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# OPERATIVE CORRECTION OF AIRCRAFT TRAJECTORIES BASED ON AIRBORNE WEATHER RADARS INFORMATION

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***Abstract***

*Trajectory prediction and optimization capabilities are considered as crucial part for efficient Air Traffic Management (ATM) operation. One of the key factors that influence onto trajectory prediction is weather situation at the departure and arrival points and along the flight route. In this context it is important to utilize widely systems of operative obtaining information about weather hazards for short-term flight trajectory correction. Airborne weather radars (AWR) are powerful and convenient tool for operative data obtaining during the aircraft flight when atmospheric and weather disturbances arise. In this paper possibilities of trajectory correction by providing accurate and operative meteorological data using the onboard radar system are shown and discussed.*

**Keywords:** meteorological radar, AWR, flight trajectory optimization algorithm

## 1. Introduction

Growth of air traffic density, increased utilization of unmanned aerial vehicles, introduction of new concepts, programs and projects of flights provides the future trends of efficient Air Traffic Management (ATM). The implementation of prospective concepts and programs is based on the significant progress and development of new technologies, systems and procedures including advances in navigation, communication and surveillance systems.

The Global Air Navigation plan [1] claims the important trends of the next 20 years. The trends of enhanced surveillance among others are:

- Different techniques will be mixed in order to obtain the best cost-effectiveness depending on local constraints;
- Cooperative surveillance will use technologies currently available using 1030/1090 MHz RF bands (SSR, Mode-S, WAM and ADS-B);
- While refinements to capabilities may be identified, it is expected that the surveillance infrastructure currently foreseen could meet all the demands placed upon it;
- The airborne part of the surveillance system will become more important and should be “future proof” and globally interoperable in order to support the various surveillance techniques which will be used;
- Improved situational awareness;
- Functionality will migrate from the ground to the air.

The prospective concepts and programs (for example, free flight concept [2], emerging Trajectory Based Operations concept [3], NextGen project [4], SESAR project [5]) imply the change of a centrally controlled ATM system to a distributed system and based on introduction of a fourth parameter in the trajectory (x, y, z, and time t). Under such demands the trajectory prediction and further correction or optimization are considered as crucial task for efficient ATM operation. One of the key factors that influence onto the trajectory prediction is weather situation at the departure and arrival points and along the flight route [6, 7]. Moreover, the concept and programs [2, 3, 4, 5] consider the reduced weather impact by introducing NextGen Network-Enabled Weather (NNEW) and direct integration of weather information into operational decision-making processes. The term Network-Enabled in this context means available, secured, real-time and useful, available on-demand meteorological information that helps to create common weather picture for analysis, and for composition forecast data available to all system users as well as for possible flight trajectory correction. This correction can be required when weather directly influence flight operation or when the weather should be checked and considered in case of potentially conflict situation. This paper considers the possibilities of short-term trajectory correction using information operative meteorological data of onboard radar system.

## 2. Prospective aviation programs and concepts and their benefits

Modern concepts and programs require transformation from so-called fragmented weather forecasting into the forecasts embedded into decisions and decision support tools in order to reduce weather impact into flight operation. This, in turn, is realized in transformation programs as NextGen Network-Enabled Weather (NNEW). The possibility to implement NNEW is based on wide use of Automatic Dependent Surveillance – Broadcast (ADS-B), System-Wide Information Management (SWIM) and Collaborative Air Traffic Management Technologies (CATM-T). SWIM and CATM-T programs provides enhancements to the existing Traffic Flow Management System by six improvements including Weather Integration and Collaborative Information Exchange.

**NextGen.** Federal Aviation Administration (FAA) has proposed modernization of USA's air transportation system to achieve safer, more efficient, and more predictable operation [8]. NextGen comprises the developed innovative and prospective technologies to achieve its goals. The main changes consider the improvements in communication, navigation and surveillance the next way:

- Aircraft should be able to receive instructions from ground for time and position identification quickly, easer and with less risk of miscommunication.
- Switching to a primarily satellite-enabled navigation system that is considered as the more precise than traditional ground-based navigation. This transformation is aimed to plan trajectory or to make short-term correction to reduce time of flight, fuel consumption, ecological influence onto surroundings.
- the surveillance system should provide participants of air traffic with clear information on significant meteorological phenomena and conditions of surrounding airspace.

**Automatic Dependent Surveillance – Broadcast.** ADS-B system periodically and automatically transmits information that is available to everyone with the appropriate receiving equipment. It is so-called "Dependent" as the position and velocity vectors are derived from the Satellite Navigation Systems. ADS-B determines the 3-dimensional position and identification of aircraft [9].

ADS-B Out broadcasts information about an aircraft's location, altitude, ground speed and other data to ground stations and other aircraft, once per second. Participants of air traffic with ADS-B In equipment can immediately receive the transmitted information.

ADS-B In allows aircraft crew to obtain information automatically about weather and traffic position if its aircraft equipped correspondingly.

The FAA indicates the improved safety, and situational awareness as the main benefits of the ADS-B utilization. The improved situational awareness due to the use of prospective systems and technologies of operative meteorological detection as well helps to realize the middle and short-term corrections of aircraft trajectories if needed.

**System-Wide Information Management (SWIM)** is intended to share "the right information to the right people and at the right time". SWIM implementation is aimed to avoid hard-wired infrastructure with limit possibilities to support huge volume of data, systems and potential information users.

The improved situational awareness is one of the SWIM benefits because it shares aeronautical, weather, and flight information in common data format. The improved efficiency is another benefit of SWIM implementation as it allows to share operative relevant, reliable, and consistent information on demand only once. Then subscribers can access information through a single connection.

**Collaborative Air Traffic Management Technologies (CATM-T)** allows to increase capacity, flexibility and efficiency by coordination of flight and flow decision-making. In this process flight planners and air traffic controllers are involved. Th main idea is that air space user`s preferences are gathered to the maximum extent possible. Then the impact of all constraints can be reduced by particular flow management actions to specific flights.

In SWIM and CATM-T programs Weather Integration, in turn, integrates the display of the Corridor Integrated Weather System (CIWS) product [9] onto the Traffic Flow management system TFMS display [10]; integrates the Route

Availability Planning Tool (RAPT) [11] onto the TFMS display. Weather integration will help to provide:

-common situation awareness between users and service providers;

-availability of weather-related data;

-increase in accuracy and display of weather information;

-improve weather-relate hazards avoidance, particularly convective weather.

It is indicated in [11] that 70% of air traffic delays are caused by significant weather phenomena. It is indicated in [9,10,11] that common use of prospective systems allows decreasing weather-related departure delays and ground holding by providing air traffic services with automated, guidance for

-Visualizing the impact of approaching weather systems

- Determining the time frame for closing and reopening departure routes

- Determining optimum departure routing on the basis of forecasts of convective weather

-Determining when to allow limited route usage during thunderstorms.

It is expected that combined use of forecasted and probabilistic information [9 and 10] helps to optimize flight trajectories to avoid convective weather hazards.

At the same time, it is indicated that modern air traffic systems do not use available nowadays systems and technologies, thus losing in efficiency of airspace and aircraft flights. Moreover, the ground-based meteorological radar systems do not allow to obtain information about upper part and top of convective formations. In this context it is crucial to utilize widely systems of operative obtaining information about weather hazards for short-term flight trajectory correction.

## 3. Medium-term and Short-term trajectory correction

There are three main approaches to the flight planning from the point of view of time that is required for the trajectory planning. They are long-term flight planning, medium-term and short-term flight planning. Long-term flight planning [12] can be used for over 30 minutes airspace planning. The meteorological materials that can be used at this level are long term forecasts and large-scale weather data including satellites and radar images.

Medium-term flight planning comprises time intervals up to 30 minutes [13,14]. This approach is used when unforeseen events in the airspace or situations that can be forecasted with low level of accuracy are appeared. This requires correction of previously calculated flight trajectory. The present weather information or short-term weather forecasts can be used at this stage of flight planning. The range of convective weather phenomena can become the factors that require medium-term flight correction or even short-term trajectory correction. Short-term trajectory correction is implemented at operational level [14] in the time intervals up to 10 minutes. The information for trajectory correction at this level is taken from the both: ground-based and onboard systems. The key information for short-term flight correction can be obtained from onboard systems including meteorological onboard radar. In Fig.1. the block-diagram that connects the three main approaches to the flight planning and possible data that can be used for each approach are shown.

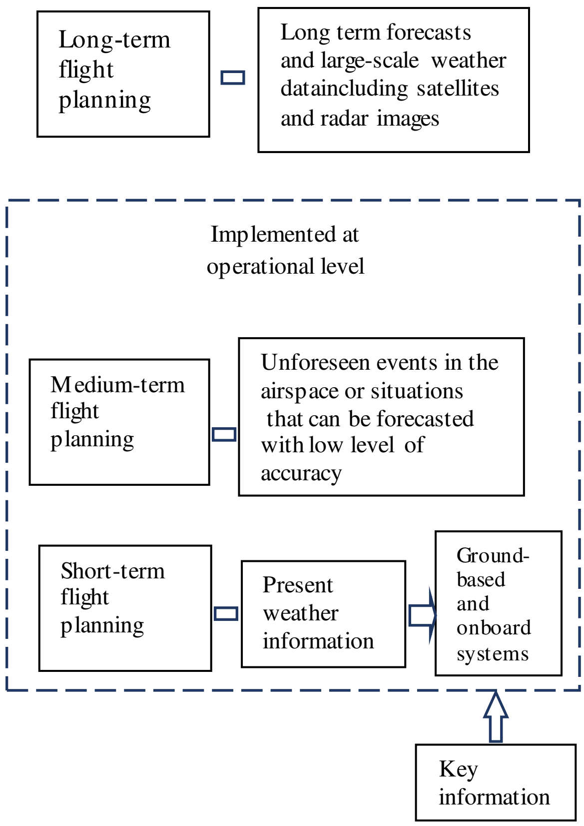


Fig.1. the block-diagram that connects the three main approaches to the flight planning and possible data that can be used for each approach

The examples of meteorological hazards that can be a reason for middle or short -term correction include convective activity, both airmass or frontal, zones of significant aircraft icing, turbulence of different nature.

In Fig.2 the convective cloud with associated activity (a), corresponding radar (b) and satellite (c) images are shown.

(a)


(b) (c)

Fig.2. Convective cloud and shower precipitation (a) and corresponding radar (b) and satellite (c) images

It is possible to see in Fig.2 b that the highest level of intensity of convective activity makes it impossible to flight in the region of the weather formation and requires the correction of prescribed flight trajectory. The satellite image confirms the presence of convective formation but does not give the evident level of danger of the phenomena. So, in this case the onboard meteorological radar gives the more precise information for decision-making for both pilot decision or automated correction of flight trajectory.

The global system for meteorological data obtaining and dissemination focusing on possibilities of modern radar onboard systems was proposed and considered in paper [15]. Some prospective of radar systems are presented and discussed in [16-18]. Taking into account the modern level of technologies development in [15] there was proposed system that consider commercial aircraft as a dynamic platform to place wide range of sensors and systems for meteorological data obtaining and exchange in the frame of the global system of observation and data exchange.

## 4. Correction method

The block diagram in Fig.3. presents the general procedure of online trajectory correction of aircraft flight using operative data from including onboard meteorological radar.

The initial flight trajectory is calculated with long-term flight planner. Then as an aircraft flight starts this primary and intended aircraft trajectory can be corrected in the frame of medium-term and short-term flight planning if required. The requirements for correction can operative information about meteorological hazards presented at the intended flight path. The updating of current situation starts from taking decision about intensity of meteorological hazards along the planned flight route. If situation is considered as potentially dangerous for flight the trajectory correction algorithm (on the basis of medium-term or short-term flight) updates the flight trajectory taking into account the current position and constrains that include aircraft performances, current air traffic situation, fuel etc.

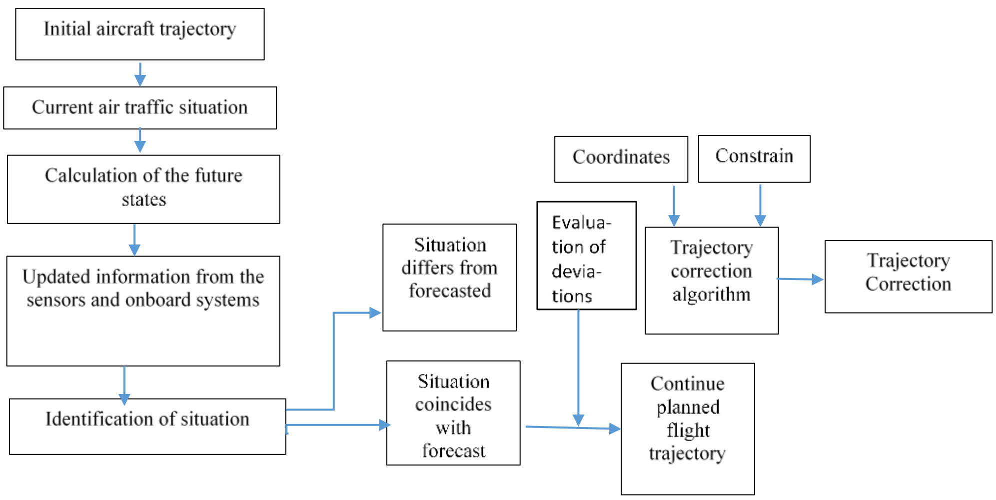


Fig. 3. Block diagram of online trajectory correction of aircraft flight route using operative meteorological data

Nowadays there are different optimal trajectory planners that can be aimed to solve specific tasks for different applications: UAV flights, space, aviation. To find the optimal flight trajectory of commercial aircrafts the most algorithms chose the objective function to reduce the fuel consumption and to shorten the flight keeping the flight safety in the priority. Thus, it is necessary to find the shortest safe distance to the destination point. Some algorithms for flight planning including Cuckoo search optimization (CK) algorithm [19], Dijkstra algorithm [20], The algorithm [21] operates to discretize the space to find the optimal path. This paper illustrates realization of the optimal trajectory planners on the base of particle swarm optimization as it was presented in [22]. In future it is reasonable to compare different algorithms from the point of view of time consumption and stability. In given paper the simulation considers the data from onboard meteorological radar about atmospheric hazards on the aircraft route as triggering factor for short-term automated flight trajectory correction.

## 5. Particle swarm optimization

Particle swarm optimization (PSO) algorithm was developed in 1995 [23] and inspired by the behaviour of social organisms in groups such a swarm behavior. PSO in its standard version is considered as rather simple algorithm and can be easily implemented. In this version of PSO the choice of new point for movement is provided by the next components: own best position based on self-experience, global best position that is based on the group experience (experiences of all the members of the swarm), random coefficients.

When particles moving the position if $i$th particle is changed according the new speed and position with each iteration $n$.

$$v_i^n = \kappa_1 v_i^{n-1} + g_1 k_2 (z_{bg} - x_i^{n-1}) + g_2 \kappa_3 (z_{bP} - x_i^{n-1}) \quad ,(1)$$

where

$v_i^n$ is of the iteration *n;*

$\kappa_1$, is inertia coefficient in the range [0,1];

$g_1$, $g_2$are trust coefficients for self-experience and group experience correspondingly

$k_2$,$\kappa_3$are two random coefficients with Gaussian distribution;

$z_{bg}$ is the best group position

$z_{bP}$ is the best particle position

$x_i$ is position vector:

$$x_i^n = x_i^{n-1} + v_i^n \quad (2)$$

During the simulation of possible situation that requires flight path correction we considered two types of information about significant meteorological formation:

-first is the forecasted area of significant (danger for flight) meteorological formation. This area is indicated with dashed red line;

-the second is the real presence of area of significant meteorological formation. This area is indicated with dash dotted blue line;

In considered situation this is the embedded frequent convective clouds. The distribution of embedded frequent convective clouds is accepted uniform for simplification. The aircraft trajectory is from point A to point B. The weather formation lies between these points as it is indicated in Fig. 3. and Fig.4. The initially planned flight path is shown with dashed red line.

Following the algorithm realization, after obtaining operative information about updated position and real presence of dangerous for flight weather formation the trajectory correction is realized. For this purpose, algorithm evaluates at least the next data:

− flight situation;

− aircraft performances;

-location and distribution of dangerous weather formation;

-dangerous weather formation intensity;

-aircraft position.

Then, having information about aircraft position of aircraft -particle the particle the shortest distance to the destination point is calculated using the objective function.

$$Course = w_1 Distance + w_2 Direction + w_2 Hazards$$

The distance component evaluates the extent of increase of flight distance when reaching the new particle position compare to the shortest distance.

The direction component evaluates the turn ratio that should not exceed the maximum possible for given type of aircraft. It depends on the aircraft performances.

The hazard component evaluates the allowed distance to the dangerous area and compare with the intended flight path. If the distance is less than it is prescribed with flight instruction to avoid hazardous area the hazard component is larger than 0.

$w_1, w_2, w_3$ are weighted coefficients.

## 6. Results analysis

In Fig.3 the initial flight trajectory (1) that is shown with dash line was chosen to avoid flying into the area of convective clouds. The flight trajectory was corrected using updated operative information including information obtained with AWR. The corrected trajectory (2) that is shown with dash dotted line demonstrates the significant distance shortening and potential benefits as improved safety and economy in fuel consumption.

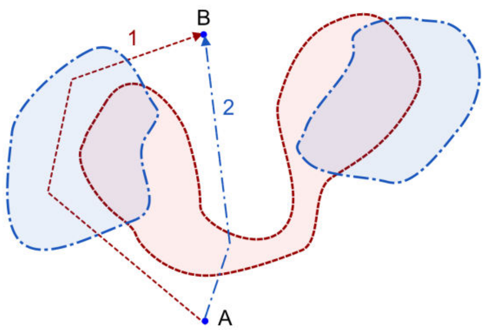


Fig.4. Initial (1) and corrected (2) flight trajectories

The situation that is shown in Fig.5 represents the initial trajectory (1) that must be corrected to avoid getting into the dangerous area. The distance of flight is increased in this case as well as fuel consumption. The trajectory correction (2) is made to avoid hazards and decrease the meteorological risks to air safety.

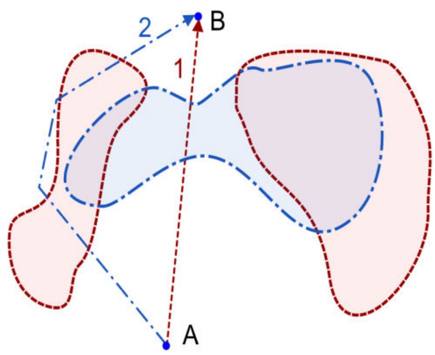


Fig.5. Initial (1) and corrected (2) flight trajectory

The flight trajectory correction shown in Fig.4 and Fig.5 are made for relatively simple situation of uniformly distributed convective clouds and operative information obtained from only one position – position of flying aircraft.

The real situation can be characterized with nonuniform distribution of hazardous meteorological elements inside the total area of coverage. In this case the flight is possible through the area of significant meteorological formations choosing the relatively safe zones. This requires the use of additional data that can be obtained from the aircrafts that are flying in the same region and can automatically disseminate the operative information. This approach can help to obtain information about interior of weather formation and make operative 3-D reconstruction of the dangerous meteorological object.

## 7. Conclusions

In this paper the benefits of utilization of onboard sensors and radar systems for operative meteorological data obtaining is shown. The aircrafts are considered as a platform for dynamic elements for data obtaining and exchange in the frame of the global system for weather information obtaining, exchange and dissimilation.

The considered approach automatically uses operative information that is of high importance for particular flight to make flight trajectory correction.

The presented approach can be used for operative information provision and decision-making support to aircraft crew. The presented algorithm of onboard automated system operation requires aircraft to be equipped with modern systems of data obtaining. Then the onboard automated system processes data and develop safe and economical way of operative flight trajectory correction. The presented approach can be used to satisfy the requirements to modern aviation tendencies and concepts as well as to improve the meteorological services provision.

As future work it will be reasonable to consider different optimal trajectory planners with larger number of sources of meteorological data including other aircrafts in considered area, satellite information, data obsolescence as well as direct integration of weather information into operational decision-making processes. Also, the optimal trajectory planners should consider the possibility to realize speed variation maneuvers.

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**Оперативна корекція траєкторії повітряного судна на основі інформації бортових метеорологічних радіолокаторів**

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Прогнозування та корекція траєкторії руху повітряного судна є одною з важливихможливостей для ефективного управління повітряним рухом. Одним з ключових факторів, що впливає на прогнозування траєкторії польоту є метеорологічний стан в аеропортах вильоту та посадки, а також впродовж траєкторії польоту. За таких умов важливим є широке використання можливостей систем оперативного одержання інформації про небезпечні погодні умови для короткочасної корекції траєкторії польоту. Бортові метеорологічні радіолокаційні системи є потужним та зручним засобом для одержання оперативних даних під час польоту у випадку виникнення несприятливих атмосферних умов. В даній роботі показані та обговорюються можливості корекції траєкторії польоту з використанням оперативної метеорологічної інформації, що одержується за допомогою бортових радіолокаційних систем.

**Ключові слова:** метеорологічний радіолокатор; бортовий радіолокатор; алгоритм оптимізації траєкторії польоту

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**Оперативная коррекция траектории воздушного судна на основе информации бортовых метеорологических радиолокаторов**

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Прогнозирование и коррекция траектории движения воздушного судна является одним из важных возможностей для эффективного управления воздушным движением. Одним из ключевых факторов, влияющих на прогнозирование траектории полета является метеорологический состояние в аэропортах вылета и посадки, а также на протяжении траектории полета. При таких условиях важным является широкое использование возможностей систем оперативного получения информации об опасных погодных условиях для кратковременной коррекции траектории полета. Бортовые метеорологические радиолокационные системы является мощным и удобным средством для получения оперативных данных во время полета в случае возникновения неблагоприятных атмосферных условий. В данной работе показаны и обсуждаются возможности коррекции траектории полета с использованием оперативной метеорологической информации, получаемой с помощью бортовых радиолокационных систем.

**Ключевые слова:** метеорологическая радиолокатор; бортовой радиолокатор; алгоритм оптимизации траектории полета

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