8.6   SOME APPLICATIONS OF THE ADVERSE WEATHER DIVERSION MODEL DIVMET

Manuela Sauer*, Ludmila Sakiew, Thomas Hauf, Patrick Hupe
Institute of Meteorology and Climatology, Leibniz Universität Hannover, Germany

ABSTRACT. A new model approach DIVMET is presented which provides safe and short aircraft trajectories through a field of thunderstorms. The latter are given as 2-dimensional polygons on a flight level and are considered as no-go-zones for any aircraft. Adverse weather is in general considered as dynamic with radar-based update rates of 5 – 15 minutes. DIVMET proposes for each given planned route an alternative route which keeps a safety distance of typically 10 NM to each storm cell and which tries to minimize the additional detour. A conventional pathfinder algorithm based on a convex hull approach is used. DIVMET has various options to account for (i) various safety distances to study the safety-cost relationship, (ii) varying the assumed conical field of view to investigate the hypothesized beneficial information-cost relationship, respectively varying the receding horizon, ranging from a purely radar based field of view to a "God's" view of unlimited knowledge, (iii) varying the hazard recognition response time to clarify the role of a wait-and-see attitude, (iv) varying the risk acceptance of a pilot when flying between two storm cells. Results of various applications are shown: (1) coupling of DIVMET with a traffic model during a squall line passage over central EUROPE in July 2010, (2) modeling the ATC sector occupancy workload during that event, (3) controller assistance for guiding aircraft through a thunderstorm field during approach. Future work will focus on safe and efficient trajectory generation within the SESAR framework.

1. INTRODUCTION

Mitigating the impact of adverse weather becomes a more and more important task for ATM. One promising methodology is the planning of adverse weather conflict free routes, near airports within the TMA, but also en-route. Available accurate weather information of the current time and the most recent past, as well as the provision of nowcasting products on the tactical time scale of one hour and even forecast products on the longer more strategic time scale, facilitate the conflict free route planning. The complexity of time dependency of both, air traffic and adverse weather, however, require numerical models to solve the latter problem. A classical approach is the coupling of an adverse weather avoidance tool with a traffic model. In the following, we describe the concept of DIVMET as one of those weather avoidance tools and give first applications. The coupling of DIVMET with a traffic model is planned for the near future. The objectives of the DIVMET modeling effort are:

- Understanding the interaction of the two complex systems air traffic and adverse weather by means of modeling.

- Modeling realistic weather related diversions. How good do they match observed ones?

- Identifying the effect of increased en route adverse weather information on fuel saving.

- Exploring the worst cases.

- Finding best ATM strategies to account for the stochastic nature of the problem.

- Development of optimum routing strategies in unpredictable adverse weather.

- Guidance provision for controllers and pilots to find a safe and efficient route through a field of thunderstorms ahead.

In this paper we give a short introduction into the DIVMET model and present some first applications. Further details are found in Hauf *et al.* (2013).

2. THE DIVMET MODEL

The DIVMET model is based on a two dimensional path finding and obstacle avoidance algorithm written in Matlab and referred to as MET2ROUTE which was developed by Sakiew and Hauf. These types of algorithms are properly known in robotics (Lozano-Perez, 1981) and often applied to other applications like weather avoidance models in aviation (e.g. Chung and Saridis, 1989).

* Corresponding author address: Manuela Sauer, Leibniz Universität Hannover, Institute of Meteorology and Climatology, Germany; e-mail: sauer@muk.uni-hannover.de

DIVMET accounts for single aircraft routing in a field of moving and developing adverse weather. For this reason, conflicts between two or more aircraft are not considered and would not be detected by DIVMET in the current version.

Basic inputs for a model run are a planned trajectory and an adverse weather situation. Among these data sets there are a few parameters that have to be specified prior to a numerical experiment. In the following we describe the basic model set-up.

2.1 MODEL SET-UP

Any planned trajectory has to consist of at least two waypoints. They can either be generated or extracted from Aeronautical Information Publications (AIP) available for all countries or from real flight data depending on the planned application.

The weather situation can either be artificially generated or gathered from available weather data. By now we focused on thunderstorms which can be extracted from radar and satellite images. Other possible weather phenomena worth to study in this context could be volcanic ash and icing situations. When considering any radar product, one can assume a certain threshold. Thunderstorm cells with a reflectivity value higher than 37 dBZ very often are accompanied by heavy precipitation, severe turbulence and lightning. Comparing flight data with weather radar data one easily recognizes that pilots try to avoid these thunderstorms (Forster and Tafferner, 2012).

To account for the movement and development of cells subsequent, a time series of radar products can be used. The accuracy of the reproduced development then depends on the update rate of the used products. Typical update rates are 15 minutes; some products provide new images every 5 minutes. In the same way it is possible to consider the future development of cells using nowcasting products. To implement those data and study the effect of forecasted developments will be part of further research in near future.

When extracting cells out of images they are reduced to a two dimensional polygon, referred to as a weather object, regardless of their vertical extent and altitude. We assume weather objects to be an impenetrable column from the ground up to the tropopause, respectively cruise altitudes. Therefore any deviation route is calculated laterally around the weather object. Overflights are not considered in the simulation as they are also not recommended in international guidelines like FAA Advisory Circular No. 00-24B.

2.2 SIMULATION

Each weather object is enlarged by a so called safety margin. International regulations require aircraft to keep a certain distance to thunderstorms. NATS (2010) states to maintain at least 10 NM to 20 NM to any thunderstorm depending on the flight level. FAA (1983) gives distances depending on the severity of the thunderstorm. Those that are identified to be severe (40 - 50dBZ = HEAVY, > 50dBZ = EXTREME according to ATC Weather Radar Echo Terms and Definitions) should be avoided by at least 20 NM. A flight between neighboring cells is allowed if the radar echoes are separated by at least 40 NM. The entire area should be circumnavigated in case of a thunderstorm coverage of 6/10 (FAA Advisory Circular No. 00-24B). The safety margin, therefore, ranges between 10 NM and 20 NM. Nevertheless observations show a lot of situations in which pilots underwent these before mentioned guidelines. In a study by DeLaura and Evans (2006) on pilots circumnavigating thunderstorms within an air corridor in the US, it was found out that the safety distances kept by individual pilots follow a distribution rather than a step function. Human factors such as the personality and the closeness of the home base determine the pilot's attitude. Also the freight on board influences the pilot's behavior. Rhoda and Pawlak (1999) as well as some air traffic controllers reported that weather hazards are often completely ignored by cargo carriers. They continue their cruise straight ahead through a convective cell probably in full awareness of the risk. Oppositely private business jets seem to be very cautious and are willing to go for a larger detour of the flight as a commercial airliner. This was confirmed by some questionnaires made during the FLYSAFE project (Thales Avionics, 2010). These facts lead us to remain the safety margin as a parameter that can be adjusted to the application.

When determining the deviation route the convex hull concept is used (Graham and Yao, 1983).

The area enclosed by this convex hull is referred to as risk area which is avoided in the simulation (Hauf *et al.*, 2013).

Another parameter is the field of view that has to be defined before each model run. In contrast to other weather avoidance algorithms DIVMET should not regularly calculate deviation routes based on the overall knowledge of the weather situation. The intension was to first represent the current deviation behavior of pilots based on their mostly limited weather knowledge in the cockpit in case of thunderstorms, before studying potential benefits of an increased weather knowledge ahead.

En route weather information for pilots is mainly limited to the on board radar and lightning detectors such as a stormscope. The latter detects low-frequency radio energy emitted by thunderstorms because of heavy vertical winds and associated atmospheric charges and discharges even before lightnings are observable (Knight, 2002). As weather data for simulations with DIVMET are gained from radar or satellite data, we focused on considering the pilot's decision making based on the on board radar. This has a certain range as well as a defined opening angle that are both transferable to the field of view of the aircraft simulated by DIVMET. The opening angle can be set to angles between 0° and 360° whereas the range attains values of 0 NM (not meaningful) up to an "unlimited" range, i.e. any range larger than the simulation area.

In case of any recognized intersection of the planned trajectory with a weather object, the decision whether to circumnavigate the weather object to the left or right has to be made. It is based on the sum of risk areas left respectively right of the intersecting route. The deviation takes place to the side of the smaller extent. When there are no limitation in the aircraft's field of view the first decision is made based on the distribution of all weather objects. Every further decision only considers the object ahead. In case of a limited knowledge of the weather ahead, only weather objects or parts of those within the field of view are recognized and considered for the calculation. It is a kind of receding horizon in which new information is gained and a steady adjustment to them is necessary at any time step. For further information see Hauf *et al.* (2013).

3 VALIDATION

In order to validate DIVMET the model output is compared to observed data. For this purpose past data of convective cells as well as actually flown trajectories for the same situation are needed.

We received some data sets of the terminal area of Hong Kong International Airport (HKIA) and use those for validation purposes. Convective cells crossed the area on September 8th, 2010 and arriving as well as departing aircraft were forced to circumnavigate the scene.

Normally DIVMET is applied to en route traffic but as we assume weather objects to be columns reaching over all vertical layers and as it is stated in FAA's guidelines not to attempt to fly under a thunderstorm because of turbulence and wind shear located there (FAA, 1983), it is reasonable to work with those available data.

Overlaid weather and flight position data are given as images. These are available every minute to account for flight position and lightning data updates. Weather data are only updated on every sixth images, respectively every 5 minutes. Weather objects are extracted as explained in section 2.1. For this case we used a threshold of 41 dBZ. Flight positions are marked by colored arrows which are distinguishable from background and weather so that they can be extracted as well. Doing so, actual reference trajectories are generated which will not become modified within the simulation but will be compared to calculated deviation routes (see black solid and dashed line in figure 1). A related planned trajectory for a flight is, in case of HKIA, a standard arrival or departure route stated in the local Aeronautical Information Publication (AIP). As actually flown routes, also in undisturbed situations, often deviate from the standard routes, an adjustment of the planned one to the reference trajectory is necessary. Both have to start and end at the same positions. In this case, one point is the airport whereas the other one is the entry or exit position A of the either arriving or departing aircraft in the considered area. Only overflights have two points in air space. For those flights routes in the upper air space have to be considered. The adjustment means that there is a transition built from the entry or exit position A to any appropriate point B of the standard route.
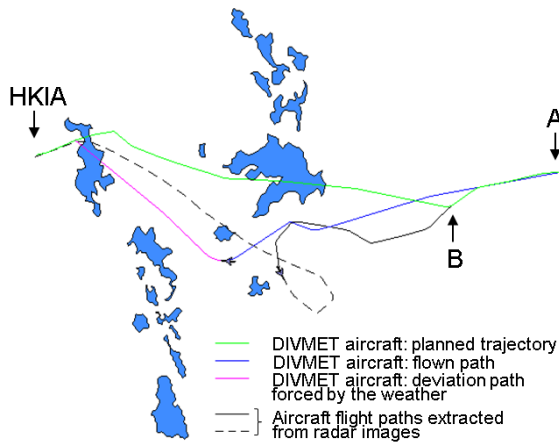
3

Figure 1: Validation of DIVMET by applying and comparing the model to a real weather situation. The modeled deviation route (blue and purple line) is based on the green planned route, has been adjusted to the weather situation (blue polygons) and is compared to the reference route (solid and dashed black line) observed in this situation.

As a result the planned route (green line in figure 1) given into DIVMET very often consists of a standard route adjusted by a transition to the observed position.

In contrast to the reference trajectory, the planned trajectory is modified throughout the simulation by DIVMET if necessary according to the weather objects, their update rates and the predefined safety margin. The resulting deviation route (blue and purple lines in figure 1) is then compared to the reference trajectory. By now this is only done by regarding the difference in distance and the visual appearance of the deviation behavior (direction, safety distance). Research on a suitable measure will be done in near future and a detailed paper on the Hong Kong case and the validation process of DIVMET will be published.

4   COUPLING TO NAVSIM

DIVMET was planned to be a stand alone model for single aircraft routing in case of adverse weather. The model is applicable to several issues. Among studies on representing past situations of single aircraft circumnavigating any adverse weather as described in the previous section, investigations are made to cover more than one aircraft. Therefore a coupling to a global air traffic model is established.

NAVSIM, a very advanced research based global air traffic simulation model developed by Rokitansky and his group at the University of Salzburg, has been identified as an appropriate counter part. This model is able to simulate up to 30000 flights per day from runway to runway and corresponding to standard routes stated in the AIP or according to real flight position data (Rokitansky, 2005; 2009; Rokitansky et al., 2007).

NAVSIM, running in Salzburg, sends aircraft IDs, current aircraft position data and further waypoints of the flight path of each aircraft in the simulation every 3 s via TCP/IP. At the current state DIVMET picks out one single aircraft ID and related flight data, checks if there is any disturbance by weather that is implemented manually in DIVMET and, as appropriate, calculates a deviation route. A new set of way points that are characteristic for the deviation route is passed back to NAVSIM. Then NAVSIM induces a heading change according to turn constraints and other flight performance indicators based on BADA data provided by Eurocontrol and head for the next waypoint. The actual flight position is passed to DIVMET further on every 3 s and a check whether any new conflict with weather objects emerged is performed. Alternatively another flight could be picked out and checked of potential conflicts by DIVMET.

In any case DIVMET's time performance has to be improved in order to continue and to extend studies in the coupled mode. A comprehensive analysis on European air traffic of July 17th, 2010 is intended. Planned routes as well as the actually flown routes are available in Salzburg and should be simulated by NAVSIM. Then a third simulation run will be done in the coupled mode. Based on the planned trajectories DIVMET will determine deviation routes which then will be compared to the actually flown ones. Studies on the benefit of an increased field of view are planned an interesting result would be whether the determined deviation routes with based on a limited or unlimited field of view better fit the observed ones.

5 APPLICATIONS

One application is a study on safety versus efficiency in a statistically distributed, simulated field of developing showers which are assumed to have to be circumnavigated. The second application, presented here, is a feasibility analysis on the shift of sector load in case of adverse weather.

5.1 SAFETY AND EFFICIENCY ANALYSIS

Studies on "safety versus efficiency" of flight trajectories are done in a simulated field of statistically behaving cells that are randomly distributed. Simulations of these cells are performed at our institute and are based on former studies on the characteristics of post-frontal precipitation structures in the mid-latitudes. Therein the evolution, development and decay of cells occurred according to statistics whereas the location of the cell's evolution is random. A displacement is achieved by a predefined (background) wind and results in a movement, but also might lead to converging cells that merge. These and other cells of a specific growth and above might split up (again) what is simulated as well.

Several simulations with DIVMET and a planned route in differently developed cell distributions were done while varying the safety margin in each model run. The relation of the considered safety distance, respectively the mean distance of the shower cells, and the resulting detour is determined and graphically shown in figure 2.
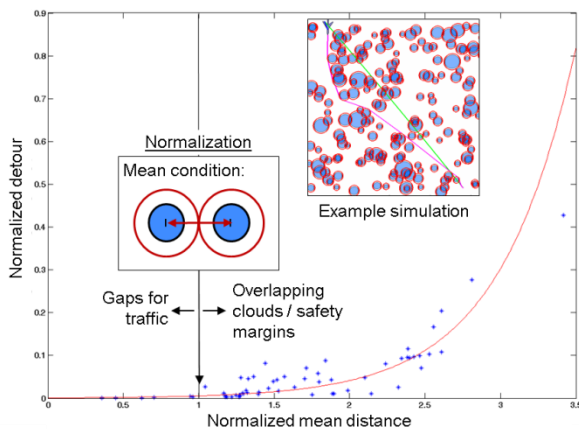
The results are normalized to be comparable. The normalized mean distance equals twice times the radius plus twice the safety distance. That means there are no gaps in mean conditions but of course some cells overlap between others gaps exists. The detour is normalized by its ratio to the length of the planned route.

The results shown in the scatterplot (figure 2) indicate that there is nearly no detour when gaps exist but that it increases exponentially in cases when the cells overlap in the mean condition. Some overlap strongly; other less and some showers, respectively risk areas, do have gaps between each other to fly through.

Extended studies, a verification of this study as well as an investigation in several studies on the impact of randomly distributed cells on air traffic, as e.g. the number of flyable routes for a certain number but different distribution of cells in a defined area, are intended.

5.2 SECTOR OCCUPANCY ANALYSES

The motivation for this analysis emerged from a real weather and traffic situation and was suggested by Austro Control, the Austrian air traffic control. In July 2010 they experienced a severe weather situation in which a squall line crossed territories of Austria, southern Germany and Czech Republic eastwards (see figure 3).

In contrast to air space handling and air traffic control in the US, Europe is distributed in small countries, with each having its own ATC which in

Figure 2: Safety versus efficiency shown by the relation of the normalized detour to the normalized mean distance.
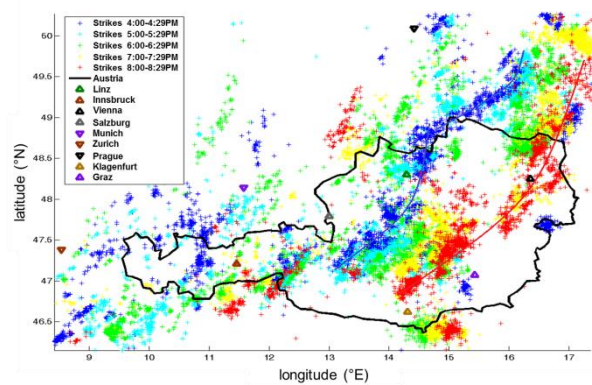

Figure 3: Lightning strikes from July 17th, 2010 located over Austria and Czech Republic recorded by ALDIS (with courtesy of Austro Control).

turn determines a couple of air space sectors in their area of responsibility. Per sector two controllers are in charge and are able and allowed to handle a certain number of aircraft simultaneously. In case of a higher demand some sectors can be split, so that a few more aircraft can be processed by additional controllers.

As especially the air space of Czech Republic was blocked in the previous discussed situation the local ATC circumnavigated the traffic to the south, to Austria. The Austrian controllers were already experiencing a high workload for keeping their traffic flow safe and guiding the flights around the convective cells. When the aircraft coming from north had been forwarded, the ATCs' workload increased additionally because they had not expected this behavior of Czech Republic's ATC and had to handle a lot more aircraft in a severe weather situation. So they suffered high pressure and maximum workload.

Out of this experience the issue emerged whether it would be possible to simulate the shift of air sector load in case of any disturbances. Based on this experience the question raise up whether a weather avoidance model such as DIVMET coupled to NAVSIM provides a benefit to ATC.

Besides the issues, whether such simulations and forecast would be realizable and if those would be helpful for ATC, the question arose, whether DIVMET is suitable for this application. Therefore we did a feasibility analysis in a generic set up and a homogeneous route distribution. It is focused on a geographic area reaching from 13°E to 17°E in longitude and starting at 47°N up to 50°N in latitudinal direction, overlapping with Austria. To account for air space sectors we, first placed the borders of artificial sectors along the integer longitudes and latitudes. Doing so, 12 sectors of a dimension of 1° x 1° each were generated. This resolution seems to be appropriate compared to real conditions over eastern Austria where the air space is horizontally divided into five sectors. Additional divisions in case of high traffic are only made in the vertical dimension.

Routes are set the way that each integer grid point on one border is directly connected with all other integer grid points on the other borders, but

not to edge points of their origin border, except those origin points located in an edge of the whole area. Those are connected to all other edge points and grid points on the opposing borders. Starting at grid point 48°N and 13°E all flights are simulated after each other in a clockwise mode without taking any route in the second direction. As a result 63 routes with the main flow from the west and north to the east emerge.

As stated above, the sector load is mainly given in a licensed number of simultaneous flights in sector without considering the distance or time an aircraft remains in this sector. We choose another measure that considers the latter and determined the flight density per grid box by the number of route points (RP). The latter are set every 15 s flight time with an assumed flight velocity of 280 ms^{-1}. The number of RP per sector is assumed to be a measure for the time and distance an aircraft stays in one sector, and therefore a more meaningful measure for the sector load and is related to the work load of a controller. At the same time the number of points and especially its change due to weather indicates the forced total detour. In the undisturbed case there are 4439 RP overall (see figure 4). When focusing on the field of sectors there is a nearly symmetric distribution of RP.
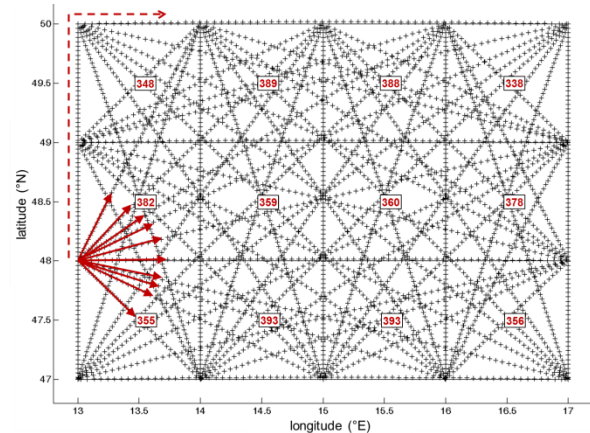

Figure 4: Study setup with 1° x 1° sectors and 63 resulting routes that connect all outer grid points. Red arrows indicate the generation of the first flights. The origin of following routes is switching, first, northward and then eastward (indicated by dashed red arrow). Each route is flown in only one direction what results in a flow mainly from west and northwest to the east. Numbers in boxes show the number of RP per sector. The overall number of RP in this case equals 4439.

Small differences are mainly caused by RP located on the borders and especially in the edges of the area. Some are appendant to the regarded sectors, others are located and would be counted in sectors north or east of the considered area.

Then, weather objects are implemented, the circumnavigation is calculated and again RP are set. These are counted per sector and compared to the undisturbed situation. The relative change is stated in each sector for one single real weather object (figure 5). The overall detour is declared by the difference in the total number of RP which is 32. Expressed in meters this number means

$$32 \cdot 15\text{ s} \cdot 280\text{ ms}^{-1} = 134400\text{ m} = 72.6\text{ NM}.$$

There have been a lot of different (sometimes artificial) weather objects implemented in the considered area and several effects, such as resulting from different field of views or objects with and without gaps, have been analyzed.

In summary, basic and anticipated effects like the avoidance of air space blocked by weather, the circumnavigation and a crowding along the convex hull of a weather object can be represented preliminarily. Larger effects in the shift of sector load can be observed when narrowing the sector size. The field of view is crucial when focusing on efficiency of routes. In the same way is the appearance of weather objects, respectively the existence of gaps between weather objects, the determinative factor. When there are wide gaps (at least two times the safety distance) in place, detours might be much smaller than in cases when the gap is to narrow or there is not any gap.

Plans to continue and expand this study are made. To represent real conditions correctly a lot of parameters have to be considered additionally. Research on this has to be done. In reality problems could emerge when passing any aircraft from one sector to the next. Conflicts are possible and the question arises what to do when a sector is occupied related to the number of aircraft allow simultaneously. Nevertheless a transition to real conditions, i.e. real trajectories as well as real air space sectors, is intended and some analysis in the coupled version of DIVMET will be made to this issue.
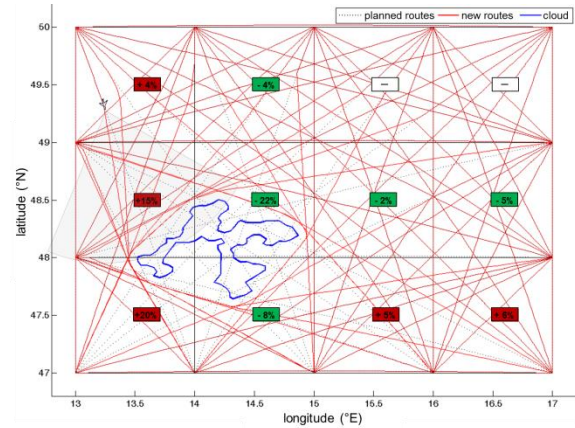

Figure 5: Deviation routes (red lines) in case of one real weather object (blue contours). The relative change of the number of RP is stated in the boxes. Red boxes indicate an increase of RP, green boxes a decrease of their number. The total number of RP equals 4471.

Altogether it became obvious that weather avoidance models may become a suitable tool for ATC to estimate and mitigate the weather impact on sector load.

6 CONCLUSION

A new adverse weather avoidance modeling tool, DIVMET, and some of the first applications are presented. DIVMET determines a safe and efficient deviation route if the original trajectory penetrates any adverse weather. International regulations regarding safety distances are satisfied but for analysis the safety distance can be reduced. Representations of actually observed pilots' behavior are possible by implementing a limited field of view which can be enlarged for studies on the benefit of an increased weather knowledge in the cockpit.

Adverse weather is given in the model as a so called weather object. It is a two-dimensional contiguous area, located horizontally in space, which is described mathematically by a polygon. Physically, the weather polygon can be thought as an impermeable column reaching over all flight levels. Thus the aircraft is forced to circumnavigate the weather object. DIVMET uses an adjusted path finding algorithm named MET2ROUTE that is based on the convex hull concept to determine a new route. More details

7

on this can be found in an upcoming paper on MET2ROUTE. Detailed information on DIVMET is provided by Hauf *et al.* (2013).

Adverse weather is allowed to move which leads to a continuous adjustment of the circumnavigation procedure. By now weather update rates in DIVMET equal those of radar products, i.e. 5 – 15 minutes. To allow for a continuous weather provision DIVMET will, in future, determine the velocity of the individual objects e.g. by correlation methods of two subsequent radar images, and then will interpolate the objects in time and space. Nowcasted cells will be implemented as well.

Validation is in process based on comparisons of actually observed routes with simulated ones in the same weather situation. Results will be published in detail in another upcoming paper.

DIVMET allows for many applications. As a stand-alone model, it is used for basic studies on the impact of various weather situations and different knowledge of the weather in the cockpit. Taking into account the uncertainty related to the generation of new cells or the decay of existing ones, and also of the storm motion, optimum strategies may be developed which account for that uncertainty. In a second mode, DIVMET is coupled to the global air traffic simulation model NAVSIM where aircraft-aircraft interaction is handled by the latter, while DIVMET makes only proposals for weather related circumnavigation. Thus traffic conflicts are separated from the weather conflict.

Two applications are discussed. The first is an analysis on safety versus efficiency in a simulated field of statistically distributed field of post-frontal showers that are assumed to be adverse weather cells which have to be avoided. The basic outcome is an exponential lengthening of the detour with increased mean overlapping of the cells, respectively risk areas. The second application is on the change of sector load when aircraft are forced to divert adverse weather. This usually poses a severe problem for ATC personnel. A feasibility analysis in an artificially generated environment is discussed and a case study on the effect of a thunderstorm squall line on the air traffic in July 2010 in Austria together with Austro Control and the University of Salzburg is being investigated.

Future work will focus on the interaction of adverse weather with many other aircraft. Apart from handling more than one aircraft by NAVSIM in the coupled mode, DIVMET, as a stand-alone model, will consider other aircraft also as impermeable objects and shall determine a safe route through the field of storms and through the field of other aircraft. In that way both, weather and air traffic, are simulated simultaneously where it still be a pairwise solution, first, rather than a multiple aircraft de-conflicted solution as done by Pannequin *et al.* (2007).

In SESAR's free-flight philosophy based on 4D-trajectories, adverse weather represents a non-communicating and in parts chaotically behaving element. Any successful 4D-trajectory management has to deal with the weather problem. DIVMET provides a first approach for the needed solution.

ACKNOWLEDGEMENTS

REFERENCES

Chung, C.H., and G. N. Saridis, 1989: An obstacle avoidance path planning by the extended VGraph Algorithm. CIRSSE-TR-89-12, Center for Intelligent Robotic Systems for Space Exploration, Rensselaer Polytechnic Institute, New York.

DeLaura, R., and J. Evans, 2011: An exploratory study of modeling enroute pilot convective storm flight deviation behavior. 12th Conference on Aviation, Range, and Aerospace Meteorology (ARAM), Jan 29 - Feb 2, 2006, Atlanta, GA.

Graham, R.L., and F.F. Yao, 1983: Finding the convex hull of a simple polygon. *J. Algorithms*, 4, 324-331.

Hauf, T., L. Sakiew, and M. Sauer, 2013: Adverse weather diversion model DIVMET. (Submitted to Journal of Aerospace Operations).

FAA, 1983: Advisory Circular – Thunderstorms. AC No. 00-24B.

Forster, C., and A. Tafferner, 2012: Nowcasting Thunderstorms for Munich Airport. In The DLR Project Wetter und Fliegen. Gerz, T., Schwarz, C. (ed.), Forschungsbericht 2012-2. Deutsches Zentrum für Luft- und Raumfahrt Oberpfaffenhofen, Braunschweig, Göttingen und Hamburg, pp. 32-45.

Knight, B., 2002: Spotting Trouble. *Aviation Safety*, Feb 2002. (Available at http://www.avweb.com/news/avionics/181954-1.html)

Lozano-Perez, T., 1981: Automatic planning of manipulator transfer movements. *IEEE Trans. Syst., Man. Cybern.*, SMC-11, 10, 681-698.

NATS, 2010: The effect of thunderstorms and associated turbulence on aircraft. Technical Note AIC: P 056/2010. UK Aeronautical Information Service: Hounslow, Middlesex.

Pannequin, J.J., A.M. Bayen, I.M. Mitchel, H. Chung, and S. Sastry, 2007: Multiple aircraft deconflicted path planning with weather avoidance constraints. *AIAA Conference on Guidance, Control and Dynamic*s, Hilton Head, South Carolina, August 20-23, 2007.

Rhoda, D., and M. Pawlak, 1999: An assessment of thunderstorm penetrations and deviation by commercial aircraft in the terminal area. Project Report NASA/A-2, 77 pp. MIT Lincoln Laboratory: Lexington, MA.

Rokitansky, C., 2005: VDL Mode 2 Capacity Analysis through Simulations: WP3.B – NAVSIM Overview and Validation Results. Eurocontrol.

Rokitansky, C., 2009: NAVSIM: Detailgenaue Simulation des heutigen/zukünftigen Flugv-erkehrs (Europa/weltweit) zur Bewertung von SESAR Konzepten und Wetterszenarien, *Presentation, pp. 52, Hannover, January 20, 2009.*

Rokitansky, C.H., and M. Ehammer, T. Gräupl, 2007: NEWSKY – Novel simulation concepts for future air traffic. In *Proceedings of 1st CEAS European Air and Space Conference*, Berlin, Germany, September 10-13, 2007, pp. 611-618.

Thales Avionics, 2010: FLYSAFE – WP 6.7.3 D6.7-3 Public - Final Publishable Report. 104 pp.