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FLIGHT CENTRIC AIR TRAFFIC CONTROL WITH AIRSTREAMS. A NEW APPROACH TO TRAFFIC FLOW MODELING

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Abstract. *This paper is relative to FC2A project that addresses a challenging approach for an environmentally friendly, more agile Air Traffic Management (ATM) framework by combining Flight Centric ATC and Airstream concepts. The day-to-day adaptation of the Airstream network to the demand of the airspace users will provide a resilient and scalable system which supports Dynamic Airspace Configuration. Driven by the digitalization of ATM, autonomous management of aircraft inside the Airstream is promoted.*

Using ENAC's simulation tool, traffic demand is decomposed into main flows by a bundling algorithm. The algorithm identifies medoids, AirStream Reference Tracks (ASRTs), characterizing these flows. The ASRTs will define the backbone of the Airstream network.

An Airstream can be compared to a corridor/highway composed of longitudinal lanes inside vertical airspace blocks. Flight families are defined based on the speed distribution of the sample. They will support the creation of the internal longitudinal structure. The traffic aggregated for each ASRT is used to model the 3D architecture of the Airstream. The number of lanes for each vertical level and the height of the blocks are generated using various indexes characterizing the mean time between aircraft on the same lane. Finally, aggregated trajectories are recomputed on the appropriate lanes.

1 INTRODUCTION

In the current context, we are facing a change of the complete paradigm of the air transportation. The drop of the air traffic during the last months let us assume a slow recovery after the crisis ends [1]. The reports from ICAO [2] and ACI [3][4] highlighted that the recovery will need to consider the evolution of the demand and the customer confidence in the means of transportation. Now, more than ever, an air transportation system, reliable, safe, environment friendly and agile, should be put in place. For the future challenges, the optimal use of the resources should be managed by means allowing to tune the capacity of the Air Navigation Service Providers according to the demand and the variation of this demand.

European airspace geographical fragmentation has been put in place to provide safe services for aircraft travelling through the airspace. A flight-centric approach opens the opportunity to distribute the traffic more evenly. Furthermore, it would prevent lost productivity in under-loaded sectors. This approach is coupled with the design of dynamic flow corridors: the Airstreams. Aircraft in Airstreams will travel efficiently within a substantial part of the corridors, with minimal interference from all other traffic, whether it is in the same direction, opposite direction or crossing traffic. Three of the prominent attributes of these flow corridors that would distinguish them from today's airways are: 1- allowance for multiple (parallel) lanes of traffic; 2- capitalization on advanced communication, navigation, and surveillance technologies to enable changes in methods of separation (e.g., self-separation), potentially reduced separation standards within the corridor; 3- dynamic activation rules to add or remove corridor structures, as needed, throughout the day. This coupled approach is pushed by Flight Centric Air Traffic Control with Airstreams project (FC2A) funded by SESAR.

The main targets for these corridors are the high density and the high complexity traffic. The Airstream network provides for this kind of traffic a set of structured flows using collaborative aircraft operations. The backbone of the network is built specifically for a traffic sample using a bundling mechanism. The goal of the bundling is to partition the dataset into groups/aggregates as homogeneous as possible and separated one to another as much as possible. The flight aggregates are then defining the main flows. The bundling mechanism

uses the trajectories (an ordered list of timestamped positions) and is based on the k-medoids clustering algorithm. This algorithm is robust with respect to outliers. Furthermore, for each cluster, the central element is a member of the aggregate, thus it is always flyable in an operational context.

Each cluster is allocated to an Airstream which is built using the intrinsic characteristics of the aggregated traffic. The main characteristics selected are the cruise flight level and the speed. The distribution of speed through the global sample allows to define speed families which are used to build the longitudinal (i.e horizontal) structure of an Airstream. The vertical structure is built using the vertical levels found in the aggregate. Various rules, applied on the aggregate, have been defined for building the final structure of the Airstream.

Finally, complexity calculation will allow to evaluate benefit of the Airstream approach. This calculation is based on local linear models and a representation of traffic situations as images whose pixels are covariance matrices [5].

2 FC2A CONCEPT

2.1 Airstream concept and principles

The study of specific airspace organization dedicated to traffic sharing similar flying characteristics and/or decreasing complexity and ATCO workload has been widely explored since decades. They have been called highways [6][7], Freeways [8][9], High Volume Tube-Shape sectors (HTS) [10] corridors [11][12]. The Airstream concept organizes flights in high density and congested areas using space-based slots and local indexed axial coordinates system to reference the aircraft along common 3-dimensional reference trajectory.

Airstreams have no nominal shape (width, height, or radius). In many situations, the central line of an airway could be adopted as an airstream reference track (ASRT), although airstream reference trajectories may present turns and may be changed according to different factors such as traffic demand and next day forecasted weather conditions.

The ASRT, is a 3D curve given by a smooth parametric mapping which produces the geocentric coordinates of its points [13]. Aircraft with different performances or selected cost indexes and speeds can be present in the same airstream but along different lanes. The lanes are surrounding the ASRT, a peripheral lane is specifically dedicated for the traffic entering or exiting the Airstream as described in Figure 1.

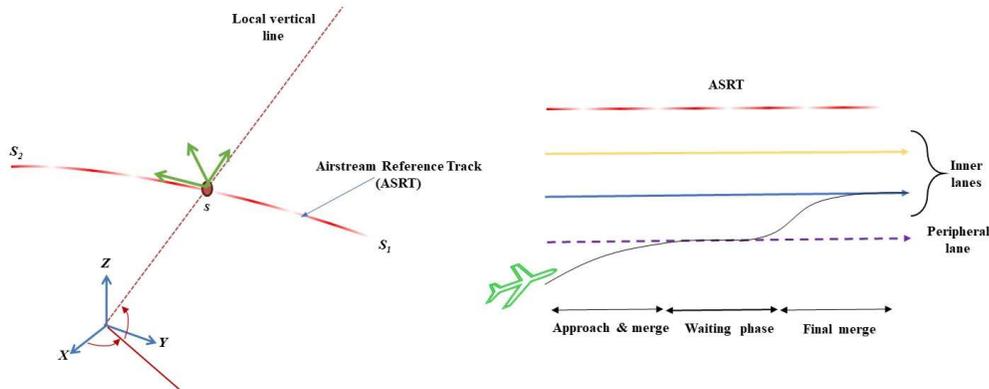


Figure 1. Airstream Reference Track and traffic lanes

In the Airstream, aircraft must comply with required navigation performance (RNP), be equipped with self-separation capability and on-board systems ensuring automated separation. Self-separation on a lane can be performed by dynamic position adjustments (ADS-B technology can provide position and speed information) [14]. The pilots will remain responsible for ensuring the safe separation with nearby aircraft by maintaining situational awareness, performing standard maneuvers and reacting to conflict resolution advices.

Time slots allocated to aircraft are translated into spatial slots. Each aircraft is supposed to remain in the center of its dedicated spatial slot moving along a lane. This center is a permanent target for its guidance system. The lanes are defined for serving a homogeneous traffic mainly driven by the aircraft performances. With the exception of the integration phase and the extraction phase, the aircraft will be assigned to a specific lane during the time spent in the Airstream. However, changing lane either vertically or horizontally, is possible thanks to specific traffic conditions. To allow these maneuvers, characteristics of adjacent lanes are overlapping to facilitate lane changes. This mechanism is possible if compatible slots are available on both lanes as presented in Figure 2.

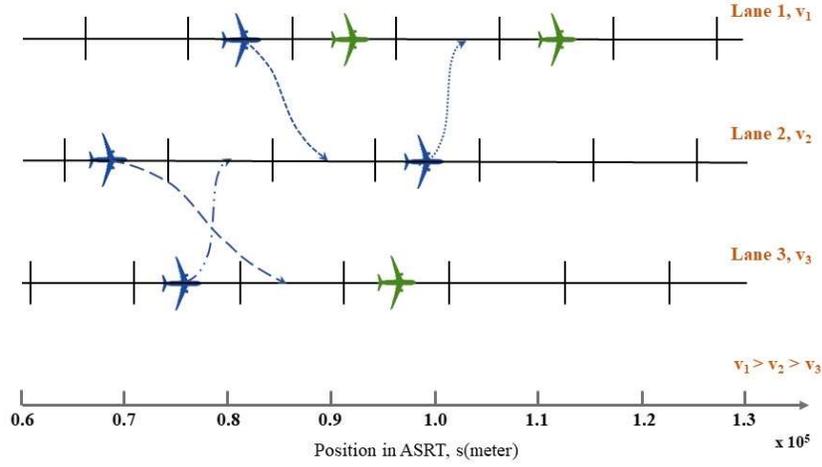


Figure 2. Aircraft changing lanes in an Airstream

In this study, the primary characteristics for defining the lane is a flight level and a speed interval. Only aircraft whose performances are compatible with this speed interval can be allocated to the lane. The flight level and speed distribution found in the traffic sample captured by an Airstream will define its structure in terms of horizontal and vertical lanes as defined in section 3.

2.2 Airstream network

The Airstream network is built using a traffic sample and aggregating flights from the sample. In FC2A project, the traffic samples used are recorded days of traffic inside the European Civil Aviation Conference (ECAC) boundaries as shown in Figure 3. Various days representing different density (low, medium, high) of traffic have been selected.

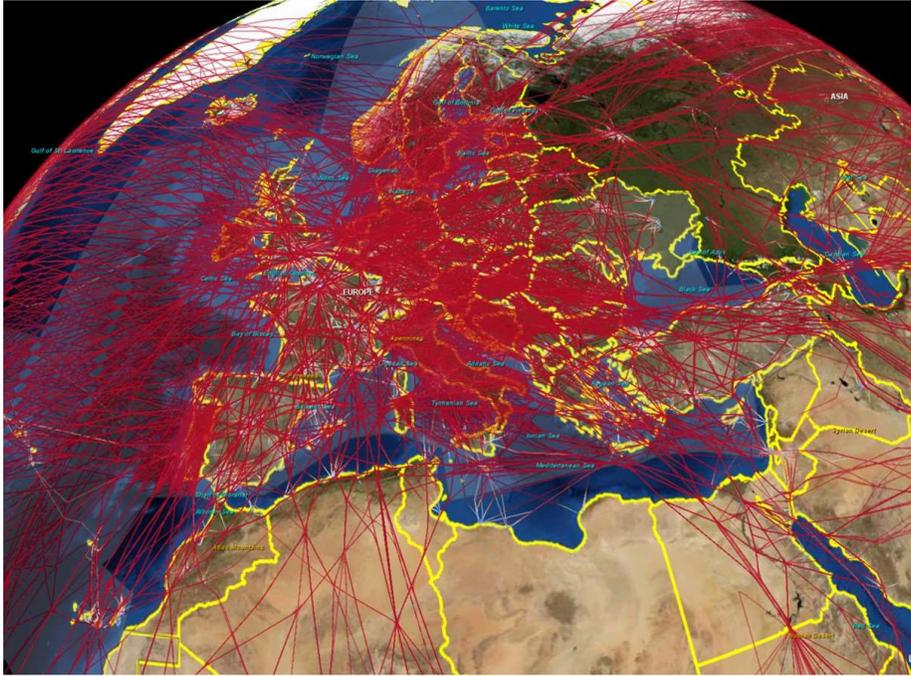


Figure 3. Traffic sample on ECAC region

The aggregation mechanism clusters trajectories. Let consider a sample of trajectories (x_1, \dots, x_N) with $d(x_i, x_j)$ be the distance between trajectories i and j . Finally, let $C: x_i \rightarrow k \in \{1 \dots K\}$ be the clustering function that maps a trajectory to its cluster number. The criterion used in trajectory clustering is the intra-cluster variance as shown in (1):

$$E(C) = \sum_{k=1}^K \sum_{C(i)=k} \sum_{C(j)=k} d(x_i, x_j) \quad (1)$$

The clustering uses the k-medoids algorithm. For each cluster the central element is a member of the sample which ensures it is always a flyable trajectory in the operational context. The central elements defined during the bundling mechanism compose the Airstream network (i.e. the collection of ASRTs). The Airstream network is similar to the standard route network, i.e. a kind of meshed network as shown in Figure 4, but with a looser mesh pattern and characterized by a variable thickness linked to the number of aggregated trajectories/flights.

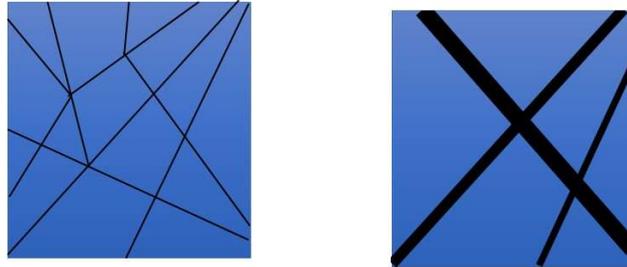


Figure 4. Published routes vs Airstreams networks

Another difference is linked to the distribution of directions of the flights in the network. In the actual route network, segregation is done using alternate Flight Levels (FL). In the Airstream network, each individual Airstream is a bidirectional structure with a segregation of direction depending of the side of the ASRT (central trajectory) like a motorway. The structure can be duplicated for multiple FLs as shown on Figure 5.

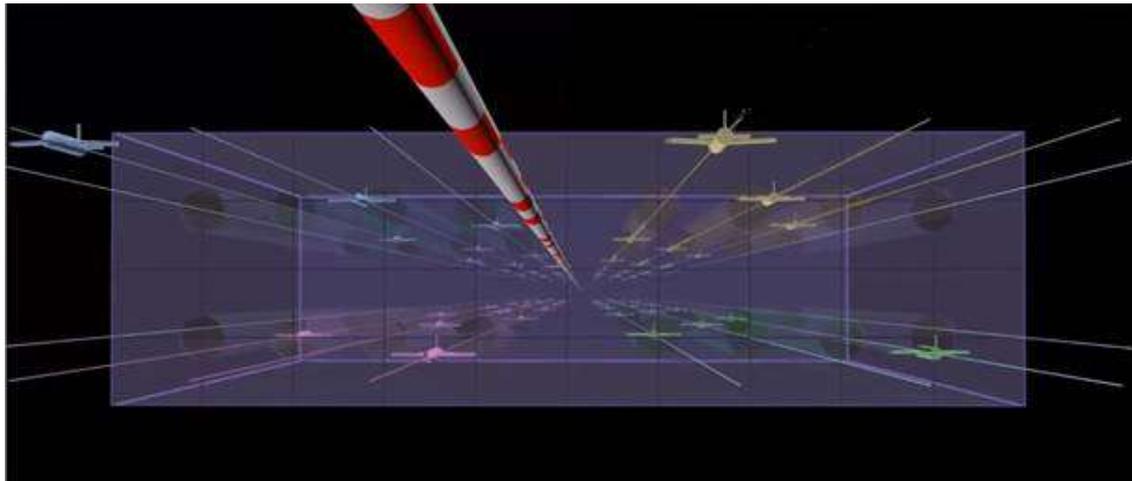


Figure 5. Vertical slice of an Airstream block

The number of horizontal lanes as well as the number of vertical ones is directly linked to the aggregated traffic characteristics like the number of different FLs or types of aircraft. These characteristics will define the individual internal structure of the Airstream as described in section 3.

3 INTERNAL STRUCTURE OF AN AIRSTREAM

To distribute the aggregated traffic evenly through the Airstream, it is necessary to define what are the main characteristics of a lane but also the global structure of the Airstream such as its longitudinal extension (i.e. the number of horizontal lanes at a given FL) and its vertical extension (i.e. the number of consecutive FLs). These characteristics will have to take into consideration the Airstream crossing management.

3.1 Lane characteristics

As mentioned, the traffic using a lane must be homogeneous, meaning aircraft allocated to the lane have similar flying envelope and capabilities. The speed is the primary criterion for defining a lane. Each lane is defined by an interval of speed known as a speed Family. The number of Families determines the maximum number of horizontal lanes available in an Airstream. To build these Families, the speed distribution (number of flights per speed) of the traffic sample is used. The speed distributions of the chosen days of traffic are very similar, showing a greater density in the speed range 330 – 520 NM (as shown in Figure 6.). It is used to define the two border-Families. The remaining part is then equally distributed among the so-called central-Families whose number is a parameter of the algorithm. Table 1. below summarizes the results for 3 central-Families.

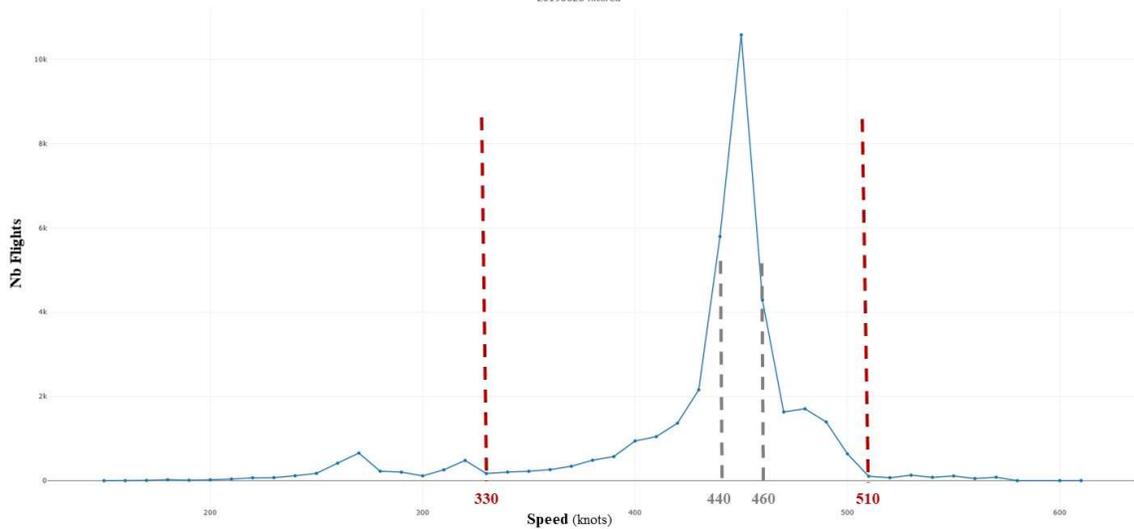


Figure 6. Speed distribution in the traffic sample

For each Family it is necessary to define an available “capacity” to compute the needed number of lanes to build the Airstream. This is performed through the Slot Index.

As mentioned earlier, each aircraft sharing a lane is at the center of a slot. Consecutive slots define a longitudinal separation (i.e. the distance between the centers of two consecutive slots) as presented in Figure 7.

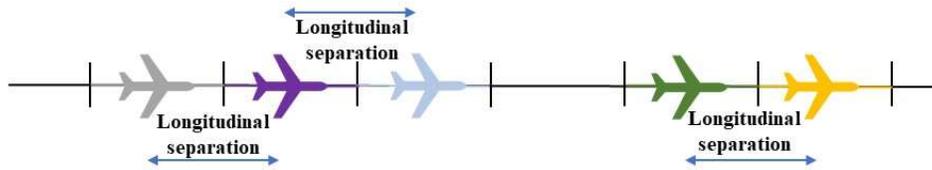


Figure 7. Example of slots distribution on a lane

The Slot Index is defined by equation (2) and represents the minimal time between two aircraft for the given Family.

$$SlotIndex = \frac{LongitudinalSeparation}{MaxSpeed} \tag{2}$$

Family	MinSpeed	MaxSpeed	SlotIndex
1	0	330	0,061
2	330	440	0,045
3	440	460	0,043
4	460	510	0,039
5	510	999	0,020

Table 1. Speed families and slot indexes for traffic sample

These Families do characterize the traffic sample. Each individual Airstream has a specific flight pattern due to the aggregated traffic. This pattern is decomposed through three criteria: direction, RFL and Speed Family. Table 2. below provides an example of possible allocation giving the number of flights (Nb Flights) for each pair flight levels (RFL) - Speed Family (Family) of the flights allocated to the Airstream’s right side (East-West direction) elements. An indicator is then needed to compare magnitude of the flow and the corresponding Family Slot Index. It is the Flow Index, evaluated using formula (3).

$$FlowIndex = \frac{24}{Nb\ Flights} \tag{3}$$

It corresponds to the mean time between two flights in a 24 hours time window.

<i>RFL</i>	<i>Family</i>	<i>Nb Flights</i>	<i>FlowIndex</i>
370	2	58	0,414
370	3	58	0,414
370	4	1	24,000
380	2	25	0,960
380	3	16	1,500
390	2	19	1,263
390	3	44	0,546
390	4	909	0,026
400	2	30	0,800
400	3	30	0,800
400	4	7	3,429

Table 2. *RFL – speed family distribution and flow indexes in an Airstream*

The ratio of these two indexes gives the occupancy rates of the Speed Families for each Flight Level and gives the number of lanes required to serve the associated traffic as explained in section 3.2.

3.2 Three-dimensional structure of an Airstream

The 3-dimensional structure is closely dependent of the aggregated traffic and can be very different from an Airstream to another. In order to avoid building a labyrinth and allowing Airstreams cross-over, a structure of vertical blocks separated by gaps is proposed. Basic rules are used to move from the specificity of aggregated traffic to the 3-dimensional structure. Various tunable parameters have been defined for supporting these rules and evaluate the various potential 3-dimensional structures. Seven parameters are defined, as presented in Table 3.

<i>Definition</i>	<i>Parameter Identifier (unit)</i>	<i>Value</i>
Floor level of the Airstreams network	MinLevel (FL)	320
Ceiling level of the Airstreams network	MaxLevel (FL)	660
Minimal distance between the centers of two consecutive slots	LongitudinalSeparation (NM)	20
Minimal density of aircraft in lane	MinLevelDensity (%)	10
Maximum number of lane by side	MaxNbLane	5
Maximum number of Flight Levels in a vertical block	MaxNbLevelinBlock	3
Minimal interval between 2 consecutive vertical blocks	MinBTInterval (FL)	10

Table 3. *Parameters setting for the 3-dimensional structure of Airstreams*

Using these parameters, seven rules are applied on the aggregated traffic:

- The traffic outside floor-ceiling levels is removed.
- The RFL-Family lanes below minimal density are removed.
- The calculation of the number of lane(s) per RFL-Families is based on the ratio Slot index over Flow index. If ratio is greater than one, two lanes have to be implemented for the same Speed Family (see Table 4.).
- If the number of lanes is greater than the maximum lane threshold, the less populated Family is removed until limit is reached.
- The number of lanes evaluation is done independently for the two sides of the Airstream (i.e. asymmetric structure is authorized).
- The number of lanes by side is homogeneous for all the levels/blocks and is set to the maximum number found.
- If a block height (i.e. consecutive levels) is greater than MaxNbLevelinBlock, less populated level is removed until limit is reached.
- If interval between 2 consecutive blocks (i.e. BreakThrough interval) is below the threshold, less populated level from one block (i.e. ceiling or floor level of the 2 blocks) is removed until limit is reached.

RFL	Family	Nb Flights	FlowIndex	SlotIndex	Ratio	Nb Lane
370	2	58	0,414	0,045	10,9%	1
370	3	58	0,414	0,043	10,4%	1
370	4	1	24,000	0,039	0,2%	1
380	2	25	0,960	0,045	4,7%	1
380	3	16	1,500	0,043	2,9%	1
390	2	19	1,263	0,045	3,6%	1
390	3	44	0,546	0,043	7,9%	1
390	4	909	0,026	0,039	148,5%	2
400	2	30	0,800	0,045	5,6%	1
400	3	30	0,800	0,043	5,4%	1
400	4	7	3,429	0,039	1,1%	1

Table 4. Lanes setting in an Airstream

Applying these rules leads to the final 3-dimensional structure of the Airstream as the example shown in Figure 8.

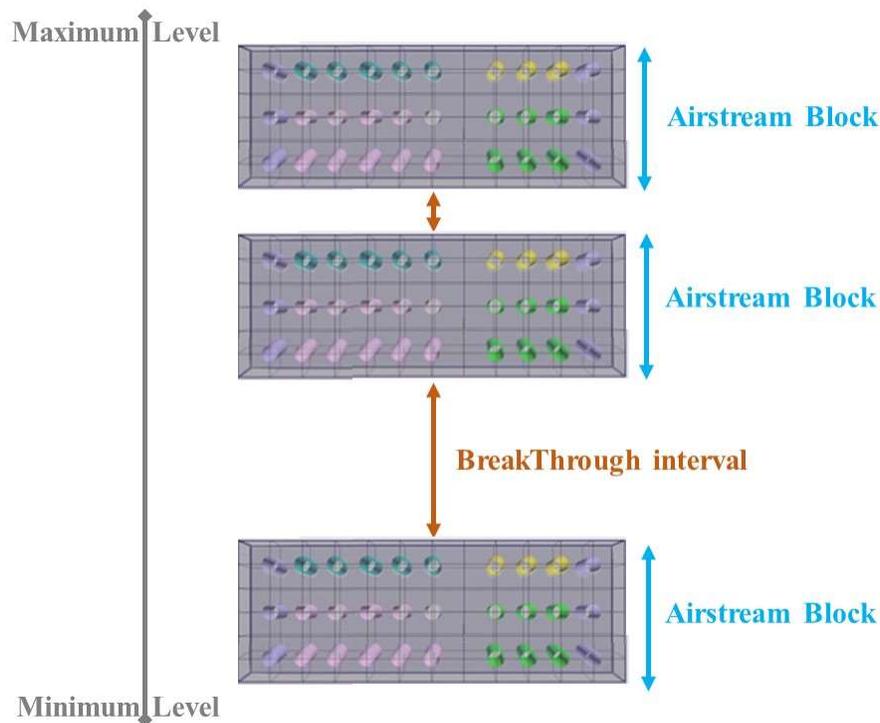


Figure 8. Vertical slice of an Airstream 3-dimensional structure

The first results show that for the traffic days used in this study, the traffic captured in the Airstreams network with these simple rules represents between 55% and 70% of the eligible traffic.

4 CONCLUSION

This work is the first step of the study of a new approach for managing traffic flows in high density and high complexity airspace in conjunction and to complement other management implementations such as Free Route. Preliminary concepts have been introduced to support this idea to obtain preliminary results. A first structure of a network of Airstreams built using the parameters and rules proposed in this paper is presented in Figure 9 below.

The next step of this study will focus on complexity evaluations using calculations based on information geometry principles.

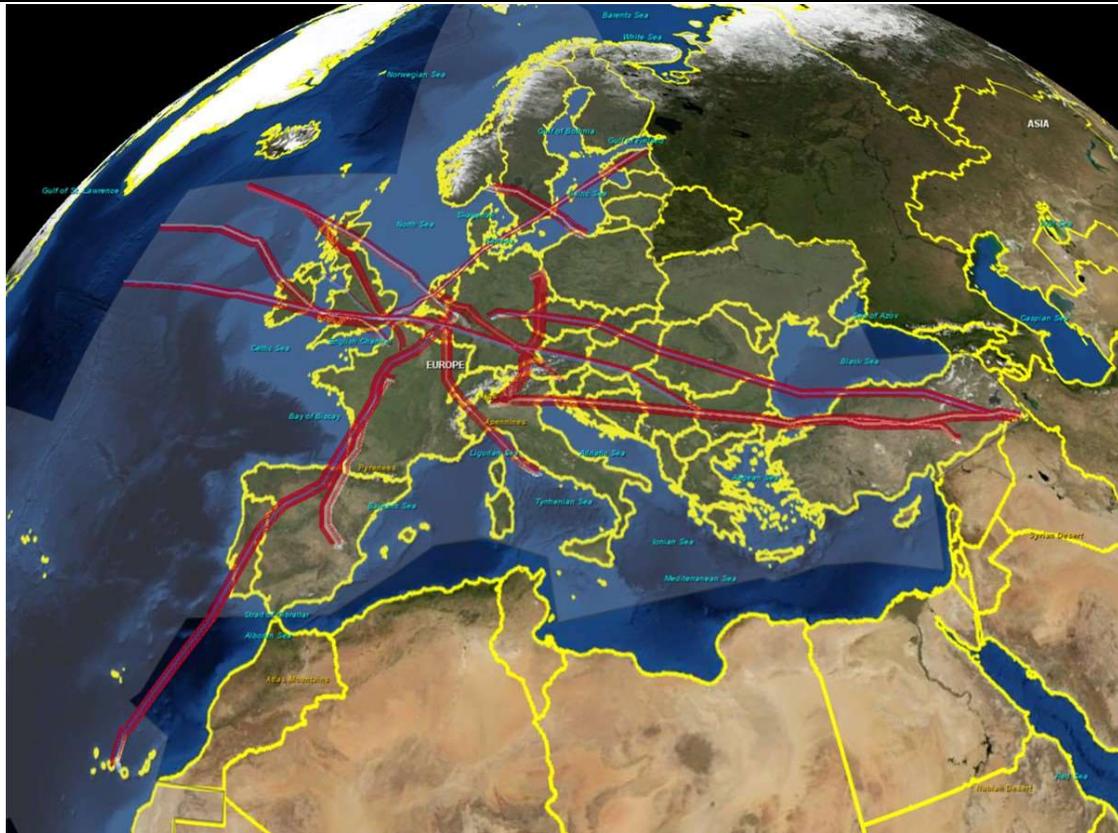


Figure 9. First results of static structure of network of Airstreams over European airspace

Complementary studies should be developed to prove the effectiveness of the proposed approach. In particular work shall be done on the validation and enhancement of the rules proposed in this paper in close cooperation with the community. Even if the basic construction rules implemented lead, in some cases, to exclude from the Airstream structure a part of the traffic initially aggregated, the preliminary results show that a reasonable part of the eligible traffic can be integrated into the Airstreams network. Refinement of these rules, such as a mechanism for reallocating flights from the deleted lanes could improve the mean ratio of the captured traffic.

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