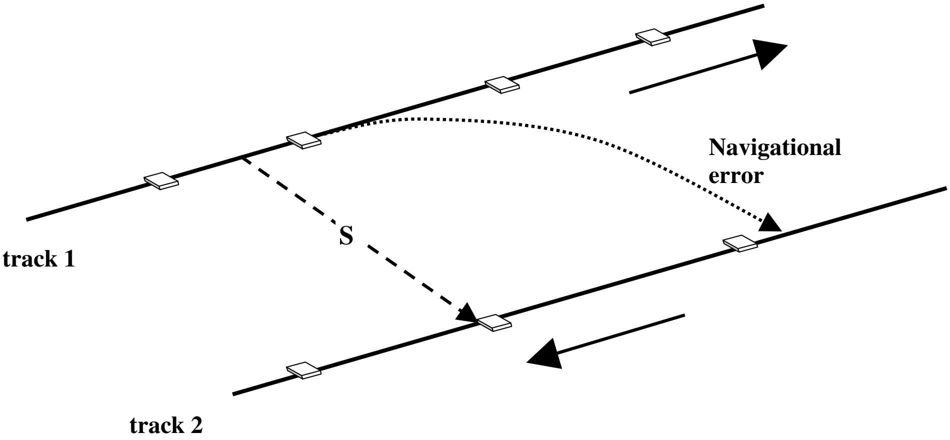

Figure 1. Aircraft on parallel tracks.

6. Calculations of non-intervention navigational performance collision risk.
7. Interventions to reduce navigational performance collision risk.
8. Modelling wrong track collision risk.
9. The practical complexities.
10. Conclusions.

2. RNP RNAV AND P-RNAV. This section sketches some relevant background on RNP and RNAV (see Gordon-Smith (2003)). RNP was formally originated through ICAO and examined by the RGCSP Panel in 1988 (RGCSP, 1988), which defined RNP by:

> 'RNP is a statement of the navigation performance accuracy necessary for operation within a defined airspace'

and RNP-x by:

> 'RNP-x specifies an accuracy of navigation such that all flights would be within x nm of the intended position for 95% of the total flying time. Thus, RNP-1 would be an implementation with a lateral track keeping accuracy of ±1 nm.'

Subsequent definitions add the phrase 'integrity, continuity, and availability' (RTCA/Eurocae (2000)). The 1988 RGCSP saw RNP as being a key concept that could deliver benefits to the aviation community and support enhanced airspace capacity, but noted:

> 'The panel concluded that the RNP cannot and should not, imply or express any separation standard or minima … The panel viewed RNP as only one factor to be used in the determination of required separation minima and an assessment of the risk level … [to include] expected traffic, route configuration, and communications, surveillance and air traffic control (ATC) services provided.' (See ICAO (1998)).

The focus on the 95% figure – approximately two standard deviations (SD) for Gaussian errors – can be traced back to the earlier successful separation minima work on the North Atlantic Region (NAT) (e.g. ICAO, 1998) based on a minimum performance standard. Three lateral navigational error criteria were developed for the

Table 1. Characteristics of *error* and *blunder*.

Characteristic	Error	Blunder
Presence	Always	Infrequent
Frequency distribution of magnitude	Any large error is less frequent than any smaller error	Within limits, any magnitude as likely as another
Effect of improvement	Reduces magnitude of error	Reduces frequency of blunder

NAT, one relating to the SD and the other two to gross navigational errors (GNE) of 30+ nm. However, only the GNE criteria fed into collision risk estimation; the first criterion being used as an initial filter to remove unsuitable navigational systems from detailed consideration.

The RNP-x type is a useful descriptor of navigational performance, but it does not specify it sufficiently for systems design purposes. The RTCA/Eurocae (2000) MASPS for RNP RNAV addresses this need. RNAV is defined by:

> 'RNAV is a method of navigation which permits aircraft operation on any desired flight path within the coverage of referenced navigation aids or within the limits of capability of self contained aids, or a combination of these.'

The RNP requirements for RNAV were specified by a set of complex and precisely defined requirements. For the separation of aircraft on parallel tracks, the two important elements are:

- 95% positioning accuracy is linked to total system error (TSE), the difference between the true position and the desired position … The desired path is that which the 'flight crew and air traffic control can expect the aircraft to fly, given a particular route leg or transition'.
- Containment: The containment limit is defined as 2 × RNP. Containment integrity is specified by the maximum allowable probability for the event that TSE is greater than the containment limit and the event has not been detected. This probability is set as 99·999%, i.e. 10^{-5}. Note that this containment limit is not defined for P-RNAV.

What do these requirements imply about collision risk? The origins of the criteria in RTCA/Eurocae (2000) do not appear to be in the published literature. The requirements appear to be reasoned and desirable ones for a high quality navigation system. They may or may not be necessary, but they are not sufficient, because as already noted, estimation of collision risk depends on more than navigation performance. To quote O'Keeffe (Nordwall, 2003): 'Required Communication Performance and Required Surveillance Performance are also necessary'.

3. NAVIGATION PERFORMANCE IN PRACTICE.

Technical phrases need to be set in the range of contexts in which they are to be used. 'Navigational performance', covers both 'errors' and 'blunders': the former are natural consequences of the technology used, which limit the accuracy with which position can be measured. Williams' (1992) simple example of a blunder is a waypoint insertion into a navigation computer. Table 1 shows the key characteristics of error and blunder.

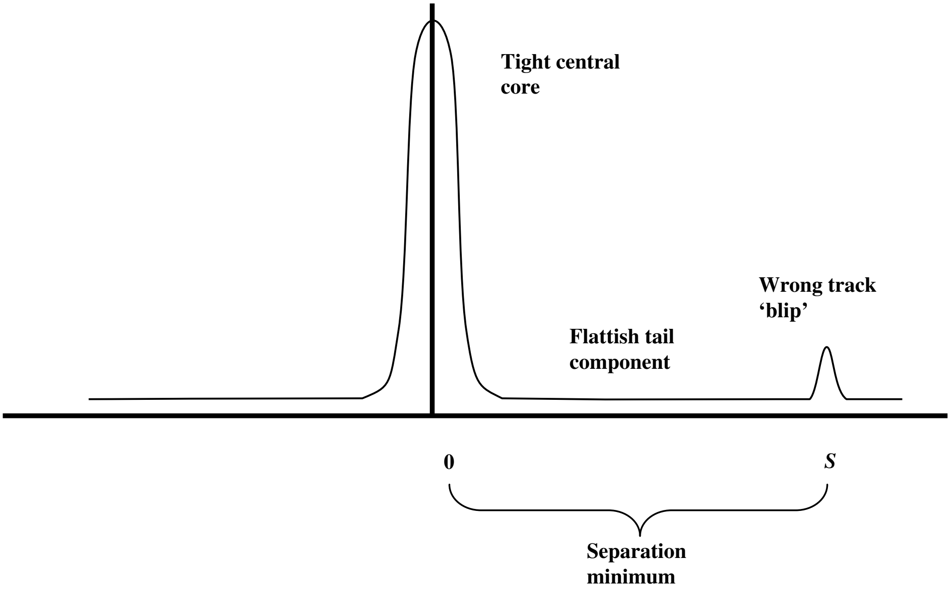

Figure 2. Illustrative potential navigation performance probability distribution $f(y)$.

The importance of this categorisation for a waypoint-based system first received attention in the work to reduce NAT separation minima following the introduction of triple-INS (Brooker and White, 1979). The nature and frequency of the observed GNEs led to very rigorous procedures being introduced for the checking of flight data and communication protocols between controllers and pilots.

The classification of NAT GNEs has become more complex in the last two decades, now having 8 categories (NATSPG, 2002). In simple terms, there are four basic NAT GNE Types, which can also be expected in P-RNAV operations:

I. Equipment failure leading to degraded performance.
II. Aircraft with inappropriate equipment for the airspace, which fails to keep to track.
III. ATC system loop error: controller and/or pilot problem, through miscommunication, misunderstanding, etc, that leads to aircraft flying on the wrong track.
IV. Waypoint error: for whatever reason, the waypoint in the FMS is incorrect.

In crude terms, Types I and II are traditional navigation error types, whereas III and IV are blunders arising for human factor (HF) reasons. Type IV is conditioned by a neighbouring track – if no ATC routeing data for such a track exists then it cannot logically be 'available' for such a blunder to occur. Hence, it is the existence of the neighbouring track that opens up such a possibility. Types I and II add tails to the navigation error distributions $f(y)$, but these will be 'normal' errors decaying rapidly with y. Type III adds a section of flat tail to $f(y)$, because the waypoint error excursion will consist of a constant speed movement to the wrong waypoint and then a constant speed movement back to the correct track. Type IV will be a small blip on the distribution at the wrong track's lateral distance.

Figure 2 is an (exaggerated) illustration of the potential distribution form when all the Types of GNE are present. The core distribution is very tight, given the very high proportion of data points within the containment distance. The flattish tail component slopes downwards slowly, given that Type I and II GNE errors and Type III blunders will contribute in this region. The blip caused by wrong track GNEs is at the separation minimum *S*, but only on the neighbouring track side. These wrong track GNEs will be treated separately here – the 'Wrong Track' case – with all other types of error/blunder being considered as 'Navigational Performance' errors.

4. SAFETY CASES AND TARGET LEVELS OF SAFETY.

How should decisions be made about new operations? In broad terms, something like a safety case has to be constructed (Profit, 1998), including:

> '… identify the hazards, assess the risks, identify the measures in place to control the risks … assurance that any risks introduced by the change … minimised as far as is reasonably practicable.'

All the consequences of changes have to be taken into account: thus a parallel route system's safety case has to take account of all the hazards implied by the whole new system. The safety tests to be made usually take the form of Target Levels of Safety (TLS).

A TLS is a key concept in aviation safety (Brooker, 2002). The TLS is a design hurdle, a quantified risk level, measured as some sort of accident rate, which a system should – i.e. in planning, design and actual performance – deliver. The current (RGCSP, 1995) TLS figure for mid-air collisions for en route flight in controlled airspace arising from 'failure of separation' in the y dimension (appropriate for parallel routes) is $0{\cdot}5 \times 10^{-8}$ fatal aircraft accidents per flying hour. This TLS covers *all* types of risk generated by the new route system, i.e. must include both Navigation Performance and Wrong Track collision risks.

Most of the practical problems are with the proper estimation of the safety level that is or would be achieved with the new system – the Actual Level of Safety (ALS) being achieved in the system. How is this to be calculated with sufficient accuracy to be confident that the ALS < TLS? The problem is often not with the actual safety of the new system but that of proving it to be safe.

5. MODELLING NAVIGATIONAL PERFORMANCE COLLISION RISK.

Probabilistic risk assessments estimate the risk of accidents by analysing the sequences and probabilities of failure events that could produce an accident. But ATC systems require probabilities to be estimated for 'human components' – the people who have to make decisions and act. It is very difficult to produce estimates of these generally rare events, and a collection of cautious assumptions produces over-pessimistic – not practically usable – risk estimates. The DNV (1997) Route Separation Standard hazard analysis presents these kinds of problems very clearly. Structurally simpler collision risk models (CRM), based on available real/simulated data of observed error rates, tend to be preferred in practice (e.g. ICAO, 1998).

Much of the CRM methodology early work is contained in papers by Reich (1966) – the 'Reich model', which is used here. Separation minima guidelines have been produced (ICAO, 1998), and there are some recent critiques and review papers

(FAA/Eurocontrol, 1998; Brooker, 2002). The baseline CRM work on dual airways is described in ICAO (1976). The dual airways framework rests on the picture in Figure 1 which shows aircraft (drawn as boxes) flying on adjacent parallel tracks 1 and 2 a distance S apart, defines axes x (along track), y (lateral to track) and z (vertical); and the aircraft are represented by boxes of dimension F, G and H respectively. Aircraft on each track have the same velocity.

An accident can occur if an aircraft on one track has a large navigational error and deviates into the path of aircraft on the adjacent track, as shown, with relative velocities u, v and w along the x, y and z axes. The collision risk is the probability that such a breakdown in achieved navigational performance could occur and that there is another aircraft on the adjacent track at the crossing point. Pro tem, suppose that ATC is 'inactive' and that there are no warning/alerting devices in operation (track deviation alert, ground-based Short Term Conflict Alert (STCA), or airborne Traffic-alert and Collision Avoidance System (TCAS). Navigational errors affecting aircraft on one track are assumed unrelated to those errors on the other track (*errors* includes blunders here).

The accident risk N_a – in terms of fatal aircraft accidents per hour – can then be estimated as (ICAO, 1976):

$$N_a = P_{xz} 2GC(S)\left\{\frac{u}{2F} + \frac{v}{2G} + \frac{w}{2H}\right\} \tag{1}$$

where P_{xz} is the proportion of hours in that aircraft are in simultaneous x and z overlap (Reich, 1966). $C(S)$ is a probability distribution describing the frequency of relative lateral errors for an aircraft pair, defined by:

$$C(S) = \int_{-\infty}^{\infty} f(y)f(S-y)dy$$

This can be rearranged as:

$$C(S) = 2\int_{-\infty}^{S/2} f(y)f(S-y)dy$$

The second function in the integrand can now be expanded out in a Taylor series. It is reasonable to suppose that $f(y)$ is highly concentrated in a region with y much less than $S/2$ and its higher derivatives are negligible, giving:

$$C(S) \cong 2f(S)$$

This is a very good approximation both for a 'flat tail' distribution (i.e. $f(y)$ heavily concentrated around $y=0$, and then flat in the region of $y=S$) and a mixed double exponential distribution (e.g. DNV, 1997). Hence, it is sufficiently accurate for candidate P-RNAV navigation performance distributions. This has immense implications: the form of the core distribution does not matter, i.e. 'normal' navigation is largely irrelevant to collision risk.

6. CALCULATIONS OF NON-INTERVENTION NAVIGATIONAL PERFORMANCE COLLISION RISK.

The ICAO (1976) model is a toolkit for collision risk estimates. These initial calculations are of 'non-intervention' – Navigation Performance – collision risk. The key question is the extrapolation of $f(y)$ to points with y values near to S. Extrapolation from a

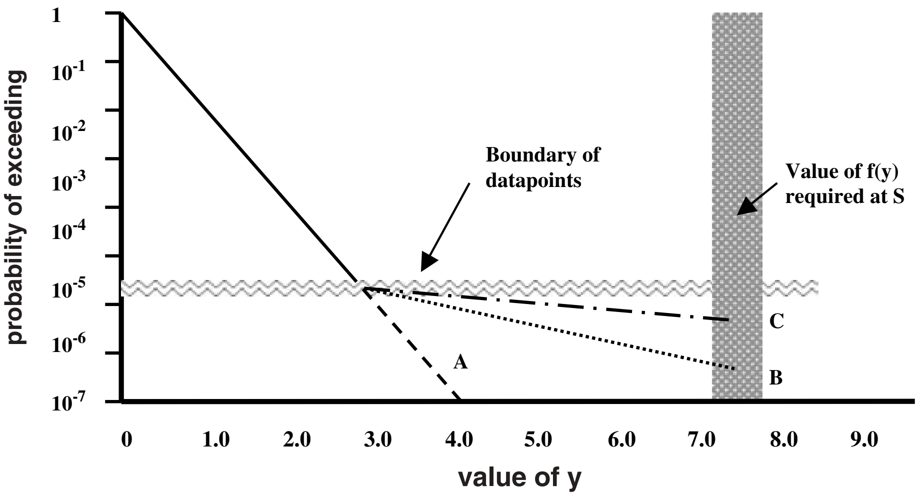

Figure 3. Illustration of potential 'cumulative' curves.

purely statistical fit would only be satisfactory if there were confidence about the underlying causal mechanisms for navigational errors. These issues are illustrated in Figure 3.

RNAV navigational performance data has been collected in several Eurocontrol exercises. In the largest one, (Eurocontrol, 1988; DNV, 1997) more than 80 000 data points were collected. The more recent Eurocontrol data collections in the 1990s have measured rather more data in total, but the underlying distribution shape has been much the same. The un-dashed part of the data line A in Figure 3 roughly approximates to the data in Eurocontrol data collections. Current P-RNAV data might be expected to be somewhat better, but probably not sufficient to shift the line A markedly. A dataset of (say) 100 000 measurements does not provide statistically guaranteed information about probability statements finer than 10^{-5}. The trend line A cannot simply be extrapolated out for the rare events that occur at or near to the separation distance *S*, shown here as around 7 nm – an approach adopted in DNV (2003). The true line, given enough data, might be B or C: it is not logical to say that either line fits the data better or that C is somehow pessimistic – and at *S* the line C is ten times higher than B.

Why is it not valid to use the extrapolation of A or to choose a line such as B as being reasonably cautious? There are two reasons: extrapolation uncertainty and causal factors. Extrapolation of the trend line A beyond the un-dashed region is on the basis of a few points in the tail region of the collected data, and the straightness of A near the data point boundary breaks down because of statistical fluctuations. The proportion of events in this extreme tail is a Poisson process, which intrinsically has high variability, so there is considerable statistical fitting uncertainty in extrapolation to the region of *S*.

Extrapolation from a purely statistical fit would only be valid if the underlying causal mechanisms are known to be preserved over the whole range of *y* values – but this is not the case (compare ICAO (1976), where there was confidence that lateral errors on VOR-defined routes increase with distance from the VOR). The different GNE Types sketched in Section 3 represent HF related factors from normal navigation. Waypoint errors are the easiest example by which to make the case: they appear as a flat tail in $f(y)$, and hence a gentle slope similar to the line C in Figure 3.

It therefore appears that the most obvious robust way of estimating $f(S)$ is to build upon data from analogous track systems. The NAT is an obvious example because of its substantial amounts of traffic and its similar operational features, such as the use of waypoints. Is there any better starting point? Navigational performance on the NAT has been a learning experience for ATC and navigation specialists, with procedures and equipment being developed continuously. The GNE statistics, although progressively reducing, are still dominated by waypoint-like errors, so what rate of waypoint-like GNEs occurs on the NAT and to what degree should this rate be modified for P-RNAV routes?

Rome and Krishnan (1990) examined NAT GNE data for the years 1983–85, and estimated the rate of waypoint errors per flight as $8{\cdot}4 \times 10^{-5}$. DNV (1997), using 1987–93 data, estimated the rate per flight as $1{\cdot}5 \times 10^{-5}$, and given about 5 waypoints, estimated the error rate per waypoint as 3×10^{-6}.

How valid would NAT data be as an indicator of P-RNAV route rates? Some relevant factors are:

- NAT routeings change from day to day because of the changes in wind forecasts – not expected to be a feature in P-RNAV routes.
- Procedural disciplines and HF lessons learnt from the NAT operation would be transferred to P-RNAV systems, so the P-RNAV GNEs would not require the lengthy learning gains seen in the NAT.
- NAT flight plans are frequently communicated only when the aircraft is en route, introducing extra potential for flight plan entry errors.
- RNP RNAV contains several features to protect against specific types of errors e.g. by use of defined databases, automatic insertion of flight plan data.

Regarding waypoints and databases JAA (2000) states that:

> '[Departure] … The creation of new waypoints by manual entry into the RNAV system by the flight crew is not permitted as it would invalidate the affected P-RNAV procedure … [Arrival] … The creation of new waypoints by manual entry into the RNAV system by the flight crew would invalidate the P-RNAV procedure and is not permitted.'

Presumably, GNEs arising from equipment failure leading to degraded performance or from aircraft with inappropriate equipment could not be eliminated a priori from P-RNAV routes. But, given the P-RNAV specifications noted above, the bulk of waypoint insertion errors should be eliminated. A factor of 1/6 might be a cautious figure for the scaling down of the waypoint error rate – but this is no more than a number chosen for some illustrative calculations. Taking this illustrative proportion of 1/6 produces an estimated waypoint error rate per waypoint of $0{\cdot}5 \times 10^{-6}$. [NB: this is consistent with data integrity requirements, such as ICAO Annex 15, that requires 'En-route NAVAIDS and fixes, holding, STAR/SID points' to have a minimum integrity of 10^{-5}.]

The risk calculation requires the terms in equation (1) to be estimated. The assumed parameter values for the kinematic factor KF (in curly brackets) are shown in Table 2. (These values are broadly in line with the values in the literature (e.g. DNV, 1997), except that the box dimensions are chosen to be slightly bigger.)

Two cases have to be calculated: same and opposite direction traffic on the two routes – KF_S and KF_O, (corresponding to N_{aS} and N_{aO}). Their values

Table 2. Kinematic factor parameter values.

Parameter	Description	Value & units
u_S	relative velocity along same direction track	35 knots
u_O	relative velocity along opposite direction track	900 knots
v	relative velocity laterally	50 knots
w	relative velocity vertically	1·5 knots
F	Length of aircraft box	0·025 nm
G	Width of aircraft box	0·025 nm
H	Height of aircraft box	0·0075 nm

are: $\mathrm{KF}_S = 3{\cdot}6 \times 10^3$ and $\mathrm{KF}_O = 3{\cdot}82 \times 10^4$. P_{xz} depends very much on what is to be assumed about the density of traffic on the routes and the proportion of aircraft in transition between flight levels – domestic airspace has much high proportions of climbing and descending traffic than the NAT. ICAO (1976) shows how its value changes when large proportions of aircraft are in climb and descent: it quotes a value of $1{\cdot}2 \times 10^{-4}$, but this was for projected busy 1980 (sic) traffic levels. Given that the P_{xz} should correspond to a planning figure for a heavily populated route system, a value of 5×10^{-4} is used here.

This leaves the lateral overlap probability $C(S)$ to be estimated, which is shown above to be equal to $2G\ 2f(S)$. For illustration, S is taken as 7 nm (see DNV (1997); Eurocontrol, 2003). The flat tail assumption means that collision risk depends on S very weakly, e.g. a doubling of S would halve the collision risk. The value of $f(S=7)$ then has to be estimated by examining the nature of the dominant waypoint errors. It can be shown that for waypoint errors $f(S) = 0{\cdot}5 \times 10^{-6} \times 1/2 \times 2 \times (1/7) = 0{\cdot}71 \times 10^{-7}$ (using analogous expressions to those in Davies and Sharpe, 1993).

The resulting estimates are: $N_{aS} = 0{\cdot}65 \times 10^{-8}$, $N_{aO} = 0{\cdot}70 \times 10^{-7}$.

As noted above, the appropriate TLS for a parallel route is $0{\cdot}5 \times 10^{-8}$ fatal aircraft accidents per flying hour, covering *all* types of risk generated by the new route system, i.e. must include both Navigation Performance and Wrong Track collision risks. The navigational performance accident rates for both same and opposite direction traffic are higher than the TLS, by factors of 1·3 and 14 respectively.

7. INTERVENTIONS TO REDUCE NAVIGATIONAL PERFORMANCE COLLISION RISK.

What difference would intervention by the controller make to Navigational Performance Collision Risk? This is the second key HF issue that needs to be understood. What about safety net, e.g. STCA, effects?

The DNV (1997) detailed investigation into parallel route hazards discusses evidence on the correction of track deviations by the pilot, with the help of onboard equipment, and the controller. In practice, the great bulk of deviations are dealt with correctly very quickly, so to gain an understanding of controller performance on the rare occasions when it is necessary to intervene, ATC simulations must be used. The question to be answered is: 'Given that a collision will happen through navigational performance errors, what is the probability that the controller will not detect and resolve adequately?'

Eurocontrol (2003) gives results from an ATC simulation in Finland on a parallel route system separated by 7 nm. Two scenarios were investigated: Without and With

Table 3. Navigation Performance Rates modified with and without STCA.

Direction	Navigation Performance Rate	Modified by Without STCA	Modified by With STCA
Same	$0{\cdot}65\times10^{-8}$	$0{\cdot}13\times10^{-8}$	$0{\cdot}03\times10^{-8}$
Opposite	$7{\cdot}0\times10^{-8}$	$1{\cdot}4\times10^{-8}$	$0{\cdot}35\times10^{-8}$

TLS for a parallel route is $0{\cdot}5\times10^{-8}$.

STCA. In the Without STCA scenario, there were 45 simulated deviations, of which 6 were judged not to have been safely resolved. In the With STCA scenario, there were 10 events and all were resolved. These simulations include a variety of deviation angles and there was some evidence that controllers more often failed to resolve those with sharp ($>10^\circ$) deviations from track, presumably because the time to collision was much shorter.

Taking these statistics at face value, the Without STCA case showed a failure rate of 13% and the With STCA one of 0%. The purely statistical bounds given comparatively small samples are quite wide: the 90% confidence limits would be about 20% in both cases. For present purposes, assume rates of 20% and 5% – arbitrary figures intended just to indicate the broad effects. [Note that no account is taken of the possibility that controllers may convert near-collisions into collisions – probably a second order effect given the simple geometries involved.] The results are shown in Table 3.

If Wrong Track collision risk can be neglected – but see the next section – then the Same Direction case is acceptable given controller intervention without STCA, but the Opposite Direction case is not acceptable even if STCA is employed. But note again that these are illustrative numbers.

But note that the current Eurocontrol Safety Regulation Commission Policy (Eurocontrol SRC, 2003) states 'The ATM system must be able to demonstrate that it satisfies applicable tolerable ATM safety minima without reliance upon the safety benefit expected to be provided by safety nets'. There is continuing debate about the appropriateness of the policy and moreover its linkage to ATC's firm foundations of TLS and hazard analysis.

8. MODELLING WRONG TRACK COLLISION RISK.

What about the collision risk arising from the aircraft being on the wrong track for the whole or part of its passage in the parallel track system? [NB: Wrong track errors on the NAT are also significant in risk terms, but the density of adjacent opposite direction track pairings is very low because of the diurnal nature of oceanic traffic.]

This Type IV risk can be modelled by taking a distribution $f(y)$ similar to that shown in Figure 2, except that all the tail section is eliminated apart from wrong track 'blips' at $\pm S$ – the aircraft is at the 'right place' but on the wrong flight path. [NB: the blip at $-S$ is there to make the function symmetric – necessary when the integral is transformed – but it does not influence the risk calculation.] The calculation goes through exactly as above and requires the convolution $C_W(y)$ to be evaluated

$$C_W(S)=2\int_{-\infty}^{S/2} f(y)f(S-y)dy$$

The second part of the integrand is non-zero only in the neighbourhood of $S=y$, and has the form $q\,f(y)$ there, as it is the same as the core distribution scaled down by a factor q. Thus,

$$C_W(S)=2q\int_{-k}^{k} f(y)f(y)dy$$

Where k is a measure of the extent of the core. A good approximation to $f(y)$ is: $f(y)=\frac{1}{2}\lambda e^{-\lambda|y|}$ which gives $C(S)$ as $q\lambda/2$. [NB: lateral offset procedures (ICAO, 2000) would not help to reduce risk here, because the aircraft is 'correctly' flying the wrong track rather than deviating onto it.]

The probability $P_{yW}(S)$ of an overlap of size $y=S$ can be shown to be (Brooker, 2003):

$$P_{yW}(S)=\left\{2G+v\left(\frac{2G}{u}\right)\right\}C_W(S)$$

Assuming that the relative lateral velocity – note this is for aircraft flying on the same track rather than for one of them deviating off track – is small compared with the relative longitudinal velocity, the term in v/u can be neglected, so:

$$P_{yW}(S)=q2G\left(\frac{\lambda}{2}\right)=qG\lambda$$

The wingspan G is taken here as 0·025 nm (about 150 feet). A suitable value for λ^{-1} is 0·29 nm (DNV, 1997 – but note that satellite-based navigation tends to produce a smaller λ^{-1}, e.g. ICAO (2000) implies a λ^{-1} of 0·078). This gives P_{yw} (S) as $0{\cdot}086q$.

The accident risk is:

$$N_{aW}=P_{xz}\times 2GC_W(S)\times\left\{\frac{u}{2F}+\frac{v}{2G}+\frac{w}{2H}\right\}$$

Ignoring the terms in v and w, given that the aircraft are flying on the 'same track' rather than deviating from a track, gives:

$$N_{aW}=P_{xz}\times 0{\cdot}086q\times\left\{\frac{u}{2F}\right\}$$

Using the value of P_{xz} of 5×10^{-4}, and u_S, u_O, F from Table 2, gives for same and opposite direction traffic respectively

$$N_{aWS}=0{\cdot}03q \text{ and } N_{aWO}=0{\cdot}77q.$$

Various estimates of q, based mainly on NAT experience, are given in the literature. DNV (1997), using 1987–93 NAT data, suggest a figure of 5×10^{-5}, presumably representative of a mature system. This gives:

$$N_{aWS}=1{\cdot}5\times10^{-6} \text{ and } N_{aWO}=3{\cdot}9\times10^{-5}$$

These are very large numbers, which would swamp the navigational performance collision risks.

Is the supposed wrong track frequency rate too high? The NAT wrong track errors could be examined in detail to determine which of them would have been likely to have occurred in a P-RNAV route system, given the causal factors involved and the extra protection offered by rigorous P-RNAV protocols and specifications. Can P-RNAV routes be programmed directionally, so that it is impossible to fly a track in the wrong direction? P-RNAV standard instrument departures (SID) and standard terminal arrival routes (STAR) cannot be flown in the wrong direction, as the flight management system (FMS) would not permit this – but is this statement an absolute guarantee? En route routeing segments presumably can be flown in either direction, so it would be necessary to define unidirectional enroute segments.

What difference would controller intervention make? There is a major difference between the same and opposite direction cases. For the first case, a controller scanning the aircraft on a track should notice that one aircraft was catching up others on the flight path. A 35 knot relative velocity implies catching up 5 nm (the usual en route radar separation minimum) over a period of about 8 minutes. If STCA were allowed into the risk calculation, it would be probable that it could detect the potential conflict well before the closest approach and in time for the controller to act appropriately. Thus, there is a good chance that the TLS could be met.

For the opposite direction case, this would be much less likely – a relative velocity of 900 knots implies a distance of 5 nm being closed in 20 seconds, very quickly for the controller, and leave little time for an adequate STCA alert. The opposite direction case would thus have inadequate safety defences.

9. SOME PRACTICAL COMPLEXITIES.

The analysis above has been for a simple route structure. In practice, things are much more complex, so a few features are noted, particularly where additional safety defences have been incorporated. Hazards in these complex ATC environments are tending to be alleviated by the use of fail-safe routeing structures.

The read across from the NAT GNEs into European operation is obvious, but is it too simple? In terminal areas, there are potentially new types of GNE, e.g. arising from turns. The aircraft can be on the correct route and the waypoint selected from the database is on the route, but might not be the correct one. Failures can therefore only be seen when the aircraft fails to turn – potentially crossing the path of another aircraft. Figure 2 could be too simple: there could be a continuum of GNEs including position errors of waypoints, wrong Nav-aid coordinates, and early or late turns.

Risk on parallel route structures is alleviated by the use of a Flight Level Orientation Scheme. A large number of parallel/near-parallel routes were introduced for Reduced Vertical Separation Minimum (RVSM), and additional routes have been provided in the Basic RNAV programme. They were all introduced to make the ATC job easier, and hence improve safety and capacity. RVSM-related routes were designed to enable the transition from non-RVSM to RVSM to be safe in the event of RT loss – i.e. to avoid opposite direction traffic at the same flight level on the same route. Hence, given RT and success in ensuring that the aircraft have changed to the RVSM level, there is not only lateral but also vertical separation. Opposite direction traffic same flight level risk then occurs only during the transition or if RT fails, therefore reducing the frequency element in the risk calculation very substantially. Additional routes have also been inserted to deconflict airspace routeings at intersections – providing vertical as well as lateral separation.

10. CONCLUSIONS.

The question posed is: "How should aircraft flying on parallel-spaced routes using P-RNAV meeting RNP and under ATC be addressed by safety studies?" This simple case is a foundation and pointer to the necessary safety analyses for more complex route structures:

1. P-RNAV specifications produce high quality navigational systems. Conventional navigational errors will probably be negligible at the kinds of separation – e.g. 7+ nm – envisaged for a parallel route system. RNP RNAV, because of the addition of a 99·999% containment requirement, will have an even smaller frequency of these errors.
2. Unfortunately, GNEs, such as incorrect waypoint insertion and choice of wrong track, are likely to be by far the dominant contributors to collision risk. Extrapolation from P-RNAV performance data is not a valid way forward. GNEs cannot reasonably be estimated by extrapolating P-RNAV data, because they are largely generated through HF issues rather than normal navigation.
3. Data from NAT track system operations on GNE rates is an obvious starting point for P-RNAV parallel route systems. The bulk of waypoint insertion errors would be eliminated by RNAV data disciplines. GNEs arising from equipment failure or from aircraft with inappropriate equipment would not be eliminated – they could equally occur in P-RNAV airspace.
4. On this basis, same direction P-RNAV parallel routeings at 7+ nm may be able to meet the TLS, assuming that the risks incurred by using the wrong track can be reduced by ATC intervention – although this may require the use of STCA. Opposite direction P-RNAV parallel routeings at 7+ nm cannot be demonstrated to meet the TLS, given the collision risks incurred by cases when aircraft use the wrong track.
5. STCA use in risk calculations raises a major issue. Current Eurocontrol SRC policy is that safety nets protection should *not* be included in risk calculations against the TLS.

Thus, P-RNAV poses some difficult problems for an authoritative safety case (for RVSM compare Eurocontrol (2001)). If P-RNAV in complex environments has inherently different ways of creating blunders than the NAT, then how can their rate be estimated with sufficient confidence? Navigation performance extrapolations and general simulations do not appear to resolve these issues, but there are possible ways forward:

1. The starting point for HF investigation would be techniques for determining the psychological mechanisms behind error generation (e.g. 'TRACEr' (Shorrock and Kirwan, 2002)).
2. There may well be further ways of reducing the level of risk for, in particular, opposite direction traffic, through procedures and database usage constraints – but it would still be necessary to prove that they are sufficiently effective.
3. Eurocontrol SRC policy on safety nets does not help with the safety case – should it be re-examined?

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