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Geovectoring: Reducing Traffic Complexity to Increase the Capacity of UAV airspace

Jacco M. Hoekstra, Joost Ellerbroek, Emmanuel Sunil, Jerom Maas
Faculty of Aerospace Engineering, TU Delft,
Delft, Netherlands

Abstract—Both U-space in Europe, as well as UTM in the USA, develop concepts and tools for UAV airspace. Enabling high-density operations is one of the goals of these studies. Past and recent studies have analysed which factors affect the capacity of a UAV airspace. An improved understanding of this can lead to control methods for capacity management. Two general principles for capacity management can be distinguished: controlling the traffic density, and controlling the traffic complexity. The first approach can be achieved using geofencing or geocaging, which is foreseen for UAV airspace. The second approach is hardly addressed in the planned concepts. In this paper a new, general concept, called geovectoring, is proposed which could increase the capacity by reducing the traffic complexity for U-Space and UTM. This paper therefore proposes to add geovectoring as a third service to the already planned concepts of geofencing and geocaging.

Keywords: UAVs; drones; RPAS; U-space; UTM; airspace; capacity; geofencing; geocaging; geovectoring

I. INTRODUCTION

The technology of UAS or drones, here referred to as UAVs, is advancing fast. This technological development opens up many new potential applications. Examples are inspection tasks for energy and agriculture, surveillance for public safety and security as well as package deliveries for emergency or premium services. By not requiring a pilot and due to the smaller size, for the same application, autonomous drones are generally cheaper, faster, cleaner and more energy efficient than their manned flying and non-flying counterparts. As a result UAVs or drones have the potential to deliver a significant contribution to society in terms of economy, sustainability and safety.

A drone outlook study by SESAR [1] expects, next to the seven million leisure drones, a fleet of 400,000 drones for commercial and government missions by 2050. The fastest growth is expected for the period from 2025 to 2035. While the largest economic impact is expected for agriculture, urban applications such as delivery and surveillance pose the largest challenge for airspace organisation due to the high concentration of vehicles flying at very low levels, over densely populated areas.

SESAR's U-space program in Europe as well as FAA's UTM program in the USA are in the process of developing concepts for updating regulations and airspace organisation for these applications in a safe and efficient way [2]. For U-space the deployment of services is divided into four steps[3]

- **U1:** U-space foundation services: e-registration, e-identification and geofencing
- **U2:** U-space initial services: flight planning, approval, tracking, information & procedures
- **U3:** U-space advanced services: complex ops in dense areas, capacity management, conflict detection & resolution
- **U4:** U-space full services: fully interfaced with manned aviation, highly automated

Enabling high-density operations with multiple automated drones under the supervision of drone operators is one of the key principles of U-space. Currently foreseen enablers for this are a combination of (dynamic) geofencing, to confine UAVs to allowed airspace, and capacity management strategies from manned aviation might be adapted for this airspace. However, recent studies [4] have indicated that, with their focus on (static) traffic density, such strategies will not be sufficient to cater the envisioned unmanned traffic densities, nor the heterogeneity of flights/missions. This can only be achieved if management of traffic complexity is taken into account. This paper proposes a potential solution to improve the efficiency, safety and capacity of very low-level airspace, which may provide a key component for capacity management in U3.

Using the results from a study which simulated extreme traffic densities [4], an analysis will be made of what affects the capacity of airspace in general. From this, two options to control the airspace capacity are presented. One is well known and in line with current developments. The second option is new and will be discussed more extensively using some examples. After a description of how this could be implemented, the paper ends with conclusions and recommendations.

II. CAPACITY OF AN AIRSPACE STRUCTURE

The capacity of an airspace is limited by safety and efficiency. When drones have a higher collision probability this affects the third-party risk as well as the economic viability. When too many conflict resolution manoeuvres are required to avoid intrusions of the protected zones of UAVs, this can lead to an inefficient flight or even lead to airspace instability due to domino effects. In both cases, the capacity is limited by the conflict rate, so how often an intrusion is predicted per time unit. Therefore, the conflict rate, which is equivalent to the conflict probability, is a useful metric for both efficiency and safety and can hence be used as an indicator for capacity: The capacity of an airspace can be expressed in terms of a maximum conflict rate.

It has been acknowledged that airspace structure and the resulting conflict rate, or demand for service, plays a role in airspace capacity [5]. In a centrally controlled airspace this maximum demand for service is determined by the workload of a controller. In future concepts, higher levels of automation and higher traffic densities will require a different approach to separation assurance. Nevertheless, the conflict rate is still an important limiting factor, albeit in a different way.

How an urban airspace should be organized to maximize capacity was investigated experimentally with massive traffic simulations in the Metropolis project [4]. The key question was whether more or less structure would benefit the capacity of the airspace. Four concepts with an increasing level of structure (see Figure 1) were tested under extreme traffic densities using batch simulations while measuring conflict rate, domino effects, intrusions and inefficiencies.

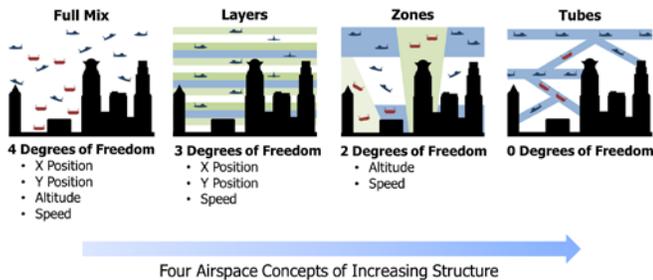


Figure 1 Metropolis airspace concepts simulated with 9.5 million flights in total

The Metropolis results showed that the so-called “Layers-concept” was the most successful in preventing a high global conflict rate with a minimum impact on the flight efficiency. In the Layers-concept the heading range, or heading span, determines in which layer a level flight is conducted to reach speed alignment within specified margins. Both when flying level in compliance with this rule or when changing altitude, the conflict detection and resolution was still active, using lateral manoeuvres to avoid having to leave the Layer when resolving conflicts.

This concept uses two methods to reduce the conflict rate: segmentation and relative speed reduction. Segmentation reduces the number of possible combinations of potentially conflicting aircraft. The faster an aircraft flies, the more airspace is crossed. Hence, on average more aircraft will be encountered. However, the relative speed is the speed at which an aircraft is encountered and it therefore scales directly with the conflict rate. These principles can be generalized for any control method used in UAV airspace capacity management. To define these control methods, the next section analyses the general principles before defining the control methods in section IV.

III. CONFLICT RATE, TRAFFIC DENSITY AND SPEED

Conflicts are defined as predicted, not actual, losses of separation. When detected in time, they are solved by what is called conflict resolution, an avoidance manoeuvre. Conflict detection and resolution (CD&R) have been studied for many years in the context of free flight and airborne separation assurance systems. Nowadays for UAVs specifically, CD&R is often referred to as ‘detect and avoid’ (DAA), but the same principles apply.

Intrusions are prevented in different phases, depending on the time to the predicted intrusion:

1. **Intrinsic prevention:** Airspace design or dynamic airspace (re)configuration to prevent conflicts
2. **Strategic resolution:** Planning of trajectories
3. **Tactical resolution:** Detect and resolve conflicts

When intrusions cannot be prevented, an additional, last minute collision avoidance safety net can be added, analogue to TCAS for manned flight.

As the first phase of the prevention of intrusions, airspace design generally aims at preventing conflicts by lowering the average conflict rate. Properties of both the traffic pattern and the airspace structure drive this conflict rate, and influence the capacity.

Two types of conflict rate should be distinguished:

- **global conflict rate:** the total number of conflicts in an airspace for all vehicles together per unit of time
- **local conflict rate:** the number of conflicts as experienced by one vehicle per unit of time

When there is no domino effect, which is to be prevented by limiting the conflict rate, the probability of a conflict of any pair of aircraft is generally independent of the number of vehicles in the airspace. If we name this probability p_2 and we call the number of aircraft in an airspace N , then the local conflict rate CR_{local} , i.e. per flight, is given by the product of this probability with the number of other aircraft (list of symbols can also be found at the end of this paper):

$$CR_{local} = (N - 1)p_2 \quad (1)$$

The global conflict rate CR_{global} is the product of the number of possible combinations of two aircraft with the conflict probability of one pair of aircraft, which multiplies equation (1) with the number of vehicles N as well as with $\frac{1}{2}$ to avoid counting every pair twice (so conflict A-B and B-A are counted as one conflict) [6][7]:

$$CR_{global} = \binom{N}{2} p_2 = \frac{1}{2} N(N - 1)p_2 \quad (2)$$

The mathematical truth is that the global conflict rate increases squared with the number of aircraft as opposed to the linear increase for the local conflict rate. The local conflict rate is per vehicle, so this is what is experienced on the airborne side.

It can be seen that lowering p_2 , the probability for any pair of aircraft to have a conflict, will have positive effect on the capacity under both centralized (e.g. strategic) and decentralized (e.g. tactical) control. By looking at which factors influence the conflict rate, Jardin [8] has expanded this into an expression which includes the average ground speed \bar{V} , the horizontal separation distance R , the airspace area A and observation interval T :

$$N_{conf} = \frac{\bar{V}R}{AT} k \Leftrightarrow CR_{global} = \frac{N_{conf}}{T} = \frac{\bar{V}R}{A} k \quad (3)$$

The average ground speed can be seen as the clock or pace of the conflict situation: when all aircraft fly twice as fast, the conflict rate will be doubled.

However, it can be shown that the factor that drives the conflict rate is not the absolute speed, but the relative speed or closure speed [9]. This relative speed is proportional to the ground speed, but can be lowered independently by not just limiting the magnitude but also the direction of the ground speed vector. This principle explains the result of the layers concept coming out best in the study mentioned before: it reduces the relative speed without concentrating traffic or reducing the route efficiency.

An analysis of the effect of the heading range can be made with some assumptions. When assuming both aircraft have a similar speed V , the relative speed can be expressed as function of

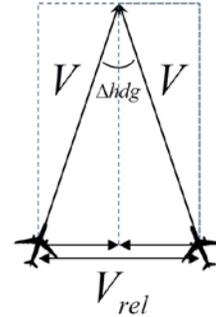


Figure 2 Converging aircraft with similar speed

From Figure 2, it can be seen that the relative speed is a function of the heading difference:

$$V_{rel} = 2V \sin\left(\frac{1}{2}|\Delta hdg|\right) \quad (4a)$$

Two simplifications are used here: the conflict-as-a-point, while with a minimum distance larger than zero, the geometry changes and the aforementioned equal speeds assumption. The effect of the conflict geometry can be ignored as long as the separation minima are small compared to the distances flown during the observation period and/or lookahead time (prediction horizon). When the two speeds are not equal, equation 4a becomes slightly more complex:

$$V_{rel} = \sqrt{V_1^2 + V_2^2 - 2V_1V_2 \cos(\Delta hdg)} \quad (4b)$$

For equal speeds this reduces to equation 4a, by using the following standard substitution:

$$\cos(\Delta hdg) = 1 - 2 \sin^2\left(\frac{1}{2}\Delta hdg\right) \quad (4c)$$

Using a uniform heading distribution over a heading range α , a probability distribution of the heading difference can be used for the simplified equation 4a, resulting in an integral which can be solved analytically. Comparable with throwing two dice, where 7 is a more likely outcome than 2 or 12, for a uniform heading range, the distribution of the heading difference is a triangle as shown in Figure 3 [10].

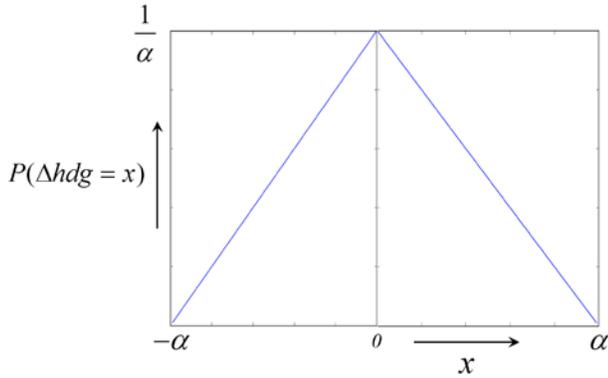


Figure 3 Distribution of heading difference when allowed heading is limited by α degrees

Averaging the combination of equation (4a) with Figure 3 results in the predicted global conflict rate [10] :

$$CR_{global} = \left(\frac{1}{2} N(N-1) \right) \frac{2R \cdot t_{lookahead}}{A} \cdot E(V_{rel}) \quad (5)$$

$$\text{with } E(V_{rel}) = \left(\frac{8V}{\alpha} \left(1 - \frac{2}{\alpha} \sin\left(\frac{1}{2}\alpha\right) \right) \right)$$

The factor which is expanded on the second line shows the effect of limiting the heading range to a span of α degrees. A further detailed explanation as well as the inclusion of the vertical dimension can be found in Sunil et al [9].

TABLE I. CONFLICT RATE CHANGE AND CAPACITY CHANGE AS A FUNCTION OF HEADING INTERVAL SIZE

Heading range α	Conflict rate change	Capacity change
360°	0 %	0%
180°	-27 %	+17%
90°	-60 %	+58%
45°	-80 %	+121%
30°	-86 %	+171%
15°	-93 %	+282%
10°	-95 %	+368%

For this paper the relevance is the principle applied here: the effect of limiting the heading range on the conflict rate, as shown in the table above, which is results from equation 5. The table clearly shows the large effect of some alignment of the speeds to reduce the relative speed and hence the conflict rate, without changing the absolute value of the speed, which is assumed to be equal or similar in this table. The last column

shows the effect on the capacity when this reduced conflict rate is used for a increase in capacity, using the inverse of equation 2 for large values of N .

The capacity analysis method has been further developed and validated experimentally [11]. A large Monte-Carlo study using the Open ATM simulator BlueSky was ran for different concepts and different types of aircraft. It tested the influence of the assumptions and simplifications like equal speed and the conflict-as-a-point geometry. The results showed a good match between what is predicted by the mathematical model and the experimental results. An example is shown in Figure 4.

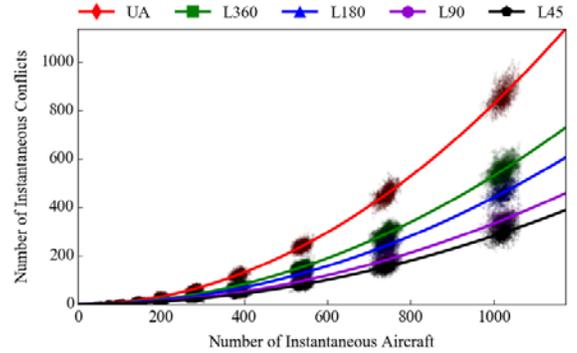


Figure 4 Experimental validations of mathematical conflict count model for different α 's (line is analytical prediction, points in clouds are experimental results)

IV. FROM ANALYSIS TO CONTROL

A. Segmentation

Airspace structures are often used to separate different traffic flows, and in this way clustering similar traffic. This can be beneficial but it can also artificially concentrate traffic, creating high densities, which has an adverse effect on safety. A positive effect of dividing an airspace into different sectors, is that the global conflict rate will be reduced due to the so-called segmentation effect. For instance, in the Layers concept mentioned in section II, the effect of creating L layers, with uniformly distributed the traffic over the L layers, can be illustrated by rewriting equation 2. The global conflict rate then becomes L times the conflict rate per layer, where the number of aircraft has been reduced by the same factor L:

$$CR_{global} = L \cdot \frac{1}{2} \frac{N}{L} \left(\frac{N}{L} - 1 \right) p_2 = \frac{N}{2} \left(\frac{N}{L} - 1 \right) p_2 \quad (6)$$

$$N \gg L \Rightarrow CR_{global}(L) \approx \frac{1}{L} CR_{global}(L=1) \quad (7)$$

The segmentation effect, due to the squared nature of equation 2, effectively divides the conflict rate by the number of groups L for high traffic densities.

Geofencing and geocaging restrict the position of UAVs. While geofencing is used mainly to define no-go areas for UAVs, geocaging can be used to keep a group of UAVs in a part of the airspace. Geocaging can exploit the segmentation effect to control and reduce the global conflict rate and thus increase the overall capacity.

B. Relative speed reduction

Table I in section II shows an example of how a heading range reduction can lower the conflict rate by limiting the relative speed. It shows that lowering of the conflict rate has the potential to realize a large increase in airspace capacity. There are other ways than layering the airspace to limit the relative speed: in general, putting limitations on any of the 3D speed vector's components of UAVs in a part of the airspace can be used to dynamically optimize convergence speeds and hence conflict probabilities in an airspace. These limits can add extra safety and capacity on top of the segmentation effect.

As currently geofencing and geocaging only limit the 3D position, this paper proposes to add a limitation the 3D speed vector components as a function of the geographical position. This principle is called geovectoring, to indicate it is a third component which logically fits in the sequence as indicated in Figure 5.

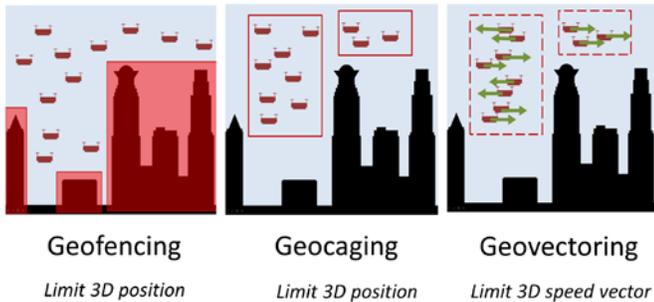


Figure 5 U-space elements for capacity management

Geovectoring differs from the normal 'vectoring' as currently used in ATC. The normal vectoring, assumes a form of direct control of the speed vector by ATC of an individual vehicle. In the geovectoring concept vectoring becomes a function of the airspace, i.e. the position, ('geo') and only an interval is specified for one or more components of the 3D speed vector, and vehicles are free to choose a velocity vector within that interval. This interval vector then applies to all vehicles in that sector.

V. GEOVECTORIZING DEFINITION

A geovector consists of two parts: the definition of an area and the definition of the allowed intervals of the speed components. The area for which the geovector is applicable can be defined as a series of (lat, lon) positions with a lower and upper altitude (prism). The area definition format can be the same as used for geofencing and geocaging. The only difference is the type and the extra information: the geovector intervals.

For practical purposes, the geovector components are polar for the horizontal speed vector, complemented by a vertical speed for the vertical dimension:

$$V_{geo} = \begin{pmatrix} GS \text{ interval} \\ \chi \text{ interval} \\ VS \text{ interval} \end{pmatrix} = \begin{pmatrix} [Groundspeed_{min}, Groundspeed_{max}] \\ [Course_{min}, Course_{max}] \\ [VerticalSpeed_{min}, VerticalSpeed_{max}] \end{pmatrix} = f(lat, lon, altitude) \quad (8)$$

As a symbolic notation, for example on a map or when describing an airspace design, it could be presented graphically for example with a format like in Figure 6.

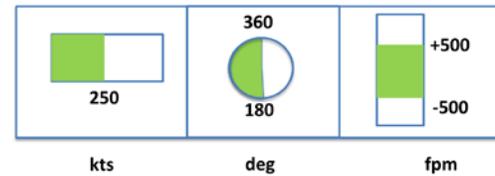


Figure 6 Symbolic representation of a geovector e.g. on a map (green zones indicate allowed ranges)

Many current airspace designs or rules can be expressed with this definition. Together with the expected demand distributions, this definition provides a baseline input needed to compare conflict rates mathematically with the analysis methods mentioned above, allowing the selection of an airspace design in a way that optimises safety and capacity.

When studying the capacity of an airspace there are basically two important aspects: the traffic density (or static density) and the traffic complexity (dynamic density) [13][14]. Using this distinction, it can be stated that geocaging & geofencing regulate the (static) traffic density, while geovectoring controls the traffic complexity, schematically it is shown in Figure 7.

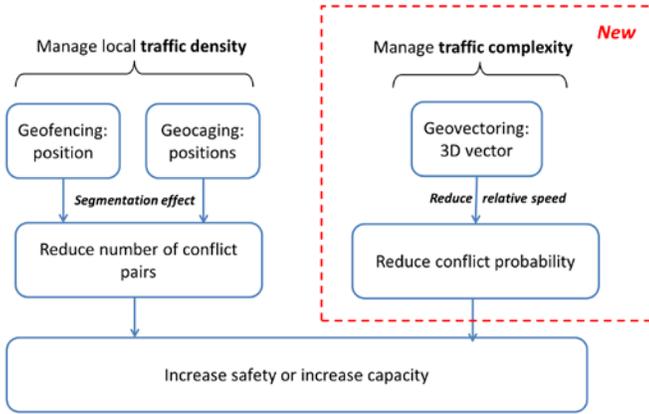


Figure 7 Geovectoring is a way to control the traffic complexity

VI. EXAMPLES OF GEOVECTORS AS AIRSPACE DESIGN SPECIFICATION

The semi-circular or hemispherical rule as used for IFR traffic below FL290 or under Reduced Vertical Separation Minima (RVSM), specifies a flight level as function of magnetic track angle: Eastbound traffic (magnetic track 000 to 179°) should use the odd thousands (FL 250, 270, etc.) while westbound traffic (magnetic track 180 to 359°) should use the even thousands (FL 260, 280, etc.). Many other already existing airspace regulations can also be defined using the geovector format, such as speed restrictions as function of altitude h , Some examples are given below

Semi-circular rule:

$$V_{\text{geo}}(h[FL]) = \left(\begin{array}{c} [0, \rightarrow) \\ \left[180^\circ \cdot \text{mod}\left(\frac{h-10}{10}, 2\right), 359^\circ - 180^\circ \cdot \text{mod}\left(\frac{h}{10}, 2\right) \right] \\ [0, 0] \end{array} \right) \quad (9)$$

Maximum speed of 250 kts below FL100 (but then as a ground speed limit!):

$$V_{\text{geo}}(h < FL100) = \left(\begin{array}{c} [0, 250 \text{ kts}] \\ [0^\circ, 360^\circ] \\ [0, 0] \end{array} \right) \quad (10)$$

A evenly distributed layers concept with L layers with is a variation on the semi-circular rule.

For layer i :

$$V_{\text{geo}}(i) = \left(\begin{array}{c} [0, \rightarrow) \\ \left[\text{mod}\left(\frac{360^\circ}{L}i, 360^\circ\right), \text{mod}\left(\frac{360^\circ}{L}(i+1), 360^\circ\right) \right] \\ [0, 0] \end{array} \right) \quad (11)$$

In general, the geovector would be specified independent per area, not with formulae but with actual numbers. First a definition of the area and then three intervals. A layers concept would thus be a series with a geovector for each layer, allowing different and less regular divisions based on demand. Geovectors can be used to define anything ranging from tubes, departing/arriving zones to layers. It is a generic format, which can therefore be implemented to be used in an automated way by UAVs control software in a similar fashion as geofencing.

Geovectors are applicable as long as the mission allows setting limits on the speed vector. A loitering surveillance or observations mission, will not allow limits on for the heading component of the geovector for instance. Similarly, there might be missions for which the required speed vector is even unpredictable, where only setting a vertical speed limit will be possible. Delivery drones are typically flying missions for which the heading component of geovector will be very useful to reduce the relative speeds.

VII. IMPLEMENTING GEOVECTORS FOR U-SPACE AND UTM

Using a list of geovectoring definitions for different areas, complex airspace designs with corridors, flow patterns, zones and layers can be defined to facilitate local circumstances or specific missions.

Two types of geovectors can be distinguished (Figure 8):

- **Static geovectors** - defined as part of a navigation database, fixed over a longer time
- **Dynamic geovectors** - may vary over time, need to be broadcasted

Dynamic geovectoring is a geovector which changes over time, this has implications for the implementation, not for the algebraic definition. The data format simply then also needs a time interval

$$V_{\text{geo}} = \left(\begin{array}{c} [Groundspeed_{\min}, Groundspeed_{\max}] \\ [Course_{\min}, Course_{\max}] \\ [VerticalSpeed_{\min}, VerticalSpeed_{\max}] \end{array} \right) = f(lat, lon, altitude, time) \quad (12)$$

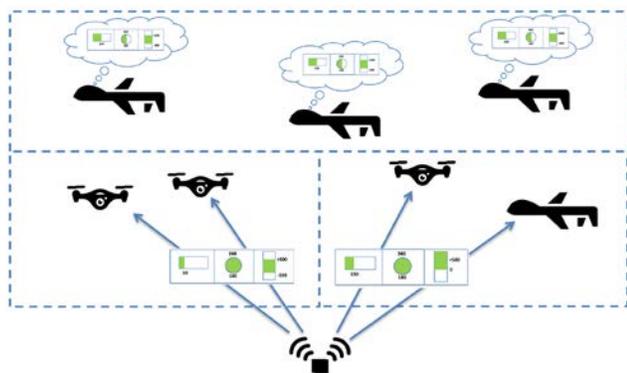


Figure 8 Geovectors can be static (navigation database) or dynamic (real-time broadcast/network service)

Dynamic geovectors require a data link protocol, which allows changing both the area specification, as well as the vector intervals over time. This could be used for reconfiguration: to adapt the airspace layout to daily or seasonal patterns, to varying densities or specific gained insights on how to optimize the airspace utilization.

Implementing a datalink protocol or a message format requires a lead time of several years, so the introduction of a dynamic geovectoring concept in e.g. the U-Space concept phase U3 needs to be prepared well in advance. Similarly, the implementation on the airborne side where this might need to be automated takes time. This increases the urgency of adopting geovectoring as a standard concept for UAV airspace.

VIII. CONCLUSION AND RECOMMENDATIONS

Both experimental as well as analytical work on airborne separation assurance and on urban airspaces with extreme densities, have contributed to our understanding of the relation between heading, speed, vertical speed, the relative speed, the conflict rate, the conflict probability and the airspace capacity.

It is now the time to research how this knowledge from the *analysis* can be used to *control* the airspace capacity where extreme densities are expected in the near future: the UAV airspace.

Currently, studies on UAV airspace design and regulations in both U-Space and UTM have been focused on capacity management by position, hence by traffic (static) density only, using concepts such as geofencing and geocaging.

To benefit from the potential applications of UAVs, geovectoring show promising possibilities for the capacity management of UAV airspace. A geovector is a three-component speed vector interval specified for a given area. Two types of geovectoring can be distinguished: static geovectoring, as part of a navigation database, and dynamic geovectoring available as real-time service via a network or broadcast system.

Geovectoring can be used to reduce the airspace complexity. It allows controlling the relative speed by specifying intervals as restrictions on the absolute 3D ground speed vector components. The geovectoring service can greatly increase the airspace capacity and improve the safety and efficiency of UAV airspace. Therefore it is important to further investigate how geovectoring protocol can be utilized in UAV airspace concepts.

IX. REFERENCES

- [1] SESAR JU, "European Drones Outlook Study – Unlocking the value for Europe", SESAR, November 2016
- [2] P. Kopardekar, S. Bradford, "UAS Traffic Management (UTM) Research Transition team (RTT) p", NASA/FAA, January 2017
- [3] SESAR JU, "U-Space Blueprint", SESAR, 2017
- [4] E. Sunil, J.M. Hoekstra et al., "Metropolis: Relating Airspace Structure and Capacity for Extreme Traffic Densities", Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015), Barcelona, 2015
- [5] M. Janic and V. Tosic, "En route sector capacity model," Transportation Science, vol. 25, no. 4, 1991
- [6] J.M. Hoekstra, R.C.J. Ruijgrok, R.N.H.W. van Gent, "Free Flight in Crowded Airspace", FAA/Eurocontrol 3rd USA/Europe Air Traffic Management R&D Seminar, Naples, June 2000
- [7] J. M. Hoekstra, R. N. H. W. van Gent, and R. C. J. Ruijgrok, "Designing for safety: the free flight air traffic management concept," Reliability Engineering & System Safety, vol. 75, no. 2, pp. 215–232, Feb. 2002
- [8] M. R. Jardin, "Analytical Relationships Between Conflict Counts and Air-Traffic Density," Journal of Guidance, Control, and Dynamics, vol. 28, no. 6, pp. 1150–1156, 2005. [Online]. Available: <http://dx.doi.org/10.2514/1.12758>
- [9] E. Sunil, Ellerbroek, J.M. Hoekstra, J. Maas, "Three-Dimensional Conflict Count Models for Unstructured and Layered Airspace Designs," submitted to Transportation Research Part C: Emerging Technologies, Dec 2017
- [10] J.M. Hoekstra, J. Maas, M. Tra, E. Sunil, "How Do Layered Airspace Design Parameters Affect Airspace Capacity and Safety?," International Conference for Research of Air Transport (ICRAT 2016), Philadelphia, 2016
- [11] E. Sunil, J. Ellerbroek, J.M. Hoekstra – "CAMDA: Capacity Assessment Method for Decentralized Air Traffic Control", submitted to International Conference for Research of Air Transport (ICRAT 2018), Barcelona, 2018
- [12] J.M. Hoekstra, Ellerbroek, J. – "BlueSky ATC Simulator Project: an Open Data and Open Source Approach", International Conference for Research of Air Transport (ICRAT 2016), Philadelphia, 2016
- [13] Laudeman, L.G., Shelden, S.G., Branstrom, R., Brasil, C.L., "Dynamic Density: An Air Traffic Management Metric", NASA/TM-1998-112226 – April 1998
- [14] Puechmorel, S., Delahaye, D., New trends in air traffic complexity. EIWAC 2009, ENRI International Workshop on ATM/CNS, Mar 2009, Tokyo, Japan. pp 55-60, 2009

List of used symbols

A	Area of the airspace
CR	Conflict rate
$E(x)$	Expected value of x
GS	Ground speed (scalar)
FL	Flight Level
L	Number of layers or subgroups in an airspace
N	Total number of aircraft in an airspace/sector
N_{conf}	Number of conflicts over a given time T
R	Horizontal separation minimum, i.e. radius of protected zone
T	Total observation duration
V	Speed, speed vector
V_{geo}	Geovector, gives three intervals for an area
VS	Vertical speed
h	Altitude
hdg	Heading
i	Iterator, counter
k	Constant
lat	Latitude
lon	Longitude
p_2	Probability to have a conflict per pair of aircraft
$t_{\text{lookahead}}$	Lookahead time of conflict detection
α	Heading span, or allowed range of headings
χ	Track angle, course