

Flow management without en route capacity limitations by pre-tactical trajectory compatibility determination

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Abstract— Airspace capacity is limited by several inter-linked factors including controller workload, traffic distribution and procedures. Aircraft cannot always fly an optimal horizontal route or vertical profile and as traffic demand continues to increase then so do delays. Much of the controller's workload is spent on tactical actions related to conflict avoidance between two or more aircraft. If potential conflicts could be identified further in advance then controller workload would be reduced and less of a factor in limiting system capacity.

This Paper discusses how future conflicts could be identified using Decision Support Tools (DST) in order to provide conflict-free trajectories in advance. Much of the research in this Paper deals with problems in estimating wind speed and direction and the impact of wind prediction errors on defining conflict-free trajectories.

To achieve this aim the Paper initially discusses lateral, longitudinal, and vertical uncertainties; the Paper then concentrates on the horizontal components (lateral and longitudinal uncertainties) and the influence of wind errors, both in direction and in speed, on defining conflict-free trajectories.

The Paper concludes, firstly, by expressing a minimum separation distance between two aircraft as a function of the angle between their tracks and an assumed wind speed prediction error, and assuming that both aircraft are at the same flight level and that lateral position errors are negligible. Secondly, the linkage between the prevailing wind direction and the relative speed vectors of the two aircraft, in terms of potential position errors, are demonstrated.

Keywords- ATM safety, ATM capacity, Trajectory Management, Decision Support Tools, Trajectories compatibility

I. INTRODUCTION

In spite of the fact that the airspace could be considered initially as an unlimited resource, this is not a true statement. For Air Traffic Management (ATM) purposes airspace is currently divided into different volumes, called Air Traffic Control (ATC) sectors, each of them controlled by an Air

Traffic Controller (ATCO). The capacity of the ATM system is limited by the amount of simultaneous traffic inside each ATC sector that an ATCO is able to handle. This amount of traffic depends on a number of factors, including the physical pattern of air routes and airports, the traffic demand distribution (both geographic and temporal), the physical volume of the sector and the ATC working procedures designed to maximise the traffic throughput. As a result, airlines cannot fly the optimal route, but the available route which permits the balance between demand and capacity for that specific time.

The continuous increase on air traffic has determined a certain degree of saturation in both Europe and US, especially in high density traffic areas, where the limiting factor on capacity is, apart from the airports capacity, the controller tactical workload in the ATC sectors. Tactical actions, taken by controllers, to avoid conflict between aircraft, have been agreed as the main bottle neck for today's ATM system. These actions grow rapidly with traffic density, limiting the number of aircraft that can be safely attended. As an example, the proportion of ATFM delay in July 2011 (see Figure 1) shows that a 61.3% (46.4% en route capacity plus 14.9 en route ATC staffing) of the delay is due to a lack of en route capacity.

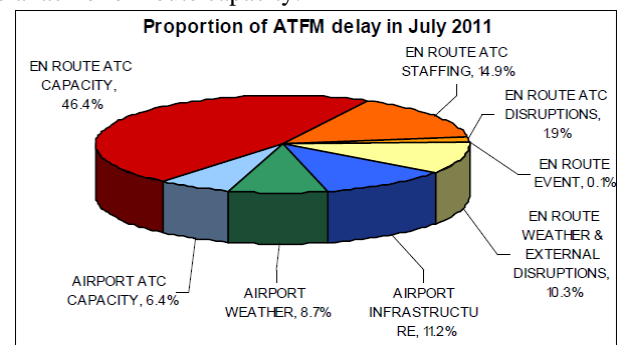


Figure 1. Proportion of ATFM delays as reported by Network Operations Report July 2011. Eurocontrol

Worldwide initiatives have been launched in order to reform the architecture of the current ATM in a way that:

- Allows airlines to decide its optimal route (operational cost reduction,
- Improves user satisfaction (predictability, overall travel time reduction)
- Reduces environmental impact (noise annoyance and air pollution)
- Improves safety (by pre-tactical compatibility among the different routes)
- Identifies possible route conflicts and could offer alternatives in the pre-tactical phase (capacity increase, delays decrease, ATC related cost reduction)

These statements constitute the goals and vision for the design of the future ATM System [1].

In order to minimise controller's tactical interventions, aircraft trajectory management shall be implemented to identify trajectories' incompatibilities in advance, proposing different alternatives to the airlines. Thus, airspace capacity will be closer to the unlimited capacity, and the ATCO work although still necessary, won't be the system limiting factor. This philosophy, underlying the Trajectory Based Operations (TBO), is the basis for the work presented in this Paper.

Future ATM will require automated Decision Support Tools (DST) to provide quasi optimal conflict-free trajectories in advance, in order to minimise the ATCO tactical interventions. Whether trajectories' incompatibilities could be identified in advance (hours before the operation), and different alternatives would be proposed to the airlines, the efficiency of the whole system will be increased and the airlines will be close to decide its optimal route (cost reductions, lower environmental impact). The ability to predict accurate aircraft trajectories is one of the fundamental issues to tackle when developing these DST.

Wind prediction error has been identified as the greatest source of error for trajectory predictions on the order of 20 minutes time horizon. Flight tests have been conducted to better understand the wind-prediction errors, to establish metrics for quantifying large errors and to validate different approaches to improved wind prediction accuracy [2]. Therefore errors in the trajectory determination produced by wind uncertainties should be considered as critical when defining these conflict-free trajectories.

II. CAPACITY VERSUS PREDICTABILITY

Keeping in mind the Future ATM main goals, defined under the European initiative [3], as the following measurable outcomes:

- 3 fold increase in capacity
- 10 fold increase in safety
- 50% reduction in ATM cost per flight

If a conflict is defined as two or more aircraft coming within the minimum allowed distance and altitude separation of each other, the minimum separation between trajectories to be declared as compatible would be established as a trade-off between capacity and predictability. The capacity, based on ATCO workload is related to the number of tactical interventions required by aircraft, whereas the predictability is related to the probability of exposition to risk, and could be defined as the degree of compliance between planned and actual aircraft positions, affecting the total system safety.

A. Predictability

A critical enabler for TBO is the availability of an accurate, planned trajectory, providing valuable information to allow more effective use of the airspace. However, there are many definitions of a trajectory. The framework developed by the FAA/Eurocontrol R&D Action Plan includes definitions of "trajectory" and "trajectory predictor" (TP) [4]: "the Predicted Trajectory describes the estimated path a moving aircraft will follow through the airspace. The Trajectory can be described mathematically by a time-ordered set of Trajectory Vectors".

There are many different stakeholders in the transition to a TBO environment, and there are many different time frames over which TBO may operate—from strategic capacity management operating on the time frame of years to short-term collision avoidance, operating up to over fraction of minutes. Therefore, it is very important to reduce the uncertainty associated with the prediction of an aircraft's future location through use of an accurate 4D Trajectory in space (latitude, longitude, altitude) and time. Trajectory uncertainties can be divided into three groups: lateral deviation uncertainties, vertical deviation uncertainties and longitudinal deviation uncertainties.

The **lateral uncertainties** are already defined within the Performance Based Navigation (PBN) Manual of ICAO, in which the Total System Error (TSE), for some specific aircraft navigation system requirements, operating in a particular airspace, supported by the appropriate navigation infrastructure, is settled. As an example, during operations in airspace or on routes designated as RNP1, the lateral system error must be within $\pm 1\text{NM}$ for at least the 95% of the total flight time. The TSE has a standard deviation composed of the standard deviation of the three errors: path definition error (PDE), Flight Technical Error (FTE), and Navigation System Error (NSE).

In order to analyse the **vertical uncertainties** two different cases should be brought into consideration. When the aircraft is establish at a defined flight level, the approach is similar to the one shown when explaining the horizontal uncertainties, as for the operations in Reduced Vertical Separation Minimum (RVSM) is defined a total vertical error of 200ft, being in this case the accuracy requirements of 3 sigma. On the other hand, when aircraft are climbing or

descending vertical uncertainties are much greater as climbing rate varies with aircraft performance and the atmospheric air speed, temperature and density.

When analysing **longitudinal uncertainties** it must be considered that aircraft use to fly most of the time at a constant airspeed of Mach number rather than at a constant ground speed and, as a consequence, the effects of wind modeling and prediction errors accumulate with time. Airlines use the wind estimation to minimise flight costs by appropriate choice of a route, cruise level and by loading the minimum necessary fuel on board. In spite of the fact that wind-field accuracy is sufficient on average, large errors occasionally exist and cause significant errors in trajectory prediction. The performance of ATM DST depends on the accuracy of the wind predictions. Studies have shown a predominant daily value for RMS vector difference of about 6m/s and large errors of 10m/s are 3% overall [2].

B. Capacity

Nowadays, for ATC purposes, the airspace is divided into sectors that are three dimensional volumes with specific dimensions and procedures depending on the type of traffic that goes through them and its physical characteristics. Each of these sectors is handled by an executive ATCO, and has a previously established capacity defined as the maximum number of aircraft that can be inside the sector within an hour. This capacity depends on the specific characteristics of each sector and it is considered as the maximum number of aircraft that the ATCO can manage keeping the safety margins applied.

As a result, a bottleneck could be identified: the ATCO is able to control a limited number of aircraft, and although the number of available sectors could be increased to cope with an increase of air traffic demand, this has a clear limitation as tiny sectors cannot be properly managed and coordination workload will increase as a consequence.

Current ATFM considers “conflict free” trajectories in an strategic/pre tactical level if they do not exceed capacity at any involved “ATC sectors”. ATC sector capacity is mainly limited by ATCOs conflict resolution workload for a given aircraft population.

As an example, some results providing a relative value of the risk for a given scenario have been obtained using real radar data in Maastricht UAC [5]. After processing 31 days of radar data (600 flights per sector a day) more than 45.000 proximate events were identified in the en-route airspace assigned to the Maastricht UAC, which involves approximately a 50% of conflicted aircraft. Considering the total number of ATC sectors, the conclusions obtained show about 75 potential conflicts per sector a day.

A potential conflict is nowadays identified when the minimum distance between two aircraft is, or is going to be

in the short term, lower than an established minimum separation standard defined by two values, the minimum horizontal and vertical separations. During the en route phase of flight, in the ECAC airspace, these values are 5 nm horizontal distance and 1,000 ft in height.

However, these current minimum separation standards were determined many years ago and they are used to facilitate conflicts resolution in an ATC environment. Trajectories compatibility should not be based in minimum separation standards but in probability of conflicts that finally would require tactical ATCO intervention. This compatibility should be established based on trade off between false alarm and misdetection probabilities.

This assumption is also made in [6] where a method of estimating conflict probability is developed in order to analyse medium term conflict detection and the implications for conflict resolution. However, if aircraft trajectories could be deconflicted time in advance the real time operation takes place, the ATCO workload per aircraft would be significantly reduced and the global system capacity and safety could be increased. This is the purpose for conflict probability analysis within this Paper.

III. HORIZONTAL MOVEMENT UNCERTAINTIES

If the aircraft kinematics is split into horizontal and vertical movements, the horizontal movement and the influence of wind errors on trajectory uncertainties are analysed in this Paper as independent from the vertical movement, taking as starting point the model presented in [7]. In order to model the aircraft kinematics the following parameters are defined:

- v_{ij} is the relative velocity vector between the two aircraft i and j involved in a proximity event.
- Intruder aircraft (AC $_j$) will be represented as a point and its speed will be the relative velocity vector.
- Reference aircraft (AC $_i$) will be stationary.
- The impact plane is defined as a generic projection plane containing the centre of AC $_i$ (assumed as static) and perpendicular to v_{ij} . This plane is represented in Figure 2.

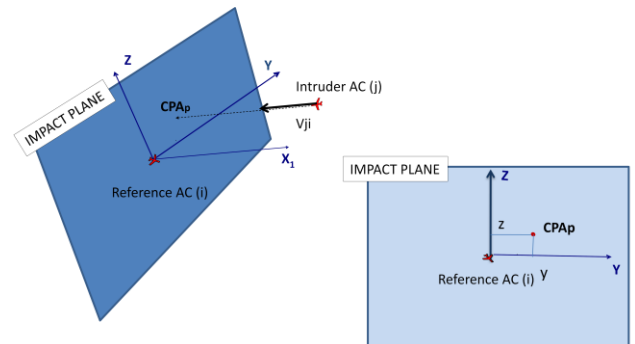


Figure 2. Impact Plane definition

Considering that the coordinates of the Closest Point of Approach (CPA) are directly related to the relative speed v_{ji} , the expression for the CPA coordinates could be calculated as the intersection of the straight line (defined using the position of aircraft j and whose direction is the same as v_{ji}) and the impact plane. The straight line equations are the following:

$$(x, y, z) = (x_j, y_j, z_j) + \lambda(v_x, v_y, v_z) \quad (1)$$

The CPA coordinates will be given as the intersection between this line and the impact plane. That involves the following condition:

$$x = x_j + \lambda v_x = 0 \quad (2)$$

As the impact plane is perpendicular to the relative speed direction (impact plane definition), it can be stated that $v_x = -v_{ji0}$ (encounter relative speed), and then:

$$\lambda = \frac{x_j}{v_{ji0}} = \text{time to CPA} = t_{CPA} \quad (3)$$

So, the estimated coordinates of the CPA are:

$$\begin{aligned} \hat{y} &= y_j + t_{CPA} v_y \\ \hat{z} &= z_j + t_{CPA} v_z \end{aligned} \quad (4)$$

The true coordinates differ from the estimated ones due to the existence of some uncertainties affecting both to the calculated position of aircraft j and to the calculated relative speed. Likewise, the true coordinates are:

$$\begin{aligned} y &= y_j + \varepsilon_{yj} + t_{CPA}(v_y + \omega_y) \\ z &= z_j + \varepsilon_{zj} + t_{CPA}(v_z + \omega_z) \end{aligned} \quad (5)$$

Where:

- $\varepsilon_{y,zj}$ is the y or z component of the aircraft j initial position coordinates uncertainty
- $\omega_{y,z}$ is the y or z component of the relative speed coordinates uncertainty

Using the covariance matrix for estimation error, given by the following expression:

$$Q = E[(\hat{x} - x)(\hat{x} - x)]^T \quad (6)$$

In this case it is obtained:

$$\hat{y} - y = -\varepsilon_{yj} - t_{CPA}\omega_y$$

$$\hat{z} - z = -\varepsilon_{zj} - t_{CPA}\omega_z \quad (7)$$

$$Q = E \begin{bmatrix} (\varepsilon_{yj} + t_{CPA}\omega_y)^2 & (\varepsilon_{yj} + t_{CPA}\omega_y)(\varepsilon_{zj} + t_{CPA}\omega_z) \\ (\varepsilon_{yj} + t_{CPA}\omega_y)(\varepsilon_{zj} + t_{CPA}\omega_z) & (\varepsilon_{zj} + t_{CPA}\omega_z)^2 \end{bmatrix}$$

The resulting general expression for covariance matrix will be simplified considering the following assumptions:

- Horizontal movement assumption: only horizontal speed components are initially considered (this imply all z components equal to zero),
- Aircraft position lateral error is considered negligible: the navigation performance proposed by PBN concept specifies that aircraft navigation system performance requirements, defined in terms of accuracy, integrity, availability, continuity and functionality required for the proposed operations, when supported by the appropriate navigation infrastructure may give values as low as a lateral deviation of 0.1 nautical miles 2-sigma. A PBN 0.1 implies that the aircraft lateral deviation is confined within 0.1NM at both sides of the track a 95% of the time (this imply $\varepsilon_{yj} \approx 0$).

Under these assumptions covariance matrix is reduced to:

$$Q = E \begin{bmatrix} (t_{CPA}\omega_y)^2 & 0 \\ 0 & 0 \end{bmatrix} \quad (8)$$

Taking into account that w_y is the y component of the relative speed coordinates uncertainty due to the influence of the wind error, it can be stated in terms of the angular deviation resulting:

$$\omega_y = v_{ji0} * \delta\theta \quad (9)$$

And then,

$$Q = E \begin{bmatrix} (t_{CPA}v_{ji0} * \delta\theta)^2 & 0 \\ 0 & 0 \end{bmatrix} \quad (10)$$

$$Q_{11} = t_{CPA}^2 v_{ji0}^2 * E(\delta\theta^2)$$

Where $\delta\theta$ was obtained in [8] as:

$$\delta\theta = \text{atan} \frac{a}{r+b} \quad (11)$$

Being:

$$\begin{aligned} a &= \cos(\theta_j - \theta_w) * \sin(\theta_{ji} - \theta_j) - \cos(\theta_i - \theta_w) * \sin(\theta_{ji} - \theta_i) \\ b &= \cos(\theta_j - \theta_w) * \cos(\theta_{ji} - \theta_j) - \cos(\theta_i - \theta_w) * \cos(\theta_{ji} - \theta_i) \\ r &= \frac{v_{ji0}}{w} \end{aligned}$$

Where:

- $\theta_{i,j,w}$ are the angles measured from the North for aircraft i, aircraft j and wind direction respectively.
- θ_{ji} is the angle measure from the north for the relative speed vector.
- w is the magnitude of wind error

Considering (11), it is shown that $\delta\theta$ depends on the geometry of the encounter and the wind error direction through the different angles $\theta_{i,j,w}$. Likewise, it depends on the ratio between the relative speed and the wind error.

On the other hand, it would be desirable to express $\delta\theta$ in relation to δw , which can be obtained using the first component of the Taylor Series development (component higher than first term are assumed negligible):

$$\delta\theta \approx f'(0)\delta w \quad (12)$$

Where the derivative at zero point is:

$$f'(0) = \frac{\partial}{\partial w} \left[\frac{a}{r+b} \right]_{w=0} = \frac{a \cdot v_{ji0}}{w^2(r^2+b^2+2rb)} \Big|_{w=0} = \frac{a}{v_{ji0}} \quad (13)$$

And then

$$\delta\theta \approx f'(0)\delta w = \frac{a}{v_{ji0}} \delta w \quad (14)$$

Therefore, the expression for variance calculation results:

$$Q_{11} = t_{CPA}^2 v_{ji0}^2 * E \left[\left(\frac{a}{v_{ji0}} \delta w \right)^2 \right] = t_{CPA}^2 a^2 * E[(\delta w)^2] = t_{CPA}^2 a^2 \sigma_w^2 \quad (15)$$

Where:

- t_{CPA} is the time for the conflict to happen, or time to CPA
- σ_w is the root mean square vector difference for wind error estimation
- a is a geometry factor which expression is (taking as reference axis and the origin for angles the direction of v_{ji0}):

$$a = \cos(\theta_w - \theta_i) \sin \theta_i - \cos(\theta_w - \theta_j) \sin \theta_j \quad (16)$$

As a conclusion, the probability distribution for CPAy coordinate determination is determined by:

$$\sigma = t_{CPA} \ a \ \sigma_w \quad (17)$$

It can also be initially assumed for the wind statistical model to respond to a modeled bias, introduced as aircraft ground speed into the flight plan, plus a Gaussian distribution $N(0, \sigma_w)$. This consideration has also been made by other authors [9,10], according to whom the along track error at a time for aircraft in level flight is well modeled by a normal distribution.

Each of the factors composing Equation (17) will be analysed and some initial considerations and results shown.

A. Time to CPA (t_{CPA})

Once a potential conflict is detected, and segments of the trajectories involved are modeled, the t_{CPA} is defined as the time for the conflict to happen. To determine its value it must be considered the predicted trajectories definition and the normal time horizon that is currently used by the prediction tools.

Network Management tools will typically work with the flight profile for the whole flight (that is an average of two hours). Whereas tactical tools may predict the flight only with regard to the current ATC sector, being the looking ahead time less than 20 minutes.

As trade-off between expected trajectories accuracy and look-ahead time must be established, it will be settled an intermediate value of **1 hour** for the calculations presented in this paper.

B. Wind error estimation: σ_w

Taking into account previous sections of this document, it will be considered an initial wind error RMS value of **6 m/s** (12kt) [2]. This value has been obtained under the following assumptions:

- A predominant daily value for RMS vector difference is of 4.5-5.5 m/s range. This value was obtained taking into account all possible forecast projections (from 0 to 6 hours).
- The forecast errors grow with the time in advance of the forecast projection, being the RMS vector difference values increase of about 1.5 m/s from 1 to 6 hours.

As it is considered that the RBT will be presented at least, about 6 hours before the operation time, a value for the RMS vector difference of 5.5m/s plus a 0.5m/s increment is settled (because most of the measures in the referenced study have been done for projections less than 6 hours in advance).

This value is very similar to the one obtained in other analysis of level flights [10], in which a rate of growth of along-track r.m.s error of 0.22NM per minute is reported.

C. Geometry Factor: *a*

Considering the expression obtained for the geometry factor calculation (17), and that dependence between Θ_i and Θ_j is:

$$\theta_i = \pi - \arcsin \left[\frac{v_j}{v_i} \sin \theta_j \right] \quad (18)$$

Taking into account that the angles are referenced to the direction of v_{ji0} it must be highlighted that there are some geometries that are not possible and therefore are being ignored in the analysis. These configurations are the following (remember that the origin of angles has been settled in v_{ji0} direction):

- **θ_i or $\theta_j = 0, \pi$** This would assume two aircraft flying a track with the same heading (under the same speed assumption, conflict no possible) or opposite heading. Although some studies [11] consider the user preferred trajectories as a total removal of the current flight level constraints based on the east/north west/south flying routes, this Paper still considers the current segregated cruise altitudes. Taking this into account, this is operationally only possible if one of them is climbing or descending. This case is not considered as only the horizontal movement is being under analysis.
- **θ_i or $\theta_j = \pi/2$** It is not possible due to obvious geometrical reasons.

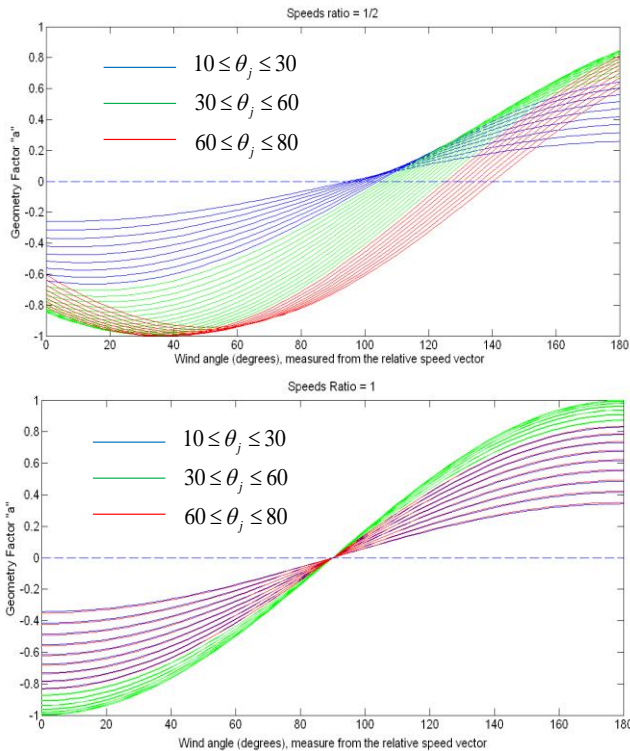


Figure 3. Geometry Factor

Figure 3 presents the calculation of the geometry factor “a” increasing Θ_j from 10 to 80 degrees (colour legend is explained), Θ_w from 0 to 180 degrees and for speeds ratio $\frac{1}{2}$ (upper part) and ratio 1 (lower part).

One of the most interesting results to analyse is the geometry of the encounter for which the geometry factor “a” reaches its maximum value. Increasing Θ_j from 10 to 80 degrees, the correspondent Θ_i angle, and the calculated Θ_w for which “a” is maximum is presented in Figure 4. From it can be learnt that if both aircraft have the same speed and the wind direction is the same of the relative speed vector ($\Theta_w=0$), “a” reaches its maximum value. On the other hand, if the speed ratio is $\frac{1}{2}$ the worst configuration (a maximum) is produced when the wind direction is close to the aircraft whose speed is minor (in this case aircraft j).

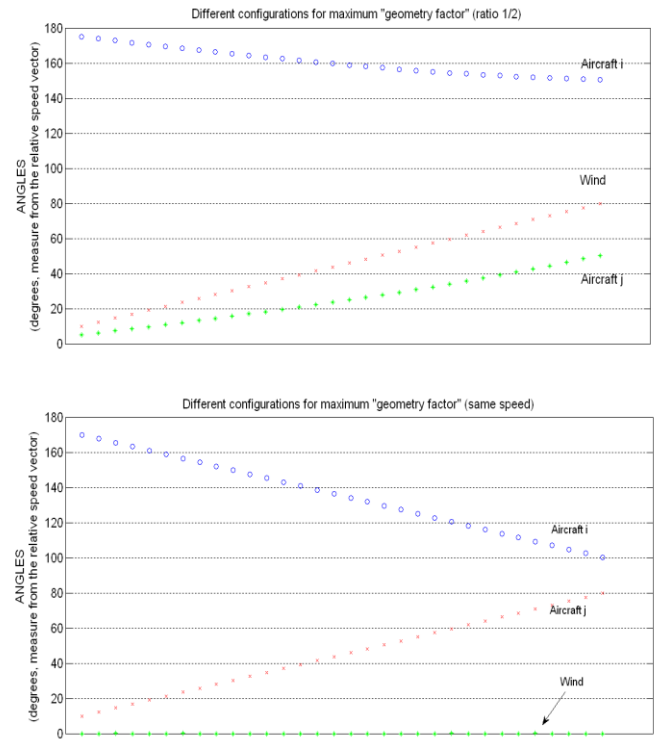


Figure 4. Encounter geometry for “a” maximum. Same speed

As the speed range for turbojets is very similar in the enroute phase of flight, from now on a ratio between aircraft speeds equal to 1 will be considered.

From the above presented results it could be calculated the “a” value for every specific wind angle knowing the aircraft speeds and the encounter angles for both aircraft (data obtained from the flight plan).

Whether the prevailing winds in the airspace where the encounter is to happen could be known in advance, an accurate value for the geometry factor “a” could be calculated. If no previous information about the wind field is

available, the wind angle that produces the higher error should be chosen in order to be conservative.

Figure 5 shows the maximum “a” values for the above presented encounter configurations.

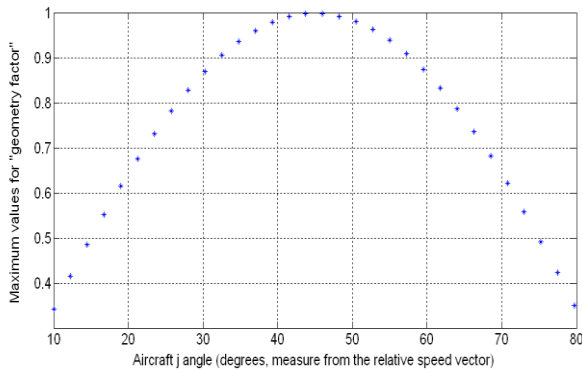


Figure 5. Maximum “a” values. Same speed

IV. TRAJECTORY COMPATIBILITY DETERMINATION

Figure 6 shows the different distribution functions obtained setting the following values for the parameters determining σ (17):

- $t_{CPA} = 60$ min
- $\sigma_w = 6$ m/s
- a = maximum values obtained for the different geometry configurations (see Figure 5)

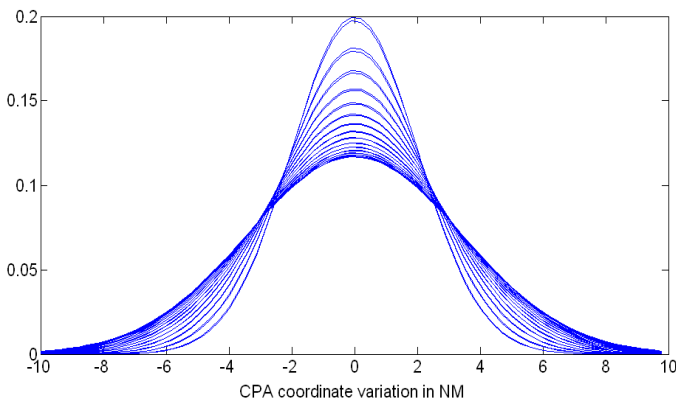


Figure 6. Probability density functions for maximum “a” values.

This functions show the probability distribution of the CPAy coordinate due to the wind error effect on the aircraft speed.

It is now to be considered that the minimum separation between the aircraft involved in the encounter must be, at least, equal to the current minimum standard separation, which is 5 NM. Furthermore, it must be settled the probability for a conflict to happen that is going to be assumed.

Based on this probability, the extra distance to be added to determine compatibility between trajectories will be

calculated. Figure 7 shows the distance calculation graphically.

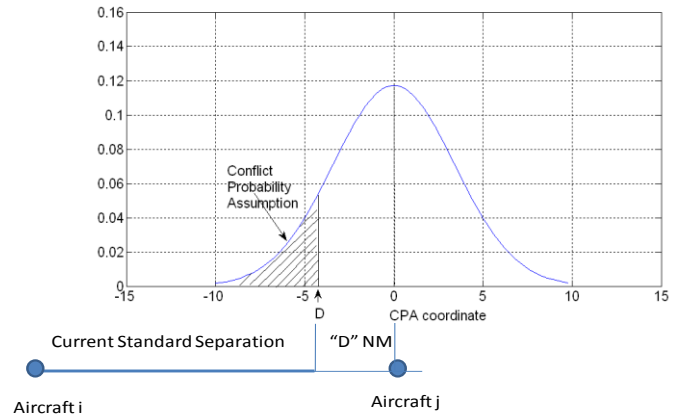


Figure 7. Probability of conflict and extra distance calculation

When analysing the reduction of separation standards using automation tools some studies [11] show a concept which uses predicted conflict uncertainty as a decision aid for traffic controllers. The medium term conflict probability assumed is $5 \cdot 10^{-2}$, since a reasonable level of missed detection is allowed, whereas the probability of conflict for short term separation assumed is 10^{-3} since the sector controller is responsible for assuming the final separation.

If we assume a threefold increase in the future air traffic demand [1], [5], the total number of flights per sector and per day could reach 1800 (same number of sectors has been assumed). As an example, the planned probability for a conflict to happen in the future ATM scenario would involve up to 6 conflicts a day to be solved by the ATC, which results in $3 \cdot 10^{-3}$, which would reduce significantly the ATC workload for conflict resolution.

Figure 8 shows the minimum distance between two trajectories for them to be considered as compatible for different geometrical configurations, and always for the wind error vector angle that produces the maximum deviation.

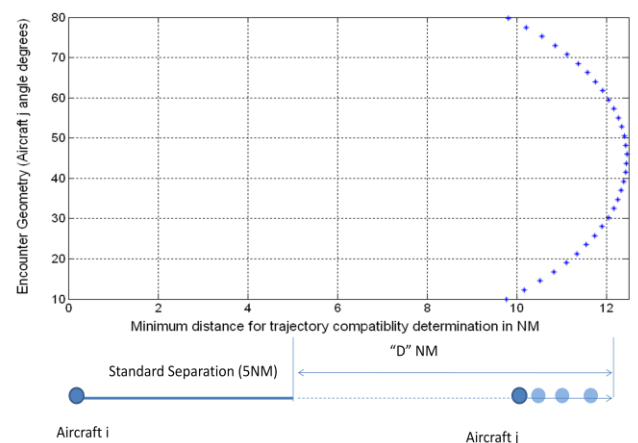


Figure 8. Extra distance calculation for trajectory compatibility.

V. CONCLUSIONS

The main initial conclusion obtained and presented in this Paper is that the minimum distance between two trajectories to be declared as compatible varies between **10 and 12 NM** depending on the encounter geometry configuration, considering a time to CPA equals to **1 hour**, and a RMS value for wind error of **6m/s** and a controller workload in the future ATM limited to **6** conflicts a day (if any other type of contingencies does not take place).

The assumptions made include the consideration that both aircraft are flying established at the same flight level and the aircraft lateral position error is negligible. The three factors affecting probability distribution for CPA coordinates determination are described in the table below.

As the range of speed for turbojet aircraft is very similar, it is considered for the final calculations that $|\vec{v}_j| = |\vec{v}_i|$.

TABLE I. FACTORS AFFECTING PROPABILITY DISTRIBUTION

t_{CPA}	a			σ_w
1 hour	Dependant on the encounter geometry ($\vec{v}_j, \vec{v}_i, \Theta_w$)			6 m/s
	\vec{v}_j	\vec{v}_i	Θ_w	
	Known through the Flight Plan (see Figure 9)		As unknown the "worst case" has been chosen for the analysis (see Figure 10). Prevailing winds could be used if any	

The encounters geometries that provides a maximum and a minimum value of "a" are shown in Figure 9. As can be seen, an angle between tracks of 90 degrees provides the maximum value, whereas angles near 180 degrees or near 0 degrees provides a minimum.

On the other hand, Figure 10 shows the wind angle that produces maximum and minimum deviation for angle between tracks of 90 degrees. The maximum wind influence happens when the wind direction is parallel to the relative speed vector, whereas the contrary takes place when the wind direction is perpendicular to it.

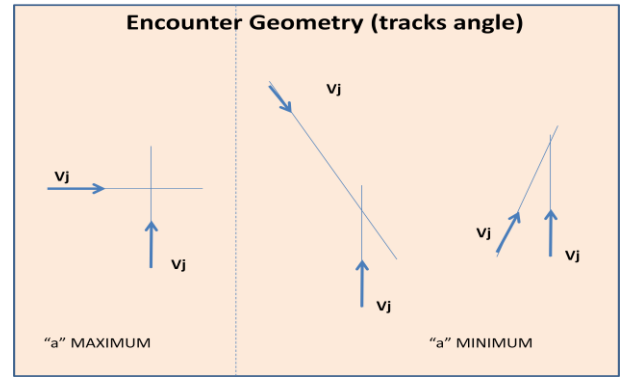


Figure 9. Different encounters geometry for maximum and minimum deviation.

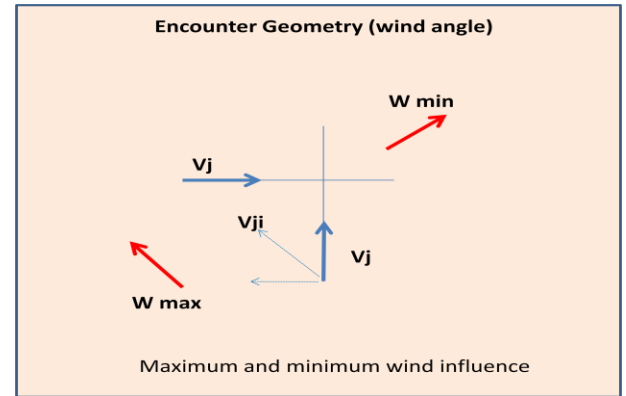


Figure 10. Wind angles for maximum deviation

REFERENCES

- [1] Strategic Guidance in Support of the Execution of the European ATM Master Plan. May 2009
- [2] Cole, R.E, et al. "Wind Prediction Accuracy for Air Traffic Management Decision Support Tools". 3rd USA/Europe Air Traffic Management R&D Seminar. Napoli, 13-16 June 2000.
- [3] Flight Path 2050. Europe's vision for aviation. Report of the High Level Group on Aviation Research.
- [4] Mondoloni, S. "Commonality in Disparate Trajectory Predictors for Air Traffic Management Applications", 24th Digital Avionics Systems Conference, Washington DC. October 2005
- [5] Saez,F.J. et al, "Development of a 3D Collision Risk Model Tool to Assess Safety in High Density en-Route Airspaces". May 2010.
- [6] Irvine, R. "A geometrical approach to conflict probability estimation" Eurcontrol Experimental Center. 4th USA/Europe ATM R&D Seminar, Santa Fe. December 2001.
- [7] Saez,F.J. et al, "CRM Model to estimate probability of potential collision for aircraft encounters in high density scenarios using stored data tracks". To be published.
- [8] Portillo, Y." Enhancement of current collision risk models taking into account atmospheric conditions". Progress Review Report. Master by Research, Cranfield University. 21/07/2011
- [9] R.A.Paielli, et al, "Conflict Probability Estimation for Free Flight", AIAA Journal of Guidance, Control and Dynamics, Vol 20, Number 3, May - June 1997, pp. 588 - 596.
- [10] R.A.Paielli, "Empirical Test of Conflict Probability Estimation", USA-Europe ATM R&D Seminar, 1998.
- [11] A. W. Warren, et al. "Conflict Probe Concepts Analysis in Support of Free Flight", Appendix B, NASA Contractor Report 201623, January 1997