Geometric Separation

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***Abstract*—This paper presents a resilient method to manage the combinational complexity of en-route aircraft separation by considering the geometric separation of aircraft routes. Aircraft pairs who's routes are separated are considered separated, whilst the separation of aircraft pairs who's routes are not separated is calculated from the sections of their routes which are not separated.**

Geometric separation; En-route separation; Free route separation; Procedural separation; Resilience.

I. Introduction

Air Traffic Control (ATC) prevents collisions by ensuring that all aircraft are safely separated from each other at all times. Every aircraft must be separated from every other aircraft, so the number of combinations of aircraft pairs increases with the square of the number of aircraft, see the blue line in Figure 1.

However, not all combinations of aircraft pairs may lose separation. Aircraft pairs that may lose separation are Traffic: represented by the green line on Figure 1. Whilst aircraft pairs that would lose separation without ATC intervention are Conflicts: represented by the red line.

ATC must resolve all of the Conflicts and monitor the Traffic to assure separation. All other combinations of aircraft pairs are not relevant since their separation is assured.

II. Background

A. Performance Based Navigation

An aircraft intending to fly through controlled airspace is required to file a flight plan. A flight plan contains the departure and destination airports and the route that the aircraft is intending to fly between them. A route may contain multiple airways and waypoints. It may also contain a Standard Instrument Departure (SID) and a Standard Terminal Arrival Route (STAR). A route can be expanded to produce an ordered list of all of the waypoints between the departure and destination, see Figure 2.

An aircraft is usually required to perform turns along its route (see [1]) either prior to reaching each waypoint (a fly-by or TF turn) or a fixed radius (RF) turn.

An aircraft is required to fly to a given navigation performance standard, see [2]. An aircraft meeting the required navigation performance standard will remain within a given distance of its route with a predefined level of confidence, this is it's navigation tolerance.

An aircraft's navigation tolerance along its route defines the horizontal path that the aircraft is required to fly within, i.e. it's flight path see Figure 3.

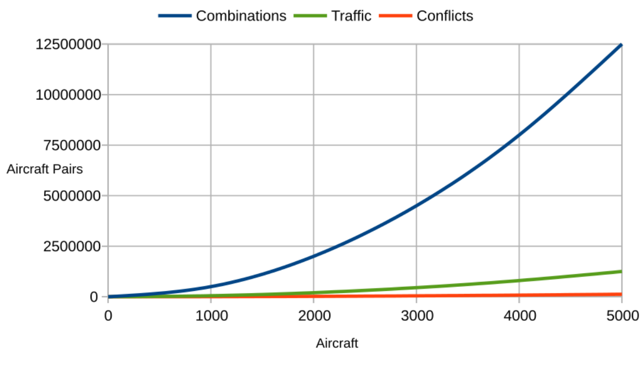

Figure 1 Aircraft pairs to separate

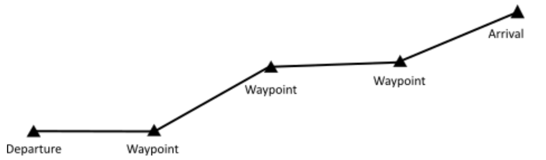

Figure 2 A Route

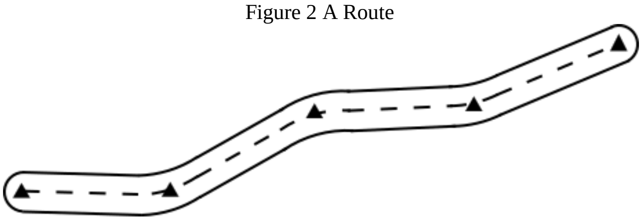

Figure 3 A Flight Path

B. *Procedural Separation*

Long before computerised ATC systems were around, ATC used procedural separation (see [3] chapter 5) to control air traffic. In procedural separation, ATC compare predicted times and flight levels of aircraft at significant points along their routes. Significant points are beacons or named points along published routes, e.g. BCN in Figure 4.

Published routes (airways, SIDs, STARs, etc.) are usually designed with significant points at locations where the routes are not horizontally separated: e.g. at intersections and junctions; such as BCN in Figure 4. Therefore routes that don't have any significant points in common are horizontally separated.

In conjunction with careful airspace design, procedural separation enables ATC to manage combinational complexity by only considering aircraft separation at points where their routes are not horizontally separated, i.e. Traffic.

By finding Traffic, procedural separation enables ATC to separate aircraft without having to consider every combination of aircraft pairs. See the green line on Figure 1.

C. *Free Routing*

A disadvantage of procedural separation is that it requires aircraft to fly along published routes (airways, etc.) which rarely provide the most direct or efficient route.

ATC would like to allow aircraft to fly more direct, "free" routes. However it is possible for horizontal separation to be lost anywhere along direct routes, not just at significant fixes, see Figure 5.

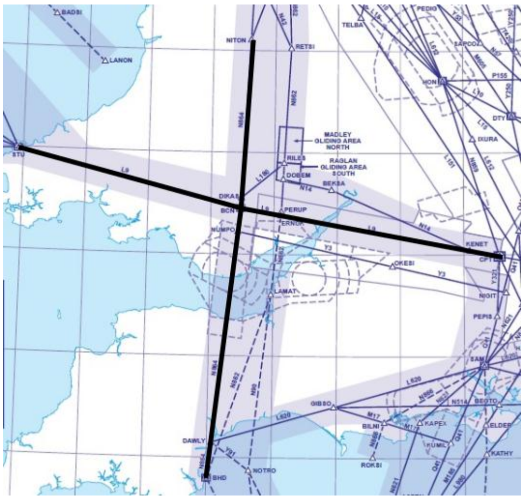

Figure 4 An Airway Intersection

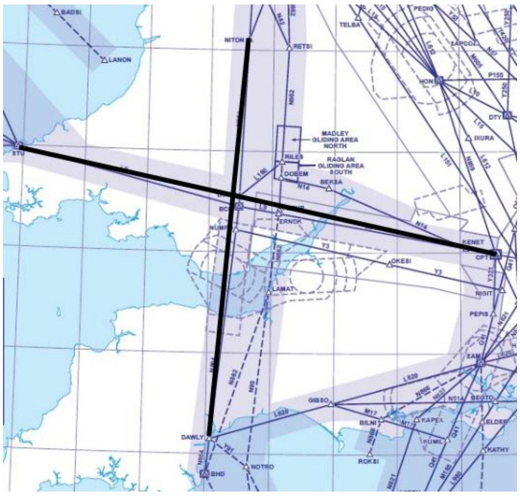

Figure 5 Direct Routes Intersection

III. GEOMETRIC SEPARATION

Powerful computers didn't exist when ATC first used procedural separation; it was inconceivable that the horizontal separation of aircraft routes could be calculated in real time back then. Computer power has grown exponentially since they were first used in ATC. Calculating precisely if (and where) a pair of aircraft routes may lose horizontal separation can now be performed very quickly, see Figure 6 and Figure 7.

In common with procedural separation, aircraft pairs whose routes are horizontally separated can be eliminated, leaving Traffic. Unlike procedural separation, the positions along aircraft routes where horizontal separation is not assured may be anywhere, not just at significant fixes, see Figure 7 and Figure 8.

Modern computing power enables the calculation of precisely if (and where) pairs of aircraft routes may lose horizontal separation in real time without requiring aircraft to fly along published routes.

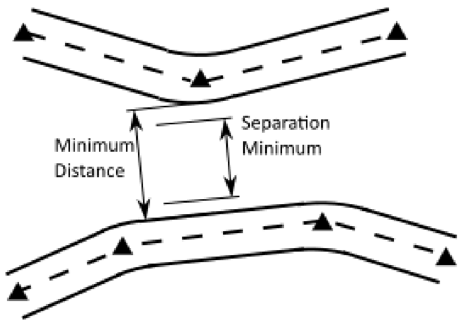

Figure 6 Separated Flight Paths

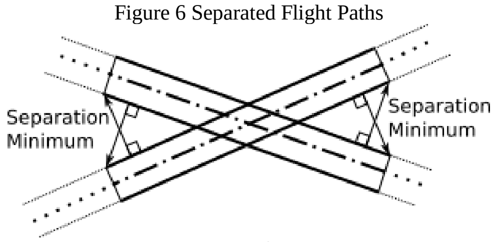

Figure 7 Conflict Paths

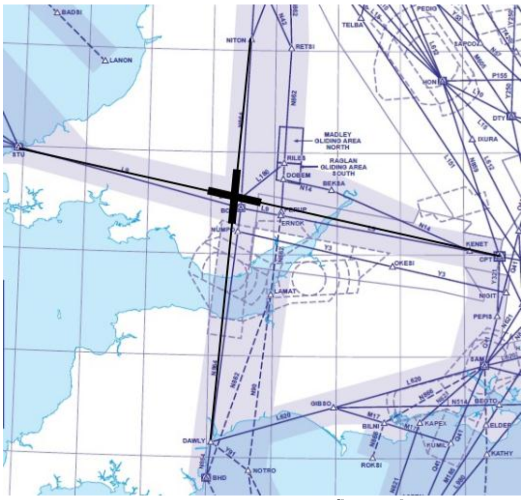

Figure 8 Direct Route Conflict Paths

A. *Conflict Paths*

The sections of aircraft routes where lateral separation is not assured are their Conflict Paths, see Figure 7 and Figure 8. The period when both aircraft may simultaneously occupy their Conflict Paths is the period when they may lose lateral separation.

The geometry of a conflict can be characterised by the relative angle of the Conflict Paths. For example, where the relative angle is obtuse the Conflict Paths are considered to be reciprocal, see Figure 9. Different conflict geometries may be subject to different separation minima, e.g.: wake vortex separation minima may apply to aircraft flying in-trail.

B. *Reference Points*

Procedural separation uses common significant points as reference points to calculate vertical and time separation between aircraft pairs. In a simple crossing case as shown in Figure 8, the intersection point can be used as a reference point. Different conflict path geometries require different reference points, e.g. see Figure 10 and Figure 11.

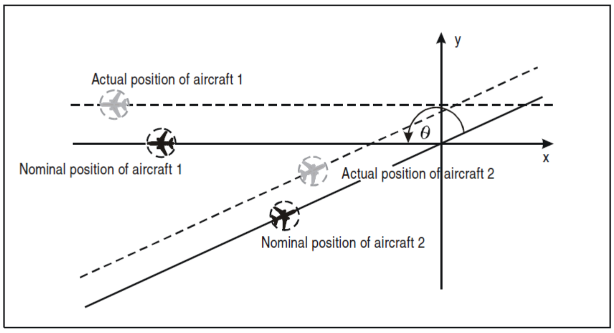

Figure 9 Conflict Path Angle
(ICAO 9689 Fig A-1-3)

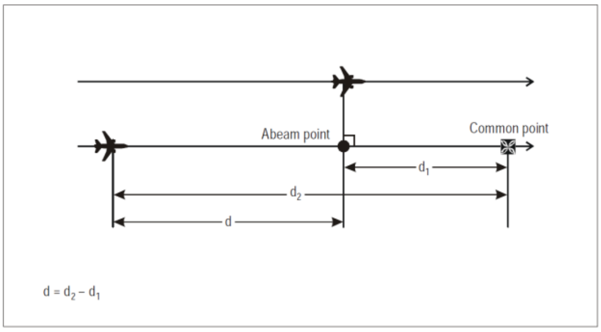

Figure 10 Parallel Route Reference Points
(ICAO 4444 Fig 5.33)

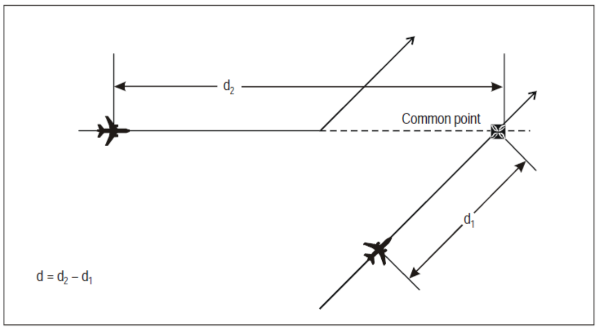

Figure 11 Non-intersecting Route Reference Point
(ICAO 4444 Fig. 5.31)

C. *Horizontal Separation*

The conflict paths and their reference points are used to calculate the longitudinal separation of an aircraft pair. Longitudinal separation is calculated from the required separation minima and the predicted times and speeds of the aircraft relative to their reference points, see Figures 7, 8, 10 and 11.

If an aircraft pair may lose lateral and longitudinal separation at the same time then the intersection of the lateral and longitudinal periods is the period when they may lose horizontal separation, see Figure 12. Otherwise the difference between the lateral and longitudinal periods is the horizontal separation time, see Figure 13. If it less than a predetermined threshold then their horizontal separation is not assured.

Note: if an aircraft pair may lose lateral and longitudinal separation at the same time then the horizontal separation time is the negation of the horizontal period.

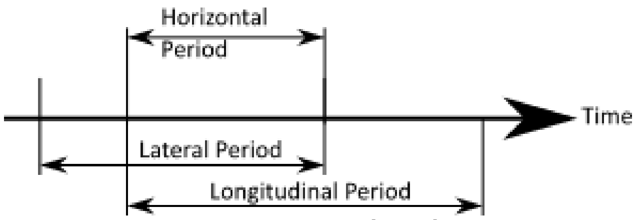

Figure 12 Horizontal Period

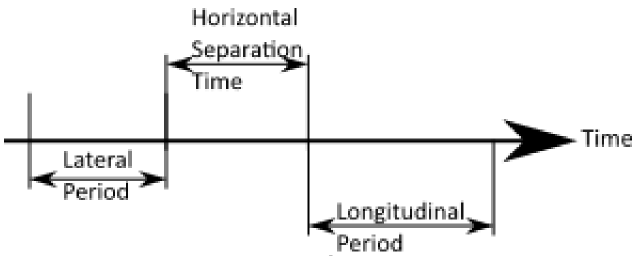

Figure 13 Horizontal Separation Time

D. Vertical Separation

The period when the difference in aircraft flight levels is predicted to be less than the minimum vertical separation distance is the period when the aircraft may lose vertical separation. Note the vertical period may be found independently of the horizontal period.

E. Overall Separation

If an aircraft pair may lose horizontal and vertical separation at the same time then the intersection of the horizontal and vertical periods is the period when they may lose overall separation, i.e. the Conflict Period see Figure 14.

Otherwise the difference between the horizontal and vertical periods is the vertical separation time, see Figure 15. If it less than a predetermined threshold then their separation is not assured.

Note: if an aircraft pair may lose horizontal and vertical separation at the same time then the vertical separation time is the negation of the conflict period.

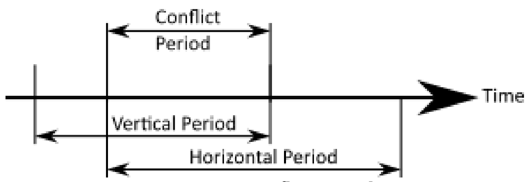

Figure 14 Conflict Period

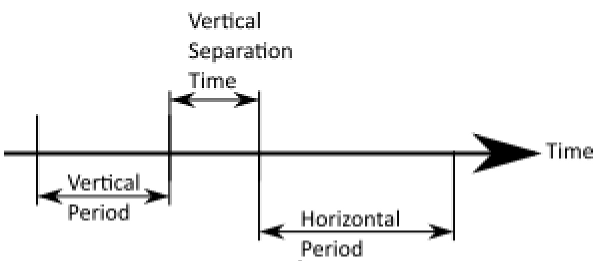

Figure 15 Vertical Separation Time

F. Separation Accuracy

The accuracy of separation data depends upon the accuracy of the input route and trajectory data. If an aircraft deviates significantly from its cleared route or trajectory then an undetected loss of separation may occur.

Modern aircraft have closed-loop systems to ensure that they don't deviate from their routes and cruising flight levels; and modern ATC systems often contain surveillance based monitoring aids to detect if aircraft deviate from their routes or cleared flight levels.

However, the times in an aircraft's trajectory are harder to monitor. Aircraft are free to fly at whatever Indicated Air Speed (IAS) or Mach number that they are capable of, whilst their ground speed is determined by air temperature, wind speed and direction. Unless an aircraft has been given a constrained time over (CTO) a specific position, trajectory times are just estimates of when aircraft are expected to fly over positions on their routes. If an aircraft flies over a position earlier or later than predicted it is not deviating from its trajectory but it may cause an undetected loss of separation.

The time when an aircraft is predicted to fly over a position may include uncertainty. I.e. predicted trajectory position times may be expressed as periods, not just as single times. Time uncertainty can be used to reduce the probability of an undetected loss of separation.

Predicted trajectories downloaded from an aircraft are expected to be more accurate than those predicted by ATC ground systems. However, both aircraft and ground system trajectories use forecast meteorological data to predict aircraft ground speed, so the accuracy of aircraft predicted trajectories is limited by the accuracy of their meteorological forecasts.

True Air Speed (TAS) is proportional to the square root of air temperature (in Kelvin). A difference in air temperature from the forecast temperature will cause an aircraft to fly slightly faster or slower than predicted. This effect is approximately 0.5 Knot per Kelvin difference at most common cruising speeds.

When an aircraft is following a route, it adjusts it's heading to so that its ground vector doesn't deviate from the route. The net effect is that any wind (or forecast wind error) acts as a headwind or a tailwind, reducing or increasing the ground speed respectively.

The effect of trajectory prediction errors on separation can be observed by monitoring the horizontal and vertical separation times of each aircraft pair. A decrease in either time indicates that their predicted separation is decreasing and that ATC intervention may be necessary to ensure separation.

IV. Test System

The test system comprised: a Scenario Player, an Aircraft Monitor and a Conflict Detector. See Figure 16.

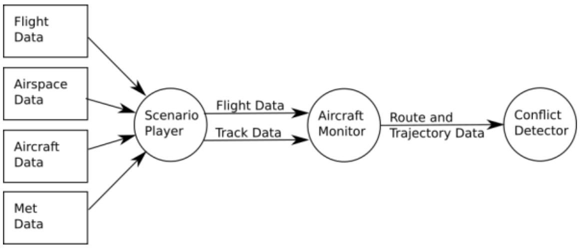

Figure 16 Test System

The Scenario Player:

- reads flight data from a file;
- performs route expansion on the filed routes of the flights using the relevant airspace data;
- performs trajectory prediction on the expanded route using aircraft performance and meteorological data;
- sends data for the flights including the expanded route and trajectory to the Aircraft Monitor;
- when run, creates track updates from its predicted trajectories.
- can be used to change the flight, trajectory and track data for the scenario flights.

The Aircraft Monitor formats flight route and trajectory data into the format required by the Conflict Detector. It sends flight route and trajectory data to the Conflict Detector whenever new flight data or track data for a known flight is received. It may also monitor whether an aircraft is within the bounds of its predicted trajectory.

The Conflict Detector is an implementation of the Via Technology Conflict Detection Algorithm [4].

Test trajectories were derived from flights that transited UK Airspace (EGTTUIR, EGTTFIR, EGPXUIR and EGPXFIR) over the AIRAC cycle from 23rd July 2015 to 19th August 2015 inclusive. Note: 24th July 2015 was the busiest day over UK airspace in 2015.

The Scenario Player created trajectories from the flight data to test the Conflict Detector. Unfortunately, it was not possible to create a trajectory for every one of the flights; some flights were being flown by unknown aircraft types, some of the routes did not contain enough fixes from the UK AIP, etc. Table 1 shows the number of trajectories created per day, total 190000.

The test system used the following parameters:

- 5NM minimum horizontal separation;
- 2NM navigation tolerance;
- and 1000 feet minimum vertical separation.

The test system was repeatedly run with the flights for each day of the AIRAC cycle.

The tests were run on an X64 Intel Core i7-6500U @ 2.60 GHz under Windows 10.

V. Results

A. Horizontal Separation

Table 2 shows the average percentage of flights whose routes were **not** horizontally separated over the UK on each day from 23rd July 2015 to 19th August 2015. The overall average was 17.721%. I.e. on average over 82% of flight routes were horizontally separated over EGTTUIR, EGTTFIR, EGPXUIR and EGPXFIR combined.

Note: the average was 20.68%.when 5NM navigation tolerance was used.

B. Horizontal Traffic

Table 3 shows the average number of other aircraft whose horizontal separation time was less than 5 minutes regardless of vertical separation. Overall, each aircraft had 11.507 other aircraft as potential traffic.

C. Conflicts

Table 4 shows the average number of other aircraft that were predicted to lose horizontal and vertical separation simultaneously. Overall, each aircraft was predicted to lose separation with 1.639 other aircraft.

D. Prototype Performance

Figure 17 shows the average time for the Conflict Detector to load new flights. Figure 17 shows that the load time increases with the square of the number of flights. It also shows that the prototype Conflict Detector can load flight data for up to 7000 aircraft in under a minute.

Figure 18 shows the average time for the Conflict Detector to load each new flight against the number of flights previously loaded. Figure 18 shows that the load time increases linearly with the number of flights. The prototype Conflict Detector took under 20mS to calculate the separation of a new flight when loaded with over 6000 flights, on average.

Figure 19 shows the average times for the Conflict Detector to re-calculate interactions for a flight upon receipt of a trajectory only update. Figure 19 shows that the update time increases linearly with the number of flights. On average, it performs trajectory updates over ten times faster than route updates.

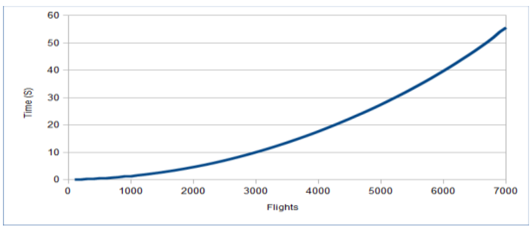

Figure 17 Overall Load Time vs Flights

Table 1 FLIGHT TRAJECTORIES PER DAY

Week Commencing	Day of Week						
	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday
23/07/2015	7070	7242	6223	6620	7048	6948	6812
30/07/2015	7050	7196	6323	6558	6931	6823	6757
06/08/2015	6920	7055	6342	6515	6871	6800	6695
13/08/2015	6811	7091	6281	6435	6952	6856	6775
Average	**7070**	**7242**	**6223**	**6620**	**7048**	**6948**	**6812**

Table 2 AVERAGE UN_SEPARATED FLIGHT ROUTE PERCENTAGE

Week Commencing	Day of Week						
	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday
23/07/2015	17.662%	17.992%	17.884%	17.728%	17.854%	18.160%	17.671%
30/07/2015	17.290%	18.091%	17.763%	17.661%	17.646%	17.761%	17.773%
06/08/2015	17.923%	17.933%	18.507%	17.934%	17.422%	17.232%	17.372%
13/08/2015	17.184%	18.129%	17.775%	17.815%	17.726%	17.276%	17.024%
Average	**17.515%**	**18.036%**	**17.982%**	**17.785%**	**17.662%**	**17.607%**	**17.460%**

Table 3 AVERAGE HORIZONTAL TRAFFIC PER FLIGHT

Week Commencing	Day of Week						
	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday
23/07/2015	12.081	12.386	10.516	11.068	12.302	12.061	11.692
30/07/2015	11.798	12.401	10.742	10.742	11.868	11.548	11.521
06/08/2015	11.900	12.118	11.194	10.955	11.550	11.311	11.143
13/08/2015	10.993	12.192	10.598	10.855	12.058	11.473	11.136
Average	**11.693**	**12.274**	**10.763**	**10.905**	**11.944**	**11.598**	**11.373**

Table 4 AVERAGE CONFLICTS PER FLIGHT

Week Commencing	Day of Week						
	Thursday	Friday	Saturday	Sunday	Monday	Tuesday	Wednesday
23/07/2015	1.732	1.766	1.402	1.503	1.732	1.711	1.659
30/07/2015	1.742	1.783	1.408	1.526	1.710	1.725	1.681
06/08/2015	1.700	1.733	1.435	1.524	1.697	1.666	1.645
13/08/2015	1.625	1.746	1.426	1.556	1.734	1.687	1.653
Average	**1.700**	**1.757**	**1.418**	**1.527**	**1.718**	**1.697**	**1.659**

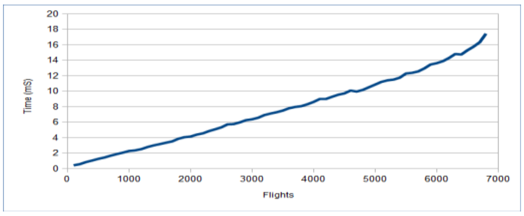

Figure 18 Per Flight Load Time vs Flights

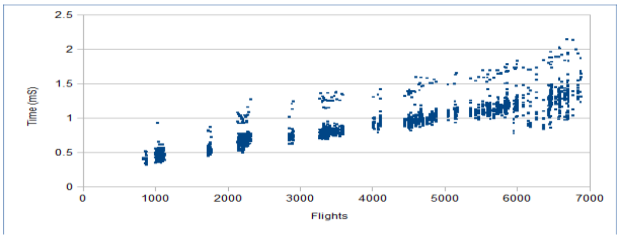

Figure 19 Average Trajectory Update Time vs Flights

VI. Analysis

A. *Route Separation*

Table **2** shows that by considering the horizontal separation of aircraft routes and their associated navigation tolerance the separation of each aircraft with over 82% of the other aircraft could be assured without considering any of their trajectories.

The proportion of aircraft whose routes are horizontally separated is expected to increase with area, making geometric separation especially useful for planning aircraft separation over large areas.

B. *Computational Performance*

The performance figures of Figures 17, 18 and 19 indicate that the prototype Conflict Detector would be capable of detecting and monitoring aircraft separation in real time over the FIRs at 2015 traffic levels.

The prototype Conflict Detector was designed to prove the new conflict detection algorithm [4]. It is a single threaded application which has not been fully optimized for computational efficiency. Conflict detection is an “embarrassingly parallel” problem that is ideally suited to a parallel processing implementation. It is expected that a parallel implementation would be much faster, especially when run on appropriate hardware.

The prototype Conflict Detector uses a very simple algorithm; more sophisticated computational geometry algorithms such as those used in [5] and [6] should also enable significant performance gains

C. *Traffic Monitoring*

Calculating aircraft separation relative to fixed reference points enables their separation to be monitored, providing resilience to inaccurate trajectory data.

TCAS Resolution Advisories (RA) can be generated when horizontal and vertical separation minima are not simultaneously breached, see [7]. By calculating horizontal and vertical separation independently, the time between losses of horizontal and vertical separation can be measured and monitored to control aircraft separation in such situations.

D. *Conflict Geometry*

Determining the geometry of conflicts from the relative angle of aircraft routes enables different separation minima to be applied to different conflict geometries. For example, where aircraft are in-trail, Wake Turbulence Separation minima may be applied see [8] and [9].

E. *Conflict Resolution*

Calculating horizontal and vertical separation independently enables potential traffic at different flight levels to be identified, providing support for “what-if” controller tools and enabling cruise climbs.

Finding potential traffic and measuring it’s separation in units of time enables conflict resolution tools to calculate the effects of time (or speed) adjustments on potential traffic downstream of a conflict.

VII. Conclusions

Geometric Separation harnesses the accuracy of both modern aircraft navigation systems and the processing power of modern computers to enable tried and trusted separation methods to be applied to separate free routing aircraft by simply calculating the minimum distance between their filed routes and comparing it to surveillance separation minima.

Trajectory Based Operations (TBO) identifies a number of different stakeholders at different time horizons, see Figure 20. Geometric Separation enables the conflict horizon to be extended so that stakeholders upstream of ATC can generate and evaluate changes to aircraft trajectories.

Geometric Separation is designed to work at the sector planning conflict horizon (see Figure 20, purple triangle). The performance figures indicate that even the prototype Conflict Detector would be capable of supporting this role at current traffic levels. However, Geometric Separation requires accurate trajectories to provide useful information at these longer conflict horizons.

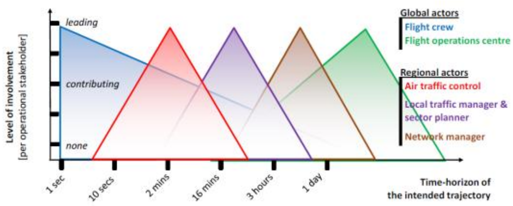

Figure 20 Stakeholder Involvement

Further research is required to determine the conflict horizons that Geometric Separation can support with predicted trajectories derived from both ground based systems and aircraft.

ACKNOWLEDGMENTS

The results were obtained using flight data kindly provided by the Eurocontrol Network Manager from the PRISME database.

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