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Lidar observations of the structure and evolution of aerosol clusters in the DELICAT project

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Abstract. The main goal of the DELICAT (DEmonstration of LIdar based CAT detection) project was to check the possibility of early detection of clear air turbulence regions by recording the intensity of reverse molecular scattering by means of a specially designed lidar mounted on the aircraft, operating in the ultraviolet range of wavelengths. Flight tests were conducted from July 17 to August 12, 2013 over the western part of Europe and the adjacent maritime territories. Although measurements in a clear sky were preferred, in most cases aerosol clusters of different power were present along the flight paths. Aerosol clusters should be considered as a source of interference, but their observations also provide an opportunity to obtain information on the properties of the aerosol and the spatial-temporal evolution of clusters. In this paper, we give statistics of observations of aerosol clusters in flights, describe the diversity of their types and trace the influence of flight parameters on the observed characteristics of clusters.

1. Introduction

Project DELICAT – DEmonstration of LIdar based Clear Air Turbulence detection [1] is aimed at solving one of the the most important tasks of aviation security – early detection of the areas of clear air turbulence ahead of the airplane. Implementation of the project began in 2009, flying tests were conducted in the summer of 2013. Project results are recognized as promising, and work is expected to continue. This is a European international project, the main whose members are [2]:

1. Thales Avionics – an international industrial group that produces information systems for aerospace, military and maritime applications;
2. CNRS – Centre National de la Recherche Scientifique, France;
3. DLR – German Aerospace Center, Germany;
4. Hovemere, Great Britain;
5. Meteo France, France;
6. NLR – Netherlands Aerospace Centre, Netherlands;
7. ONERA – Office National d'Etudes et de Recherches Aérospatiales, France;
8. INOE 2000 – National Institute for Research and Development in Optoelectronic, Romania;
9. A.M. Obukhov Institute of Atmospheric Physics Russian Academy of Sciences, Russia (team leader M.E. Gorbunov);



10. Laser Diagnostic Instruments, Estonia;
11. Warsaw University, Poland;
12. EADS – Innovation Works, Germany.

Employees of the Laboratory of Turbulence and Wave Propagation of the A.M. Obukhov Institute of Atmospheric Physics RAS participated in the discussion of the formulation of the problem and worked with the project measurement data [2, 3].

Early detection of clear air turbulence areas is an important practical problem (hereinafter, clear air turbulence will be briefly denoted by CAT). CAT occurs at altitudes greater than 5 km in clear weather or in the presence of high-level clouds and, as is known, is not detected either visually or by meteoradars. Stock time after its detection should be sufficient to ensure that passengers had time to fasten seat belts, that is not less than 2-3 minutes. Unfastened passengers in serious cases pierce the head of the ceiling, the last big event of this kind happened in 2017 with an Aeroflot plane flying to Bangkok, where there were 27 affected. The importance of this problem is emphasized by the fact that the number of accidents involving the entry of aircraft in the atmospheric turbulence, increases about 3 times faster than the number of flights, as figure 1 shows [4].

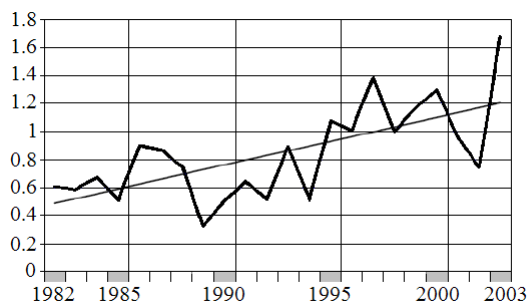


Figure 1. The number of turbulence accidents per million departures for the period 1982-2003 in USA.

In 40% of cases, this is the clear air turbulence. The number of precedents of aircraft hit in CAT by different sources varies from 750 to 1500 per year. Most do not cause harm to passengers and crew, but airlines suffer from delays and interruptions of flights (only in the USA, the damage is estimated at half a billion dollars a year). About one hundred people are injured in a year, and this becomes a problem also for insurance companies.

2. The DELICAT project description

The authors of the DELICAT project suggest the following way of solving the problem: using an ultraviolet lidar mounted on the aircraft, register the intensity of backscattered laser radiation on a sufficiently large distance in front of the course and determine the presence of a turbulence region from the disturbances of intensity.

A detailed description of the lidar can be found, for example, in [5]. Its main characteristics are: wavelength 355 nm, pulse duration 7 ns, pulse frequency 100 Hz, beam angular divergence 0.2 mrad, receiver diameter 14 cm. The lidar has 2 receiving channels: co- and cross-polarization. The minimum distance is 1.5 km, the maximum distance is 15 km, which corresponds to 1 – 1.5 min flight. Resolution by distance is 5 m. A mirror system is installed that directs probing beam forward at the airplane course. There is also a filter that cuts off solar radiation with a passband of 0.5 nm. In the flight tests, the aircraft Cessna-citation-2 was involved, owned by the Netherlands Aerospace Center. The aircraft was retrofitted to work with the lidar in the cabin.

Flights were conducted from Amsterdam's Schiphol Airport from July 17 to August 12, 2013. Flights occurred over the western part of Europe with the British Isles and the adjacent maritime territories. Flights are numbered from 1 to 11, in 4 cases in one day 2 flights were performed. Flight 1 was training, its data are incomplete and were not processed. In accordance with mission of the project flights were conducted under clear weather conditions.

Statistics of the number of measurement data is: the total flight time is approximately 33 hours; the total duration of measurements for flights from 2 to 11 is almost 16 hours; the total duration of measurements in the allocated zones is about 6 hours (zones – the selected sections of the trajectories, in which the height and flight direction vary slightly, and the compensation system of deviations of the probing beam from the flight direction works sufficiently reliably, that is, the areas of most reliable measurements); the total amount of data obtained is ~ 1.1 terabytes.

The following flight parameters are attached to the measurement data: altitude, angles of pitch, yaw and roll, vertical acceleration, GPS-coordinates and air speed. Thus, for every moment of data recording, it is known in what conditions they are received. The data are collected in groups, the duration of the each group is 695 seconds, the gap between groups is 5 seconds.

In figure 2 for all flights their altitudes are shown: they vary from 7.5 to almost 12 km. In all, 30 zones marked in gray are selected in the flights, measurements were produced in 27 of them. By this time, we mainly considered the data in zones and their environs, in our further plans – the study of all available information.

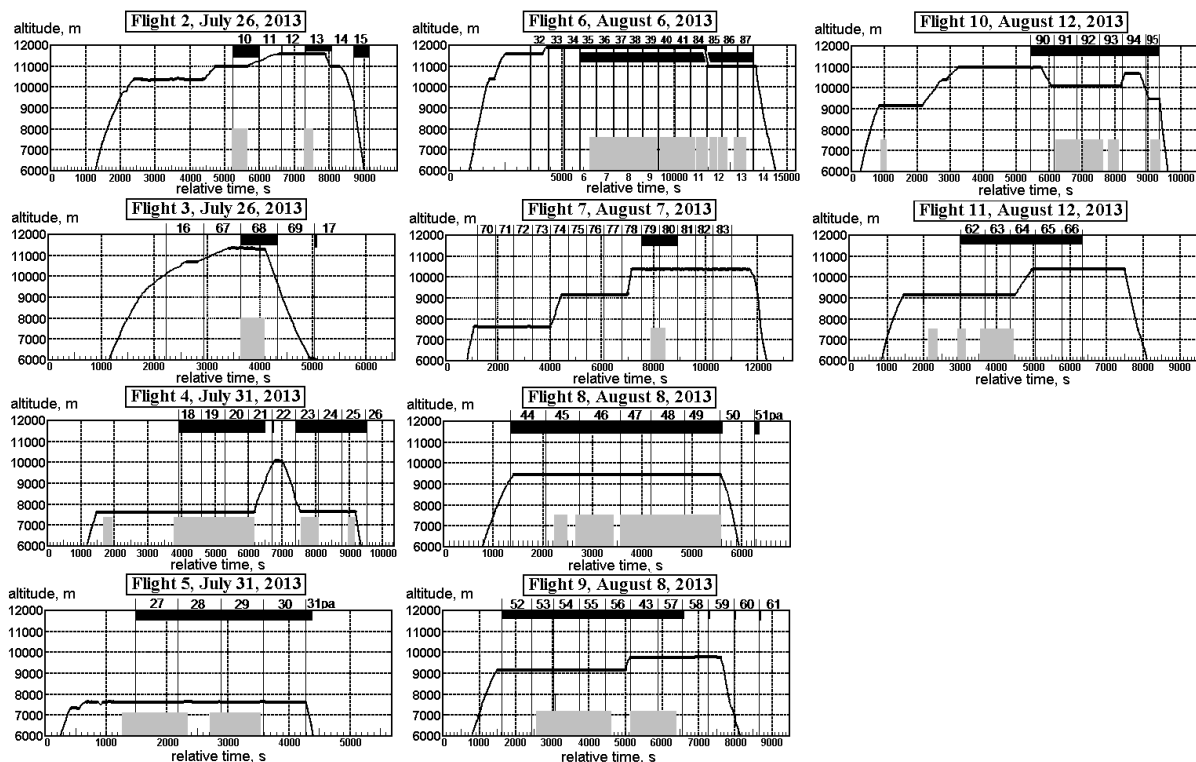


Figure 2. Altitude information for all flights. The black regions mark processed data groups, the gray regions below each picture denote zones.

3. Analysis of the data obtained

An example of data of backscattered intensity for 2 polarizations is shown in figure 3. These data can be represented in different ways, we chose a simple version, in which the abscissa is the distance from the aircraft, the ordinate is the time, and intensity was multiplied by the square of the distance to compensate for the divergence of the ray.

The movement of the aircraft is one-dimensional – it moves along a certain line, the data on intensity at the time of the first lidar pulse are laid on a straight line, corresponding to this instant of time, for the next pulse they fall on the next straight line, etc., as a result we obtain a two-dimensional space-time picture. For the primary reduction of the noise effect, we averaged the data for 3 points in distance and 9 points in time, thus the spatial resolution is 15 meters, and the temporary resolution is

0.09 seconds. In figure 3 you can see in this representation an aerosol cloud or a turbulence area (they look about the same). Intensity in the cross-polarization channel, as a rule, is substantially less, and in many cases, as in this figure, analysis shows that in this channel there is mainly noise.

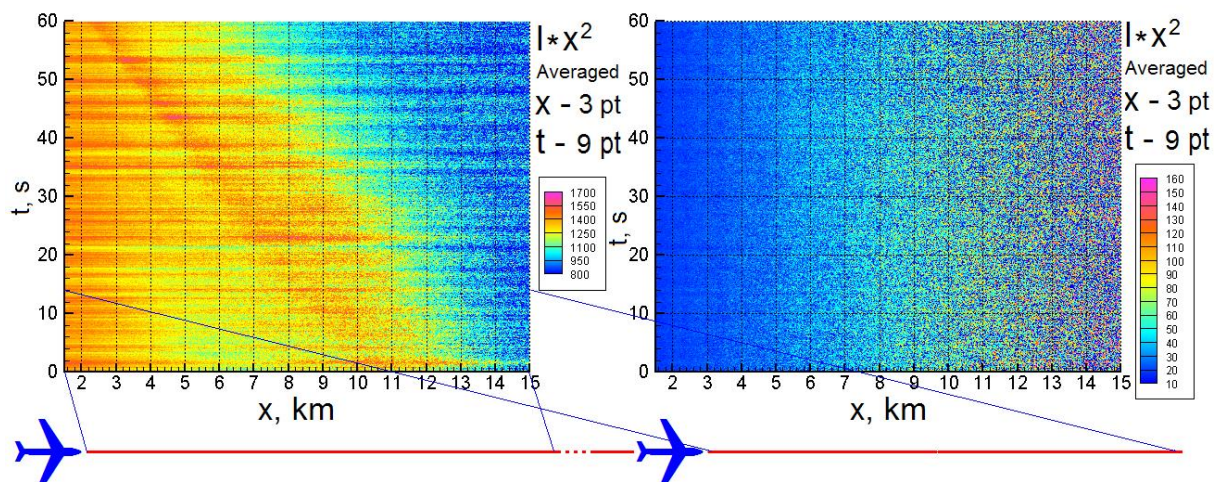


Figure 3. The backscated intensity multiplied by the square of the distance and averaged over 3 points of distance and 9 time points. Left – co-polarization, right – cross-polarization. Flight 4, July 31, 2013, zone 5, UTC 11:47:05.66 - 11:48:05.66, the height 7600 m.

Aerosol clusters and/or CAT were recorded in each flight. Following the main authors of the project, we will call an aerosol all types of particles, occurring in the data – this can be water aerosol, dust particles, etc. The problem of identifying the aerosol type in this paper is not posed.

Aerosol performs in 3 roles: 1) it can be a means for testing and validating the measurement process, 2) it is a hindrance, distorting information about the possible areas of CAT, 3) it is the object of study, in particular, the study of the dimensions and the spatial-temporal evolution of its clusters. There are not so many aircraft lidar studies of aerosol – their review can be found in [3], so the DELICAT data is of great interest.

The main task at this stage of the work was more careful study areas of aerosol or CAT in the zones and their vicinity, since the authors of the project paid attention only to especially outstanding details. We identified 3 areas of work: 1) an overview of the data in and around the zones; 2) development of a methodology for the isolation of weak aerosol clusters; 3) analysis of the size and space-time evolution of aerosol regions.

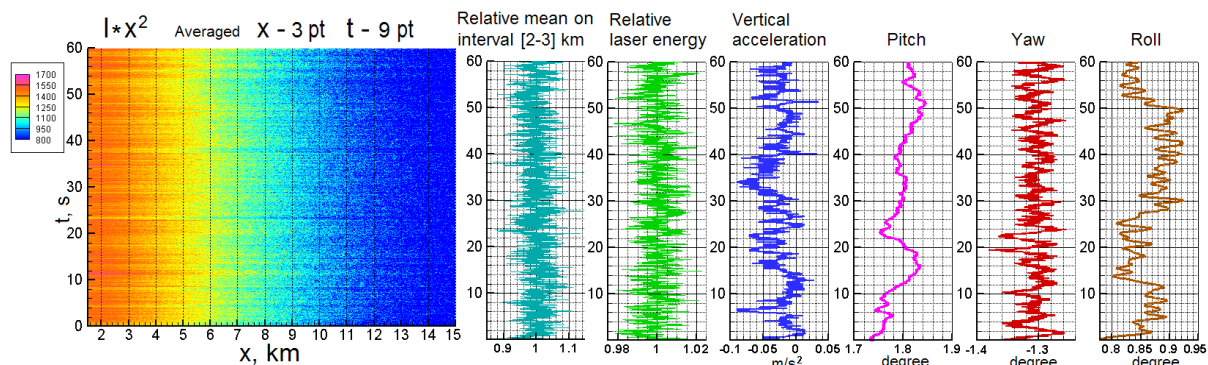


Figure 4. Intensity in the co-polarization and the flight parameters. Flight 4, July 31, 2013, zone 5, UTC 11:39:40.66 - 11:40:40.66, the height 7600 m.

Figure 4 shows a typical picture of the intensity for the region free from any structures. Intensity fluctuations are clearly seen in the course of time. Methodical part of the work was to consider the possibility for repression noise of measurements by normalization of each horizontal line data to mean for the selected interval distances in which intensity with distance varies slightly – usually these intervals were 2-3, 2-4 or 3-4 km. To make sure that we are dealing with real noise, we evaluated the correlations of fluctuations in the mean intensity values for this interval with fluctuations of such flight parameters as pitch, yaw and roll angles, vertical acceleration and laser energy.

Significant correlations were not found, therefore we consider such fluctuations of intensity over time as noise. The total decrease in backscattering intensity with the distance from the aircraft is explained mainly by molecular scattering. We compared the relative intensities time-averaged and corrected for noise in several areas that are free of observables details, with relative intensity of molecular scattering calculated from the model of standard atmosphere. As can be seen in figure 5, the agreement is better for low flights, and, as a rule, deteriorates with increasing altitude.

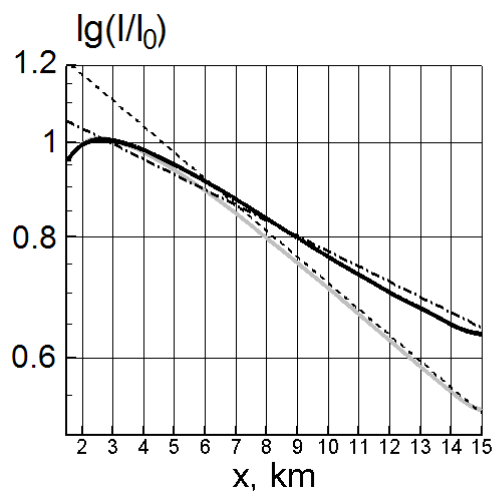


Figure 5. Solid lines: the relative intensity in the co-polarization. Black – flight 9, August 8, 2013, zone 21, UTC 20:11:18.95 - 20:12:18.94, the height 9300 m, gray – flight 5, July 31, 2013, zone 8, UTC 15:37:09.38 - 15:38:09.36, the height 7750 m. The dashed and dashed-dot lines – corresponding relative intensities of molecular scattering.

Apparently, in many cases we are dealing with the background aerosol. The shape of the curves for distances from the aircraft less than 6-7 km, is obviously the characteristics of the equipment. Therefore, for the final normalization, we used such curves which may be called "sensitivity curves".

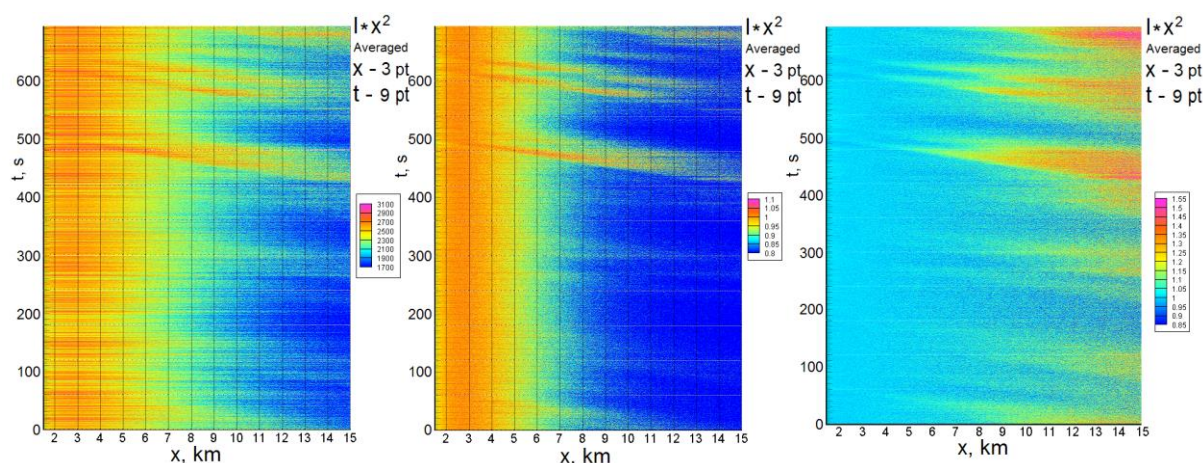


Figure 6. The result of data processing, allowing to see the fine structure of weak clusters aerosol (flight 9, August 8, 2013, zone 21, UTC 20:08:18.95 - 20:19:53.95, the height 9400 m). Left – initial

data, in the center – normalized to the average value of the intensity in the interval [2-4] km, on the right – additionally normalized to the sensitivity curve.

Figure 6 shows an example of processing of received data for areas where the power of the aerosol clusters is relatively small and it is necessary to reveal their fine structure. First, we eliminate the noise by normalizing to an average value of interval of 2-4 km, then correct for the sensitivity curve obtained in the near by time region free from clusters. The result is a detailed structure of clusters, which can be considered for spatial and temporal evolution.

These are clusters of relatively low power. But in the observations there are examples of more dense structures shown in figure 7, to which such a detailed processing is not necessary. The most powerful clusters were observed in flight 9, part of which passed over the Alps. In detail, the region of strong clouds can be considered only with an exponential distribution of levels. Here we are possibly dealing also with the region of turbulence.

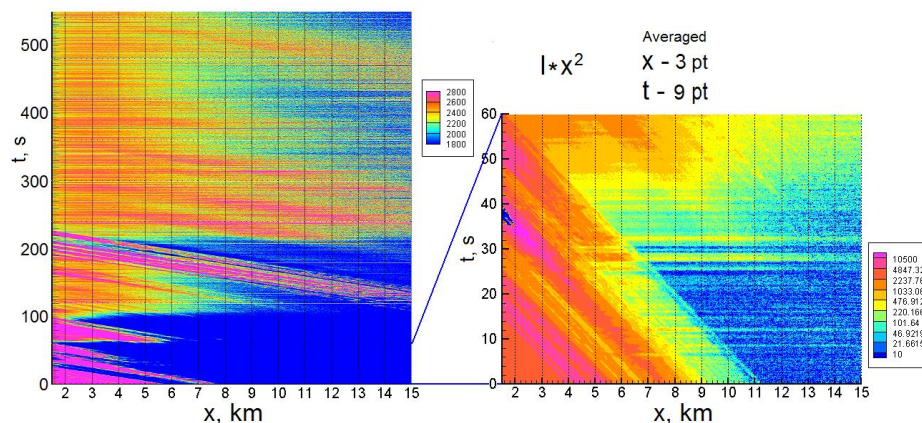


Figure 7. The denser structures and/or turbulence regions observed in flight 9 (8 August 2013, zone 22, UTC 20:21:39 - 20:43:28, the height 10000 m). On the right – 550 seconds of data, presented in the usual way, on the left – a 60-second segment in the exponential representation of intensity.

4. Conclusions

During the implementation of the DELICAT project, interesting data on atmospheric aerosol at heights of 7.5 to 12 km were obtained. An overview of the measurement data in allocated zones and their environs is fulfilled. Aerosol clusters and, possibly, areas of turbulence are present in 14 of the 27 zones, of which in 2 cases the clusters are weak, in 3 cases rather powerful, in the rest – of intermediate power. Data allow to evaluate characteristic dimensions of aerosol clusters (several kilometers) and to trace their time evolution (lifetimes of 20-30 seconds). Outside the zones, areas of climb and descent can be used to obtain estimates of the vertical dimensions of clusters, in some cases they reach 800 m. We propose to continue studying this material.

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