On the Applicability of Free-Flight Mode in European Airspace

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Abstract

Free Flight Mode in EATMS [1] has been defined as operations comprising free-routing and autonomous separation in Free-Flight Airspace. Investigations into this concept started at EUROCONTROL in late 95, under the acronym FREER. Results of feasibility studies have been presented elsewhere [2,6,7,8]. In this paper, we focus on the results of a model-based simulation incorporating autonomous aircraft operations, and aiming at evaluating the applicability of the Free-Flight Mode in ECAC airspace.

Based on a simple model of free-routing, and a model of free-maneuvering, in which the coordination of separation actions are governed by the FREER Extended Flight Rules [3], associated with an automatic conflict resolution mechanism [4] that simulates separation maneuvers, 76 simulations were run with estimated ECAC traffic in 2015. Data gathered from these simulations is analyzed into applicability indicators. Are presented in this paper the indicators relating to geographical representation of traffic density across ECAC airspace; number of conflicts detected and resolved by the pilots per flight-hour and per traffic density, and variation of number of conflicts with respect to changes in ADS-B look-ahead time.

Index Terms-- EATMS Concept, Airborne Autonomous Separation, Airborne Separation Assurance System, Free route, Free-maneuvering, Free flight mode

1 Introduction

The collaboration between European Union project MAICA [5], through one of its partner, Alcatel-Alsthom ISR, and EUROCONTROL Experimental Center, was started in Mid 1997 to evaluate the applicability of Autonomous Aircraft Operations in Free-Flight Airspace. This concept has been investigated in the FREER project [6,7] to establish the base lines for Free-Flight Mode in EATMS.

The objectives of this study consists in:

- Evaluating at the global level, *i.e*. in realistic European situations, the concept of autonomous separation and free-route operations at a more microscopic level,
- Analyzing the complexity of the situations that pilots of autonomous aircraft, in en-route phase, would have to handle in different areas, and for different traffic densities.

To reach these objectives, a simulation tool, named MARS (Multiple Autonomous aiRcraft Simulation) was developed at Alcatel ISR. This simulator implements in particular the Extended Flight Rules (EFR) [3], and the Generic Algorithmic Resolution Service (GEARS) conflict resolution algorithm [4] owned and made available by EUROCONTROL EEC.

MARS models the autonomous aircraft environment, in the time frame of 2015, as follows:

- Autonomous aircraft fly in segregated area, namely Free-Flight Airspace (FFAS of EATMS airspace regime), in which they are responsible for their navigation and separation assurance. There is no fixed-route structure in this area.
- An autonomous aircraft enters the FFAS at an entry point and leaves it at an exit point. These points are defined by computing the intersections between the FFAS and the current fixed route network. This allows defining, at once, the characteristics of the traffic flow between an entry and an exit point in term of distribution of flight levels, and aircraft types.
- To model free-route operations, which is different from direct routes between entry and exit points, a virtual waypoint is randomly selected between these fixed points for each aircraft. The set made of the entry point, the virtual waypoint and the exit point represents the preferred trajectory of the aircraft. This model avoids opposite traffic flows often occur in direct route simulations.
- During its flight, an aircraft can deviate from its trajectory, *e.g.* to deal with external events such as conflict resolutions. When such maneuvers are finished, the aircraft heads at either its virtual waypoint or its exit point, depending on its position.
- Flight Levels allowed for an aircraft are the current FL allocation with RVSM using the "*single alternate*" conversion rule defined by EUROCONTROL.
- During its flight an autonomous aircraft is allowed to change FL as long as the new selected FL is compatible with its current FL and the RVSM conversion rule. In MARS, as external impacts on FL changes such as weather conditions, fuel consumption, *etc.* are not modeled, the FL changes are randomly selected by the aircraft using a probabilistic function.
- Autonomous aircraft can modify its trajectory in the FFAS only if its new trajectory is free of conflict with its useful ADS-B radius *i.e.* at least 90NM, conformed to EFR procedures [2].
- Autonomous aircraft broadcast their position and their predicted trajectory to the other aircraft using ADS-B. The range of ADS-B is limited to a maximum of 150NM. The length of the transmitted trajectories is also limited in time and varies in the simulations.
- Autonomous aircraft are able to compute their separation infringements (conflicts) with all the aircraft located within ADS-B range. The range is modeled as look-ahead time, and varies from 2 to 10 minutes.
- Autonomous aircraft are able to solve the conflicts in which they are involved. In MARS, the implementation of the resolution strategy is as follows:

1. Only one aircraft is in charge of the resolution for conflicts between 2 aircraft. This aircraft is selected by the EFR [3,8] defined in FREER.
2. This aircraft computes all the solutions to solve the conflict, taking into account the potential conflicts with all the other aircraft located within ADS-B range. Information regarding other aircraft trajectories is limited to the look-ahead time. The trajectories corresponding to these solutions must be free of conflicts during a certain time that can not exceed the look-ahead time. A solution is made of a list of sequential vertical and lateral maneuvers. These solutions are computed by an extension of the GEARS algorithm [4] from EUROCONTROL.
3. The aircraft selects the best-suited solution to solve the conflict using criteria such as the distance to the exit point at the end of the resolution maneuver.

2. Description of the study

Using MARS, the autonomous aircraft concept was studied following 3 different directions:

1. Firstly, a geographical analysis was carried out in order to assess the applicability of this concept in European areas with various traffic densities,
2. Secondly, the impact of the variation in the look-ahead time parameter was examined,
3. Finally, a comparison was made between several conflict resolution strategies.

An area of interest was defined (from 34° to 74° Latitudes and from –14° to 25° Longitudes) and a set of sub-areas extracted from it. These areas are presented in Figure 1.

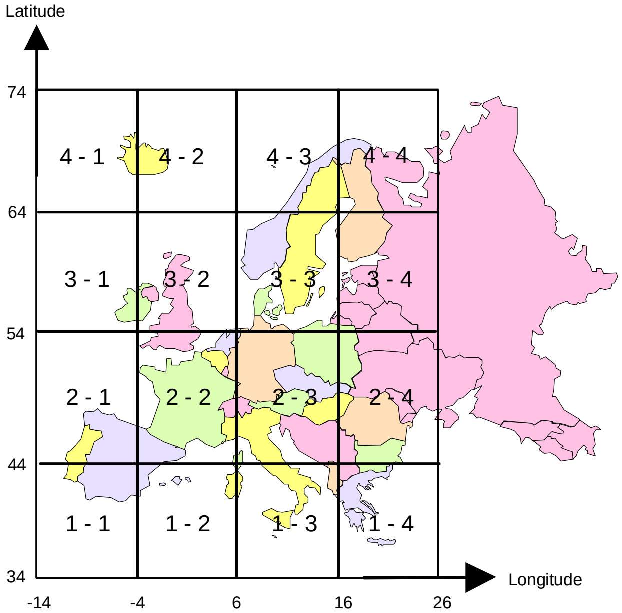

Figure 1: Geographical Decomposition of the ECAC areas into zones of interest.

For each zone of interest, traffic densities are sampled from the EUROCONTROL forecast traffic in 2015. Four traffic samples are used for each zone, each sample is defined with an "hourly weight" (HW). The HW of an hour represents the percentage of the daily traffic that flies during this particular hour. Four typical densities are used to represent:

1. Overnight traffic from 10 p.m. to 4 a.m.: HW = 2%,
2. Early morning/evening traffic from 5 to 6 am and from 8 to 9p.m. : HW = 4%,
3. Normal/daily traffic: 7 a.m. to 7 p.m. HW = 7%,
4. Peak hour traffic (worst case): HW = 10%.

Figure 2 shows the trends of traffic densities and their associated hourly weights.

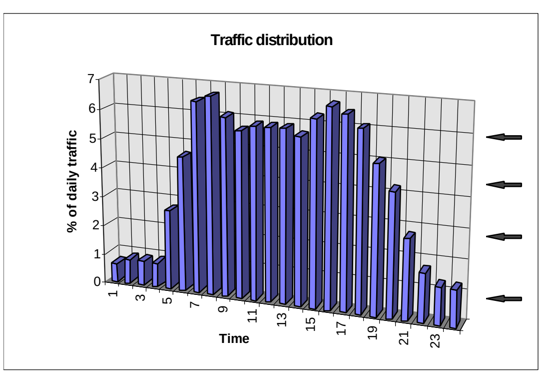

Figure 2: Trends of Traffic Densities and Their Associated Hourly Weights used in the Simulations.

In total, 76 simulations were run with four traffic densities on 1 full area, 16 sub-areas, and 2 concatenations of areas (2-1 with 2-2, and 2-2 with 2-3). We only focus on the traffic at FL290 and above.

3. Major Assumptions

A; Airspace regimes and flight phases

The airspace is considered as being based on three airspace regimes:

– Managed Airspace (MAS),
– Free Flight Airspace (FFAS), and
– Unmanaged Airspace (UMAS),

As defined in the EATMS OCD [1]. The simulations performed address the behavior of aircraft inside the FFAS, assuming that FFAS floor is at FL 290. The management of the interfaces with the other airspace regimes is not taken into account.

B. RVSM

The classical bipolar partition of FL is assumed to be the standard rules but RVSM, as defined by the “single alternate” rule, is taken into account. Table 1 presents the list of FL allowed versus aircraft heading:

Heading range	Allowed FL
0 - 179	50 - 70 - ... - 290 - 310 - 330 - 350 - 370 - 390
180 - 359	60 - 80 - ... - 300 - 320 - 340 - 360 - 380 - 400

Table 1: FL distribution

C. Separation Standards

The separation standards taken into account are current standards:

– 5 NM for lateral separation,
– 1000 feet for vertical separation.

D. Aircraft equipment

The FFAS is restricted to suitably equipped aircraft able to cope with the autonomous aircraft operation. We assumed that these aircraft must be able to:

– Know their own position (GPS, GNSS),
– Achieve their own navigation (4D-FMS),

– Carry out their separation assurance (ADS-B, ASAS),
– Broadcast their own data (position, identity, and intents) to other aircraft to compute traffic situations.

In all simulations it was assumed that all aircraft were suitably equipped and that all these equipment were perfectly working (no error, no failure). However, the following constraints were taken into account:

– The range of the data link used for ADS-B is limited
– The "length" of the predicted trajectories used to compute conflicts is limited (look-ahead time).

In most of the simulations, the ADS-B range was set to 150 NM and the look-ahead time to 10 minutes. Look ahead times of 8, 5, 3 and 2 minutes were introduced only to analyze impacts of changes in this parameters.

E. Free Route Structure

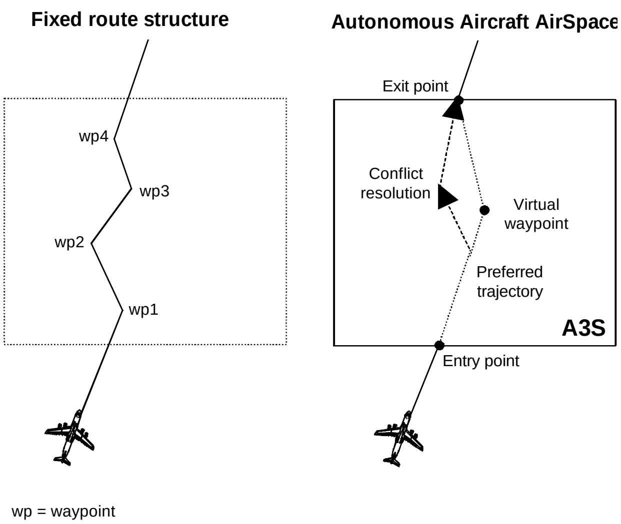

Figure 3 Assumption for Free-Routing

4. Main results

As a result of these simulations, a set of maps was drawn to outline the values measured. The measured complexity indicators in each sub-area are:

- The average traffic density in terms of number of aircraft per hour and per 1MKm²,
- The average number of conflicts "seen" by a pilot per flight hour,
- The average number of conflicts actively solved by a pilot per flight hour,
- The average number of conflict per 1MKm² per hour,
- The average instantaneous number of clusters in 1MKm²,
- The average flight time without conflict,
- The normalized average flight time without conflict,
- Impacts in terms of conflicts to be solved by an autonomous aircraft from different look-ahead times (2 to 10 minutes).
- Impacts of various strategies used for conflict solving.

In this paper we will present only the indicators that could allow the determination of applicability of free flight mode in Europe airspace: Traffic density and associated conflicts.

A. Average Traffic Density

This analysis deals with the applicability parameters of free flight mode in whole ECAC area above FL 290. The main parameters have been set as follows:

Parameter	Value
ADS-B range	150 NM
Look-ahead time	10 mn
Time before conflict resolution activation	4 to 8 mn
Cluster parameter	5 mn

Latitude	from 34° to 74°
Longitude	14°W to 26°E
FL	above FL 290
Surface	11.500.000 km²
Scenario duration	25000 seconds
Time threshold before CI computing	7000 seconds
Hourly weights	2%, 4%, 7%,10%

The distribution in percent of the traffic versus the heading is as follows:

Heading	HW (in % of daily traffic)			
	2%	4%	7%	10%
0 - 90°	23	22	22	23
90 - 180°	25	27	26	27
180 - 270°	26	24	26	25
270 - 360°	26	26	26	25

Figure 4 shows the distribution of traffic density per hour throughout the ECAC airspace at nighttime (HW =2%). One can note that traffic density is very low in northern Europe with less than 2O aircraft per hour per 1 Million square kilometers (MKm^2). In the southern part, the traffic density is about 20 to 100 aircraft per hour, except the region 2-2 and 2-3 where the density is 100 to 300 aircraft per hour and per $1MKm^2$

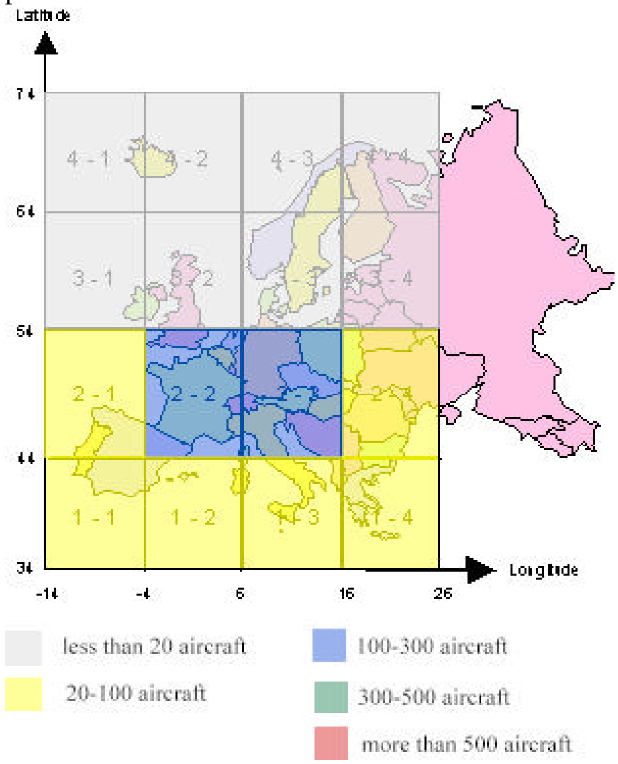

Figure 4 Average Traffic Density in Europe in 2015 from FL 290 upward, early morning (5 to 6 a.m.) and late evening (9 to 10 p.m. ; HW=4%)

Traffic Densities in early morning (5 to 6 a.m.) and late evening (9 to 10 p.m.) are shown in Figure 5. Highest density is about 321 aircraft per hour in the region covering France, Benelux, and Southern United Kingdom (279 aircraft over $850,000Km^2$). Average density turns around 20-100 aircraft in northern Europe and 100-300 aircraft per hour in its southern part.

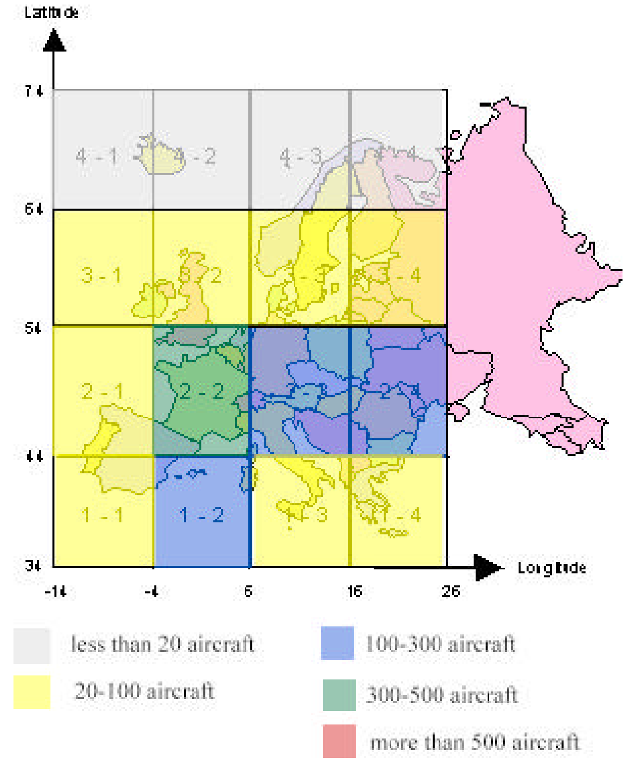

Figure 5 Average Traffic Density in Europe in 2015 from FL 290 upward at Night-time (10 p.m. to 5 a.m. ; HW=2%)

During daily normal operations between 7 a.m. and 9 p.m., highest density is detected in Area 2-2 and 2-3 (France, Benelux, and Southern UK), run to about 519 aircraft per hour per $1MKm^2$.

Details of traffic densities in representative areas are as follows:

Area	Surface	Min.	Max.	Mean.
1-1	970,000	101	139	120
1-2	970,000	158	214	187
1-3	970,000	104	148	124
1-4	970,000	147	188	165
2-1	820,000	57	90	72
2-2	850,000	391	452	410
2-3	820,000	409	457	437
2-4	820,000	181	223	199
3-1	640,000	12	43	26
3-2	640,000	10	34	22
3-3	640,000	44	102	70
3-4	640,000	31	66	47

Figure 6 shows traffic densities in Europe in 2015 during normal hours:

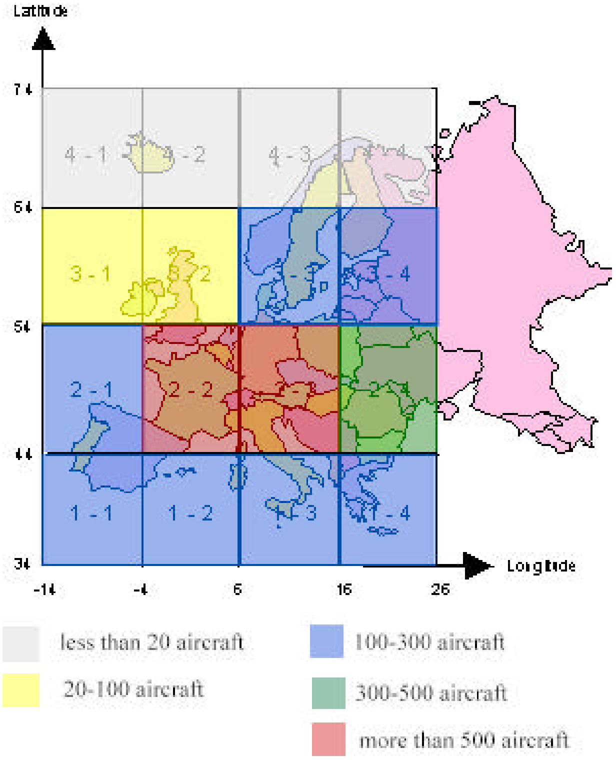

Figure 6 Average Traffic Density in Europe in 2015 from FL 290 upward, peak hours (HW=10%)

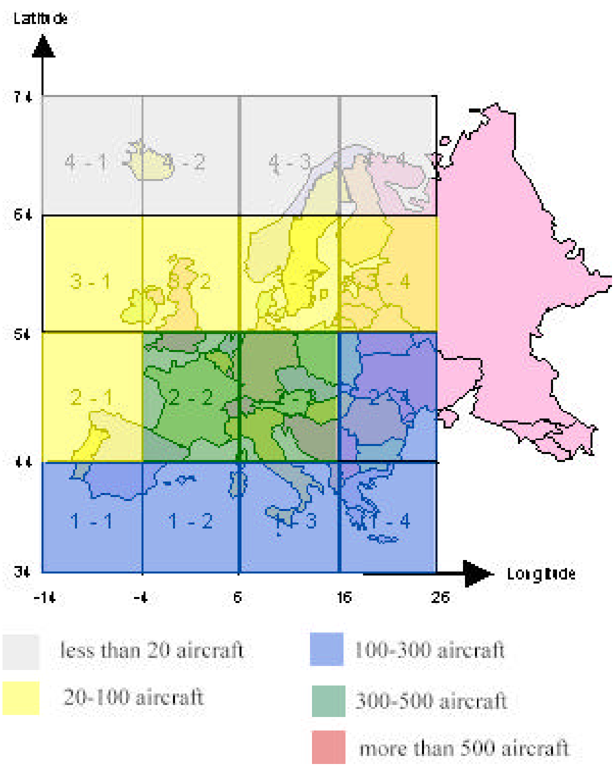

Figure 7 Average Traffic Density in Europe in 2015 from FL 290 upward, normal time (8 a.m. to 5 p.m.; HW=7%)

Highest densities are found in Areas 2-2 and 2-3 with up to 760 aircraft per hour and per 1MKm^2. Normalized traffic densities during peak hours are shown in Figure 7.

It was assumed in FREER studies that Free Flight Mode in EATMS could be applied to low-density airspace. It were demonstrated from our simulations the trends of densities not only in terms of geographical areas but also in terms of times of the day.

B. Number of ADS-B Detected and Resolved Conflicts

In order to help determining the threshold of density for free flight mode, we were interested in studying the number of conflicts that a pilot would have to solve during an hour of flight.

Based on initial assumption of 10 minutes of look-ahead time for ADS-B, detected conflicts were counted and normalized into number of detected conflicts per hour of flight and per traffic density.

For a flight of a normalized duration of 1 hour, the average number of conflicts is:

– 0,05 conflicts per hour with density of 20 aircraft per 1MKm^2.
– 0,23 conflicts per hour with density of 100 aircraft per 1MKm^2.
– 0,70 conflicts per hour with density of 300 aircraft per 1MKm^2.
– 1,20 conflicts per hour with density of 500 aircraft per 1MKm^2.

1,70 conflicts per hour with density of 770 aircraft per 1MKm^2 (maximum density in 2015).

A regression analysis was performed and shown in Figures 8 and 9. Figure 8 shows detailed figures for densities lower than 150 aircraft. Figure 9 shows global trends

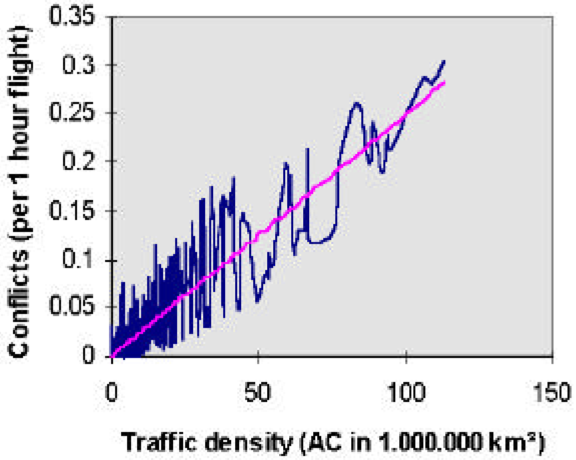

Figure 8 Trends of ADS-B detected conflicts per hour of flight in low-density airspace

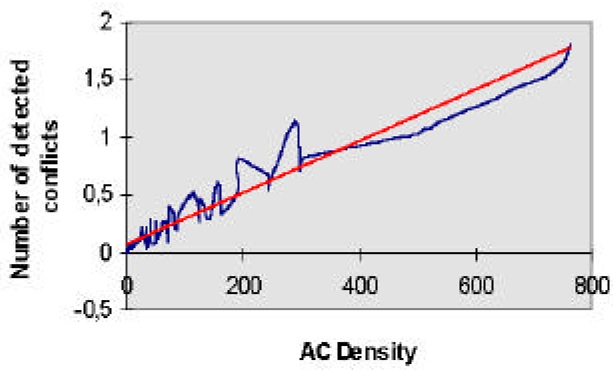

Figure 9 Trends of ADS-B detected conflicts per hour of flight with respect to traffic densities (number of aircraft per hour and per 1MKm2).

Within FREER studies, it was assumed that the coordination of conflict resolution be determined by a set of rules, namely Extended Flight Rules (EFR) [3].

Following EFR, for encounters in autonomous operations or free flight mode, priorities are set for aircraft involving in the encounters, and maneuvers avoiding an encounter are to be performed by least priority aircraft. In other words, in case of encounters between two aircraft, only one aircraft will make the maneuver.

The EFR has been encoded in the simulators and among others, it allowed the extraction of number of actively resolved conflicts by an aircraft. In Figure 10, for the five scenarios retained, the respective numbers of actively resolved conflicts by an aircraft are:

- 0,02 with density of 20 aircraft per 1MKm^2.
- 0,08 with density of 100 aircraft per 1MKm^2.
- 0,31 with density of 300 aircraft per 1MKm^2.
- 0,52 with density of 500 aircraft per 1MKm^2.

0,70 with density of 770 aircraft per 1MKm^2 (maximum density in 2015).

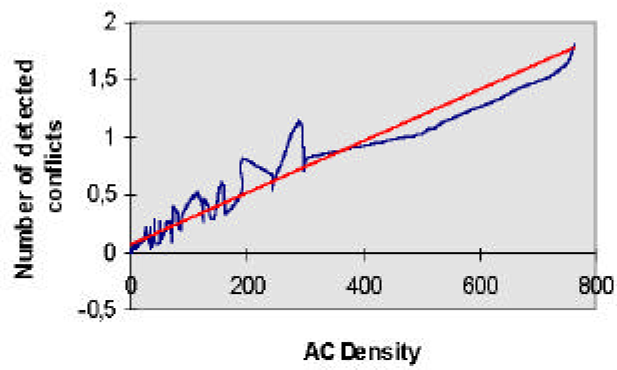

Figure 10 Average number of actively resolved conflict by an aircraft during 1 hour of flight with respect to variations in traffic density

These indicators can be used to determine the threshold of density for free flight mode, depending on the acceptance of pilots.

It is shown that for 10 minutes of look-ahead for ADS-B, the highest number of conflicts detected in highest density in 2015 turns around 1,7 conflicts per hour, and an aircraft will have to resolve, in this worst case, an average of 0,7 conflict per hour.

5. CONCLUSION

Assuming that the acceptable number of conflicts per hour of flight is 1, and the acceptable number of actively resolved conflicts is 0.5, a threshold of density can be deduced at 400 aircraft per hour and per 1MKm^2. In other words, with this assumption, the area of applicability of Free Flight in Europe covers all ECAC airspace from FL 290 upward at all time, except Areas 2-2 and 2-3 during peak hours.

It's finally worth noting that the results obtained so far are purely experimental. Operational feasibility, human factor analysis, and affordability of the concept are yet to be investigated.

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