Towards Systematic Air Traffic Management in a Regular Lattice

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[Abstract] A regular lattice combines two ideas: a repeating (or regular) airspace structure and layers of parallel tracks. A repeating or regular airspace structure has several advantages over an irregular structure. The skills or methods used to control traffic in one part of the structure are applicable throughout the structure. Regularity gives rise to multiple routes between two points with similar distances flown in each direction and at each flight level. Flow management can select routes which distribute traffic over a region. The same mechanism could be used to choose routes which avoid reserved areas. Properties which apply to an element of the airspace apply wherever that element is repeated, so that reasoning about a small region of the airspace can immediately be scaled up to apply to a much larger region. Layers of parallel tracks eliminate crossing conflicts between aircraft which are flying straight and level. Together with measures to preserve the stability of traffic flows (sufficient spacing, speed regulation, or ASAS sequencing procedures), traffic may be separated into two easily identifiable populations: a "stable" population of cruising aircraft, which require low controller monitoring per aircraft, since there are no crossing conflicts between cruising aircraft, and a population of aircraft in “transition” to or from the stable state, which require greater monitoring. A regular lattice allows a fine-grained decomposition into sectors. This would allow air traffic control to be performed by a greater number of controllers, so increasing the capacity of the system. Results from fast-time simulations are reported.

I. Introduction: goals, problems and opportunities

A. SESAR Goals
The European Commission’s (EC) expectation for Single European Sky ATM Research (SESAR) is that it will deliver a European Air Traffic Management (ATM) System for 2020 and beyond which can meet the following goals relative to today’s performance [SESAR1]:
- Safety Increase 10 times
- Capacity Increase 3 times
- ATM costs Divide by 2
- Environmental impact Reduce by 10%

B. Safety
On July 1st 2002 a Tupolev TU154M passenger aircraft and a Boeing 757-200 cargo aircraft collided near the German town of Überlingen killing all passengers and crew. [AX001-1-2002]. Figure 1 [taken from AX001-1-2002 - A1&3] shows the paths of the aircraft, and their positions about 3 minutes before the accident. Both aircraft were at the same flight level. If, at this time, an instruction had been given to either aircraft to modify its trajectory the situation would have been quite nominal. The accident illustrates a feature of the air traffic control system: aircraft with converging headings may cruise at the same flight level. There are many barriers to the occurrence of conflict and collision, and even should all the barriers fail collision is unlikely. One of the most important barriers is the vigilance of the air traffic controller. However, human vigilance cannot be infallible and the airborne collision avoidance system (ACAS/TCAS) cannot guarantee the prevention of collision. It would be desirable, wherever feasible, to reduce the dependence of the safety of the air traffic control system on human vigilance.
C. An opportunity – area navigation

Navigation from departure to destination has been one of the important challenges in the history of aviation. Simple radio navigation beacons allowed aircraft to fly from point to point along their routes, but have also constrained airspace design. The advent of area navigation, which allows aircraft to fly arbitrary routes, opens the door to new airspace design possibilities. Airspace design as an approach to improving the capacity of the air traffic management system is also attractive in view of the difficulties involved in conceiving, approving and deploying technology-based solutions.

A. SuperHighway

The approach described is being investigated as the second operational concept scenario of the European Commission SuperHighway project [SHP].

II. Background

The regular lattice approach was described in [ATM R&D]. [LPT] proposed the use of layers of parallel tracks. Layers are vertically separated from one another. Within a layer aircraft are only allowed to fly along parallel tracks which are laterally separated, either in one direction or the opposite direction. The directions of the tracks change from one layer to another. This scheme eliminates crossing conflicts between aircraft flying straight and level in layers.

To navigate from one point to another in such a system, it is necessary to approximate the direct route between the points by first flying in one direction in one layer and then follow a second direction in an adjacent layer.

III. Lattice Design Basics

The airspace structure presented here is destined for dense, upper airspace regions in which aircraft are flying “from everywhere to everywhere”. The essential problem here is one of crossing trajectories. The design of the lower airspace structure in which aircraft climb from departure airports to the lattice, and descend from the lattice to destination airports, is not addressed here.

A. Number of pairs of directions

The number of pairs of directions is a basic parameter in the design of the lattice. An important consideration in the choice of the number of pairs of directions is fuel efficiency, for reasons of cost and environmental impact. Fuel efficiency can be broken into horizontal and vertical efficiency.

The fast-time simulation results reported later include fuel consumption figures for various airspace schemes.
B. Vertical structure

The stack of four layers may be repeated, so that for each allowed direction more than one flight level is possible.

As shown in the above scheme, the direction of the tracks increases by 45 degrees in a clockwise direction on climbing from one layer to the layer above. When a cruising aircraft turns 45° to the right [clockwise] it has to climb 1000 feet to reach a level consistent with its new direction. Similarly, if it turns 45° to the left [anti-clockwise] it has to descend 1000 feet.

C. Horizontal structure

If the spacing between diagonal tracks is chosen appropriately (relative to the spacing between horizontal and vertical tracks) a regular lattice can be constructed:

In a regular lattice the layout of junctions is identical throughout the network. A repeating or regular airspace structure has several advantages over an irregular structure: operating procedures are the same throughout the structure, so that the skills required to control traffic in one part of the network are applicable throughout the network; regularity gives rise to many routes between two nodes with similar lengths. Flow management can select routes which distribute traffic evenly over a region. The same mechanism could be used to choose routes which avoid reserved areas. Furthermore, properties (e.g. safety) which apply to a an element of the airspace may apply wherever that element is repeated, so that reasoning about a small region of the airspace can be scaled up to apply to a much larger region. Different lattice designs are possible. This paper is based on the horizontal structure shown below:

For a given basic lattice structure, different horizontal route cross-sections or lane layouts can be considered. For example, a route might have one or more lanes; it might be mono-directional or bi-directional; it might have joining and leaving lanes.

By replacing lines in a basic lattice with a route cross-section more elaborate lattices can be generated. For more details see [ATM R&D].

This paper will describe mono-directional routes primarily because procedures for turning (left or right) are symmetrical and more straightforward in this case.
D. Turning places

Depending upon the directions of the tracks, none, two or four turns are possible at junctions. The choice of track directions shown below gives rise to a uniform distribution of turning places.

IV. Lattice Design and Operation

Consideration of how a lattice might be operated leads to further constraints on the design of a lattice. Basic operations which must be accommodated are:

- Joining the lattice
- Turning and merging

A. Aircraft Performance

Some examples of aircraft performance, specifically the rate of climb of heavy aircraft and the turn radius of fast aircraft, will be helpful when considering lattice dimensions and operation. For a heavily loaded B747 the rate of climb is about 1000 feet per minute at FL290 and it decreases from there to the aircraft's ceiling. An aircraft cruising at 480 knots and banking at 15° has a radius of turn of 12.5 nautical miles.

B. Joining the lattice

Aircraft, including slow climbing aircraft, should be able to climb to appropriate cruise levels without encountering traffic on crossing tracks. Crossing tracks are not an obstacle for aircraft joining the lowest layer of the lattice. Access to the lowest layer is straightforward for all aircraft types.

The lattice spacing can be defined to be the distance between adjacent crossings in the larger of the two grids (see figure 5). If the lattice spacing is reduced the number of tracks (per unit distance) increases, and so, therefore, does the physical capacity of the lattice. On the other hand, slow climbing aircraft require a large lattice spacing if they are to be able to join the lattice in a single climb without encountering crossing traffic. Lattice spacing also has some impact on distance flown (see later).

Where should an aircraft join a lattice? It is assumed that when an aircraft reaches the lattice flight levels it will be heading towards its destination. Suppose that lattice layers begin at FL300. An aircraft must climb from its departure airport to reach the lattice. To climb to FL300 takes 10 to 25 minutes, depending upon the rate of climb of the aircraft. The distance flown during this time is of the order of 60 to 150 nautical miles. Placing circles with these radii around the departure airport allows likely joining places to be identified. Similarly the places at which aircraft would leave the lattice can be identified:

The places at which aircraft can join and leave the lattice are evenly distributed in relation to the airport. Furthermore, each airport will, in general, have a set of places at which traffic joins and leaves the lattice which is independent of other airports.

There are various ways in which an aircraft can climb into a lattice, depending upon its rate of climb. An aircraft can climb directly to a segment. Alternatively it can climb in steps first to one segment (e.g. green) and then turn and climb to another (e.g. blue). Having joined the lattice an aircraft may also climb to a level in the same direction but 4000 feet higher.

In this paper we assume that aircraft which are admitted to the lattice can climb at 1000 feet per minute or more. Special procedures would be needed to allow slow climbing aircraft to enter the lattice.

The bottom layer is accessible to all aircraft types without turning and we can choose which colour of track is the bottom layer. The above diagram is drawn with the intention that the brown layer be the bottom layer. The brown layer is chosen as the bottom layer because it is thought that the North-West – South-East direction is probably the predominant axis in Europe.
C. Turning and merging

Consider an aircraft turning from a green track to a blue track:

If, at a junction, an aircraft turns from one direction to another, without changing flight level, then it will be vertically separated from traffic cruising at the correct flight level in the new direction, at least until the next junction is reached. For example, an aircraft initially flying to the North-East on a green track, which turns to the East without changing flight level, will find itself beneath traffic cruising Eastwards on a blue track.

Aircraft turning from the green track can be considered to turn onto a joining lane which is vertically separated from the blue track. The task of the controller responsible for the blue track is to merge aircraft from the green joining lane onto the blue track. This can be done by vectoring before moving the aircraft vertically into gaps in the traffic on the blue track. A basic assumption is that gaps will be available. The likely availability of gaps in the traffic would be a goal of flow management. In the worst case, an extreme form of vectoring – a go-around – could be used to delay an aircraft until a suitable gap becomes available.

With the pattern of turning places shown earlier traffic joins a track from at most one other direction.

D. Vertical movement and merging

It is desirable that climbing and descending traffic be separated from one another and from cruising traffic. One way of doing this is to allow for climbing and descending regions offset from each track by at least the required horizontal separation. Continuing the preceding example, figure 9 shows horizontal and vertical views of the climbing and descending regions.

On diagonal climbing and descending lanes the distance which is usable for moving vertically alternates from one cell to another. To avoid increasing the lattice spacing when climbing and descending lanes are added, an operating rule can be introduced such that aircraft on diagonal climbing or descending lanes may only climb or descend in alternate cells, i.e. where sufficient space is available. This rule would have to be taken into account in flight planning, not least since it affects the points at which an aircraft on a diagonal route will enter or leave the lattice.
Aircraft on diagonal climbing (or descending) lanes may perform climbs (or descents) of 4000 feet. The climb (or descent) begins when the aircraft has crossed a perpendicular track (and its climbing and descending lanes).

Assuming aircraft admitted into the lattice have a minimum rate of climb of 1000 feet per minute, and a maximum speed of 8 nautical miles per minute, then in order to climb 4000 feet a distance of 32 nautical miles is needed. If climbing and descending lanes are separated by 6 miles from the central lane, then the diagonal cell should have a side of at least $32 + 2 \times 6 = 44$ miles.

Aircraft on red or blue tracks which wish to climb (or descend) 4000 feet should, in general, perform two step climbs (or descents) of 2000 feet in order to avoid perpendicular crossing traffic on diagonal tracks. The first step begins when the aircraft has crossed a perpendicular track. The aircraft is then handed over to the next sector (same direction, different level). The second step begins when the aircraft has passed an obstructing diagonal track (see figure 11).
When a climbing or descending aircraft reaches the level at which it wishes to cruise it levels off into what is effectively a laterally offset joining lane. As before, the task of the controller is then to merge the aircraft into the central track, by vectoring it into a suitable gap.

From figure 12, which shows the complete pattern of climbing and descending places it can be seen that the climbing and descending places do not intersect other climbing and descending places.

E. Sectorisation
A regular lattice route structure allows airspace to be divided into a regular pattern of control sectors. If there are sufficiently many control sectors, then it may be possible to divide the workload required to separate a given level of traffic amongst a greater number of controllers, giving a lower workload per controller. Alternatively, at a given level of workload per controller, an increase in the number of sectors would allow a greater level of traffic to be separated.

Consider a single layer of parallel tracks, for example, a red layer. In this layer, a first level of decomposition can be obtained by providing flat control areas (shown in pink) which are aligned with and enclose the tracks in the layer.
For aircraft which are cruising along the tracks, the workload required should be low, particularly if catch-up conflicts can be prevented through appropriate spacing, e.g. through speed regulation or ASAS spacing. Much of the work associated with operating a lattice will be linked to aircraft joining and leaving tracks. The pink regions shown above can be further subdivided into a set of identical elementary flat sectors, so dividing the workload amongst a greater number of controllers.

Focussing on a single sector, some of the basic operations common to all sectors are apparent:

Aircraft are linked to sectors according to their position (horizontal and vertical) but also according to their direction of flight. For example, when a cruising aircraft at a red level turns to the green direction, it must be handed over to the green sector.

The increased predictability of aircraft movements within the lattice would allow most control instructions to be issued via datalink. Voice communication could be reserved for exceptional situations.

F. Mapping a lattice onto a region of a round world

A lattice can be built up around a set of grid points, each defined by a latitude and longitude.

One approach is to define one set of parallel tracks along lines of longitude and another along lines of latitude. The cells so defined should be big enough to allow the possibility of enclosing a climbing circle for slow climbers (see earlier). In particular, the longitude difference between adjacent North-South tracks should be sufficient, at the Northernmost end of the lattice, to enclose a turning circle. As one moves Southwards the distance between adjacent lines of longitude increases. If the distance between adjacent East-West tracks increases in the same way, then cells will remain square, and the allowed directions of flight will be the same across the lattice.

Figure 20 shows such a lattice in a Mercator projection. In this projection, the cells appear to be the same size. On the Earth the cells get bigger as one moves Southwards. On the other hand the directions of the tracks are correctly represented.
G. Multiple routes

The principle of layers of parallel tracks requires a flight to approximate a straight line between two points by two flight legs in (adjacent) directions. In general there is a parallelogram of possible routes from one point to another. On a flat plane these routes would have identical lengths. Furthermore, they would have identical distances flown in each direction. Because of the link between flight level and direction all routes would have the same distances flown at each flight level. On a sphere these properties will not be identical, but they can be expected to be similar.

The existence of multiple routes with similar properties has various advantages:

- Flow management can select routes which contribute to a desired traffic distribution over a region.
- Similarly, routes can be selected which are not blocked by active reserved (military) areas.
- Because of the similar distances flown in each direction and at each flight level the flight times for all of the routes in the parallelogram will be similar. This would contribute to the predictability of airline operations. Also the effect of the wind can be expected to be similar for all the routes in the parallelogram, since wind speed and direction are a function of flight level, and since their impact depends upon the direction of flight.

In the case that a route through the lattice which corresponds to a single direction is blocked by a reserved area, additional distance can be added to yield alternative routes.

Another approach would be to deform the lattice around the reserved area, but this would require a redefinition of routes as opposed to re-routing through routes with a fixed definition.

V. Fast-time simulation results

A prototype fast-time simulator has been adapted, and some preliminary simulations performed, to allow comparison of the lattice to other airspace schemes. The simulations were performed for a basic lattice without climbing and descending lanes. Estimates are made for numbers of conflicts with the addition of climbing and descending lanes.

A volume of interest was defined corresponding to a lattice which approximately covers the European "core area", see figure 16. The floor of the volume of interest was set at 30 000 feet.

To construct a traffic sample, a preliminary simulation was conducted using the SESAR 2005 (regulated, noisy) traffic sample. Flights were direct. It was assumed that all aircraft had nominal mass, and that they wished to climb to the highest flight level consistent with the length of flight and the ceiling of the aircraft. No flight level allocation scheme was applied. Flights which transited the volume of interest during the 24 hour period of the 19th July were added to a traffic subset. There were 12 717 such flights.

A series of simulations was run using this traffic subset, in which the routing and cruise level allocation schemes within the volume of interest were varied. Outside the volume of interest aircraft flew directly and there were no constraints on cruise level, so that changes in total fuel consumption were attributable only to changes of routing and cruise level schemes within the volume of interest. Conflict detection was only preformed within the volume of interest. The various schemes applied in the volume of interest are summarised in table 3.

The simulations have since been repeated using SESAR 2020 traffic.
### Table 1: SESAR 2005 Traffic - Summary of fast-time simulation results

<table>
<thead>
<tr>
<th>#</th>
<th>Horizontal navigation</th>
<th>Cruise level allocation scheme</th>
<th>Total number of flights entering volume of interest</th>
<th>Total number of conflicts</th>
<th>Conflicts in which one or both aircraft are moving vertically</th>
<th>Conflicts in which both aircraft are level</th>
<th>Total fuel consumption / kilotonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Fly direct</td>
<td>Unconstrained</td>
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<td>5266</td>
<td>2568</td>
<td>119</td>
<td>2579 18 2561</td>
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<td>3469</td>
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<tr>
<td>3</td>
<td>Flight plan routes</td>
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<td>2006</td>
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<tr>
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<td>2274</td>
<td>1042</td>
<td>1232 240 240 0</td>
</tr>
</tbody>
</table>

|   |                        |                                |                                              |                          |                                                          |                                          |                                      |

### Table 2: SESAR 2020 Traffic - Summary of fast-time simulation results

<table>
<thead>
<tr>
<th>#</th>
<th>Horizontal navigation</th>
<th>Cruise level allocation scheme</th>
<th>Total number of flights entering volume of interest</th>
<th>Total number of conflicts</th>
<th>Conflicts in which one or both aircraft are moving vertically</th>
<th>Conflicts in which both aircraft are level</th>
<th>Total fuel consumption / kilotonnes</th>
<th>Fuel consumption in area of interest / kilotonnes</th>
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<tr>
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</table>
A. Safety

No attempt has been made to perform a safety analysis for a lattice. However, one of the objectives of the lattice structure is to eliminate crossing conflicts between cruising aircraft. As can be seen from table 3, the lattice simulations confirm this property.

B. Fuel consumption

Fuel consumption is an important indicator from both economic and environmental perspectives. For the simulations with 2005 traffic, total fuel consumption was the only fuel consumption metric recorded. For the 2020 traffic, fuel consumed within the area of interest was recorded.

Simulation 2020#3 (flight plan routes, semi-circular flight level allocation) fulfils the requirement to avoid reserved areas. The fuel consumed within the area of interest was about 3.8% greater than when following direct routes (together with the semi-circular rule, simulation 2020#2).

The fuel consumed in the area of interest in simulation 2020#4 (lattice navigation, with a longitudinal lattice spacing of 70 nautical miles, without any consideration of reserved areas) was about 3.4% greater than in simulation 2020#2 (direct routes, semi-circular flight level allocation).

The figure below shows the distribution of horizontal inefficiency, for lattice simulation 2005#4, where horizontal inefficiency is defined as the ratio of the distance flown to the departure-destination distance.

![Figure 18: Distribution of horizontal inefficiency for lattice simulation 2005#4](image1.png)

![Figure 19: Example of an inefficient short haul flight](image2.png)

Short haul flights suffer greater horizontal inefficiencies than long haul flights, but they are also better candidates for level capping beneath the lattice.

C. ATM efficiency

1. SESAR 2005 traffic

In the lattice simulation with a lattice spacing of 70 nautical miles (simulation 2005#4), the total number of conflicts is 3631. Comparing this with simulation 2005#2, the approximation to conventional routing and flight level allocation in the absence of reserved areas, the number of conflicts (in the lattice simulation) is about 5% greater. This increase is surprising, since 2400 level-level crossing conflicts which occurred in the 2005#2 baseline have been eliminated.
Looking more closely into the breakdown by conflict type, there are 2006 conflicts (about 55%) in which one or both aircraft are moving vertically (when the conflict is first detected), but which are moving in the same direction horizontally. These conflicts are due to the mixing of climbing, descending and cruising aircraft flying along the same horizontal paths. In other words, the concentration of flights onto the same paths creates conflicts as aircraft climb and descend. A possible solution to this problem, which will be the subject of a future simulation, would be an improved lattice design with the addition of joining and leaving lanes, as discussed earlier, in order to separate climbing, descending and cruising aircraft. In simulation 2005#4 there were 950 short-lived (i.e. not merging) conflicts between aircraft with differing attitudes flying in the same direction. Other things being equal, the addition of joining and leaving lanes could potentially reduce the total number of conflicts by this amount, giving a total of 2681, which would represent a reduction of about 22% compared with direct routes and the semi-circular rule (simulation 2005#2).

2. **SESAR 2020 traffic**

In the lattice simulation with a lattice spacing of 70 nautical miles (simulation 2020#4), the total number of conflicts is 9447. Comparing this with simulation 2020#2, the approximation to conventional routing and flight level allocation in the absence of reserved areas, the number of conflicts (in the lattice simulation) is about 3% greater.

In simulation 2020#4 there were 2427 short-lived (i.e. not merging) conflicts between aircraft with differing attitudes flying in the same direction. Other things being equal, the addition of joining and leaving lanes could potentially reduce the total number of conflicts by this amount, giving a total of 7020, which would represent a reduction of about 26% compared with direct routes and the semi-circular rule (simulation 2020#2).

D. **Capacity**

Total workload has not yet been estimated. It is expected that capacity increase would be closely related to an increase in the number of sectors (controllers) in an airspace i.e. to an increase in the available workload.

VI. **Conclusions and future work**

A regular lattice could have several advantages compared with a conventional, irregular airspace structure:

- A regular structure allows airspace design solutions to be replicated throughout a region.
- Operating procedures or methods would be common throughout a region.
- A regular lattice can eliminate, by design, crossing conflicts between cruising aircraft.
- Together with measures to preserve the stability of traffic flows (sufficient spacing, speed regulation, or ASAS sequencing procedures), traffic may be separated into two easily identifiable populations: a "stable" population of cruising aircraft, which require low controller monitoring per aircraft, since there are no crossing conflicts between cruising aircraft, and a population of aircraft in "transition" to or from the stable state, which require greater monitoring.
• The existence of equivalent routes could facilitate traffic distribution and rerouting around reserved areas, with small impact on the predictability of airline operations.
• A fine-grained decomposition into sectors would allow air traffic control to be performed by a greater number of controllers, so increasing the capacity of the system.

Preliminary fast-time simulation of a lattice with a minimum longitudinal spacing of 70 nautical miles using SESAR 2005 and 2020 traffic confirms the elimination of crossing conflicts between cruising aircraft. Compared with a direct routing baseline, fuel consumption in the area of interest increased by 3.4% (using SESAR 2020 traffic). The total number of conflicts increased by 5% (2005) and 3% (2020). However, it is estimated that a decrease of about 22% (2005) to 26% (2020) could be achieved through an improved design in which joining and leaving lanes separate same direction climbing, cruising and descending aircraft.

Future work should include the estimation of airspace capacity, the detailed specification and testing of operating procedures and the incorporation of reserved areas.

References

[AX001-1-2/02] Investigation Report AX001-2/02, German Federal Bureau of Aircraft Accidents Investigation, May 2004
[AX001-1-2/02 - A1&3] Appendices 1 & 3