SESAR Engage KTN – catalyst fund project final technical report

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1. Abstract and executive summary

1.1 Abstract

PSA-Met integrates new meteorological capabilities in the storm avoidance process, namely, probabilistic nowcasts. These new meteorological products provide not only a forecast of the storm's evolution, but also information about the uncertainty of the convective cells. PSA-Met develops a probabilistic weather-avoidance concept, according to which, the required inputs are a probabilistic nowcast and a risk level, which is an adjustable parameter intended to define the avoidance strategy. The output is a unique avoidance trajectory that takes into account the uncertainty of the convective cells, obtained for the given risk level. Simulation results show that the predictability, the safety and the workload of pilots and air traffic controllers are improved, although with a small loss of flight efficiency. This new weather avoidance concept will be used in a follow-up project, whose objective will be to develop a Medium-Term Storm Avoidance tool intended to enhance air traffic control efficiency.

1.2 Executive summary

Weather can significantly affect aircraft operations. In particular, thunderstorms and the additional associated phenomena (i.e. hail, severe icing, and severe turbulence) present serious hazards to aviation. Furthermore, the apparent motion of the individual storm cells comprising the storm field is not deterministic but has a stochastic component in it.

The major risk mitigation measure for thunderstorm hazards is thunderstorm avoidance. However, the avoidance deviations increase the flight time and, therefore, the fuel consumption, thus negatively impacting the flight efficiency and the environment. Additionally, the flight crew workload increases significantly, and so does the workload of air traffic controllers. This increase in the controllers' workload translates into a reduction of the airspace capacity, eventually leading to further delays and inefficiencies.

The problem addressed by PSA-Met is the impact of weather-related hazardous events (thunderstorms) and its mitigation measures (storm avoidance) on flight efficiency and air traffic control. Particularly, PSA-Met is framed in the context of 'TBO-Met' (SESAR funded project, H2020-SESAR-2015-1, Grant Agreement 699294), and is fully aligned with the challenge *Efficient provision and use of meteorological information in ATM* of the Engage Knowledge Transfer Network (thematic challenge 3), as described next.

In TBO-Met, a probabilistic approach to en-route sector demand prediction at tactical level subject to thunderstorm activity was presented. The developed methodology requires the use of a storm-avoidance tool; in particular DIVMET (property of MeteoSolutions GmbH) was used, a deterministic algorithm. Since this methodology follows an ensemble-based approach, in TBO-Met an ensemble of deviation trajectories for each flight was obtained, using the deterministic DIVMET algorithm several times. Note that DIVMET did not provide a unique avoidance route that took into account the uncertainty information about the storm cells available.

Hence, the goal of PSA-Met is to develop a probabilistic version of DIVMET (named DIVMET-P), capable of generating probabilistic weather avoidance routes. The required input for DIVMET-P is a probabilistic nowcast, providing information about the uncertainty of the convective cells, and a risk level, which is an adjustable parameter intended to define the avoidance strategy. By properly choosing the risk level, one can obtain safer and more predictable, intermediate solutions between underreacting and overreacting to the weather hazard information. The output is a unique avoidance route that takes into account the uncertainty of the convective cells, obtained for the given risk level.

To achieve the desired goal of PSA-Met, a methodology has been implemented, which consists of three steps: 1) concept development, 2) software development, and 3) concept assessment (via simulation).

This project has contributed to the development of tools that integrate the uncertainty of meteorological disruptive events. The improvement of the state of the art is clear: following today's practice, the deviations and delay caused by a storm are not anticipated in the reference trajectory (which is not modified to face the storm) but they are tactically generated. Conversely, following the PSA-Met concept, i.e., replacing the reference trajectory with a probabilistic avoidance trajectory, some of the inevitable weather-related deviations and delays are anticipated, leading to smaller subsequent tactical deviations and delays at the cost of a slight increase in the executed time of arrival. Equivalently, the predictability, the safety and the workload of pilots and air traffic controllers are improved, at the cost of a small loss of flight efficiency.

From the point of view of air traffic controllers and pilots, the benefit of the concept developed in this project is the possibility of being informed, some time before facing the thunderstorm, about the best/safer avoidance strategy. This improves situational awareness and contributes to better-informed decision-making.

From the point of view of air traffic flow management, there is great interest in the probabilistic analysis of demand and capacity of en-route sectors when affected by adverse weather. With the development of a probabilistic storm-avoidance concept, we take a step forward towards enhancing the predictability of each individual flight and, thus, the predictability of the demand.

This new weather avoidance concept would allow air traffic controllers to be involved with a more active role in the storm avoidance process, because it would provide them with more resources to better organise the traffic. To assist them in this new role, USE has devised a decision-support tool called MTSA: Medium-Term Storm Avoidance, for which a probabilistic storm avoidance tool, such as DIVMET-P, will be the key enabler. MTSA tool will help controllers to determine an appropriate avoidance route for each flight predicted to run into storm cells; however, it is intended to complement, not replace, the current practice in which pilots evade storms using the on-board weather radar. With the MTSA tool, the workload of tactical and planning tasks is expected to become more evenly balanced, enhancing sector team efficiency and providing a safer and better service to airspace users, and to reduce the trajectory uncertainty associated to storm avoidance.

As part of the project, a preliminary description of the MTSA tool concept has been developed, and, additionally, there has been an external assessment, namely, a consultation to stakeholders (pilots and air traffic controllers) about this tool concept, which has received a very positive feedback. This early involvement of target users (airlines and air navigation service providers) has led to a better identification of the required capabilities of the MTSA tool, its potential contexts of use, and the related operational concepts and their possible implications.

2. Overview of PSA-Met project

2.1 Operational/technical context

Weather can significantly affect aircraft operations. In particular, thunderstorms and the additional associated phenomena (i.e. hail, severe icing, and severe turbulence) present serious hazards to aviation. These hazards can lead to structural damage, injuries to crew and passengers, loss of separation/level bust as a result of an inability to maintain the assigned level, and loss of control [1]. Furthermore, the individual storm cells comprising the storm field change with time and their evolution is very difficult to predict. Some grow strongly, others decay, new ones appear, some merge and some split. The apparent motion of the storm field is not deterministic but has a stochastic component in it.

The major risk mitigation measure for thunderstorm hazards is thunderstorm avoidance. During the flight planning stage, aircraft operators have the opportunity of planning the routes to avoid areas of predicted storm activity. Once airborne, pilots are responsible of in-flight avoidance. For this purpose, aircraft are equipped with weather radar, which provides an indication of the convective-weather intensity coming ahead [2]. The recommendation is that a cumulonimbus should be cleared by a minimum of 5000 ft vertically or 20 NM laterally to minimize the risk of encountering severe turbulence. These tactical diversions increase the flight time and, therefore, the fuel consumption, thus negatively impacting flight efficiency and the environment. Additionally, the flight crew workload also increases significantly in a weather avoidance scenario not just because of the decision-making associated with weather avoidance but also because of turbulence, management of in-flight icing, and increased communications.

In convective scenarios, the workload of air traffic controllers also rises significantly, mainly because the air traffic becomes irregular and difficult to anticipate and there is less available airspace for conflict resolution. This increase in controllers' workload translates into a reduction of the airspace capacity. If the traffic demand exceeds the capacity, flow management regulations may be applied, such as re-routings or regulated take-off times, which cause further delays and inefficiencies.

Hence, in a nutshell, the **problem addressed** by PSA-Met is the impact of weather-related hazardous events (thunderstorms) and its mitigation measures (storm avoidance) on flight efficiency and air traffic control (ATC).

2.2 Project scope and objectives

One of the objectives of the Engage KTN thematic challenge *Efficient provision and use of meteorological information in ATM* is the integration of suitable meteorological information into ATM stakeholders' planning and decision-making processes through the development of user-support tools. PSA-Met is clearly under the scope of this challenge because it proposes to integrate new meteorological capabilities in the storm avoidance process, namely, ground-based probabilistic forecasts of the storm evolution, referred to as probabilistic nowcasts. These forecasts obtain the storm information from a cluster of ground-based weather radars (meteorological radar composite data), which has a larger coverage area than on-board weather radars. Using the composite radar data, it is possible to stochastically extrapolate the development of the storm for the upcoming hour. The meteorological information consists mainly of forecasts of the individual storm cells, their positions, extents, strengths, and cloud heights. Nowcasts are released every few minutes, e.g. 5 or 10 minutes, and provide the meteorological information for equally spaced sampling times.

Thunderstorm activity affected by uncertainty has already been taken into account in TBO-Met, which addressed the tactical prediction of en-route sector demand using an ensemble-based stochastic methodology. On one hand, this methodology takes into account the stochastic evolution of the convective cells obtained from nowcasts. On the other hand, it applies a deterministic storm-avoidance tool several times with an ensemble-based approach to obtain an ensemble of deviation trajectories, that is, efficient and safe routes to the final destination. In particular, the storm avoidance tool used in TBO-Met is DIVMET [3], which was developed by Prof. Hauf at the Leibniz Universität Hannover and is by now a property of MeteoSolutions GmbH.

Thus, as already indicated, DIVMET does not provide a unique avoidance route that takes into account the information available about the uncertainty of the storm cells. This shortcoming defines **the goal of PSA-Met:** to develop a probabilistic version of DIVMET (say DIVMET-P), capable of generating probabilistic weather avoidance routes, which are avoidance routes that take into account the uncertainty information available.

To properly limit the scope of this project, we consider the en-route phase, with constant altitude flights and time-evolving meteorology. The storm cells are modelled in 2D because, in practice, the storm avoidance is typically 2D (storm cells are rarely flown over because it is deemed to be too risky). However, extension to a 3D model would be straightforward because, on one hand, some nowcasts also provide radar echo top information and, on the other hand, DIVMET features 3D avoidance manoeuvres when the flight level is close enough to the radar echo top of a storm cell.

Thanks to the integration of these new meteorological capabilities, DIVMET-P enables the anticipation of the avoidance manoeuvres, resulting in more predictable and safer deviations that decrease the subsequent tactical interventions. Since the information is available on ground, air traffic controllers can be involved with a more active role in the storm avoidance process, providing them with more resources to better organize the traffic.

Three objectives are identified to achieve the desired goal of PSA-Met:

- O1: Development of the concept to generate a probabilistic weather avoidance route.
- O2: Development of the software to implement the concept.
- O3: Concept assessment (via simulation).

As a final remark, in this project, we concentrate on a short-term solution (the development of DIVMET-P) and focus our research on a well-defined application (a Medium-Term Storm Avoidance tool – MTSA, as described in Section 2.6).

2.3 Research carried out

Three main activities have been carried out in PSA-Met, each activity associated to one objective, namely:

- A1: Concept development (objective O1, led by University of Seville)
- A2: Software development (objective O2, led by MeteoSolutions)
- A3: Concept assessment (objective O3, led by University of Seville)

In the following, we summarise the technical progress made, which includes a description of 1) the required meteorological input, 2) the concept developed, 3) the software developed, and 4) the assessment performed.

1.- Meteorological input

DIVMET-P requires a probabilistic nowcast as input; in particular, in this project, we consider an ensemble nowcast. Such an advanced product is under development by the meteorological agencies, but, to the best of our knowledge, is still not available. The definition of a procedure to deliver a probabilistic nowcast with an ensemble-based approach is, indeed, out of the scope of this project. However, until such an advanced meteorological product is available, a way of delivering an ensemble of nowcasts has to be devised. Hence, a statistical procedure has been developed in this project, which takes a deterministic nowcast as input and provides a probabilistic nowcast that follows an ensemble-based approach.

Deterministic nowcast

Nowcast models for convective weather phenomena usually use radar or satellite data, some in combination with wind data. Some nowcasts identify storms as objects in the current radar image at the prediction time T_P, extracting polygonal areas that exceed a certain reflectivity level in the radar image (e.g. 37dBZ is a widely used threshold to identify storms). In this case, the motion of any storm is determined by analysing available successive radar images up to T_P and serves as the base for further extrapolation to times $T_P + \Delta t$, $T_P + 2\Delta t$, …, $T_P + (M-1)\Delta t$, with $T_F = (M-1)\Delta t$ being the nowcast lead time. This approach is called cell tracking and is suitable for identifying and tracking severe convective storms [4]. Following this approach, the nowcast can be seen as a set of M frames (one frame per nowcast sampling time, including the prediction time), and each one is composed of a set of storm cells characterised by their geometry and location.

Some other nowcast models process the complete radar reflectivity image, and extrapolates the whole radar image to the sampling times already defined ($T_P + k\Delta t$, with $k = 1, \dots, M-1$). In this case, the nowcast does not identify storms, but it is a set of M frames (one frame per nowcast sampling time, including the prediction time), each one being composed of a radar image.

In PSA-Met, a cell tracking approach is assumed to be followed by the deterministic nowcast. However, the methodology is still applicable when the nowcast consists of radar images. In that case, a pre-processing has to be applied to extract polygons of thunderstorm cells from the raster data. This extraction relies on the principle that each raster element with a RADAR reflectivity greater than a suitable threshold (for instance, 37dBZ) belongs to an area of heavy rainfall and most likely to a thunderstorm cell. Then, by grouping these raster elements, contours enclosing storm cells are obtained. In PSA-Met, this task is performed with `CbRiskService`, which will be explained in more detail in the software development section.

Ensemble of nowcasts

To develop a probabilistic nowcast, we assume that the main source of uncertainty is the location of the individual storm cells. Hence, we apply a similar procedure as the one used in TBO-Met project, which generates each nowcast ensemble member by randomly perturbing the position of the storm cells predicted by the deterministic nowcast. The displacement errors of any storm cell at any nowcast sampling time are taken as independent Gaussian random variables. The standard deviations increase with the forecast sampling time and are consistent with the empirical laws by Sauer et al. [5]. Both space and temporal correlations of displacement errors are neglected. Following this procedure, each ensemble member contains the same pieces of information as the deterministic nowcast, namely, a set of M frames (one frame per nowcast sampling time), and each one is composed of a set of storm cells characterised by their geometry and their location.

2.- Concept description

Executed avoidance trajectories appear to have a stochastic nature; hence, one might consider the storm avoidance routes as realisations of a stochastic process. There are two main sources of uncertainty contributing to this stochastic appearance/nature: 1) meteorological uncertainty (the uncertainty inherent to the weather forecast process) and 2) operational uncertainty (the uncertainty associated to the unknown avoidance strategy followed by the pilot). Although there might be a consistent individual behaviour, the overall avoidance effect appears as being stochastic.

The required input for DIVMET-P is composed of a reference trajectory, the wind and temperature fields, a probabilistic nowcast (providing information about the uncertainty of the convective cells), and a risk level, which is an adjustable parameter intended to define the avoidance strategy. The output is a probabilistic avoidance trajectory, which is a unique trajectory obtained for a given risk level. A high-level conceptual description of DIVMET-P is sketched in Fig. 1.

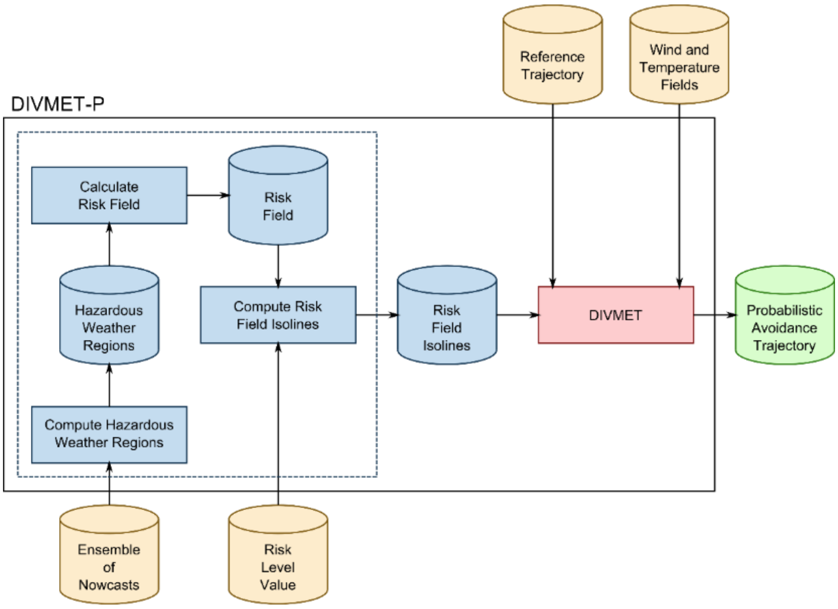

Figure 1. DIVMET-P block diagram.

DIVMET-P performs the following four steps. First, it computes the *hazardous weather regions* by extending every storm cell with a safety margin, which is done for each ensemble member of the probabilistic nowcast. Appropriate filtering is applied to merge intersecting regions and remove regions inside other regions.

Then, DIVMET-P computes the probability that a given location be affected by adverse weather at a given nowcast sampling time, which is called risk in the context of this project. The spatial risk distribution obtained is referred to as ***risk field***. To obtain the risk field for each nowcast sampling time, an airspace tessellation is assumed so that it is divided into tiles, which are defined by a given grid. Then, the risk field at a given grid tile is computed as the percentage of ensemble members forecasting that grid tile to be covered by a hazardous weather region for that nowcast sampling time, ranging from 0% to 100%. For instance, a 40% risk at a given grid tile and for a nowcast sampling time means that this tile is expected to be covered by a hazardous weather region in 40% of the ensemble members of the probabilistic nowcast at that nowcast sampling time.

Afterwards, DIVMET-P proceeds to obtain the risk field isolines that correspond to the given risk level value. The risk level is a user-selectable parameter introduced in DIVMET-P to control the modelling of the no-fly zones so as to capture the different avoidance strategies that can be adopted when facing uncertain weather hazards. The risk level is taken as the maximum admissible risk in the avoidance strategy; hence, it ranges from 0% (accounting for the most conservative avoidance strategy) to 100% (accounting for the riskiest avoidance strategy). Therefore, the areas where the risk field is higher than or equal to the specified risk level are to be taken as no-fly zones, and the boundaries of these areas are defined by the risk field isolines that correspond to the selected risk level. Note that there is one risk field per nowcast sampling time; accordingly, DIVMET-P computes a possibly different set of no-fly zones for each nowcast sampling time, leading to a time-evolving description of the no-fly zones.

Finally, once the set of no-fly zones has been obtained from the given probabilistic nowcast and the specified risk level, DIVMET is applied to obtain the corresponding avoidance route, which circumvents the no-fly zones and reattaches to the given reference trajectory. This probabilistic avoidance route is a unique planned route to avoid the storm cells for the given risk level. Again, as an example, the avoidance route for risk level 40% is such that the probability that each point of the route be inside a storm cell is equal or lower than 40 %. It is important to remark that DIVMET-P also provides an estimation of the flight times along the route.

The risk level is expected to have an important effect on the resulting avoidance route. The choice of a high risk level is equivalent to deciding to deviate very little from the reference trajectory, what in principle could seem to be beneficial, but would require to face the eventual incursions into storm cells tactically, which is neither efficient nor safe. Conversely, choosing a small enough risk level would allow to prevent the avoidance trajectory from zigzagging around the hazardous regions and from getting into narrow corridors between pairs of them. However, on one hand, a small risk level would reduce the airspace permeability and, thus, would increase the interactions with other trajectories and, on the other hand, it would lead to proactively solving contingencies that might not even happen, increasing the deviation from the reference trajectory. Therefore, by properly choosing the risk level (for some intermediate values) one can obtain safer and more efficient intermediate solutions between underreacting and overreacting to the weather hazard information.

3.- Software development

An overview of the software components is shown in Fig. 2. On the left side one has the data preparation for ground speed modelling by, first, retrieving wind (u, v) and temperature (T) data from a Numerical Weather Prediction model, and, second, adding interpolated values of u, v, and T to the reference trajectory which is finally processed by DIVMET. This is done by the python scripts `cdsapi_uvT.py` and `uvTOnTrajectory.py`, respectively. On the right side, the processing of ensemble hazardous weather regions to risk field isolines (risk polygons) by `CBRiskService` is shown. These two blocks are described next.

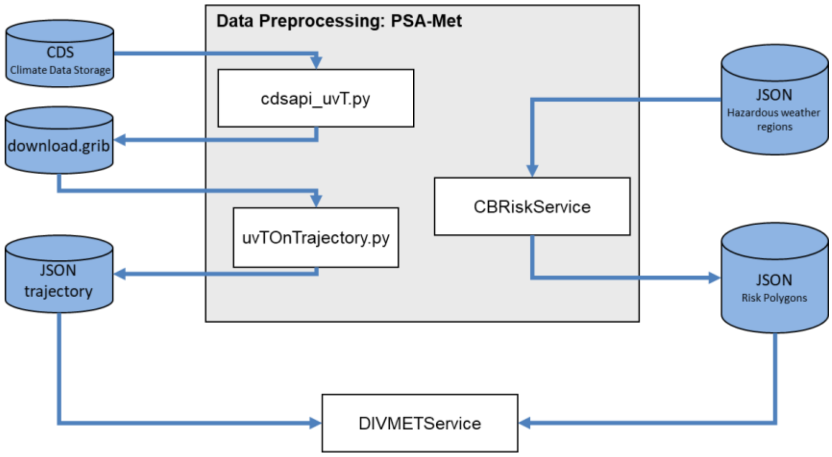

Figure 2: Overview of the software components implemented in PSA-Met.

Data Processing for Ground Speed

In this project the DIVMET algorithm has been improved by a more realistic modelling of ground speed. The data (Mach number, horizontal wind, temperature on flight level) which are needed for the calculations is transferred to DIVMET as attributes of the reference trajectory of the flight.

In DIVMET the ground speed is used when moving the aircraft along the planned route. Accordingly, a ground speed value is obtained for each waypoint. In order to move the aircraft between two waypoints, which might have different ground speeds, we take the average value of these.

In order to model the ground speed of an aircraft in cruise flight, the horizontal wind and the air temperature are needed, which are taken from forecasts from ECMWF (European Centre for Medium-

Range Weather Forecasts). The data is downloaded by using the CDS API (Climate Data Store Application Program Interface). To do this a python script called `cdsapi_uvT.py` is used. In this project the python script downloads temperature and u-v-components of wind for a given time interval and pressure levels from 350hPa through 100hPa and stores these in GRIB format in file "download.grib". As commercial aircraft typically cruise in these altitudes, the data retrieval is limited to these pressure levels to save resources and download time.

For each trajectory waypoint (Latitude, Longitude, Flight level) the appropriate wind and temperature values are extracted from the model grid by bilinear interpolation and added to the waypoint attributes of the trajectory. As the model data is given in pressure levels and aircraft trajectories refer to flight levels, the flight levels are transformed to pressure levels by using the formulas of the ICAO standard atmosphere.

The trajectory is put out to file in JSON format for further use in DIVMET.

Software Development and Execution

The software has been implemented in python programming language (python 3). It uses various python packages, among others numpy (numpy.org), a package for scientific computing and eccodes of ECMWF to read GRIB data. The name of the program is `uvTOnTrajectory.py`. The software is executed under Linux operating system in a bash shell environment and is controlled by command line options and preferences file.

Data Processing for Probabilistic Hazardous Weather Regions

The task here is to determine the risk fields by taking as input an ensemble of hazardous weather regions. The risk field is determined by analysing the overlap of the ensemble members. Regions with a high number of overlapping polygons are supposed to pose a higher hazardous weather risk than regions with a low number of overlapping polygons.

The risk field calculation is performed in four steps:

a) Input of ensemble polygons of hazardous weather regions.

The ensemble data is provided as files, one per ensemble member. Therefore, we have N files for N ensemble members. Each file contains observed and forecasted polygons of hazardous weather regions up to a short term forecast horizon of 60 min in 10 min forecast steps (in total $M = 7$ frames). The files are structured according to a JSON (Java Script Object Notation) scheme. For a given nowcast sampling time the software reads all polygons from the N files and holds these in memory.

b) Rasterising of ensemble polygons to determine the risk field.

In order to determine the risk field, the polygons have to be rasterised first. This is done with the so-called *Scan Line Algorithm*. The size of the raster elements (or tiles) is a configurable parameter; considering the same resolution as the radar reflectivity image used to generate the deterministic nowcast can be seen as a good starting point. After this, for each raster element, the number of covering polygon regions is counted and the percentage for all ensemble members is calculated. The result is the risk field.

c) Extraction of risk field isolines.

The task is to extract isolines from the rasterised risk field which enclose raster elements bigger or equal than a given risk level value. A polygon extraction algorithm has been implemented to do this; we have considered a *boundary following* algorithm.

d) Output of risk field isolines as polygons.

For a given risk level value the software writes polygons to file. Each file relates to a specific forecast lead time. The data is put out on the file system in human readable JSON format and machine-readable binary format for faster input in DIVMET.

Software Development and Execution

The software is written in C++ programming language. Among others it uses C++ software library *hyla* which is owned by MeteoSolutions GmbH. The name of the software is `CBRiskService`. The software is executed under Linux operating system in a bash shell environment and is controlled by command line options and preferences file.

The software implementations of the algorithms were tested on small grids with generic polygons which have certain features i.e. concave bays or holes. The expected results have been determined manually and are compared with the calculated results by unit tests. To assure high quality standards, other important modules of the software were also tested by automatic unit tests on artificial data. The software was also tested in-house on real data.

4.- Concept Assessment

The objective of the concept assessment is twofold. First, to study the effects of the risk level on the probabilistic weather avoidance routes. Second, to evaluate the costs and benefits resulting from the aircraft following these avoidance routes. This evaluation focuses on the following performance areas: flight efficiency, flight predictability, safety, and workload.

The assessment is based on fast-time simulations of different scenarios. Each scenario corresponds to a real storm situation and comprises a set of synthetic flights that pass through the region affected by the storm. Since the scope of this project is the en-route phase, all flights are operated at constant altitude and speed.

For each flight, one has the following trajectories:

- Reference trajectory: Planned trajectory the aircraft agreed to fly before encountering the storm.
- Probabilistic avoidance trajectory: Planned route generated using DIVMET-P and the weather forecasts, and its corresponding flight times, which avoids the no-fly-zones obtained for a selected risk-level value and reattaches to the reference trajectory.
- Executed reference trajectory: Trajectory flown by the aircraft when it executes the reference trajectory and faces the weather realisation. In this trajectory, the aircraft may tactically deviate to circumvent the realised storm cells.
- Executed avoidance trajectory: Trajectory flown by the aircraft when it executes the avoidance trajectory and faces the weather realisation. As in the previous one, the aircraft may tactically deviate to circumvent the realised storm cells.

For each scenario, the simulation process is as follows. Each scenario starts at a given time; at that time, the positions of all the aircraft, their reference trajectories, and the probabilistic storm forecasts for the next hour are known. First, different probabilistic avoidance trajectories are generated for each aircraft, each one for a different risk-level value. Then, the execution of each avoidance trajectory is simulated using the deterministic DIVMET and the weather realisations. The executed reference trajectories are also simulated; they represent today's practice, where the flights follow the reference trajectories and storms are just tactically faced. Once all the simulations are performed, then the obtained paths and flight times are analysed.

The assessment has been performed in four steps:

1) gathering and processing of the required meteorological input;
2) definition of the simulation scenarios, including the indicators used for the assessment;
3) conduction of the simulations, using the software developed in A2; and
4) analysis of the results.

The meteorological data input and processing are presented next, as well as the scenarios and the indicators. The results are analysed in Section 2.4.

Meteorological data input and processing

For the deterministic nowcast, the NowCastMIX-Aviation (NCM-A) is considered. NCM-A is a product of the Germany's National Meteorological Service (Deutscher Wetterdienst, DWD) that offers RADAR reflectivities in dBZ as short-term forecasts and covers a large area of Central Europe. The NCM-A data comes as raster data in GRIB file format with a spatial resolution of 1x1km. Each file contains 13 GRIB messages, one message for the observation and 12 messages of forecasts up to one hour in 5-minute time resolution; in other words, the nowcast sampling interval considered is $\Delta t = 5$ min, and the nowcast lead time is $T_F = 60$ min, so that it has 13 frames ($M = 13$). The update cycle of NCM-A data is 5 minutes as well. The weather realisations are also obtained from NCM-A. They are given in the first message (weather observation) of consecutive NCM-A releases.

DWD provided data for five complete days (6th, 9th, 15th, 22nd, and 29th June 2017), among which the scenarios for the simulations were chosen. As NCM-A data are stored as raster data, it was necessary to obtain polygons of thunderstorm cells from the raster, as explained in the meteorological input section. A RADAR reflectivity threshold of 37dBZ was taken. Furthermore, as NCM-A data does not contain probabilistic information, the polygons of heavy rainfall were perturbed in location (as already explained) to produce an artificial ensemble of nowcasts, resulting in 100 ensemble members for each NCM-A nowcast.

As an additional meteorological input, the concept of probabilistic avoidance routes allows for the consideration of arbitrary wind and temperature fields (and so does DIVMET-P); however, to ease the interpretation of the results, the international standard atmosphere with no wind is assumed for the simulations.

Simulation scenarios

The three scenarios correspond to real heavy storm episodes that took place over Germany on 6th, 22nd and 29th June 2017. The starting times of these scenarios are 21:00, 14:00, and 20:30, respectively.

One thousand flights are considered in each scenario. The flights are generated so as to have very demanding scenarios: each reference trajectory is devised to interact with at least one forecasted storm cell. Because the locations of the storm cells are different for each scenario, the flights and their reference trajectories are also different for each scenario. They are randomly generated according to the following criteria:

- The initial location and course of each flight are such that every aircraft is initially located at 20 minutes from the first encounter with a no-fly zone corresponding to the 10% risk isoline (twenty minutes is the time horizon envisioned for the future Medium-Term Storm Avoidance tool).
- The reference trajectories are flown at constant course and the airspeed is 230 m/s (approximately equivalent to Mach 0.78 at FL 360).
- The time to the final point is 60 minutes, and this point is outside the 10% no-fly zones.
- All reference trajectories lie within the NCM-A coverage area.

The safety margin considered in the assessment is 10 NM, which is smaller than the one recommended by the authorities, 20 NM. This margin has been reduced because the scenarios are so demanding that, for 20 NM, a large proportion of flights were not satisfactorily simulated. Nevertheless, this reduction does not affect the generality of the results.

In order to analyse the effects of the risk level value, the probabilistic avoidance routes are generated for five different values of this parameter: 10%, 30%, 50%, 70%, and 90%. One simulation per scenario and risk level value has been performed.

As an example, the flights of the Scenario 3 are shown in Fig. 3, along with the NCM-A coverage area (included as a reference).

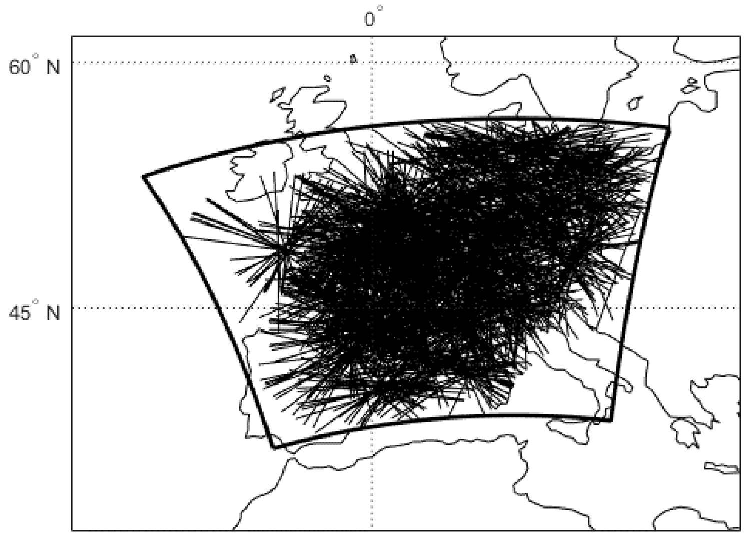

Figure 3. Scenario 3: Reference trajectories.

Assessment indicators

To study the effects of the risk level on the probabilistic weather avoidance trajectories, we focus on the following two results for each scenario and risk level value:

- Avoidance trajectories different from the corresponding reference trajectories.

  An avoidance trajectory is considered to be different from a reference trajectory if it is laterally deviated more than 0.5 NM. The indicator to analyse this result is the percentage of avoidance trajectories that deviate from their corresponding reference trajectories.

- Difference between the arrival times of the avoidance trajectories and the arrival times of the corresponding reference trajectories.

  The difference between these arrival times is related to the length of the deviations. The larger the difference, the larger the deviation. Four indicators are defined: the median (50th percentile), the interquartile range (difference between 75th and 25th percentiles), the average and the standard deviation of this difference.

To evaluate the costs and benefits resulting from the aircraft following the avoidance routes, we focus on the following three results for each scenario and risk level value:

- Difference between the arrival times of the executed avoidance trajectories and the arrival times of the corresponding executed reference trajectories.

The difference between these arrival times indicates whether the flights arrive earlier or later to their destinations than today's practice and, consequently, if they spend more or less fuel due to executing the avoidance trajectories. Therefore, it shows how the flight efficiency is affected. As before, four indicators are defined: the median, the interquartile range, the average and the standard deviation of this difference.

- Difference between the arrival times of the executed trajectories (both reference and avoidance) and the arrival times of the corresponding planned trajectories (both reference and avoidance).

  The difference between the arrival time of the executed trajectory and the arrival time of the planned trajectory is related to the predictability of the flight. The smaller the difference between the executed arrival time and the planned one, the better the predictability. This result is also related to the magnitude of the tactical deviations; the larger the difference, the larger the tactical deviations. Again, four indicators are defined: the median, the interquartile range, the average and the standard deviation of this difference.

- Tactical deviations per flight.

  An aircraft is tactically deviated from its planned trajectory (reference or avoidance trajectory) if the corresponding executed trajectory is deviated more than 0.5 NM from this planned trajectory. Multiple deviations may occur if, after the first deviation, the aircraft reattaches to the planned trajectory for at least 10 NM and then it deviates again. This result is related to: 1) the safety of the flights, because a pilot has to deviate tactically when the planned trajectory runs into a realised storm cell in order to avoid the associated hazardous phenomena, and 2) the workload of pilots and controllers, because in a tactical deviation the pilot is taking corrective actions that have to be coordinated with the air traffic controller.

  The indicator is the average number of deviations per flight.

2.4 Results

In this section, the main project's scientific results are summarised. First, an illustrative example of application is presented, which shows the potential of PSA-Met concept to facilitate an enhanced storm-avoidance process. Then, the results of the concept assessment are presented. All the exercises have been performed using the synthetic ensemble nowcast and the DIVMET-P concept already described.

1.- Illustrative example

In this example of application, several probabilistic avoidance routes are computed for one of the flights considered in scenario 2, namely, flight #929. The corresponding reference route is originally planned at constant course from an initial waypoint at 42.2260° N, 9.3642° E, to a final waypoint at 46.8390° N, 1.1576° E; the initial time (which coincides with the prediction time, T_P) is 14:00, 22nd June 2017.

The NCM-A deterministic nowcast corresponding to that prediction time has been pre-processed to obtain the polygons of thunderstorm cells at each nowcast sampling time. These are depicted in Fig. 4 in blue for the observation at the nowcast prediction time and in red for the subsequent sampling times. Note that the figure only covers an area close to the considered flight, whose reference route is also shown.

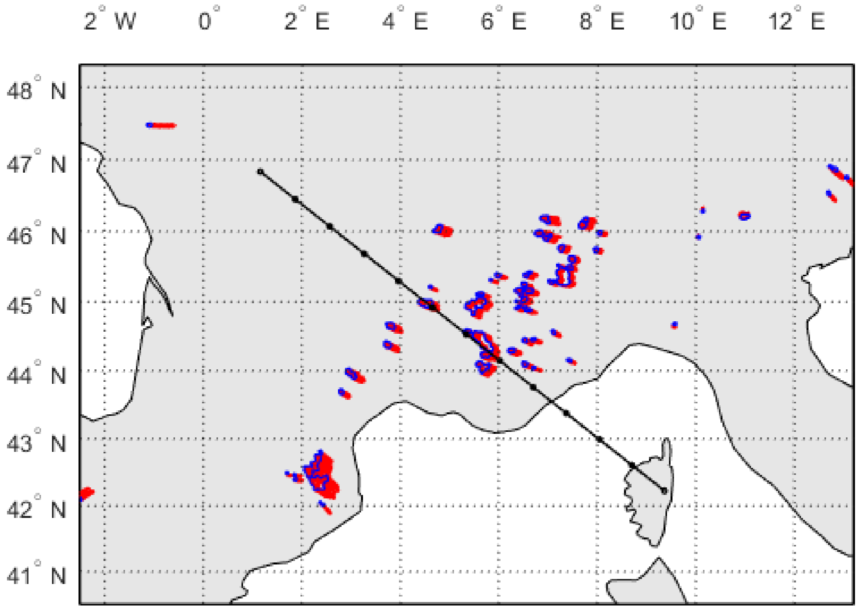

Figure 4. Thunderstorm cells nowcasted at 14:00, 22/06/2017, and reference route of the flight considered. Observation at T_P (blue), future extrapolations (red), and reference route (black).

Then, the ensemble of nowcasts is generated according to the procedure explained before. The polygons describing the individual storm cells at $T_P + 20$ min for all the ensemble members are depicted in Fig. 5 (recall that a total of 100 members have been generated), whereas those corresponding to the 50th ensemble member are depicted in Fig. 6. A close comparison of both pictures gives a clear impression of the uncertainty in the location of the storm cells at that forecast sampling time.

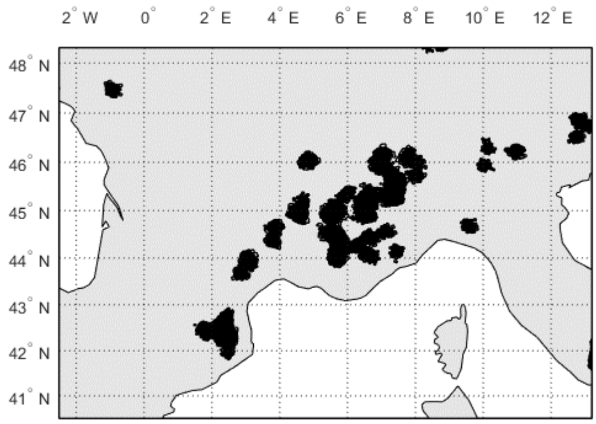

Figure 5. Joint picture of all the nowcast ensemble members at $T_P + 20$ min.

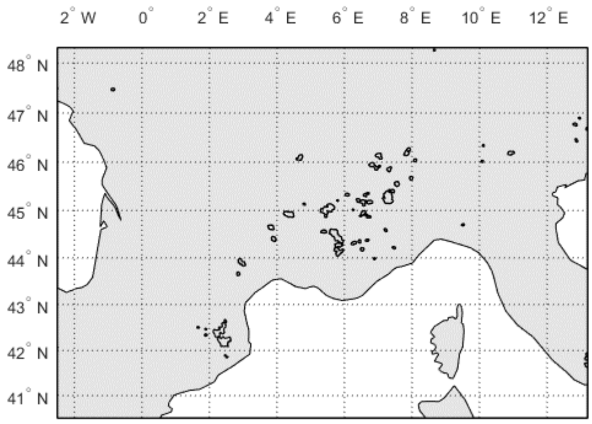

Figure 6. Ensemble member #50 at $T_P + 20$ min.

Once the enhanced meteorological input is available, the first step in DIVMET-P is the computation of the hazardous weather regions, as explained above. This gives a set of polygons for each nowcast ensemble member at each nowcast sampling time. The hazardous weather regions at $T_P + 20$ min, for the 50th ensemble member, and for a 10 NM safety margin are depicted in Fig. 7 (in yellow) along with the corresponding individual storm cells (in black). The clustering effect is clearly visible in this image.

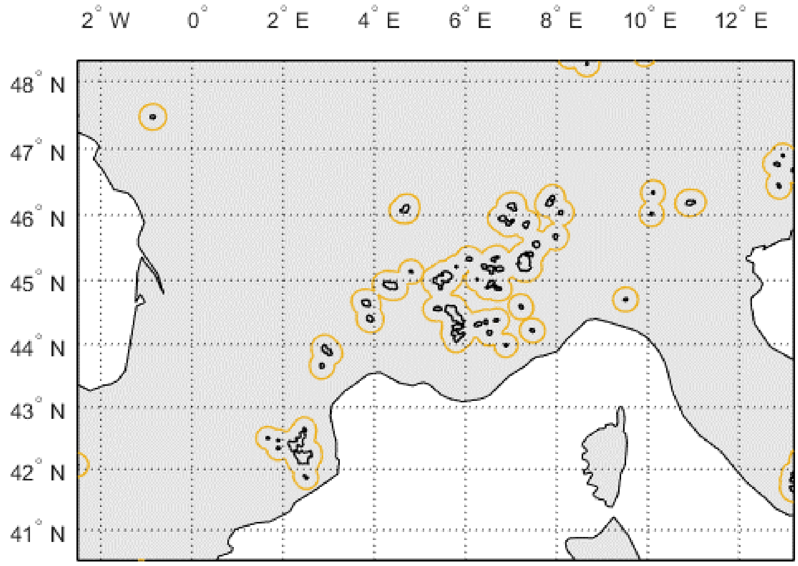

Figure 7. Hazardous weather regions for a 10 NM safety margin.
Ensemble member #50 at $T_P + 20$ min.

The next computation performed by DIVMET-P is the determination of the risk field associated to the hazardous weather regions, for a given safety margin. Fig. 8 shows the risk field at $T_P + 20$ min for a 10 NM safety margin. Then, the risk field isolines are computed for a given risk level value. In this example, results are presented for some risk level values (10%, 50%, and 90%) in Fig. 9.

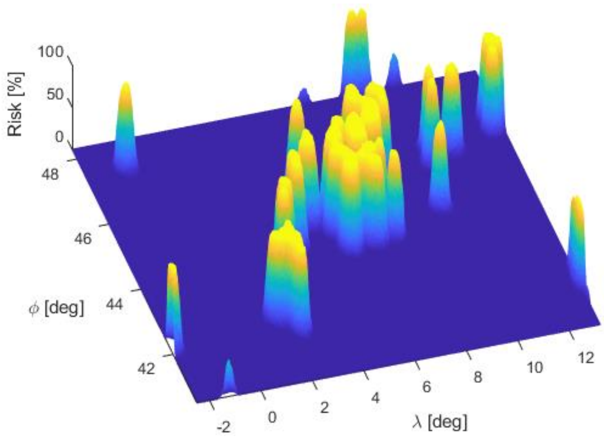

Figure 8. Risk field at $T_P + 20$ min for a 10 NM safety margin.

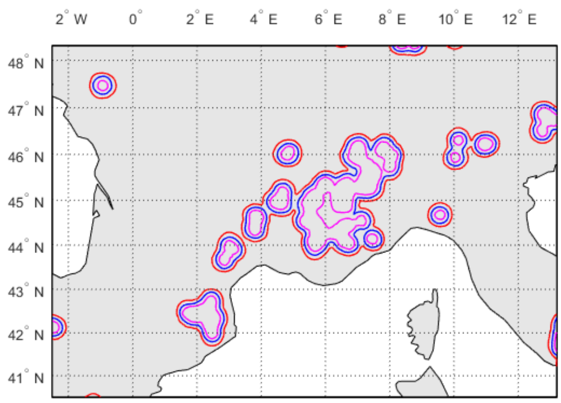

Figure 9. Risk field isolines at $T_P + 20$ min. Risk level values 10% (red), 50% (blue), and 90% (magenta).

Finally, DIVMET is applied to obtain the corresponding avoidance route, which circumvents the no-fly zones and reattaches to the given reference trajectory. The probabilistic avoidance trajectories corresponding to two different risk level values (50% and 90%) are given in Figs. 10 and 11, respectively. These figures show the expected effect that the magnitude of diversion shrinks with growing risk level value.

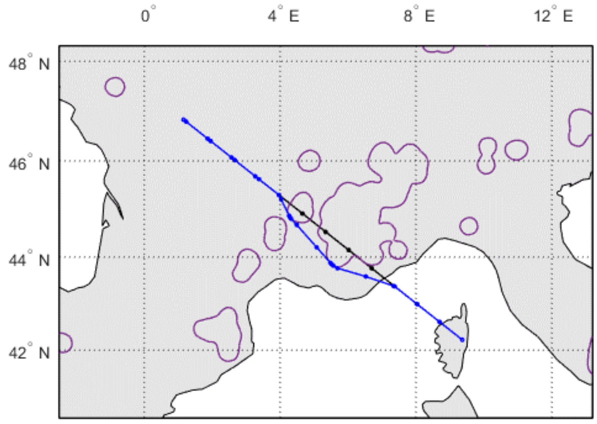

Figure 10. Probabilistic avoidance route for a 50% risk level value.
Reference trajectory (black), avoidance trajectory (blue), and risk isolines at $T_P + 30$ min (purple).

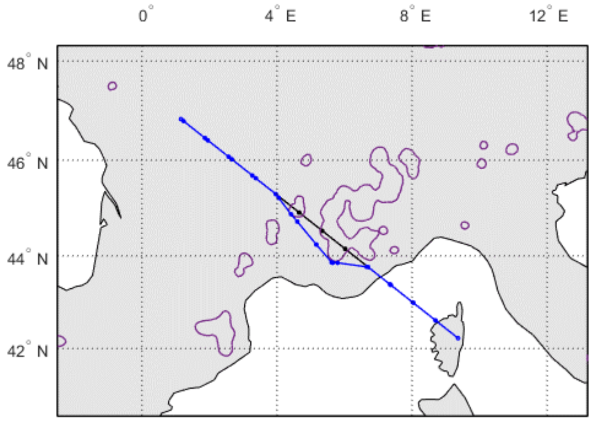

Figure 11. Probabilistic avoidance route for a 90% risk level value.
Reference trajectory (black), avoidance trajectory (blue), and risk isolines at $T_P + 30$ min (purple).

2.- Results of the concept assessment

The three scenarios have been fruitfully simulated, and all of them provide similar results. For this reason and for the sake of clarity, only results for the third scenario (20:30, 29th June 2017) are presented next. The successful flights in this scenario are 988; the indicators are computed for these flights.

Notice that the average and the standard deviation are sensitive to outliers. Therefore, those indicators that make use of these two statistics may not follow smooth trends but present some ripples.

Effects of the risk level on the probabilistic weather avoidance trajectories

The percentage of avoidance trajectories different from the corresponding reference trajectories is shown in Table 1. It can be seen that the percentage values are quite large in all cases; that is because all flights have been generated to encounter the storm, resulting in very severe scenarios. Also, it can be seen that these numbers decrease as the risk level increases; since the no-fly-zones become smaller for larger values of the risk level, less flights are affected by the storm.

	Risk level				
	10%	30%	50%	70%	90%
Percentage	90.6	87.0	85.3	81.2	72.2

Table 1. Percentage of avoidance trajectories different from the corresponding reference trajectories.

The difference between the arrival times of the avoidance trajectories and the arrival times of the corresponding reference trajectories is shown in Fig. 12. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol. Because the reference trajectories were defined at constant course, practically all deviations result in a delay, leading to positive time differences.

The median, the interquartile range, the average, and the standard deviation are presented in Table 2. It can be seen that the median and the average take moderate values (up to 1-2 minutes for risk level 10%) and are smaller for larger risk level values (0.25-1 minute for risk level 90%). This decrement comes from less aircraft being deviated for larger risk level values but also from smaller deviations of those that are still deviated. The interquartile range and the standard deviation indicate that this decrement is general for all flights because they also tend to decrease as the risk level increases.

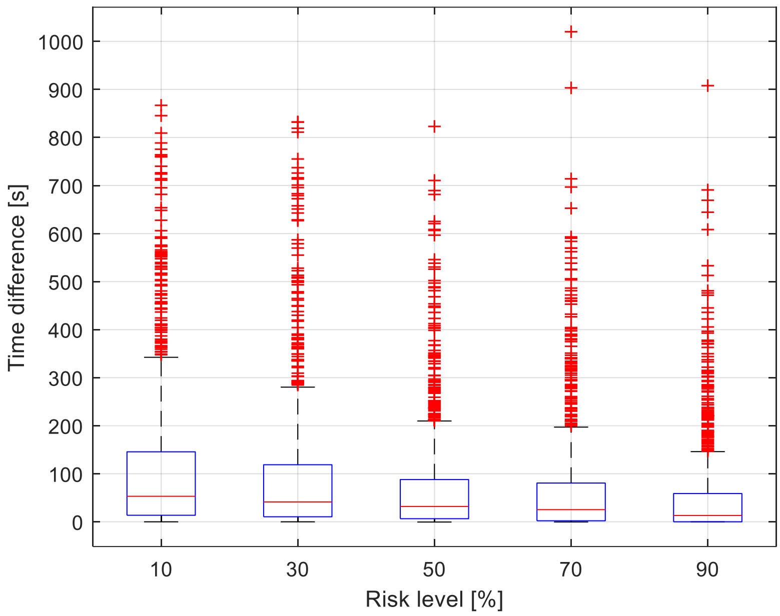

Figure 12. Difference between the arrival times of the avoidance trajectories and the arrival times of the corresponding reference trajectories.

	Risk level				
	10%	30%	50%	70%	90%
Median [s]	53.10	41.36	31.95	25.31	13.17
Interquartile range [s]	132.11	108.31	81.49	78.50	58.81
Average [s]	112.87	94.64	73.61	70.58	54.34
Standard deviation [s]	153.11	138.84	110.64	117.86	97.76

Table 2. Difference between the arrival times of the avoidance trajectories and the arrival times of the corresponding reference trajectories.

Costs and benefits resulting from the aircraft following the avoidance routes

Starting with the flight efficiency, the difference between the arrival times of the executed avoidance trajectories and the arrival times of the corresponding executed reference trajectories is shown in Fig. 13. Positive and negative time differences can be observed in the figure: a positive value means that the aircraft would arrive later to its destination if it executed the avoidance route (thus consuming more fuel), and a negative value means that it would arrive earlier (saving fuel).

The median and the average, see Table 3, show that, for all risk levels, there is a penalty for executing the avoidance route; however, this penalty is small (less than 1 minute for risk level 10%) and decreases as the risk level increases (being as small as a few seconds for risk level 90%). Again, the interquartile range and the standard deviation indicate that this decrement is general for all flights. Therefore, the flight efficiency is not improved, but is only slightly penalised.

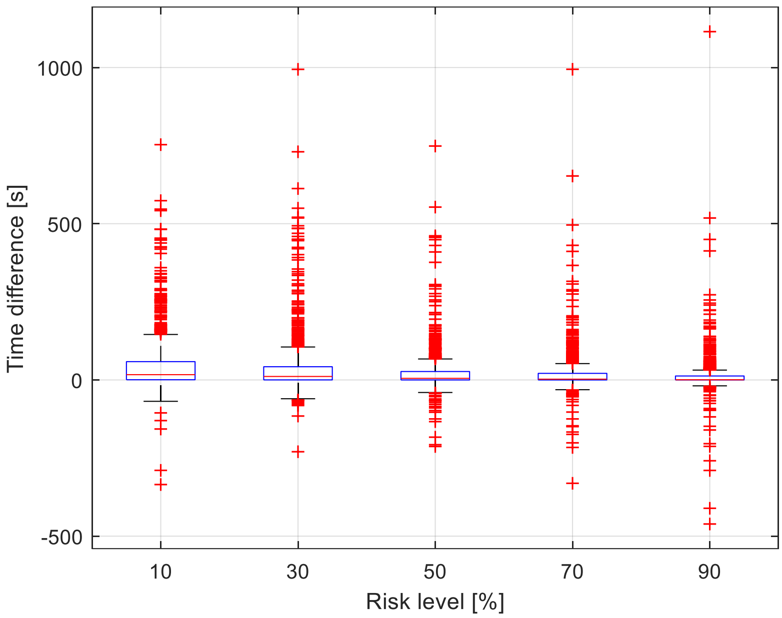

Figure 13. Difference between the arrival times of the executed avoidance trajectories and the arrival times of the corresponding executed reference trajectories.

	Risk level				
	10%	30%	50%	70%	90%
Median [s]	16.84	11.08	5.10	2.44	0.54
Interquartile range [s]	58.00	42.15	26.90	21.06	12.66
Average [s]	48.14	40.00	23.63	19.36	12.76
Standard deviation [s]	89.92	89.69	64.53	63.88	61.65

Table 3. Difference between the arrival times of the executed avoidance trajectories and the arrival times of the corresponding executed reference trajectories.

The predictability is presented in Fig. 14 as the difference between the arrival times of the executed trajectories and the arrival times of the corresponding planned trajectories (either the avoidance or the reference trajectories). A positive value means that the aircraft arrives later than planned and a negative value means that it arrives earlier; in both cases, the predictability is adversely affected because the aircraft does not arrive when it was planned to arrive. It can be seen in the figure that following the reference trajectories leads to worse predictability: the aircraft consistently arrive later, and present the larger values of median/average delay and dispersion (interquartile range and standard deviation). Following the avoidance route substantially improves the predictability, even for high risk-level values; for example, for risk level 90% the median and the average are cut by half, and the interquartile range and the standard deviation are also reduced in a similar proportion. Smaller risk-level values further improve the predictability; for the smaller considered risk level value, 10%, the median is practically zero. This improvement in the predictability also indicates that the avoidance routes reduce the magnitude of the tactical deviations.

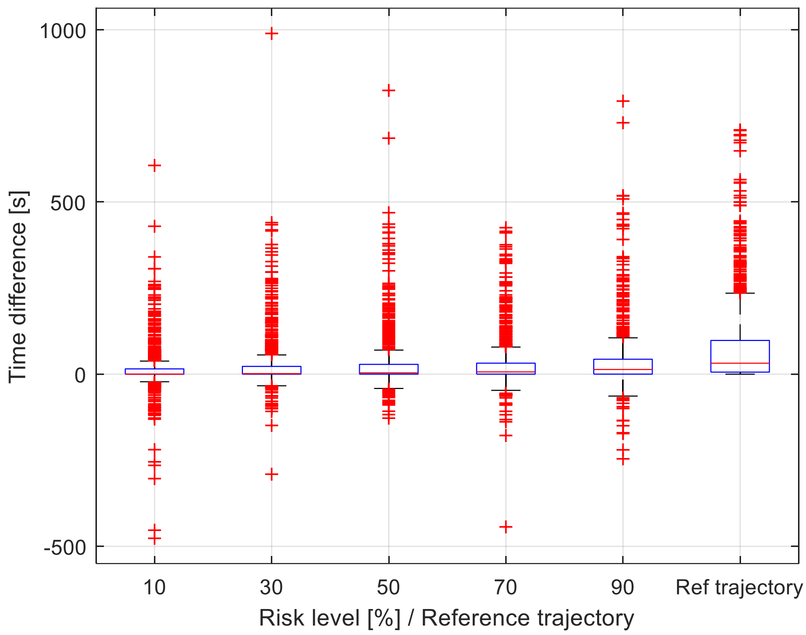

Figure 14. Difference between the arrival times of the executed trajectories and the arrival times of the corresponding planned trajectories.

	Risk level					Reference trajectory
	10%	30%	50%	70%	90%	
Median [s]	0.05	1.54	3.78	6.62	13.55	31.73
Interquartile range [s]	15.30	22.50	28.40	31.86	43.27	91.99
Average [s]	14.39	24.48	29.14	27.90	37.54	79.13
Standard deviation [s]	60.53	70.01	76.72	66.28	81.40	116.44

Table 4. Difference between the arrival times of the executed trajectories and the arrival times of the corresponding planned trajectories.

The average number of tactical deviations per flight is shown in Table 5 for aircraft following the avoidance and the reference routes. The number of deviations for high values of the risk level (70 and 90%) are very similar to today's practice, but they are smaller for medium and small risk-level values (≤50%). Notice also that, although the number of deviations is not improved for high risk-level values, the results presented in Table 4 showed that these deviations are smaller. Therefore, the safety of the flights and the workload of pilots and controllers can be improved: less tactical deviations are required and the remaining deviations are smaller, facilitating the work in the cockpit and the coordination with ATC.

	Risk level					Reference trajectory
	10%	30%	50%	70%	90%	
Average	0.669	0.769	0.869	0.963	1.020	0.991

Table 5. Average number of tactical deviations per flight.

To summarize the previous results, it can be said that, in today's practice, the deviations and delays caused by storms are not anticipated in the planned trajectories (the reference trajectories, which are not modified to face the storm) but they are tactically generated. According to the concept proposed in this project, the avoidance trajectory anticipates some of these deviations and delays (see Fig. 12), so that the tactical deviations and delays are smaller (see Fig. 14). At the end, the arrival time when executing the avoidance trajectory is only slightly worse than today's practice (see Fig. 13). The results are positive; the predictability, the safety and the workload are improved at the cost of some flight efficiency.

2.5 Stakeholders consultation

The acceptability of the concept by the stakeholders was already identified in the project proposal as a possible future barrier towards maturing the concept. As a measure to overcome this, we originally considered arranging meetings with stakeholders at the beginning of the project to obtain a first-hand expert description of current practice and future expectations, which would serve as a valuable reference to align the project activities. However, we decided at the project's kick-off meeting to postpone these meetings closer to the end of the project, so as to present them a more mature view on the probabilistic storm avoidance concept, and ask for their assessment.

Due to the COVID-19 pandemic situation, traveling to have face-to-face meetings was discarded. Hence, as no travel expenses were to be met, two decisions were made. First, to devote an additional effort (originally unforeseen) to develop in detail the MTSA tool concept described below. Second, not to present the concept of probabilistic storm avoidance to the stakeholders involved (pilots and air traffic controllers), but to present the MTSA tool concept specifically and ask them for an external assessment of it. This early involvement of target users, airlines and air navigation service providers (ANSP) was expected to allow us to better identify the required capabilities of MTSA, its potential contexts of use, and the related operational concepts and their possible implications.

2.6 MTSA tool concept

The new weather avoidance concept developed in this project would allow air traffic controllers to be involved with a more active role in the storm avoidance process, because it would provide them with more resources to better organise the traffic. To assist them in this new role USE has devised a decision-support tool called MTSA: Medium-Term Storm Avoidance, for which a probabilistic storm avoidance tool, such as DIVMET-P, will be the key enabler.

MTSA tool will detect and warn the controllers of those flights predicted to run into storm cells in the next 20 minutes. MTSA tool will help controllers to determine an appropriate avoidance route for each flight. Once the controllers decide that an avoidance route fits the traffic situation, the pilots will be offered this route. MTSA tool is intended to complement, not replace, the current practice in which pilots evade the storm using the on-board weather radar. If during the execution of the avoidance route the pilot notices that the aircraft runs into any storm cell, then the pilot will still be allowed to perform tactical diversions. With MTSA tool, the workload of tactical and planning tasks is expected to become more evenly balanced, enhancing sector team efficiency and providing a safer and better service to airspace users, and to reduce the trajectory uncertainty associated to storm avoidance.

1.- MTSA Brochure

The aforementioned unforeseen effort was mainly put to deliver an unplanned project output, namely, a Brochure entitled MTSA — MEDIUM-TERM STORM AVOIDANCE (a tool for air traffic controllers to help pilots avoid a storm), see **Annex II**. It addresses the motivation for MTSA tool, describes how it would work, includes its scheme of use, and summarises the expected benefits of such a tool.

2.- Stakeholders questionnaire

As already indicated, an external assessment from stakeholders (air traffic controllers and pilots) has been also performed. To guide them through their assessments, we prepared two brief questionnaires, which are included below:

Questions for pilots

- Would you trust route deviations, suggested by air traffic controllers, based on MTSA tool? If not, why not?
- Would you accept route deviations about 15 minutes/100 NM before encountering the storm cell?
- What restrictions/actual strategies should meet the avoidance routes to be accepted by you? (For example, to keep a larger distance from the storm if it is being avoided on its advancing side.)
- What other comments would you like to add?

Questions for air traffic controllers

- Would you trust route deviations suggested by MTSA tool? If not, why not?
- Do you think that three avoidance categories are appropriate? Would you like to have more or less categories?
- How would you like the weather information to be displayed (e.g., over the radar display)? Would you like to see the risk field?
- How would you like the avoidance route to be displayed (e.g., over the weather information)?
- What restrictions/actual strategies should meet the avoidance routes to be accepted by you? (For example, to keep a distance from the sector boundary.)
- Should MTSA either be an independent tool or integrated within the Medium-Term Conflict Detection (MTCD) tool?
- What other features should MTSA have?
- What other comments would you like to add?

3.- Results of the stakeholders consultation

We have received two responses, one from a pilot and the other one from an air traffic controller, and both assessments of the proposed MTSA tool concept have been very positive (see **Annex III**). Both of them are open to include this tool on daily operations once its effectivity is proven through validation.

The pilot informs that they can accept deviations proposed by ATC, even if they start 100 NM in advance, as long as they comply with the restrictions they have from company policy. They can also accept assumable impact on fuel and time consumption if the negative effects from having storm cells on their path are reduced. Moreover, he suggests to 1) increase the commander's participation in deciding which avoidance route option to follow, and 2) in order to not increase the radio congestion, to connect MTSA with a datalink, e.g. Controller Pilot Data Link Communications (CPDLC), to send the avoidance routes to the aircraft without making additional radio communications.

The air traffic controller expresses his concerns that the avoidance routes may penetrate military areas or segregated airspaces, that is something than MTSA should handle. In his opinion, MTCD and MTSA should be completely independent (in that case, the interaction between both tools should be carefully analysed). Also, MTSA should consider the three-dimensionality of the storms. In addition, he recommends to 1) represent the avoidance routes with distinguishable colours, 2) show the weather information and risk field as optional layers on their displays, analogously to others already existing tools, and 3) define the number of proposed trajectories once more experience is gained with this concept.

3. Conclusions, next steps and lessons learned

3.1 Conclusions

PSA-Met project has contributed to show that the uncertainty present in the storm-avoidance process can be taken into account. Hence, the development of tools that integrate this type of uncertainty is shown to be viable. This integration would lead to having an improved situational awareness, which in turn would facilitate an anticipated and better-informed decision making. The expected benefits will come from the identification of more efficient and safer storm-avoidance strategies.

As an evidence of the feasibility of such tools, we have successfully developed a probabilistic weather-avoidance concept, based on the use of probabilistic weather nowcasts; this concept constitutes a clear contribution to advancing the state of the art in storm avoidance, which is presently based on deterministic nowcasting.

Moreover, the probabilistic weather-avoidance concept has crystallised into a probabilistic version of DIVMET, called DIVMET-P. This software has allowed for the conduction of a concept assessment, which provided a preliminary quantification of the costs and benefits resulting from the aircraft following probabilistic weather-avoidance trajectories. As a general remark, by replacing the reference trajectory with a probabilistic avoidance trajectory, some of the inevitable weather-related deviations and delays are anticipated, leading to smaller subsequent tactical deviations and delays, at the cost of a slight increase in the executed time of arrival. Equivalently, the predictability, the safety and the workload are improved at the cost of a small loss of flight efficiency.

Ensuring high quality of the meteorological data is important to maximize the benefits of the concept proposed in PSA-Met. The results of the assessment have been obtained with a synthetic probabilistic nowcast because genuine probabilistic nowcasts are not yet available (they are under development, for example, in FMP-Met project). We consider that there is room for improvement once genuine probabilistic nowcasts become ready for use; in particular, we expect that the predictability, safety, and workload could be further improved, and that the negative effects on the flight efficiency could be reduced or even reversed.

Another relevant point is that further improvements are needed in the trajectory simulator. Some difficulties have been encountered when simulating with a safety margin of 20 NM, which need to be solved. In addition, further expansions are needed to improve the acceptability by pilots and controllers: integration of common airlines policies to avoid storms, and inclusion of restrictions to prevent the flights from invading active airspace restrictions or adjacent sectors.

Finally, PSA-Met project has taken a step beyond the development and assessment of probabilistic weather-avoidance concept: the MTSA tool concept has been defined in detail and externally assessed by the stakeholders involved, namely, pilots and air traffic controllers. Their good reception provides encouragement to proceed with the development of MTSA, which will help maturing the TRL of a technical solution envisioned for the generation of storm-avoidance trajectories to be used by controllers in support of pilots.

3.2 Next steps

On the one hand, a project forthcoming output is planned, consisting of a conference paper at SESAR Innovation Days 2020, to be held from 7th to 10th December 2020, in Budapest, Hungary. This paper will summarise the key project results and outcomes, and serve as a dissemination activity.

On the other hand, to bring current research to higher technology readiness levels, the following two research actions are planned: The Use of DIVMET-P in FMP-Met (which is a current action), and the development of MTSA tool (which is an envisioned action). Both are further explained below.

1.- Use of DIVMET-P in FMP-Met

FMP-Met is an active, SESAR-funded project (under call SESAR-ER4-05-2019) focused on the provision of enhanced information to improve the FMP decision-making process when subject to the effects of convective weather. In this project, DIVMET-P will be used as a key enabler for uncertainty integration in trajectory prediction for short look-ahead times, as explained below.

Trajectory prediction with a short look-ahead time is mainly based on storm avoidance tools; FMP-Met project will use DIVMET, which, as already indicated, is deterministic. However, the two main sources of uncertainty are to be considered: the meteorological uncertainty (uncertainty linked to the future location of the convective cells) and the operational uncertainty (the uncertainty linked to the storm avoidance strategy).

First, FMP-Met proposes to incorporate the operational uncertainty by altering the reference trajectory that enters into the DIVMET tool. The revised reference trajectory will be the probabilistic avoidance trajectory provided by DIVMET-P, thanks to the fact that an avoidance strategy can be captured by adjusting the risk level value considered. The methodology proposed consists in running DIVMET-P several times for the same probabilistic nowcast and the same original reference trajectory, but considering a set of different values for the risk level. In the framework of the FMP-Met project, the output of these multiple runs of DIVMET-P will serve as a set of possible revised reference trajectories, being able to reflect different avoidance strategies.

And second, to take into account the stochastic evolution of the convective cells, an ensemble-based approach is adopted, using a nowcast ensemble (probabilistic nowcast). If the aircraft followed the revised reference trajectory, it could still encounter some weather hazardous zones for some of the nowcast ensemble members, which of course have to be avoided. Hence, after the application of DIVMET-P, an ensemble-based application of DIVMET (Ensemble DIVMET) will be performed, that is, the deterministic storm avoidance tool will be applied several times, with the different members of the ensemble nowcast, to obtain an ensemble of deviation trajectories that accounts for the meteorological uncertainty. Therefore, for a given value of the risk level, an ensemble of potential executed trajectories (one per nowcast ensemble member) is obtained. Repeating this process for a set of values of the risk level, we will end up deriving a final set of ensembles of potential executed trajectories, which accounts not only for weather uncertainty but also for operational uncertainty.

2.- Development of MTSA

As part of PSA-Met project, we have defined in detail the MTSA tool concept, which has been well received by the stakeholders involved, namely, pilots and air traffic controllers. Such a good reception encourages us to proceed with the development of MTSA tool; in particular with:

- inclusion of genuine probabilistic forecasts,
- enhanced trajectory simulator capabilities,
- further identification and development of MTSA capacities,
- definition of actor’s roles and responsibilities, and

- interaction with already existing tools (e.g., MTCD).

To that end, we envision competing for funding in the following calls for proposal within the framework of SESAR, with a project consortium that will include ANSPs and airlines.

3.3 Lessons learned

In order to identify how well the project has progressed, we have posed and answered two questions.

What went well?

First, we would like to remark that, when the unforeseen event of confinement due to COVID-19 pandemic occurred, we were able to flexibly adapt not only the ways of working within the project and communicating among us, but also the scope of the project, redirecting our efforts to mature the MTSA concept.

Another strong point of the project has been the early involvement of target users (airlines and ANSPs) within the research and development process, which can facilitate the transition from exploratory research to application-oriented research.

Moreover, although not originally planned, the German National Weather Service (Deutscher Wetterdienst) has provided meteorological information (nowcasts) quickly and easily.

What could have been done better?

A criticism that can be raised is that the consultation to stakeholders could have been extended to a more numerous set of people and organisations. In particular, only one air traffic controller and one pilot have been surveyed. However, this was due to the fact that this consultation had to be started at short notice and carried out in a relatively short time.

4. References

4.1 Project outputs

- MTSA — MEDIUM-TERM STORM AVOIDANCE (a tool for air traffic controllers to help pilots avoid a storm).
- Franco, A. Valenzuela, D. Rivas, D. Sacher and J. Lang, “Probabilistic Weather Avoidance Routes for Medium-Term Storm Avoidance”, In preparation for the 10th SESAR Innovation Days, Budapest, Hungary, 2020.

4.2 Other

[1] https://www.skybrary.aero/index.php/ATC_Operations_in_Weather_Avoidance_Scenarios

[2] https://www.skybrary.aero/index.php/Weather_Radar:_Storm_Avoidance

[3] T. Hauf, L. Sakiew, and M. Sauer, “Adverse weather diversion model DIVMET,” Journal of Aerospace Operations, nº 2, pp. 115-133, 2013.

[4] World Meteorological Organization, “Guidelines for Nowcasting Techniques”, WMO-No. 1198, 2017.

[5] M. Sauer, T. Hauf, and C. Forster, “Uncertainty analysis of thunderstorm nowcasts for utilization in aircraft routing,” Proc. 4th SESAR Innovation Days, Madrid, Spain, 2014.

Acknowledgments

The partners thank Germany's National Meteorological Service (Deutscher Wetterdienst (DWD)) for providing the needed nowcasts out of their NowCastMIX-Aviation product, and the anonymous stakeholders for their assessments.

Annex I: Acronyms

Term	Definition
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATM	Air Traffic Management
CPDLC	Controller Pilot Data Link Communications
DWD	Deutscher Wetterdienst
FMP	Flow Management Position
FMP-Met	Meteorological uncertainty management for Flow Management Positions
JSON	JavaScript Object Notation
KTN	Knowledge Transfer Network
MTCD	Medium-Term Conflict Detection
MTSA	Medium-Term Storm Avoidance
NCM-A	NowCastMIX-Aviation
NM	Nautical Miles
PSA-Met	Probabilistic Weather Avoidance Routes for Medium-Term Storm Avoidance
TBO-Met	Meteorological Uncertainty Management for Trajectory Based Operations
TRL	Technology Readiness Level

Annex II: MTSA Brochure

MTSA — MEDIUM-TERM STORM AVOIDANCE

(a tool for air traffic controllers to help pilots avoid a storm)

Motivation

Weather can significantly affect aircraft operations. In particular, thunderstorms and the additional associated phenomena (i.e. hail, severe icing, and severe turbulence) present serious hazards to aviation. These hazards can lead to structural damage, injuries to crew and passengers, loss of separation/level bust as a result of an inability to maintain the assigned level, and loss of control [1]. Furthermore, the individual storm cells comprising the storm field change with time and their evolution is very difficult to predict. Some grow strongly, others decay, new ones appear, some merge and some split. The apparent motion of the storm field is not deterministic but has a stochastic component in it.

During the flight planning stage, aircraft operators have the opportunity of planning the routes to avoid areas of predicted storm activity. Once airborne, pilots are responsible of in-flight avoidance. For this purpose, aircraft are equipped with weather radar, which provides an indication of the convective-weather intensity coming ahead [2]. The recommendation is that a cumulonimbus should be cleared by a minimum of 5000 ft vertically and 20 NM laterally to minimize the risk of encountering severe turbulence. These tactical diversions increase the flight time and, as a consequence, the fuel consumption, thus negatively impacting the flight efficiency and the environment. Additionally, the flight crew workload also increases significantly in a weather avoidance scenario not just because of the decision-making associated with weather avoidance but also because of turbulence, management of in-flight icing, and increased communications.

In convective scenarios, the workload of air traffic controllers also rises significantly. The causes of this increase are disparate, among others [1]:

- The traffic flow becomes irregular and not easy to anticipate because of the changing intensity of storm cells and the routing decisions of the aircraft.
- Less airspace is available for conflict resolution tasks.
- New random crossing points appear as a result of the non-standard traffic patterns.
- The communications with pilots and controllers in adjacent sectors increase.
- Aircraft deviating from its planned route may penetrate another sector without prior notification.
- Possible suspension of the Reduced Vertical Separation Minimum (RVSM) airspace that could lead to lack of available flight levels.

This increase in the controllers' workload translates into a reduction of the airspace capacity. If the traffic demand exceeds the capacity, flow management regulations may be applied, such as re-routings or regulated take-off times, which cause further delays and inefficiencies.

MTSA concept

To overcome these difficulties, we propose to integrate new meteorological capabilities in the storm avoidance process, namely, ground-based probabilistic forecasts of the storm evolution, referred to as probabilistic nowcasts. These forecasts obtain the storm information from ground weather radars, which have a greater coverage area than the airborne weather radar, and are able to stochastically extrapolate the development of the storm for the upcoming hour. The meteorological information consists mainly of forecasts of the individual storm cells, their positions, extents, strengths, and cloud heights. Nowcasts are released every some minutes, e.g. 5 or 10 minutes, and provide the meteorological information for equally spaced sampling times.

The integration of these new meteorological capabilities will enable the anticipation of the avoidance manoeuvres, resulting in more efficient and safe deviations that will decrease the subsequent tactical interventions. Since the information is available on ground, air traffic controllers can be involved with a more active role in the storm avoidance process, providing them with more resources to better organize the traffic.

The previous ideas are materialized in MTSA: Medium-Term Storm Avoidance, a tool for air traffic controllers. MTSA will detect and warn the controllers of those flights predicted to run into storm cells in the next 20 minutes. MTSA will help controllers to determine an appropriate avoidance route for each flight. Once the controllers decide that an avoidance route fits the traffic situation, the pilots will be offered this route.

MTSA is intended to complement, not replace, the current practice in which pilots evade the storm using the airborne weather radar. If during the execution of the avoidance route the pilot notices that the aircraft runs into any storm cell, then the pilot will still be allowed to perform tactical diversions.

In the future, the MTSA tool should be integrated with the Medium-Term Conflict Detection (MTCD) tool, so that the proposed avoidance routes be also conflict-free.

How MTSA works

Firstly, MTSA processes the probabilistic nowcast to obtain risk fields for each sampling time. The risk at each location and sampling time is the probability of that location at that time being affected by hazardous weather regions. A hazardous weather region is the result of enlarging a storm cell by a safety margin of 20 NM to take into account the recommended distance to avoid encountering severe turbulence. The risk ranges from 0% to 100%.

A schematic example of a risk field generated by a single hazardous weather region is shown in Figure 1. It can be seen that those locations surely affected by the hazardous weather region (risk value 100%) are inside the deterministic region, and those locations definitely not affected (risk value 0%) are beyond it.

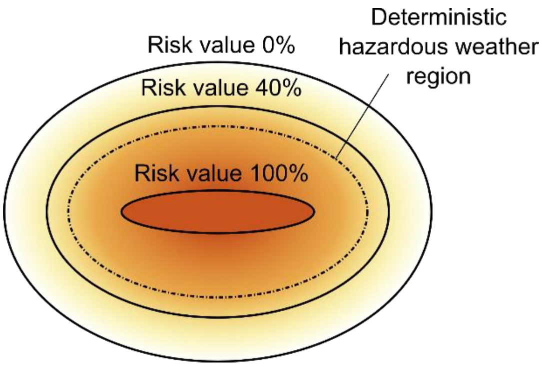

Figure 1. Example of risk field.

Then, for each flight, MTSA evaluates the risk along its planned route. The tool will notify the controllers of those flights that encounter a risk above a detection threshold. For each one of these flights, MTSA will offer the controllers the option to manually or automatically generate an avoidance route.

When the avoidance route is to be manually created, MTSA will offer the option to edit a tentative route by changing the upcoming points, as it is done nowadays in the MTCD tool. Then, MTSA will evaluate the maximum risk that this tentative route encounters. The higher the maximum risk value, the higher the probability that posterior tactical interventions will be needed and, therefore, the higher the tactical workload. According to the maximum risk value, MTSA will show the route classified in one of the following three categories (see Figure 2):

- ***Reactive avoidance route*** - for high risk values. Usually, routes in this category will be very close to the planned route. A reactive route is similar to today's practice: the flight follows the planned route and reacts when a storm cell is materialized along its way. A reactive route can be appropriate if the traffic situation or the surrounding airspace does not allow for large deviations.
- ***Proactive avoidance route*** - for small risk values. Usually, routes in this category will be the most deviated from the planned route, because they anticipate the most the storm avoidance. A proactive route goes through low risk areas, therefore the encounters with storm cells are unlikely and the flight becomes very predictable. If the traffic situation or the surrounding airspace allows it, it is the best option to largely alleviate the tactical workload.
- ***Balanced avoidance route*** - for intermediate risk values. Usually, routes in this category are close to the planned route, but they avoid the high-risk areas, thus anticipating the deviations and decreasing the encounters with the storm cells. A balanced route reduces the tactical workload and the total flown distance (after the tactical diversions); it represents an equilibrium between the need for posterior tactical interventions and the deviation from the planned route.

When the avoidance route is automatically created by MTSA, the controller will have the option to choose between three different routes: each one corresponding to one of the previously described categories. Internally, MTSA associates each category with a maximum admissible risk. MTSA obtains each route as the shortest deviation from the original flight plan that avoids regions with risks above the maximum admissible risk of the category.

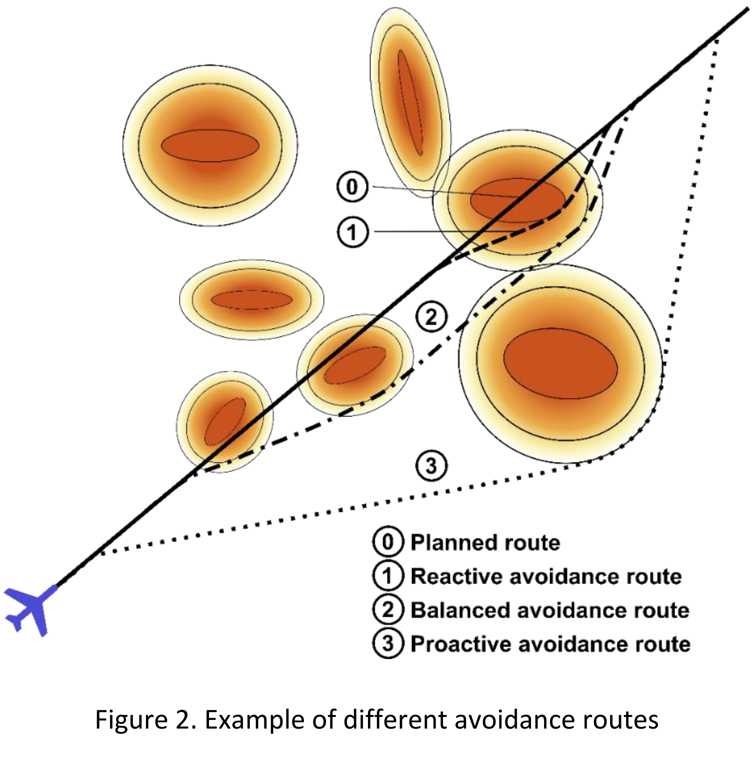

Figure 2. Example of different avoidance routes

MTSA scheme of use

MTSA could include the following steps (analogous to MTCD steps [3]):

- MTSA detects potential storm encounters within the look-ahead time period (i.e. 20 minutes) based on current flight information and probabilistic nowcasts, and the planning controller is notified.
- The planning controller monitoring/scanning process results in awareness of the notification provided by MTSA.
- The planning controller assimilates the information while assessing the potential storm encounter and then decides whether to monitor or to act on the information and its content. The controller will ask MTSA to generate or generate himself a reactive, proactive, or balanced avoidance route. This should result in the planning controller providing a resolution of the storm encounter by:
    - ignoring it (i.e. due to foreseen circumstances the storm encounter will not occur); or
    - resolving it by asking the tactical controller (if the aircraft is inside the sector) or the adjacent sector (if the aircraft has not yet entered the sector) to modify the aircraft route; or
    - deciding that the storm encounter is purely tactical and manageable by the tactical controller and therefore transferring it to him/her.

In the current ATM paradigm, the avoidance route can be implemented by vectoring or direct routes, whereas in the future Trajectory-Based Operations the avoidance route will be directly uploaded to the aircraft.

Expected benefits

MTSA will allow air traffic controllers and pilots to be informed, some time before facing the thunderstorm, as to the best/safer avoidance strategy, allowing them for anticipated and better-informed decision-making. The avoidance routes will be less exposed to severe weather, reducing the need for posterior tactical interventions, and, therefore,

- the workload of pilots will be reduced;
- the workload of tactical and planning tasks will be more evenly balanced, reducing the workload of tactical controllers; and
- the traffic flow will become easier to anticipate.

As a result of these benefits, MTSA tool is also expected to improve the safety, efficiency, and predictability of operations of the ATM system.

Bibliography

[1] https://www.skybrary.aero/index.php/ATC_Operations_in_Weather_Avoidance_Scenarios
[2] https://www.skybrary.aero/index.php/Weather_Radar:_Storm_Avoidance
[3] https://www.skybrary.aero/index.php/Medium_Term_Conflict_Detection_(MTCD)

Annex III: Stakeholder's reply to MTSA brochure

1.- ATCO's reply

Would you trust route deviations suggested by MTSA tool? If not, why not?

Yes, but, like any new tool, it must prove its worth and not create false indications. That is, in the corresponding safety study, it should not add a workload if there is no benefit.

Do you think that three avoidance categories are appropriate? Would you like to have more or less categories?

Yes, they are well expressed. It is after gaining experience in its use that a fine tuning could be considered.

How would you like the weather information to be displayed (e.g., over the radar display)? Would you like to see the risk field?

It has to be an optional layer (like those existing today) that overlaps the radar signal. As for the risk possibilities, it should be another additional option.

How would you like the avoidance route to be displayed (e.g., over the weather information)?

It should be displayed with the same logic of colours as when a change of route is proposed nowadays: the proposed route would appear in yellow, whereas the current one would appear in orange. When the new route is accepted, because the pilot has entered it, the controller would accept and enter it in the system.

What restrictions/actual strategies should meet the avoidance routes to be accepted by you? (For example, to keep a distance from the sector boundary.)

I am not concerned with avoiding neighbouring sectors or FIRs, but with incursions into military areas or segregated airspaces.

Should MTSA either be an independent tool or integrated within MTCD?

They should be absolutely independent, as MTCD deals with a certain risk whereas MTSA addresses a possibility that can be ignored or dealt with different strategies.

What other features should MTSA have?

MTSA should provide not just 2D information, but 3D information. As for the turbulence, a change in flight level usually leads to a change in the intensity.

What other comments would you like to add?

The tool is based on two pillars: accuracy/reliability of information and user confidence. Its eventual implementation would require a long validation period.

2.- Pilot's reply

Would you trust route deviations, suggested by air traffic controllers, based on MTSA tool? If not, why not?

MTSA seems to be based on ground radars that are more advance and accurate than the ones we have airborne, with the advantage of predicting the development of the cells giving extra and reliable information to ATC, who will be in charge of telling us the deviation route to follow.

First of all, I will trust these route deviations once the Radars used are conveniently tested and with proven effectiveness.

I will also need to know that ATC is fully trained on the use of these new technology and procedures, having the commander of the aircraft always the last word on whether following the instructed deviations or not.

Would you accept route deviations about 15 minutes/100 NM before encountering the storm cell?
Sure, if this can help in overall effectiveness of the operation as you have mentioned in the system description like reducing workload, reducing slots and all the negative effects from having storm cell on our path, and always having no negative impact or at least an assumable impact on fuel and time consumption, I will have no problem on deviating 100 NM in advance.

What restrictions/actual strategies should meet the avoidance routes to be accepted by you? (For example, to keep a larger distance from the storm if it is being avoided on its advancing side.)
I can accept deviations as long as they comply with the restrictions we have for company policy, being always more restrictive on the safe side.

In my case, *[airline name removed]* state that we have to consider a minimum distance of 40 NM from the convective cloud to make the decision for avoidance maneuver having always a margin of at least 20NM laterally and 5000 ft vertically.

As far as I know, each airline state their own minimum margins. So I understand that every pilot will decline any avoidance route that does not comply with the minimums stated by his own Operator.

What other comments would you like to add?
As you mention, the MTSA, when the route is automatically created, will give three possible avoidance routes for every flight, having ATC the possibility of choosing one. I think that having time and NM enough from the storm cells, that decision should be taken by the commander of the aircraft.

A key point on all this could be the way in which ATC communicates the information to the aircraft. If it is done by vectoring or by direct to, this will not solve the “chaos” that occurs on the radio in this kind of situation, as they will need to vector all the aircrafts affected, possibly congesting the radio. As a suggestion, it may be possible to link MTSA with CPDLC in order to send the possible avoidance routes, being the pilots able to choose their preferred option without making any radio communication.