MATHEMATICAL MODELING OF PROCESSES AND SYSTEMS

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ON THE PROBLEMS OF RADAR DETECTION OF ZONES OF POSSIBLE AIRCRAFT ICING-IN-FLIGHT

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Abstract**—***This paper analyzes the conditions of formation and detection of zones of probable aircraft icing in the flight. The existing polarimetric radar detection algorithm, that was initially proposed by F. Yanovsky and A. Shupyatsky for hazardous icing zones is described. It is shown that initial conditions for it correct operation suggest of distribution of different types of hydrometeors (supercooled water drops and ice crystals) in the space. It occurs in the case of stratiform scenario formation of icing conditions in the clouds. It is shown that stratiform scenario is not the only possible scenario of icing condition forming. In another scenario, formation of zones of dangerous icing theoretically allows simultaneous presence in the resolution volume of both types of hydrometeors: water droplets and ice crystals.*

Index Terms—Polarimetric radar; in-flight icing; hydrometeors.

I. INTRODUCTION

Aircraft icing is considered of dangerous meteorological phenomenon. The essence of the danger that when tiny supercooled water droplets collide with the surface of the aircraft, they form an ice cover. It has a number of negative consequences. In particular, the weight of the aircraft increases, the aerodynamic qualities become much worse, can happen stopping the engine. This affects the safety of the flight, and may even lead to disaster.

In order to remove the ice cover, aircrafts are usually equipped with anti-icing systems. These systems can remove parts of the ice cover with the airframe, wings, propellers, and some other places. Deicing systems can operate using mechanical, chemical or thermal principles [1]. However, not all aircraft can be equipped with anti-icing systems, not all aircraft surfaces can be protected, and operation of such systems requires additional costs of energy and fuel. Therefore, the best way to prevent this dangerous meteorological phenomenon is to predict it early to avoid the danger zone.

Methods and technologies that are used today for early diagnosis of the zone of possible icing can be classified as follows: 1) The reports of pilots (pilot reports – PIREPs), 2) weather forecasting (modeling climate and weather), and 3) monitoring the weather situation by terrestrial, airborne or satellite meteorological equipment [1], [2]. This article focuses on methods and tools of airborne remote sensing for early warning in-flight icing.

In [3] – [5] are developed and clearly demonstrated the theoretical aspects of the detection of icing. In order to create a dangerous to fly zone a certain amount of supercooled water droplets in the liquid phase on the flight route of the aircraft is required. Freezing and becoming crystals, cloud particles no longer pose a threat, as in contact with the surface of the aircraft just repelled from it.

Previously proposed polarimetric methods and algorithms [3], [5] are capable in principle distinguish from water drops from ice crystals. However, they do not take into account the diversity of natural scenarios of formation of aircraft icing conditions in different situations. This may lead to reduced reliability for the identification of hazardous flight zones in some cases, or vice versa, generate false alarm about the presence of such zones.

The purpose of this paper is to consider new factors that were not considered previously, to test the polarimetric approach, and create of more reliable and efficient algorithm.

II. AIRCRAFT ICING DETECTION ALGORITHM

Obviously, to prevent the accident, the pilot of the aircraft should avoid contact with the aircraft of supercooled water droplets. There is a theoretical possibility of detecting the presence of liquid droplets using data from airborne weather radar [3], [4], [6]. The basic idea of this method is that the water droplets and ice crystals scatters of the incident electromagnetic waves in different ways. The polarization of the reflected field depends on the shape, size, orientation, and type of particle [8]. The polarimetric algorithm [3], [5] of detection supercooled water drops is based on the measurement of two polarimetric variables: differential reflectivity (DR) and linear depolarization ratio (LDR):

$$Z_{DR} = 10 \cdot \lg(P_{hh} / P_{vv}), \tag{1}$$

$$LDR = 10 \cdot \lg(P_{hv} / P_{vv}), \tag{2}$$

where P_{hh} is received power of the horizontally polarized components of the reflected signal from the horizontally polarized pulse; P_{vv} is received power of the vertically polarized components of the reflected signal from the vertically polarized pulse; P_{hv} is received power of the horizontally polarized components of the reflected signal from the vertically polarized pulse.

Liquid-drop cloud without rain consists of small droplets having almost spherical shape. That is why the polarization does not play a significant role in the scattering in such clouds. Reflected power signal obtained in the horizontal and vertical planes are almost identical. Therefore, the cross-polarization component is close to zero, and *LDR* tends to minus infinity. Mathematical modeling of the backscattered signal in case of small cloud droplets gives the calculated values about 0 dB for Z_{DR}, and up to -75 dB *LDR* [3], [9]. And these values do not depend on the scan angle (relative to the radar antenna).

Rain **(**without the turbulence) is characterized by drops of ordered orientation in the vertical plane. Z_{DR} maximum value observed in a horizontal (or nearly horizontal), scanning angle. This is because the projection of the drops into a plane perpendicular to the scanning beam gives an ellipse with the largest difference between the horizontal and vertical axes. DR can be equal to 0.5 dB (in the case of a small rain) up to 3…45 dB in the case of strong rain. Linear depolarization ratio in case of rain may be in the range of -35 ... -25 dB [3], [9].

In the case of *ice crystals*, there is no clear relationship between size and shape of the backscatterer, as is observed for raindrops. An important feature of the crystals compared with rain clouds is more chaotic orientation of the particles in space. Mathematical modeling gives the calculated values from 9 dB in the case of strong vertically oriented ice crystals to -9 dB in the case of a horizontal arrangement of space. Usually this value lies in a more limited range from -3 to 3 dB [7], [9].

Linear depolarization ratio value for crystals may be in the range of -14 ... -16 dB (for uniform distribution of crystal axis orientation) or -25 ... -30 dB (when ordered orientation in a vertical or horizontal plane occurs) [3], [7]. Linear depolarization ratio is an informative parameter, however, it is difficult to measure a small value because of the very low values of cross-polarization components of the reflected signal. Moreover, DR as indicated above, also contain important information.

Figure 1 schematically shows of Shupyatsky-Yanovsky algorithm [3], [5], using these two parameters (DR and LDR), to distinguish ice crystals and liquid droplets from the backscattered signal. This can help to identify dangerous zones.

The algorithm works as follows:

– Transmit horizontally or vertically polarized *h* and *v* probe pulses, receive horizontally or vertically polarized *h* and *v* components of the reflected signal for each transmitted pulse, measure the power of the main (P_{hh} and P_{vv}) and orthogonal (P_{hv} and P_{vv}) components of the reflected signal, measure the temperature of hydrometeorological formation in the resolution volume.

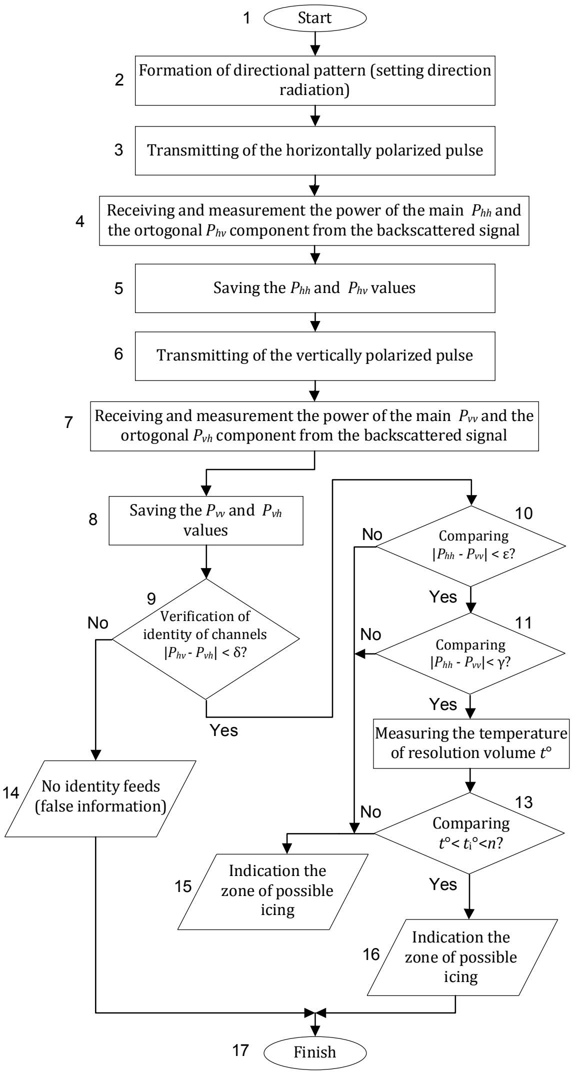


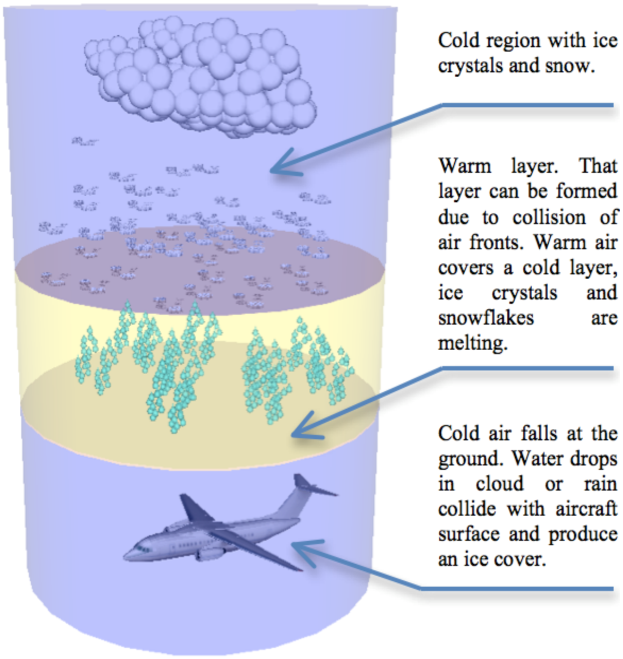
Fig. 1. Logical polarimetric detection algorithm

– Then compare the values of the power of two components of the reflected signal P_{hh} and P_{vv}; using results of this comparison, the values of the orthogonal components P_{hv}, P_{vh} and the known value of temperature one make a decision on the presence or absence potentially dangerous zone in the volume of space, which is defined by the radiation direction, the delay time of reflected signals and duration of radar pulses. If the temperature of the object is below the freezing point of water and at the same time the conditions $P_{hh} = P_{vv}$ and $P_{hv} = P_{vh} = 0$ are true, then one make a decision on the availability icing zone, and in the opposite case – a decision about absence of the dangerous zone.

The algorithm described above assumes a clear distinction between types of hydrometeors and does not imply the simultaneous presence in the volume of liquid droplets and ice crystals.

III. DIFFERENT SCENARIOS OF FORMATION ICING ZONES

Let us consider now some theoretical scenarios, which, given the physical processes in the clouds, can explain a principle of formation of icing zones in the atmosphere. The description below is based on an algorithm that is used in the terrestrial system of project ADWICE for meteorological forecasting and alerting about possible aircraft icing [2], [10]. There are four different scenarios for the formation of regions of supercooled water droplets. The first scenario – a *freezing rain scenario* [2], [10]. To implement it a warm layer of air at a temperature above 0°C is needed, which creates a vertical inversion temperature in the atmosphere (Fig. 2).


Cold region with ice crystals and snow.

Warm layer. That layer can be formed due to collision of air fronts. Warm air covers a cold layer, ice crystals and snowflakes are melting.

Cold air falls at the ground. Water drops in cloud or rain collide with aircraft surface and produce an ice cover.

Fig. 2. Freezing rain scenario

Cloud particles (hydrometeors), such as snowflakes or ice crystals fall out of the clouds in the upper tier and while going down pass through a layer of warm air. If the thickness of the warm layer and its temperature is sufficiently high, snowflakes starting to melt and crystals turn into water droplets. More dropping below drop enters the negative temperature zone. If the droplet size is large enough, they cannot freeze during the fall and become ice after the collision with the surface of the plane, creating a threat of serious icing.

Next scenario of the formation called *stratiform* (Fig. 3) [2], [10]. Stratiform scenario also explains the existence of liquid precipitation in cold temperatures, which cause the formation of ice on aircraft surfaces. But the mechanism of formation of liquid droplets is fundamentally different than in the case of freezing rain.

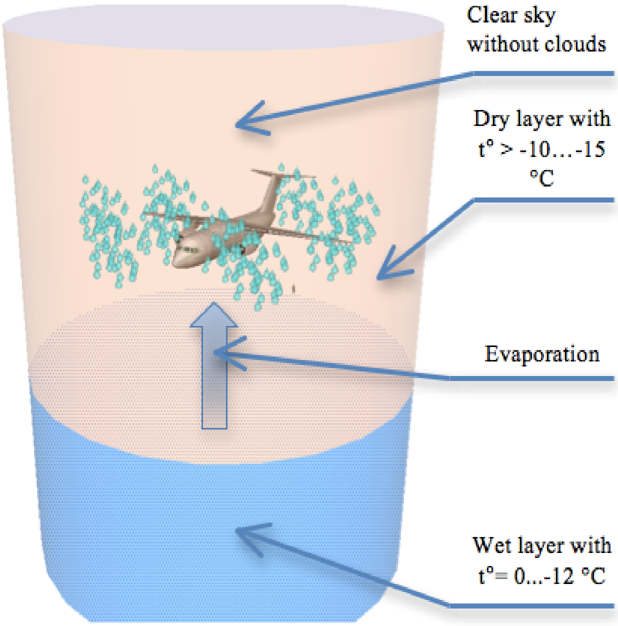


Fig. 3. Stratiform icing scenario

If there is a layer of humid air with a relative humidity above 85 % and the temperature t = 0..-12 °C, which borders with the top region of relatively dry air then small supercooled water droplets are formed due to the classic processes of evaporation and condensation. This so-called warm rain formation mechanism [2], [10]. Such atmospheric region typically observed near the ocean or large bodies of water.

Mechanism of formation of warm rain explains how liquid droplets may occur and remain in liquid phase at temperatures below the freezing point. It is known that in warm cloud (with a positive temperature) hydrometeors begin to form and grow as a result of condensation, the collision and coalescence of water droplets. Depending on weather conditions, cold cloud (partially or completely chilled to sub-zero temperatures) may contain ice crystals or droplets of supercooled liquid hydrometeors both.

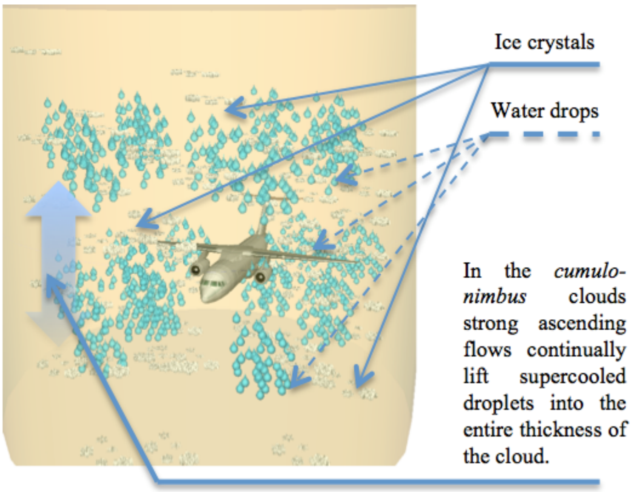
The appearance of ice crystals cleanses the water droplets from the clouds, because the crystals act as nuclei of new crystallization.

Thus, in order to have a high concentration of water droplets of supercooled cloud should have a minimum content of ice crystals, whether or not they have the general [2], [10]. There are two main parameters that determine whether the cloud be supercooled droplets cloud or ice crystals cloud. These parameters are the size of the droplets and the temperature of the cloud. Rain in the cloud is formed, if its drops less than 30 microns [2]. Large droplet size of about 200 microns, may start to crystallize at a temperature of about -5 ° C, but smaller droplets of 40 to 100 microns, the crystallization starts at a temperature of about -10 ... -15 ° C [2].

Thus, when the cloud has a temperature of 0 to -10°C it tends to form ice crystals, if they were not present before, and if there are not of large drops in the cloud. At temperatures below -15 ° C, begin to form dendritic ice crystals form, and their number is growing rapidly, as they start to fall as snow.

During the fall, they are faced with supercooled water droplets and initiate new processes of crystallization. In order to have the icing condition, atmosphere over the supercooled cloud should be dry, as all the crystals that fall from the clouds above will quickly clean of supercooled liquid droplets. Temperature of top layer must not exceed -10 ° C, since at lower temperature crystals start to form in the cloud. Number of small water droplets correlates with cleanliness of air, ie with the amount of condensation nuclei. Typically, a marine air contains about 100 condensation nuclei in 1 cm^3, which are mainly particles of sea salt. Continental air contains about 400 of condensation nuclei in 1 cm3. This is mostly dust particles [2].

The third scenario is *convective* icing (Fig. 4) [2], [10]. Probability of convective scenario occurs in all convective clouds with a vertical extent of at least 3000 m, and the temperature in the range 0... 20°C [2].



In the *cumulonimbus* clouds strong ascending flows continually lift supercooled droplets into the entire thickness of the cloud.

Fig. 4. Convective icing scenario

This scenario is caused by the vertical movement of air within the cloud layers. Thus, the transfer of moisture from the bottom up creating a lot of supercooled droplets. The rate of crystallization in the clouds is not usually so great to instantly turn drops into ice crystals [2]. Severe icing in cumulonimbus clouds can occur throughout the entire volume up to the top of the clouds.

If none of the above described scenarios of icing formation detected, but the temperature and humidity are in a certain range of values, there still exists the possibility of icing in accordance with the so-called *general* scenario [2], [10].

In addition to these four scenarios, it is logical to suppose another scenario icing scenario of *rapid descent*.

When the aircraft makes a rapid descent from a great height with a strong negative temperature in the area of warm humid air (cloud), its metal surface may not be enough time to warm up and get a positive temperature. Thus, any cloud with a certain content of water can be dangerous in this case.

III. CONCLUSIONS

The paper discusses and analyzes the conditions of formation and detection zones of probable aircraft icing.

Detailed consideration of these conditions, it is clear that the condition of a clear division of hydrometeors, depending on their phase state (ice or water droplets), which is required for correct operation of the algorithm Shupyatskogo-Yanovsky [3], [5] is not always satisfied. Namely, this condition is satisfied only in stratiform icing scenario. To verify the correctness of the algorithm and evaluate its reliability in other scenarios further investigations required, since these scenarios allow for the simultaneous presence of crystals and drops in a resolution volume.

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О. А. Пітерцев. О проблемах радіолокаційного виявлення зон можливого обледеніння літаків у польоті

Розглянуто механізми формування зон можливого обледеніння літаків у польоті. Наведено алгоритм радіолокаційного виявлення таких зон, та умови його застосування. Показано, що здатність існуючого алгоритму виявити загрозу обледеніння під польоту повітряного судна залежить від механізму формування такої зони у атмосфері.

Ключові слова: поляриметричний радіолокатор; загроза обледеніння у польоті; гідрометеори.

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А. А. Питерцев. О проблемах радиолокационного обнаружения зон возможного обледенения самолетов в полете

Рассмотрены механизмы формирования зон возможного обледенения самолетов в полете. Приведен алгоритм радиолокационного обнаружения таких зон, и условия его применения. Показано, что способность существующего алгоритма выявить угрозу обледенения во время полета воздушного судна зависит от механизма формирования такой зоны в атмосфере.

Ключевые слова: поляриметрический радиолокатор; угроза обледенения в полете; гидрометеоры.

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