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Safety and Security in Traffic
Original Scientific Paper
Accepted: Sept. 26, 2007
Approved: May 13, 2008

TRANSITION FLIGHT BETWEEN THE AUTONOMOUS FLIGHT AIRSPACE AND AUTOMATED AIRSPACE

ABSTRACT

The paper proposes a novel Autonomous Flight Airspace concept as a bridge between pure innovation and integration of the existing and envisioned highly automated ATM concepts, methodologies, metrics, and procedures. Novel technologies, operations, and procedures will lead to air traffic flows with novel properties which together with adapted geometry and organization of airspace will define the complexities of air traffic situations in the Autonomous Flight Airspace and in its neighbourhood. The problem of transition flights to and from the Autonomous Flight Airspace is addressed from the complexity of in-flight traffic situations and consequent increase in conflicts between aircraft in the area perspective. Those are the driving criteria for the positioning of transition layers between the Autonomous Flight Airspace and the controlled airspace, their organization, and management of traffic flows in both zones adjacent to the boundary between them as well.

KEY WORDS

Autonomous Flight Airspace, automated airspace, transition flight, airspace organization, traffic flow management, strategic conflict avoidance

1. INTRODUCTION

The Autonomous Flight Airspace (AFA) is the evolutional offspring of the Free Flight Airspace (FFA), and enabler of integrated flight operations of aircraft with autonomous flight capabilities (e.g. Unmanned Aircraft Systems - UAS).

In the FFA the responsibilities for the airborne spacing and separation assurance are delegated to the flight crews on board aircraft, and the ground-based Air Traffic Management (ATM) is to resume the separation authority in emergencies only. Therefore, humans are the decision-makers, as well as operatives in the FFA.

As the airborne separation assurance is a fundamental principle of the FFA and the Airborne Separation Assurance System (ASAS) its main enabler, the AFA introduces the autonomous airborne separation assurance with Autonomous-ASAS (AASAS). The characteristic of the AFA is the machine-based decision-making, and the AFA is restricted to the ASAS and AASAS equipped aircraft but both types with autonomous flight capabilities. In the future the only humans-in-the-loop conducting flight operations through AFA are ground-based UAS operators and traffic flow managers of the next ATM generation, and systems supervisors (*pilots of present-day terminology*) onboard remnant old-school manned aircraft. Based on 4D trajectory planning the AASAS concept covers machine-based (a) traffic situational awareness, and (b) airborne spacing and self-separation assurance through (c) autonomous in-flight conflict detection and resolution.

The AFA topic is not only important for the implementation of non-segregated UAS flight operations, but also for the future air transport system responding to the society's emerging needs (which are not limited to enabling permeability of increasing volume of air traffic, but include other issues; e.g. airborne security when it is necessary for the pilot to transfer their responsibilities to an automatic system due to a hijack situation for flight trajectory protection and safe automatic return to the ground as envisioned in [1]).

Analogous to the traffic complexity at both highway ends, the air traffic is inherently complex especially in both zones adjacent to the boundary between the AFA (or FFA) and non-autonomous (or un-free) flight airspace (non-AFA). The number (quantum) of conflicts between aircraft is proportional to the complexity of the in-flight traffic situation [5]. For AFA implementation (or any airspace organization with changing delegation of responsibilities for the airborne spacing and separation assurance), the transition flights between the AFA and non-AFA therefore represent a critical safety issue of which an investigation is presented.

2. PROBLEM OF TRANSITION FLIGHTS

The complexity of air traffic and quantum of in-flight conflicts between aircraft in the AFA (or FFA) and its non-AFA neighborhood can be investigated using the theory of airspace fractal dimensions proposed by Mondoloni and Liang in [6]. This theory was introduced as a methodology capable of simultaneously distinguishing between the complexity of air traffic situation as a consequence of air traffic flow management, and complexity of air traffic situation as a consequence of geometry and organization of airspace. The fractal dimension is a number $D \in \{D \in \mathbb{R}, 1 \le D \le 3\}$ assigned to the particular flight corresponding to the freedom of aircraft motion. As shown in Table 1, with increasing freedom of movement the fractal dimension of flight increases, and vice versa.

Table 1 - Airspace fractal dimension

Scenario / Degrees of Freedom				Fractal Dimension
Airway Network	Heading	Air-speed	Top of Descent	
D	D	D	D	1.0
D	n/a	F	n/a	2.0
e	F	D	n/a	2.0
e	F	n/a	D	2.0
n/a	D	F	F	2.1
e	F	n/a	F	2.4
e	F	F	n/a	2.6

Airspace	Controlled Airspace / Transition Areas form 10,000ft to FL410; 120nm box around airport	1.22 – 1.39
	Upper Control Area upper airspace above FL240	1.13 – 1.32
	TMA/CTA – Terminal and Control Area form 10,000ft to FL240	1.2

Legend	D	Determined parameter
	F	Free parameter
	e	Exclusive parameter
	n/a	Undefined parameter

The table data are compiled from [6].

The relation between aircraft in-flight conflict rate *CR* and airspace fractal dimension *D* was derived in [6] as:

$$CR = \frac{vN}{r}\left(\frac{r}{l}\right)^{D} \qquad (1)$$

where v is the relative speed of aircraft, r is a separation minimum, and l is the linear dimension of airspace with fractal dimension D. The protected zone around the aircraft is only a fraction of the entire airspace, so the separation minimum is lesser than the linear dimension of airspace $r < l$, and obviously from (1) the frequency of in-flight conflicts decreases exponentially if fractal dimension of aircraft flight increases. Alternatively the number of in-flight conflict encounters C threatening aircraft ($dC = CR\ dt$) increases with decreasing freedom of its flight ΔD, and their relation can be approximated from data provided in [6] as:

$$\int CRdt \approx 11.472 - 2.452\Delta D \qquad (2)$$

Since the descending and/or climbing aircraft through the sector of level cruising flights increases markedly the air traffic controller's workload [3], and consequently decreases the sector throughput, earlier studies such as [2] anticipated mostly level transition flights from the FFA (applicable to the AFA as well). Level transition flights to and from the AFA (or FFA) require that the AFA (or FFA) and the controlled airspace (CA) are positioned side by side as shown in Figure 1, which again increases the air traffic controller's workload while dealing with the mix of differently equipped aircraft subjected to essentially different procedures, namely the mix of controlled flights and autonomous (or free) flights en-route to or from the AFA (or FFA). However, to gain increased airspace capacity and flight economics simultaneously with decreased emissions from optimized flights, the AFA (or FFA) should and will extend above CA (Fig. 2). Obviously there is more than one reason to consider a transition to and from the AFA (or FFA) while aircraft are climbing or descending.

In Figure 1 the flight safety related problem of level transition flight to and from the AFA (or FFA) is shown (since they are equivalent, only transitions from the AFA are explained). The transition flight from the AFA into the CA results in significantly decreased freedom of flight; aircraft flight might be dictated directly by the ATM or at least to a certain extent confined by the network of airways. Because of the decreasing freedom of flight the fractal dimension of aircraft flight will decrease (Table 1) and consequently the in-flight conflict encounter for transitioning aircraft will inevitability increase (2). The greater the differences between fractal dimensions of flight in the AFA and CA, the greater the increase in conflict encounter menacing transitioning aircraft at the boundary between the AFA and CA.

The greatest (50%) decrease of fractal dimension of flight and the resulting drastic 135% increase of conflict encounters (2) occurs, as shown in Figure 2, when an aircraft transits the border between the AFA (or FFA) and the CA through the arbitrary place (TC) at level flight and enters directly into the network of airways of CA.

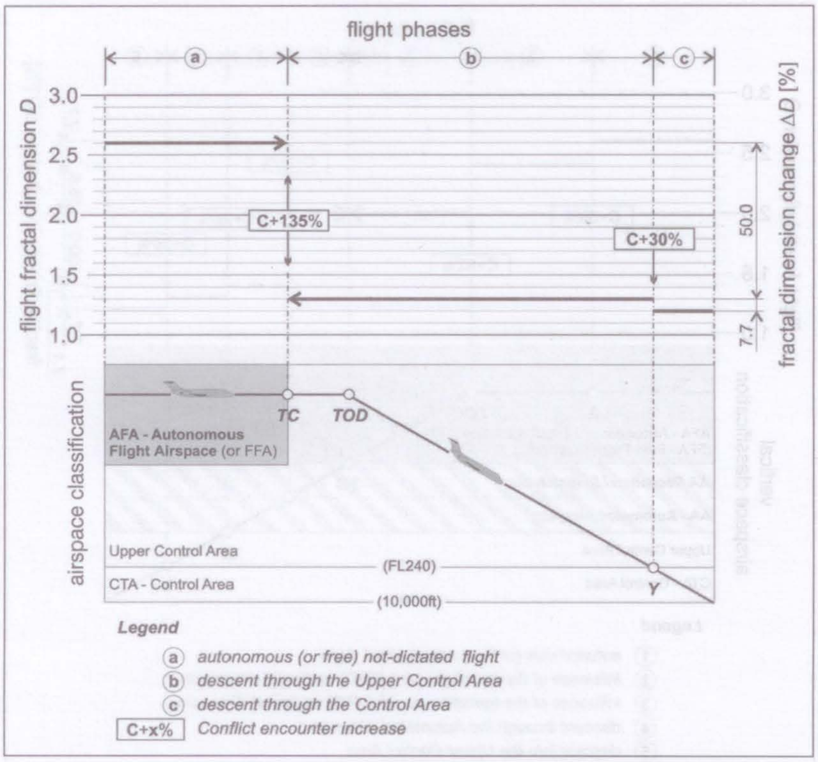

Figure 1 - Drastic increase in conflict at level transition from AFA

3. CONFLICT INCREASE DISPERSION ALONG THE TRANSITION FLIGHT

The solution to the problem of transition flight conflict encounter increase at the border between the AFA (or FFA) and the CA consists of:

1. the transition to and from the AFA (or FFA) into the CA in non-level flight; i.e., introduction of transition in descent and climb;
2. gradually decreased degree of freedom of flight in the direction from the AFA (or FFA) into the CA; i.e., progressively dictated parameters of flight along the transitioning route before an aircraft leaves the AFA (or FFA), upon leaving the AFA, and afterwards while flying in the CA (and vice versa, for the flight in the opposite direction transitioning to the AFA (or FFA));
3. CA organization and air traffic flow regulation adequate to the procedures of autonomously (or free) flying aircraft entering from the AFA (or FFA) and mixing with the rest of the traffic.

The proposed solution to the transitioning flight problem is presented in Figure 2. It is shown how drastic increase in conflict encounter imminent to an aircraft at the AFA border in level transition flight (Fig. 1) is dispersed securing reduced severity of conflict encounters along its transitioning trajectory.

The top of descent (TOD) determination in the AFA has a two-fold impact on the freedom of flight decrease while an aircraft is still flying in the AFA. Determination of the TOD in the AFA itself (Table 1), as the trajectory determination factor, reduces the fractal dimension of flight even before an aircraft reaches the edge of the AFA (Z; Fig. 2). Furthermore, the TOD can only be determined by the intersection of an aircraft cruising level and the trajectory of its descent (with a constant rate of descent to the assigned destination) through the rest of the transitioning aircraft free transition corridor (TC; Fig. 2) closest to the optimal route through the border between the AFA and CA. The transition corridor (TC) is a one-way passage in the transition layer through which an aircraft flies from the AFA into the CA (and vice versa); at the same time, it is the starting point of a particular airway in the CA. The TC defines the three-dimensional position of an aircraft transitioning from the AFA and direction of flight in the CA adjacent to the transition layer; consequently the TC is the restrictive factor which decreases freedom of aircraft movement and the fractal dimension of its flight (Table 1). Recurrently determined TOD and TC define the route of an aircraft leaving the AFA, and by gradually decreasing its freedom of flight dispersing threatening conflict encounters with the neighbouring aircraft along its way.

Descending from the AFA via the TC an aircraft enters the CA. In the part of the CA that borders upon the AFA it is of critical importance that the autonomous flights can be safely integrated with the rest of non-autonomous traffic, and that the airspace organization including traffic flow management enables a

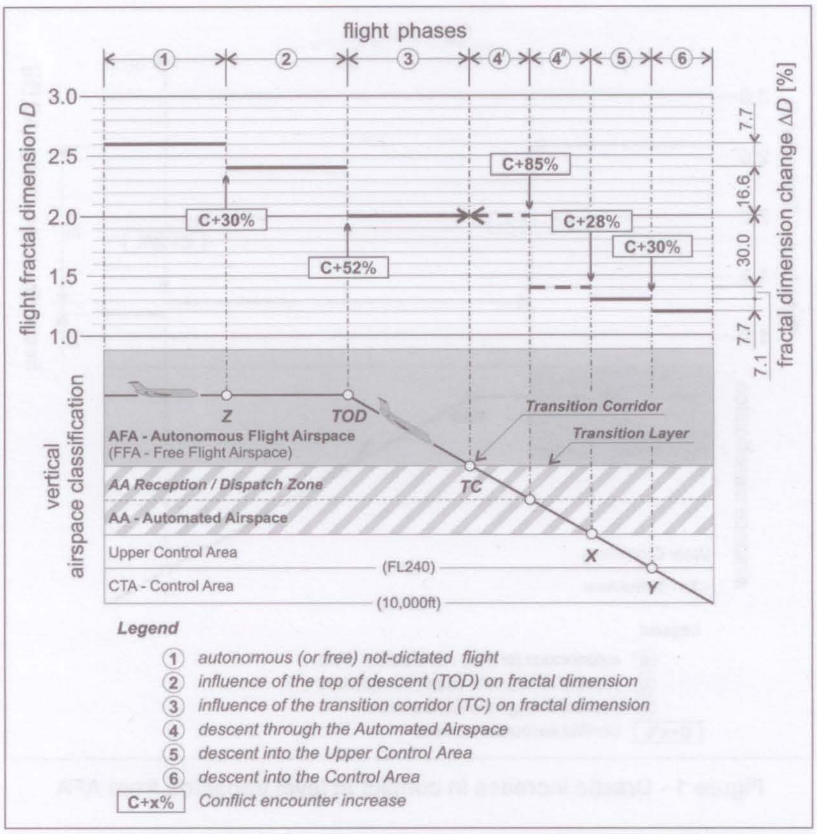

Figure 2 - Conflict increase dispersion along descending transition from AFA

fractal dimension comparable to the fractal dimension of the AFA. Both major criteria of the CA bordering the AFA are met with the Automated Airspace (AA) type of CA proposed in [4], if a reception zone is introduced into the AA at its border with the AFA.

The AA is based upon the ground-based automation system that provides in-flight separation assurance via data-link communication for properly equipped aircraft. The ground-based automation system issue clearances for aircraft intended trajectories and/or it can upload safe trajectories directly into the flight management system module of the AASAS of the autonomous aircraft and ASAS of the non-autonomous aircraft.

The roles of controllers in the AA are the strategic control of traffic flow, handling of exceptional traffic situations, and monitoring and control of unequipped aircraft [4]. Therefore, the AA enables the autonomous and non-autonomous aircraft mix.

The reception zone is an integral part of the AA adjacent to the border with the AFA (flying in the opposite direction an aircraft leaves the AA through the dispatch zone). The concourse pattern of airways starting in the AA reception zone with each TC at the border with the AFA is adjusted to match the directions of cardinal routes of the AFA; their geometry and organization serves as a collector of air traffic flowing together from various TCs onto the main central airways of the AA. The airways structure and the management of traffic flow, i.e. the aircraft trajectory control and restrictions, are such that the fractal dimension of the AA reception zone corresponds to the AFA fractal dimension. The fractal dimension of a flight upon crossing the border between the AFA and AA reception zone remains unchanged allowing that in the most critical part of the transition flight in the vicinity of the TC and in the TC the conflict encounter does not increase for the transitioning aircraft (Fig. 2).

Descending through the CA below the AA the aircraft traverse airspace sectors of different classes with progressively increased restrictions and control (dictation) of its trajectory each time the sector boundary is crossed, leading to non-severe but gradual increase in conflicts in succession of each sector boundary crossing (X, Y; Fig. 2). However, the greatest fractal dimension of a non-AA CA is far less than the AA reception zone fractal dimension. Consequently, the greatest (30%) change of fractal dimension of a transitioning flight is expected to occur in the AA resulting in an 85% increase in conflict encounter (2) threatening the descending aircraft (Fig. 2).

The challenge of the AA organization and traffic flow regulation is to progressively dictate the flight of the transitioning aircraft to secure gradual decrease in AA fractal dimension in the direction away from the transition layer from the value corresponding to the AFA fractal dimension with a value similar to the upper CA fractal dimension. That way the expected increase in conflict is dispersed further along the entire descending trajectory through the AA. The spacing and separation assurance actors in the AA are the AASAS of the autonomous aircraft, the ASAS of a free-flying aircraft, crews of unequipped aircraft, the ground-based separation assurance automation system, and the AA strategic traffic flow controller; but parallel to the human error hazard, a data-link communication failure imposes the greatest risk for flight safety in the AA.

4. AUTONOMOUS FLIGHT AIRSPACE

For the safety of aircraft flying in the AFA and AA, both are demarcated by the transition layer (TL), defined by the entry and exit plane that are separated at least by the vertical separation minimum. The AFA extends above the entry plane, while the AA is positioned below the exit plane (Fig. 3). Aircraft transition to and from the AFA through the bordered tube-like transition corridor (TC) at the TL.

Aircraft flows from either side of the TL converging for transit through the TCs, leading to the traffic dynamic density increase on either side of the TL in its proximity (applying the WJHTC/Titan Systems Metric: the convergence recognition index, separation critically index, and degrees of freedom index will be the most critical [5]). Traditionally, the traffic dynamic density is limited by the air traffic controller workload; however, even in the AFA or AA the dynamic density will still remain a limiting factor because of the limited airborne and ground-based separation assurance system processor power as well as limited data-link bandwidth. The dynamic airspace sectorization will ensure that the air traffic dynamic density does not reach its limits by the TL shifting. The (pressure) altitude of the TL is proportional to the air traffic dynamic density trend; if it increases, for example, the TL will ascend, resulting in AA vertical expansion simultaneously with the AFA *contraction* (Fig. 3).

In the AFA and AA aircraft, in-flight spacing and separation relies on the machine-based decision-making ASAS; in the AFA the AASAS responsibility extends to the exit plane of the TL, while in the AA the ground-based automation ASAS responsibilities extend to the entry plane of the TL. Since the exit plane does not coincide with the entry plane the airborne spacing and separation of aircraft responsibilities are shared in the TL between the AASAS onboard autonomous aircraft and the ground-based automation ASAS of the AA. Because of the shared responsibilities for airborne separation the entrance and exit TCs must be separated; aircraft fly from the AFA through the exit TC, while they enter the AFA through the entry TC (Fig. 3). Consequently, and considering anew the fact that airborne separation is based upon the machine-based decision-making in the AFA and AA, any conflict avoidance manoeuvring can only be coordinated implicitly between the AASAS and/or ASAS onboard aircraft involved in the conflict encounter, including implicit coordination of the future 4D trajectories of aircraft in the area.

Since AASAS of autonomously flying aircraft is still responsible for the in-flight spacing and separation when the transitioning aircraft is in the TC at the exit plane of the TL, the AASAS has to be capable of detecting possible conflict situations with aircraft flying in the AA even before the time of transition from the AFA. Actually, the rest of the transitioning aircraft-free, and especially conflict-free exit TC can only be selected (determined) in the process of aircraft descent trajectory from the AFA definition before the TOD is reached, if accurate prediction along the de-

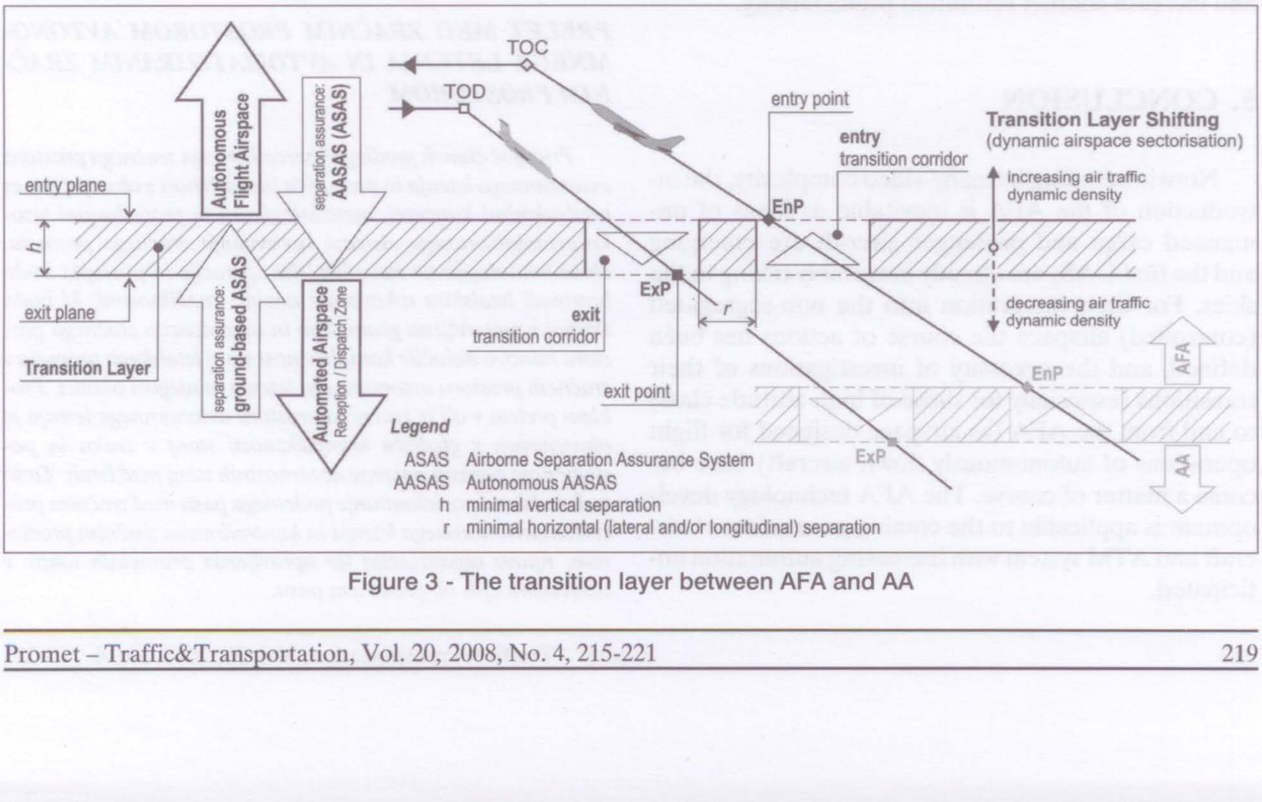

Figure 3 - The transition layer between AFA and AA

scending route and across the TL airborne traffic situation can be made. The longer look-ahead time for accurate and stable 4D prediction of an airborne traffic situation demands an accurate model of aircraft future relative positions based on their real future ground speeds, their future intents, as well as on the future area weather conditions. (Similar requirements are applicable for the ground-based ASAS of the AA since it is responsible for airborne aircraft spacing and separation in the TC at the entry plane of TL.)

Rules-of-the-sky tailored to the AFA flight operations are necessary for competitive rivalry for the best optimal trajectory prevention, and because conflict avoidance manoeuvring can only be coordinated implicitly between AASAS and/or ASAS onboard aircraft. For the transition flight to and from the AFA safety, a pair of rules apply. *The priority flight (first) rule*: "An aircraft that flies lower than the other aircraft involved in the conflict encounter when conflict is detected has the right-of-way." The rule therefore implies that only a higher flying-aircraft is responsible for resolving the conflict situation. Since the AFA extends above the AA the autonomous aircraft flying in the AFA are obliged to manoeuvre for menacing conflict resolution in case they are encountering conflict with an aircraft climbing to enter the AFA from the AA, and in their envisioned descent transition from the AFA. This priority rule also defines the minimum separation between the entry and the exit plane, as well as minimum separation between the entry and the exit TCs at the TL for unnecessary aircraft manoeuvring in the AFA prevention. *A manoeuvre flight (second) rule*: "After a conflict is detected, it is prohibited for the aircraft which has the right-of-way to alter the planned trajectory until the conflict is resolved." A pair of rules is therefore defined to ensure reliable implicit coordination of conflict avoidance manoeuvring and increase conflict resolution predictability.

5. CONCLUSION

Notwithstanding its many-sided complexity, the introduction of the AFA is inevitable as ideas of unmanned cargo and passenger aircraft are emerging and the first UASs are already inexorably taking to the skies. For their integration into the non-segregated (controlled) airspace the course of actions has been defined, and the necessity of investigations of their transitions (especially for those of high altitude class) to and from the AFA (as airspace designed for flight operations of autonomously flown aircraft) have become a matter of course. The AFA technology development is applicable to the coming generation of aircraft and ATM system with increasing automation anticipated.

Imminent increase in conflict encounter threatening aircraft transitioning to and from the AFA can be dispersed along the entire trajectory of aircraft with reduced severity of each remaining area of increase in conflicts with the introduction of descending or climbing transitions and AA reception/dispatch zone below the AFA where the expected aircraft mix can be handled. The enabling technology is a machine-based decision-making airborne AASAS and ground-based automation ASAS communicating by data link. A plain proof is provided that the AFA and autonomous flight operations are feasible and basic-level AFA operational procedures are introduced. Crucial to the AFA introduction feasibility are the technologies enabling: (a) sufficient bandwidth for reliable data-link communications, (b) capability to predict accurate and stable future 4D traffic situations with sufficient look-ahead time, (c) multi-factor analyses for real-time determination of safe transitioning trajectory including determination of the TOD, TC, and AA reception/dispatch zone collector airway selection, (d) adaptive airways structuring of AA, and (e) dynamic airspace sectorization.

ACKNOWLEDGEMENTS

This material is based upon the work supported by the Slovenian Research Agency Target Research Program - Science for Peace and Security under Grant No.: M2-0118.

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POVZETEK

PRELET MED ZRAČNIM PROSTOROM AVTONOMNEGA LETENJA IN AVTOMATIZIRANIM ZRAČNIM PROSTOROM

Pričujoč članek predlaga izviren koncept zračnega prostora avtonomnega letenja in premošča inovativnost z obstoječimi in predvidenimi koncepti, metodologijami in procedurami visoko-avtomatiziranega sistema upravljanja zračnega prometa. Nove tehnologije ter nove letalske operacije in postopki bodo botrovali letalskim tokovom z novimi značilnostmi, ki bodo skupaj s prenovljeno geometrijo in organizacijo zračnega prostora nanovo določile kompleksnost stanj letalskega prometa v zračnem prostoru avtonomnega letenja in njegovi okolici. Problem preleta v ali iz zračnega prostora avtonomnega letenja je obravnavan z gledišča kompleksnosti stanj v zraku in posledičnega porasta pojavov nevarnostnih stanj med letali. To so tudi sodila za pozicioniranje preletnega pasu med zračnim prostorom avtonomnega letenja in kontroliranim zračnim prostorom, njuno organizacijo ter upravljanja prometnih tokov v obeh območjih ob preletnem pasu.

KLJUČNE BESEDE

zračni prostor avtonomnega letenja, avtomatiziran zračni prostor, prelet, organizacija zračnega prostora, upravljanje prometnih tokov, strateško izogibanje nevarnostnim

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