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Non-Conflict Air Traffic Control in Flight-Path Straightening Operations ⋆

Sergey I. Kumkov * **Sergey G. Pyatko** ** **Mikhail M. Ovchinnikov** *

* *Krasovskii Institute of Mathematics and Mechanics, UrB RAS, Ekaterinburg, S. Kovalevskaya str, 16, 620990, Russia (e-mail: kumkov@imm.uran.ru).*

** *New Information Technologies in Aviation, NITA, Llc., St-Petersburg, Vzletnaya str, 15A, 196210, Russia (e-mail: boss@nita.ru)*

Abstract: Increasing the density of aircraft traffic and complication of schemes of the air traffic control (ATC) create difficulties for the air traffic control operator to make "by-hands" decisions for organization of non-conflict motions and providing their optimality on some criteria. Under this, the operator needs fore-handed analysis of his possible decisions and recommendations (from the automated ATC System) for detecting and solving possible conflict situations (of dangerous closing or approach). The paper is devoted to elaboration of algorithms of using the procedures for straightening the aircraft flight-paths w.r.t. its previous flight plan trajectories. Possible induced conflict situations are detected and necessary recommendations for their exclusion are given.

Keywords: air traffic, control, point merging, conflict, flight-path straightening, optimal motion.

1. INTRODUCTION

Technologies of air traffic control (ATC) (see, Korolev (2000), Pyatko (2004)) comprise many instructions, rules, constrains, and demands onto ATC operator's decisions for procedures with an aircraft under control.

So, in contemporary complicated schemes of aircraft motions and under increasing the density of aircraft traffic, it becomes difficult for the ATC operator to implement detecting possible conflict situations, to make "by-hands" decisions for their solving, and to satisfy an additional criterion: to provide minimal flight-time expenditures of aircraft till the landing. This criterion is very important for air-carrier companies from economic standpoint. So, the operator needs corresponding recommendations from the automated ATC control system.

In previous investigations Kumkov (2018), Kumkov (2016), Kumkov (2013), algorithms have been elaborated for merging the aircraft flows into non-conflict pre-landing queue without using the straightening flight-paths.

Direction of aircraft along the straightening flight-paths gives additional instrument to minimize the flight-time expenditures from the aircraft input point till its merging into the non-conflict landing queue.

In the paper, the algorithms are described for solving the problem of straightening the flight-paths with exclusion of appearing the conflict in a model ATC zone. But elaborated algorithms can be applied to investigate straightening operation in other ATC zones.

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Results of computation are presented to the ATC operator in the form of recommendations.

2. AIR TRAFFIC CONTROL ZONE

Scheme of a model ATC zone (with conditional names of check points) is shown in Fig. 1. Here, the boundaries of airport zone is drawn in solid red polygonal line. Trajectories of approaching the ten air flows are marked in black. The triangles are check points. Ovals at the input points of each approaching trajectory are so-called *standard schemes of previous delay*. These schemes are used for aircraft necessary delay of large value. After entering at their input points and beginning the control, motions of the aircraft flows have peculiarities.

Flow 1 RALUB from the input point RALUB (flight level 5700 m, nominal velocity 138 m/sec) moves along its own flight plan trajectory through point TUNED (flight level 5400 m, nominal velocity 138 m/sec) and point BIKMA (flight level 5100 m, nominal velocity 132 m/sec) up to the point SS014 (flight level 2700 m, nominal velocity 118 m/sec). This point is the beginning one of the delay arc DA4 (Figs. 3 and 4 below).

Flow 2 ARTEM from the input point AKERA (flight level 5400 m, nominal velocity 138 m/sec) through the point ATMEB (flight level 4800 m, nominal velocity 136 m/sec) and the point ARTEM (flight level 4500 m, nominal velocity 136 m/sec) goes to the point SS024 (flight level 4200 m, nominal velocity 134 m/sec).

Flow 3 SOPUS from the input point BANAM (flight level 5700 m, nominal velocity 138 m/sec) through the point SOPUS (flight level 4500 m, nominal velocity 136 m/sec) goes to the point SS024 (flight level 4200 m, nom-

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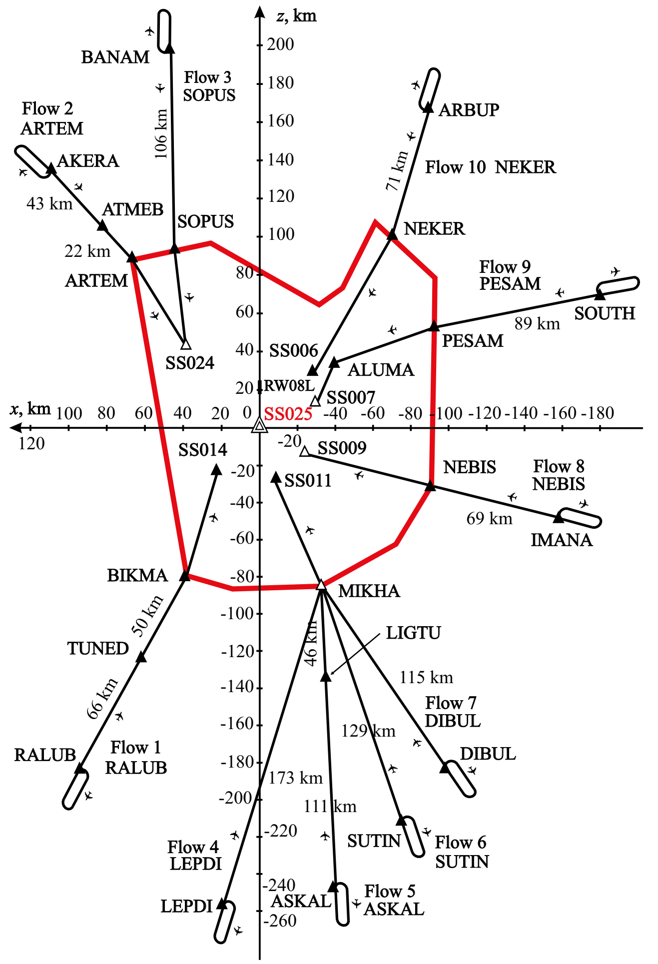

Fig. 1. Model air traffic control zone and the approach trajectories of ten arriving aircraft flows.

inal velocity 134 m/sec).
The point SS024 is the point of preliminary merging the flows ARTEM and SOPUS into the flow ARTEM/SOPUS.

Flow 4 LEPDI goes from the initial point LEPDI (flight level 6000 m, nominal velocity 140 m/sec) up to the point MIKHA (flight level 3300 m, nominal velocity 130 m/sec).

Flow 5 ASKAL from the initial point ASKAL (flight level 5700 m, nominal velocity 138 m/sec) moves through the point LIGTU (flight level 3300 m, nominal velocity 130 m/sec) up to the point MIKHA (flight level 3000 m, nominal velocity 125 m/sec).

Flow 6 SUTIN from the initial point SUTIN (flight 5400 m, nominal velocity 138 m/sec) moves to the point MIKHA (flight level 2700 m, nominal velocity 125 m/sec).

Flow 7 DIBUL from the initial point DIBUL (flight level 5100 m, nominal velocity 138 m/sec) moves to the point MIKHA (flight level 2400 m, nominal velocity 125 m/sec).
From the point MIKHA, Flows 4 LEPDI, 5 ASKAL, 6 SUTIN, and 7 DIBUL continuously descend to the point SS011 (flight level 2100 m, nominal velocity 117 m/sec).
The point SS011 is the point of these four flows preliminary merging (flight level 2100 m, nominal velocity 117 m/sec) and the initial point of the delay arc DA1 (Fig 3).

Flow 8 NEBIS from the initial point IMANA (flight level 6000 m, nominal velocity 140 m/sec) moves through the point NEBIS (flight level 4200 m, nominal velocity 136 m/sec) up to the point SS009 (flight level 1800 m, nominal velocity 117 m/sec).

Flow 9 PESAM from the initial point SOUTH (flight level 6000 m, nominal velocity 140 m/sec) moves through the point PESAM (flight level 4200 m, nominal velocity 138 m/sec) and the point ALUMA (flight level 3300 m, nominal velocity 130 m/sec) up to the point SS007 (flight level 2100 m, nominal with velocity 120 m/sec).

Flow 10 NEKER from the initial point ARBUP (flight level 6600 m, nominal velocity 144 m/sec) moves through point NEKER (flight level 4200 m, nominal velocity 138 m/sec) to the point SS006 (flight level 3000 m, nominal velocity 130 m/sec).

Around all nominal velocities, interval of its admissible values can be $[-10.0, +10.0]$ m/sec for possible variations by the operator.
Further motions of flows are shown in Figs. 2 and 3. In these figures, the airport runway for landing is marked by the symbol RW08L and thick horizontal segment.

The ATC operator has opportunity to shorten, *i.e.*,

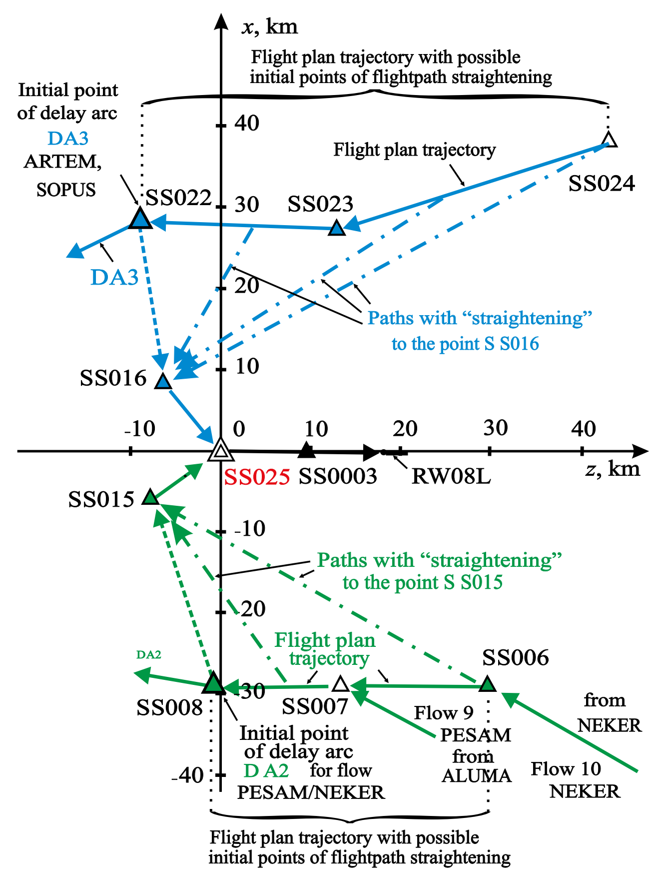

Fig. 2. Flight-path straightening.

to *straighten* flight-paths of aircraft w.r.t. their nominal flight-plan trajectories. In practice, such operation is performed to minimize an aircraft arriving-time.

For instance, aircraft in the joint flow ARTEM/SOPUS (Fig. 2) can be directed from the flight plan trajectories SS024–SS023 and SS023–SS022 forwardly to the intermediate point SS016. Similarly, aircraft in the joint flow PESAM/NEKER (Fig. 2) can be directed from the flight plan trajectories SS006–SS007 and SS007–SS008 forwardly to the intermediate point SS015. From the intermediate points SS015 and SS016, the aircraft goes to the point

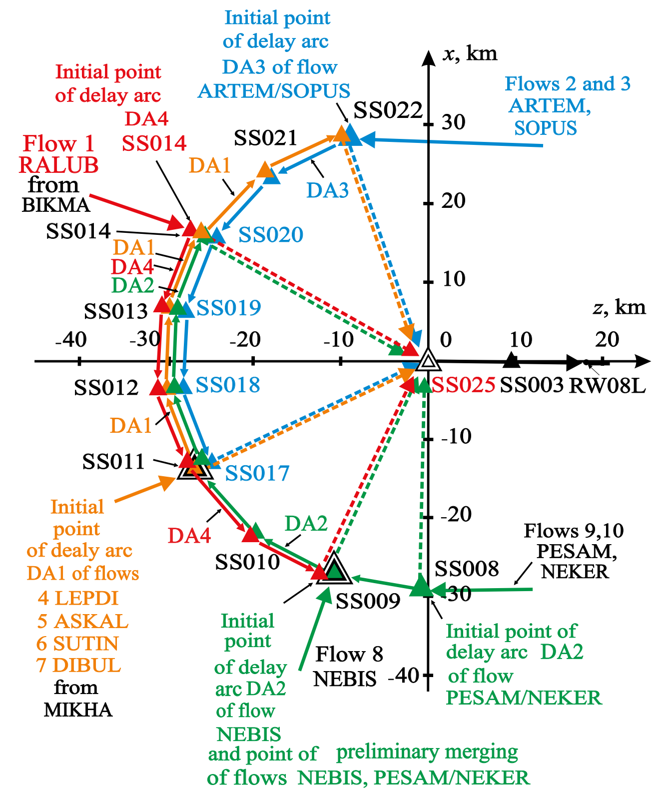

Fig. 3. Model point-merge scheme for ten flows (in the horizontal plane).

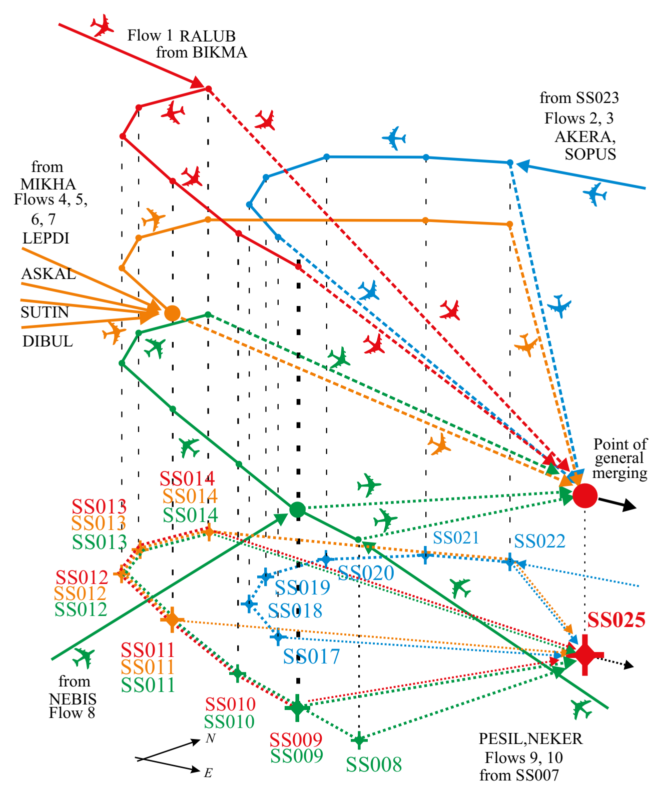

Fig. 4. Space structure of the model point-merge scheme for ten flows.

SS025 of flows general merging.

Figures 3 and 4 illustrate application of so-called "point-merge scheme" for non-conflict merging the ten aircraft flows into the pre-landing queue. The scheme comprises the delay arcs (DA's) that are approximately concentric w.r.t. the point SS025 of general merging. Each flow has its own DA (Fig. 4), and these delay arcs are safely separated in the space (Fig. 4).

In the scheme, the safe time separation interval $\tau_{\rm mrg}$ (at the point SS025 of general merging) between aircraft in the landing queue is provided by necessary relative delay (or acceleration) of each aircraft w.r.t. the previous (or successive) one.

3. STRAIGHTENING. PROBLEM FORMULATION

Controllable motions of aircraft along their flight-paths are described by the standard system of ordinary differential equations GOST (80)

$$\begin{aligned}
&x' = V\cos\theta\cos\psi,\\
&z' = V\cos\theta\sin\psi,\\
&y' = V\sin\theta,\\
&V' = au_1(t), \qquad a = \text{const},\ |u_1(t)| \le 1,\\
&\psi' = bu_2(t)/V, \quad b = \text{const},\ |u_2(t)| \le 1,\\
&\theta' = cu_3(t)/V, \quad c = \text{const},\ |u_3(t)| \le 1,
\end{aligned} \tag{1}$$

where x, z, y are the aircraft coordinates; ψ is the path heading; θ is the velocity angle; V is the spatial (true) velocity; a is the bound onto the longitudinal acceleration; u_1 is the control in the longitudinal channel; b is the bound onto acceleration in the lateral channel; u_2 is the control in the lateral channel; c is the bound onto acceleration in the vertical channel; u_3 is the control in the vertical channel. In model example under consideration, the controls u_1, u_2, and u_3 are elaborated for each aircraft by their model autopilots and provide motions *along the prescribed* trajectories of the flight plans or straightened ones.

One of the most effective way for automation of the ATC systems is in accurate formalization and taking into account all the demands and rules on ATC. Especially, it is actual in operations with the contemporary point-merge schemes NASA (2011), Eurocontrol (2010), Boursier (2007) for overcoming the conflict situations in the cases of multi-flows air traffic.

In the example under consideration (Figs. 1–4), it is necessary to provide non-conflict merging of ten flows and to minimize the summary time expenditure on aircraft motions till the general merging. Here, the ATC operator has the following opportunities:

– to delay aircraft on its schemes of preliminary delay (Fig. 1, ovals);
– to delay aircraft by decreasing their velocities (in the admissible intervals) along the flight plan trajectories;
– to accelerate aircraft by increasing their velocities (in the admissible intervals) along the flight plan trajectories;
– to delay aircraft on their delay arcs (DA1 – DA4) of the point-merge scheme (Figs. 3 and 4);
– to use mentioned straightening the aircraft flight-paths for flows ARTEM, SOPUS and PESAM, NEKER (Fig. 2).

After the input point and moving over its nominal flight plan trajectory, each aircraft has its nominal time $T_{i,nom}$ of motion to the point of general merging. Under delay on the time interval $\tau_{i,\rm del}$ or acceleration on the time interval $\tau_{i,\rm acc}$, the aircraft spends the time of arriving at the merge point

$$T_{i,\rm arr} = T_{i,\rm nom} + \tau_{i,\rm del} - \tau_{i,\rm acc}. \tag{2}$$

Let summary N aircraft in the shown flows (Figs. 1–4) arrive. The additional criterion on the control is *to minimize* the summary value

$$T_{\text{sum}} = \sum_{i=\overline{1,N}} T_{i,\text{arr}}. \quad (3)$$

Problem formulation. *For the given model ATC zone and scheme of possible straightening trajectories for aircraft of the Flows* 2, 3, 9, *and* 10, *it is necessary to elaborate algorithms of their merging into the non-conflict pre-landing queue at the point* SS025 *with minimization of criterion* (3). *Results of computation have to be presented to the ATC operator in the form of recommendations.*

Control of each aircraft begins from the passage the input point and ends at passage the point SS025 of general merging of all flows.

4. PROBLEM SOLVING

The following **basic algorithms** (and procedures) have been elaborated.

A) The instant of entering (by each aircraft) its input point (Fig. 1, points RALUB, AKERA, BANAM, LEPDI, ASKAL, SUTIN, DIBUL, IMANA, SOUTH, and ARBUP) is checked.

B) Prediction of its nominal arriving instant $t_{i,\text{arr,nom}}$ at the point SS025 is performed. For prediction, the nominal velocity regime and nominal flight plan trajectory of each aircraft is used. For example, for Flow 1, one uses the nominal trajectory RALUB–TUNED–BIKMA–SS014 (Fig. 1) and SS014–SS025 (Fig. 3).

C) For all aircraft that are under control, the collection of their arriving instants is ordered into the sequence by increasing.

D) Detection of possible predicted conflict situations is performed by using the prescribed value of the safe time interval τ_{mrg} (Fig. 5a,b and Fig. 6a).

E) If for solving the conflicts the *delay procedures* are chosen, then successively for each conflicting aircraft, the **minimal** necessary value of its *delay* τ_{del} w.r.t. the preceding aircraft is calculated (Fig. 5a). As the result (Fig. 5c), the non-conflict sequence of predicted arriving instants is formed.

F) If for solving the conflicts the *acceleration procedures* are chosen, then successively for each conflicting aircraft (Fig. 6a), the **minimal** necessary value of its *acceleration* τ_{acc} w.r.t. the succeeding aircraft is calculated (Fig. 6b). As the result (Fig. 6b), the non-conflict sequence of predicted arriving instants is formed with the safe time intervals τ_{mrg}. Note that the acceleration procedures are more preferable since they (together with resolving the conflicts) simultaneously provide the desirable minimization of the aircraft time expenditure till arriving at the general merging point.

G) To provide reliable detection of possible conflict situation and its solving, these procedures are performed in a cycle mode with sufficiently small time-step (*e.g.*, of 1 sec).

As it was mentioned in Introduction, the algorithms of delay (or acceleration) have been elaborated for merging several aircraft flows into non-conflict pre-landing queue without using the straightening flight-paths.

Direction of aircraft along the straightening flight-path

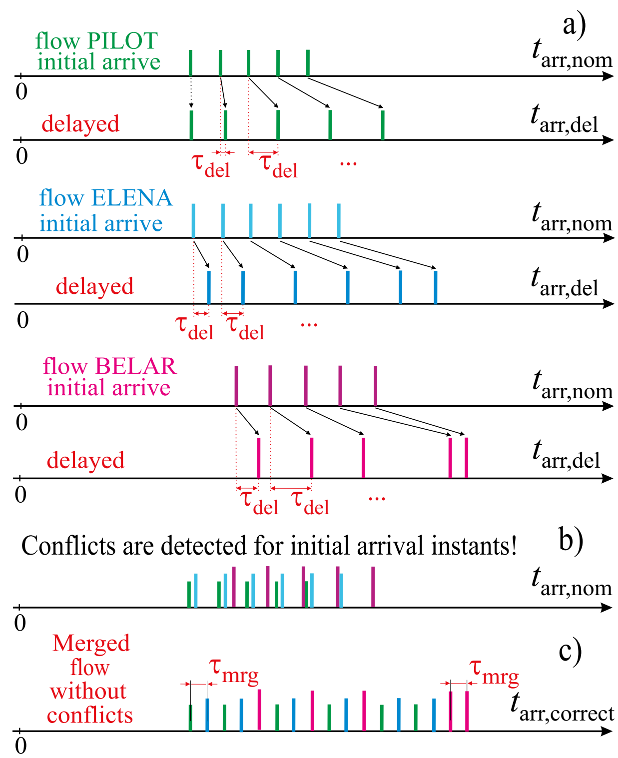

Fig. 5. Solving the conflict situations by aircraft delays.

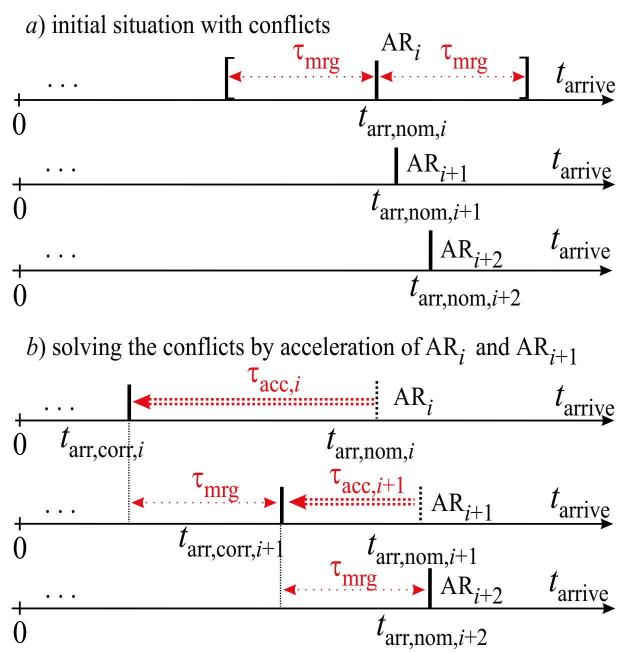

Fig. 6. Solving the conflict situations by aircraft acceleration.

gives additional instrument to minimize the flight-time expenditures from the aircraft input point till its merging into the pre-landing queue (Fig. 2, at the point SS025 of general merging).

In the model ATC zone under consideration, this regime is activated only on the shown parts of the flight plans (Fig. 2) till achieving by aircraft the initial points its delay arcs DA2 and DA3 (Figs. 2 and 3). If the straightening regime is *inadmissible* or *has not been activated* by the ATC operator, the aircraft of these flows are controlled (on its trajectories and delay arcs) as the aircraft of all other flows.

If the ATC operator makes a decision to straighten some aircraft, he can meet the following cases (Fig. 7). Here, the double arrows show at what position the predicted arriving instant $t_{\text{arr,str}}$ will shift if the operator chooses some straightening flight-path with decreasing value τ_{str} of motion time along it.

The straightening operation can give merging without conflict (Fig. 7a). But in our investigation with *ten arriving flows* and, especially, under increasing their densities, straightening can lead to appearing the so-called *influenced conflict situations*. Figure 7b illustrates such cases with the straightened aircraft AR_{str} w.r.t the previous one (of number $i+1$) with the earlier instant t_{i+1}, or w.r.t. one (number $i+2$) with the later instant t_{i+2} of arriving. Moreover, after beginning by the straightened aircraft its straightening motion (under initial absence of predicted conflict), the conflict can arise in the case of *appearing another aircraft* (Fig. 7c, number $i+3$, arriving instant t_{i+3}, in green) from some other flow, for example, with earlier arriving.

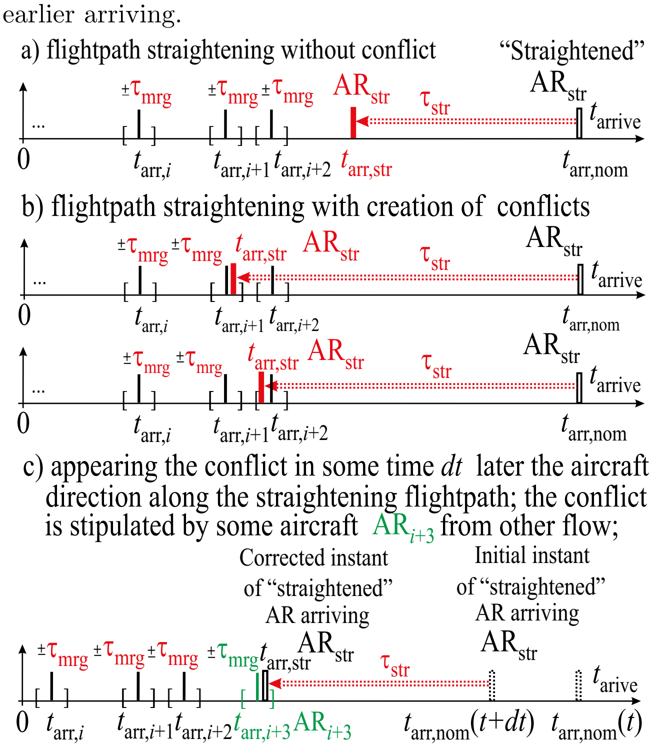

Fig. 7. Arriving instants (to the point SS025 of general merging) under flight-path straightening.

In the automated ATC systems, the main approach to exclude the influenced conflict situations is in analysis of the operator's version of straightening with giving him both complete predicted information about such a conflict and necessary recommendation for its avoiding.

In the regime of flight-path straightening, the mentioned **basic algorithms** A) – G) were adjusted for analysis of possible ATC operator's decision on flight-path straightening and analysis of possible appearing conflict situations. If the regime is activated, the straightened aircraft is further processed as an *ordinary one* till the predicted instants of arriving.

Suppose that the ATC operator chooses to straighten some aircraft of Flows 2, 3 or 9, 10. If so, the operator is immediately provided by recommendations on necessary delays (or accelerations) of the aircraft (including the straightened one). So, for any ATC operator's decision, he can make it with necessary recommendations guaranteeing the non-conflict merging of all flows under control and simultaneous minimization of each aircraft flight-time expenditures till achieving the point of general merging. The algorithms approved to be sufficiently universal: the straightening chosen by the operator is processed as a new version of the aircraft flight plan.

5. SIMULATION RESULTS

Figure 8 presents results of non-conflict motion of aircraft under operation of algorithms of the flight-path straightening. Here, trajectories with straightening the aircraft AKERA-3450 and ARBUP-3250 are shown in dashes. The aircraft AKERA-3450 was directed from the point SS024 to the point SS016 with admissible increasing its velocity up to 115.6 m/sec. The aircraft ARBUP-3250 was directed from the trajectory segment SS006–SS007 to the point SS015 with admissible increasing its velocity up to 120.1 m/sec.

Straightening the aircraft AKERA-3450 provided to safe about 5 minutes of its motion time from the initial point SS024 of straightening to the point SS025 of flows general murging. Under other conditions in flows with straightening, the time gain was from 4 to 11 minutes.

Simultaneously, the safe time (and space) separation is provided between aircraft IMANA-3360 – AKERA-3450 – ARBUP-3250 in the merging operation.

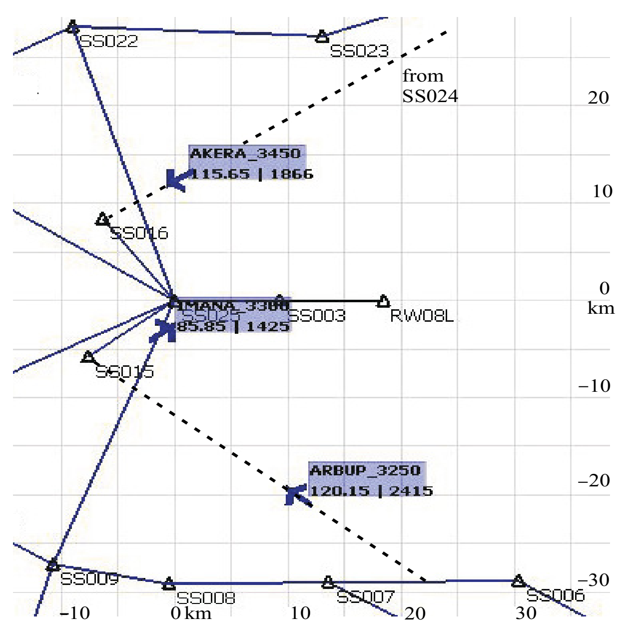

Fig. 8. Motion of aircraft with flight-path straightening; non-conflict straightened trajectories of aircraft AKERA-3450 and ARBUP-3250 (in dashes) with shortened motion times

Figure 9 shows the final non-conflict landing queue after merging aircraft of flows DIBUL, LEPDI, ASKAL, SUTIN (from the MIKHA-point) with "straightened" and accelerated aircraft BANAM-7000 and SOUTH-6950. Note (see instants-markers in the shadowed labels) that in the non-conflict landing queue the accelerated aircraft BANAM-7000 goes significantly ahead of all aircraft from the

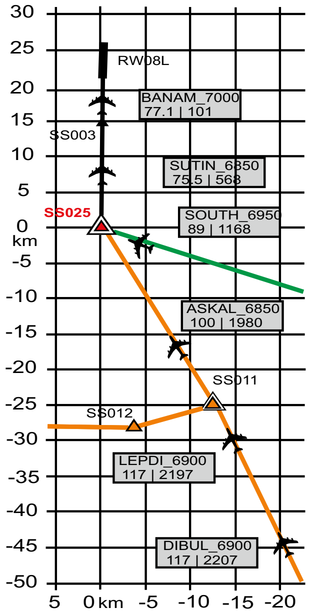

Fig. 9. Motion of aircraft after flight-path straightening; example of final non-conflict landing queue after merging

MIKHA-point. Similarly, the accelerated aircraft SOUTH-6950 was inserted into the queue ahead of aircraft ASKAL-6850, LEPDI-6900, and DIBUL-6900 coming from the MIKHA-point. It is seen that under the merging algorithms functioning, the time (and spacial) separation is reliably provided in the landing queue, between all foregoing and after-going aircraft.

Figure 10 shows the *dynamic scale* of the current arriving instances. The scale was elaborated to provide current visual check of arriving instants for the operator. From the initial situation (Fig. 10a), the multiple conflicts are seen at $t = 612$ sec. Successful solving these conflicts at $t = 1736$ sec is illustrated on Fig. 10b after implementation the operator's recommendations.

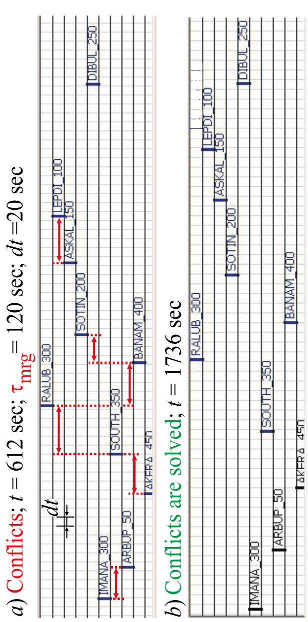

Fig. 10. Solving multiple conflicts; a) the initial picture with multiple conflicts; b) picture without conflicts

6. CONCLUSION

Simulation in the considered scheme of merging confirms that application of the flight-path straightening in control of many aircraft flows can be recommended to use the straightening schemes in ATC zones. It shows that essential shortage of motion time for straightened aircraft can be successfully provided and algorithms for merging can be elaborated for ten airflows non-conflict merged landing queue with necessary safe intervals between landing aircraft.

Elaborated algorithms of straightening are universal. They can be used simultaneously with the point-merge scheme, can significantly increase traffic capacity of the ATC zone and can be applied to any initial flight plans in it.

Application of trajectory straightening in multi-flows schemes (with obligatory providing overall motion safety) needs further detailed investigations. In particular, the general principles must be formulated for constructing the flight-path straightening with check of influenced conflict situations.

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