Case Study of Adverse Weather Avoidance Modelling

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***Abstract*—Adverse weather conditions like thunderstorms cause about 50 % of all aircraft delays. Avoiding the hazards generally results in additional workload for air traffic controllers. The project MET4ATM deals with a case study for the 17 July 2010, when several flights in the Austrian and the Czech airspace had to be diverted due to several thunderstorms. One aim of MET4ATM is to estimate the benefit of ground-based weather information for ATM in such a case with regard to sector occupancies. This paper deals with an application of the weather avoidance model DIVMET coupled to the air traffic model NAVSIM. Aircraft are simulated based on the flight plan route and diverted around the storms keeping a safety margin. The analysis of the simulated trajectories compared with actually flown routes provides promising results in terms of optimized trajectories.**

I. Introduction

Significant weather is known to have an impact on air traffic with regard to the safety or efficiency of a flight. To keep the risk on-route as small as possible, potential hazards will be avoided by pilots and air traffic control officers (ATCO), respectively. Such potential hazards may be areas with increased turbulence or icing occurrence as well as thunderstorms which often go along with the two aforementioned phenomena.

On 17 July 2010, a storm event affected the air traffic in Austria and the Czech Republic massively. Preceding a cold front, several thunderstorms developed over Austria. In the afternoon storms merged to a squall line, moving from west to east. According to the lightning data of the Austrian Lightning Detection and Information System (ALDIS), approximately 300,000 lightnings were detected in the Central European region on 17 July 2010. Due to this weather situation, Austro Control GmbH, the Austrian authority for air traffic control, was faced with a maximum workload of its ATCO ([1]).

To be prepared more accurately for shifts of the sector occupancy in future, Austro Control suggested a study called MET4ATM which deals with the investigation of the avoidance behaviour of pilots by using the example of 17 July 2010. The actually flown flights can be compared with simulated flights that consider all the weather information.

Theoretical investigations of sector occupancies have already been made (see [2]). In this paper the first application of the coupled mode of the 2D weather avoidance model DIVMET and the global 4D air traffic simulation model NAVSIM is presented. DIVMET calculates trajectories for a single aircraft based on weather radar polygons. In order to display realistic flight behaviour, central functions of DIVMET are coupled with NAVSIM. The methodology of doing so is described below.

II. Methodology and Models

NAVSIM allows for simulating the worldwide air traffic. Up to 300,000 flights per day can be handled by the model. On 17 July 2010, up to 26,000 flights were scheduled over Europe (traffic demand). In addition to the traffic demand also the actual number of flights (traffic load) and the flight path of each flight, based on Correlated Position Report (CPR) data, is available for that day ([3]). In order to limit the case study on the essentials, an area of relevance was defined. Since, as introduced above, the Austrian airspace was affected by the storms in particular, especially in the afternoon, the area of relevance approximately extends from 7° E to 18° E and from 45° N to 52° N (see fig. 1). About 1,800 flights have been detected in this area on 17 July 2010 between 12:00 UTC and 18:00 UTC. They are to be simulated and taken into account for a sector analysis. The latter will be part of research in the near future.

By coupling DIVMET with NAVSIM, realistic simulations are possible inclusively the consideration of weather information. In the following we focus on the individual models and their capabilities.

A. NAVSIM

The global air traffic simulation model NAVSIM is used at the University of Salzburg. Since all aircraft have simultaneous access to several hundred thousand of ATM data, NAVSIM achieves such a good performance, which explains why it is a very realistic model. Also the Flight Management Systems (FMS) of aircraft are simulated simultaneously ([4], [5]).

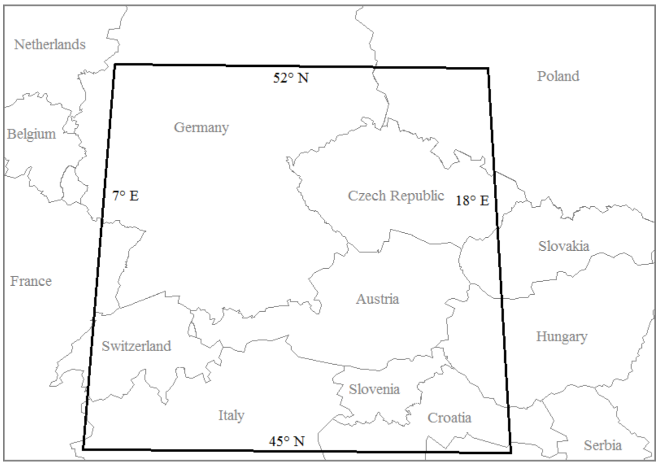


Fig. 1. Central Europe and the area of relevance: The map roughly represents the region of the Central European Weather Radar Network (CERAD). The frame depicted in black highlights the area of relevance for the case study.

A NAVSIM simulation consists of three elementary steps. At the beginning input data is retrieved. This includes navigation data and flight plan (FPL) data for all aircraft to be simulated. This information, the traffic demand, is extracted from the Central Flow Management Unit (CFMU) data from EUROCONTROL and consists of waypoints associated with overflight times. NAVSIM also uses meteorological data for airports, i. e. Meteorological Aerodrome Reports (METAR); Terminal Aerodrome Forecasts (TAF) and wind information in different flight levels can also be included if required. In addition, for each aircraft the performance is determined from Base of Aircraft Data (BADA) in order to simulate any type of aircraft realistically. This information includes, for example, the characteristics of the take-off and landing phases. Depending on the aircraft type and its speed, curve radii can be taken into account.

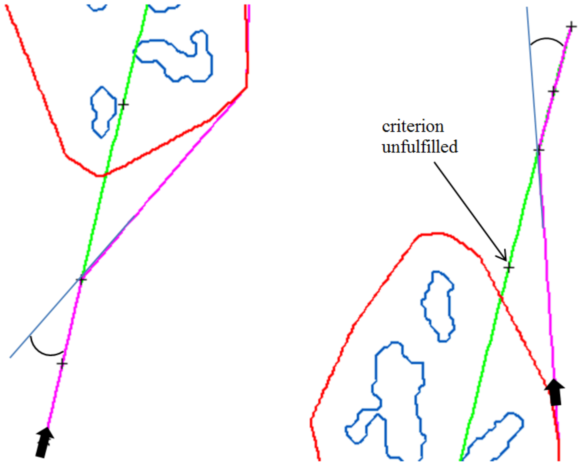
The second step is the simulation process. It comprises, inter alia, the display on a realistic radar screen, the execution of the aircraft motion, and the simulation of FMS functions.

In the last step, output data is produced. By using the recorded aircraft positions complex scenarios can be visualized and evaluated afterwards.

Thus, this simulation tool provides a realistic representation of the entire air traffic from gate to gate. In this context, NAVSIM can also detect conflicts between two aircraft. However, deconfliction is not implemented yet.

B. DIVMET

DIVMET was developed at the University of Hanover in order to investigate the behaviour of a pilot or a controller in conflict situations with adverse weather. As in the case of the 17 July 2010, the model can also be used for re-analysing adverse weather situations. Furthermore, theoretical studies on sector occupancies have been carried out (see [2], [6]).



(a) (b)

Fig. 2. The approach of the angular criterion (a) when leaving the planned route and (b) when rejoining it: The depicted angle is the heading change at a predefined waypoint (+) between the planned route (green) and the diversion route (magenta) which was determined to avoid the weather objects (blue). In (b) the heading change at the closest waypoint outside the risk area (red) would be greater than 30°, so the waypoint is neglected.

The central processes in the model start with scanning the weather polygons that have been extracted, for example, from radar data. The weather objects are then extended by a safety margin. When flying around a thunderstorm, the safety distance should be at least 10 NM ([7]), in cases of severe storms, i. e. a precipitation radar signal with a reflectivity greater than 40 dBZ, at least 20 NM ([8]). Depending on the pilot, this minimum distance is not respected in all situations. Referring to [9], this particularly applies for pilots of cargo flights. To be able to adjust DIVMET to various situations, the safety margin is kept as a variable parameter.

The extended weather object is enclosed by a convex hull that finally represents the risk area. The latter will be avoided in the simulation if the object affects the current route. When determining an alternative route, different options exist alongside the immediate diversion with direct flight to the destination. The options have already been mentioned in [10] as recent and future advancement of the model. They include a delayed leaving of the FPL route if the weather situation allows for it. Similarly, returning to the route at predefined waypoints has been implemented in DIVMET by now. The combination of these two options results in the option of smallest deviation from the planned route. For the three cases an angular criterion is active which ensures that the heading change does not exceed 30° at leave and return waypoints (fig. 2). This value was chosen in consultation with ATCO in Vienna.

Another parameter is the extension of the weather radar field of view. If one assumes a data link to the cockpit, the virtual range of the on-board radar is chosen to be that

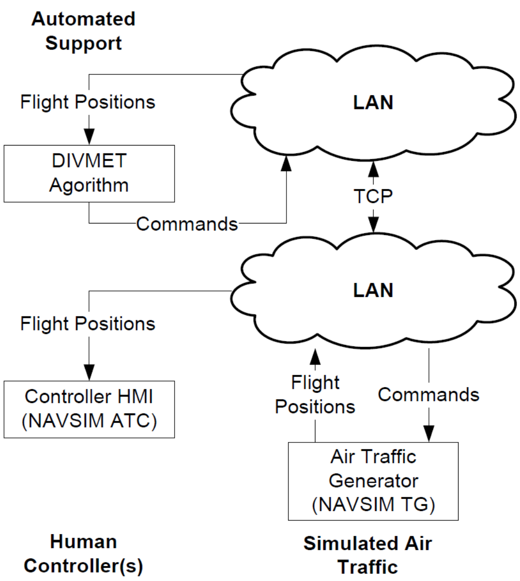


Fig. 3. Simulation set-up for using the support tool DIVMET with NAVSIM ([12]).

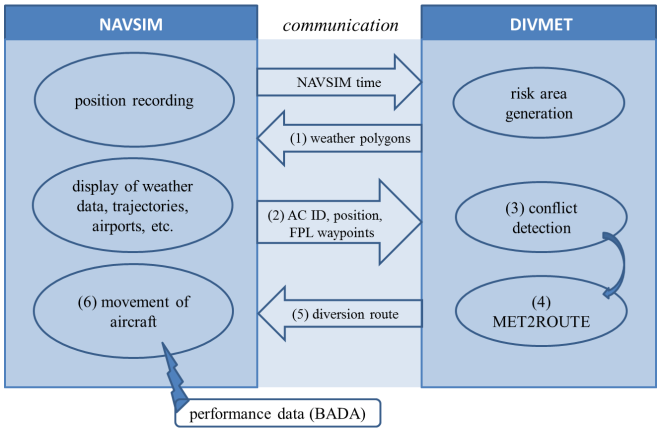


Fig. 4. Illustration of the information exchange whilst the coupling of DIVMET with NAVSIM: The schematic diagram points out the steps as described in the text and the essential functions of both models for the use in coupled mode. The route passed in step (5) only includes the cornerstones of the diversion route which is calculated by DIVMET or, more precisely, by the MET2ROUTE algorithm (see [10] for a description).

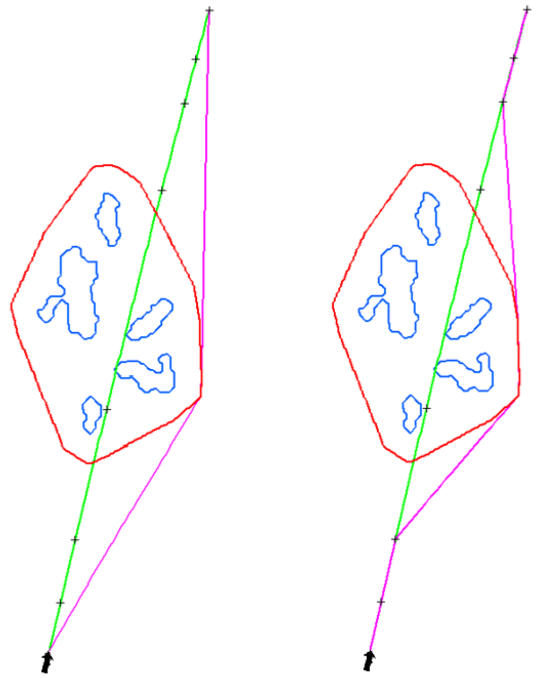
big that all weather objects are recognized. In this case, the current route must only be checked for conflicts in case of a weather update. If the field of view is limited, the route may need to be constantly adapted to new weather information.

DIVMET guides the movement of the aircraft by using a simple kinematic model. To reflect the flight performances more accurately, NAVSIM performs the movement of the aircraft for this case study.

C. *The coupling of DIVMET with NAVSIM*

For coupling the central DIVMET functions with NAVSIM, the simulation set-up, which is based on the concept described in [11], is schematically represented by figure 3. As described in [12], the interface to send and receive state and commands is implemented as a software library. A simple XML format is used as presentation layer. The storage of all exchanged information, e. g. the position data, enables a later replay and evaluations of the simulation scenarios.

The exchange of information between the two models is illustrated in figure 4 and takes place as follows: (1) DIVMET provides NAVSIM with the current weather polygons for visualization purposes. (2) DIVMET receives the aircraft ID, the current position and the flight plan data for each flight. (3) Based on this data DIVMET checks the remaining route with regard to weather conflicts. If there is none, the exchange of information for this flight is terminated and (2) is repeated for the next flight. (4) If a conflict exists for the remaining route, DIVMET calculates a diversion route. In the coupled mode, the directly-to-destination option and the alternative of smallest deviation are available (fig. 5). (5) DIVMET passes back the leave waypoint, the coordinates along the detour route and the return waypoint. (6) NAVSIM moves the flight along the adapted route by taking the respective aircraft performance into account.



(a) (b)

Fig. 5. Route options for calculating the diversion route (magenta) in the coupled mode of DIVMET and NAVSIM: The risk area (red), which includes a safety margin around the weather objects (blue), requires the aircraft to leave the planned route (green). In (a) the directly-to-destination option is illustrated. (b) shows the smallest deviation taking the angular criterion into account which is the reason for not rejoining at the first waypoint (+) beyond the risk area.

The steps (2) through (6) are carried out for all aircraft which are currently located in the simulation. If the simulation is performed in full view mode, the steps (2) through (6) are repeated after a weather update only. In case of a limited field of view they need to be repeated more frequently.

Step (1) is only required at times with new weather information. Polygons are available every 15 minutes from weather radar images. Due to interpolated images weather information updates are possible every 5 minutes as well. The extracted polygons are precipitation areas with a reflectivity of at least 37 dBZ as these values are often accompanied by lightning, severe turbulence and heavy precipitation ([13]).

In NAVSIM, all 1,800 flights that take place in the area of relevance are shown simultaneously by default. Flight plan routes are visualized as well as alternative routes if the latter are necessary for a flight. A great advantage of NAVSIM is that the actually flown route on 17 July 2010 is also shown on the screen, hereinafter referred to as CPR route. However, one can select a single flight, for which the FPL route, the CPR route and, where appropriate, the diversion route will be shown separately. Thus, differences can be observed at first glance. In a log file the positions of the simulated and CPR routes are recorded every minute. With this data a detailed analysis and comparison of the detour can be made and one can draw conclusions about the benefits and the knowledge of weather information.

In the simulation the start time of the FPL route is adjusted to the start time of the CPR route, which in turn means that the simulated flight starts at the same time, even if the flight was scheduled to start earlier (or later). The purpose of this adjustment is that both flights can be compared with each other appropriately since they are performed on the basis of the same weather situation. The reason for the delayed departure time of the actual flight is of secondary importance for this case study – delays in operating procedures at the airport may have different causes.

Two more aspects are not taken into account so far. On the one hand, the information from the weather radar is limited to the region of the Central European Weather Radar Network (CERAD, see fig. 1). Flights that go beyond might have avoided more weather conflicts that cannot be taken into account in the simulation. On the other hand, weather objects, which cover the current position or the destination airport, are ignored by DIVMET so far. That is why flights head through these risk areas in the simulation. In reality, there are other solutions, e. g. switching the destination airport or remaining in holdings.

III. Application Example

Various applications are conceivable for the 17 July 2010, e. g. the observation of a single aircraft or the handling of the entire air traffic over Central Europe. The last-mentioned scenario is a target-aimed part of the MET4ATM project for the purpose of making statements on sector capacities.

Initial studies refer to a single aircraft in order to clarify differences caused by the chosen safety margins. In addition, the field of view is varied and the avoidance behaviour with full view is compared with the pilot's view mode. The latter case implies a limited field of view for the pilot, especially if his knowledge is based on the on-board radar. According to [10], typical dimensions for the field of view of the on-board radar are a range of at least 80 NM and an aperture angle of about 120°. When referring to the pilot's view mode below, these values are intended.

Since the deliberate return to the FPL route seems closer to reality than the directly-to-destination alternative, we only consider the first option, the smallest deviation, for this first application. Additionally, the more a flight deviates from its FPL route, the more communication might be necessary between the ATCO and the pilots (and possibly the adjacent ATC sectors) and the bigger is the workload.

For the flight AUA131L from Vienna (LOWW, Austria) to Frankfurt (EDDF, Germany) two simulations for the safety margins 5 NM, 10 NM and 15 NM are performed – each in the pilot's view mode and with full view.

IV. Simulation Results

An overview of the simulated routes based on the recorded position data every minute is given in figure 6.

The depicted weather objects are only those that have been relevant for the route guidance at the particular time. This means, for example, that the weather polygon with ID 37 has contributed to the course shortly after the start (14:35 UTC) just like the object with ID 22 at a later time (15:05 UTC). Thus, the figure illustrates that the CPR route of AUA131L apparently falls below the aforementioned minimum safety distance of 10 NM at two objects (ID 31 and ID 22). In case of the weather object with ID 14 it has to be stated that its influence is limited to the routes which are coloured in blue (5 NM safety margin). The actual flight was not noticeably affected (see fig. 7) as the reflectivity was less than 37 dBZ while passing through this area.

In this context it should be mentioned again that only those weather objects which exceed the threshold are considered in the route determination. The actual clouds and thunderstorms perceived by the pilots usually have a larger spatial extent than the represented ones. Moreover, the update interval of the pilot's on-board weather radar is less than the applied interval of the interpolated radar data (5 min). The application of even more frequent weather updates for the route determination might be helpful and would in principle be possible. Due to extensive computation times this case study has been carried out without it.

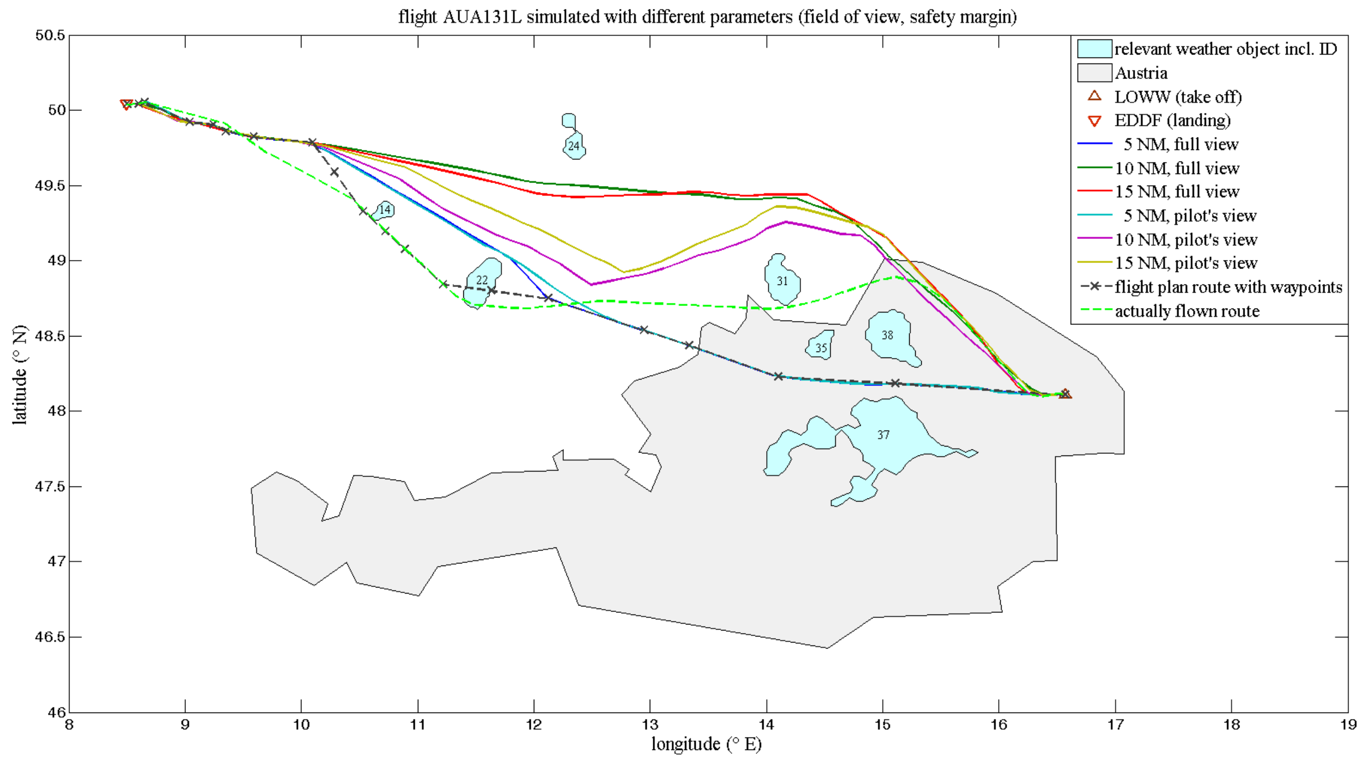


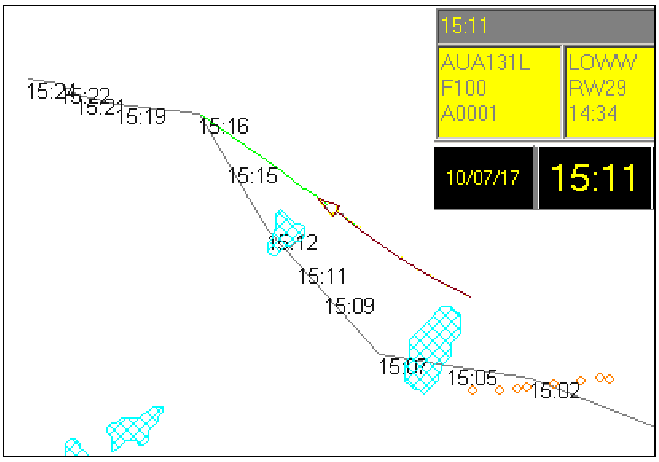
Fig. 6. Comparison of several simulations with the FPL route and the CPR route on 17 July 2010: For each of the three chosen safety margins two simulations have been performed. In pilot's view mode, the range of the on-board weather radar is 80 NM and the aperture angle is 120°. In full view mode all weather objects can be recognized at the same time. The latter generally results in more beneficial diversion routes than with a limited field of view. Note that only a selection of weather objects is displayed, namely those which have been relevant for the route guidance at the particular time. Thus, it appears that the actual flight does not consider a minimum distance of 10 NM to the hazards with ID 31 and ID 22, respectively. The situation for the weather object with ID 14 is explained in figure 7.

Whilst the trajectories with a safety margin of 5 NM reveal hardly any differences between pilot's view and full view, larger safety margins result in obvious differences between the chosen fields of view. In full view mode, all weather objects are known at the same time. While avoiding the weather object with ID 31, obstacles in the medium part of the FPL route have already been recognized. Thus a return ahead of the object with ID 22 can be excluded. In the pilot's view mode, however, these obstacles have not been detectable at the same time because they were outside the range of 80 NM. Therefore, the corresponding routes proceed initially in southwestern direction before they head to the same rejoin waypoint as the other simulated flights. Due to this manoeuvre two flights took longer detour.

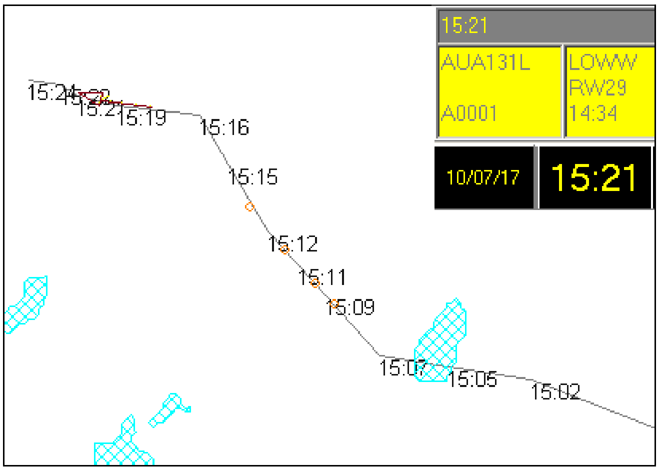
All in all, figure 6 clearly shows that the simulations with 5 NM safety margin result in the smallest deviation from the FPL route. Using safety margins of 10 NM and 15 NM, the simulated routes significantly differ from the middle section of the FPL route. In the initial flight phase, however, they coincide with the actual flight, which then returns to the planned route – by falling below the minimum safety margin. As a result of returning, this flight is delayed even though it shortens the FPL route in the final section. The reason for the latter manoeuvre is not known. Situational regulations in the Approach Control would be obvious.

To quantify the differences between the shown routes, the path lengths of all routes are determined. The deviations of the simulated trajectories from the FPL or CPR route enable an initial evaluation of the benefits of the discussed methodology for ATM purposes, although significantly more flights and data must be evaluated in order to make basic statements.

The distances and deviations for the simulations represented in figure 6 are listed in table I (fv: full view, pv: pilot's view). The FPL route results in a track length of 358 NM. In correspondence with figure 6, the distance of the CPR route is longer by 14.1 NM. This equals to approximately 4 % of the planned route. Also the flights in the pilot's view mode with safety margins of 10 NM and 15 NM, respectively, differ from the FPL route in this order and are delayed if one assumes the same average speed. In full view mode the comparably simulated flights should arrive earlier than the planned flight (10 NM) or almost simultaneously (15 NM). However, in these cases the deviation from the CPR route is largest. The most striking reductions in track length with regard to the FPL have



(a)



(b)

Fig. 7. Screenshots of the NAVSIM workspace for the simulation with a safety margin of 5 NM and full view mode: The second half of the FPL route is depicted as grey line. The time stamps mark the scheduled transit times which are adjusted to the departure time of the CPR flight. Weather objects are displayed in blue. (a) is a screenshot at 15:11 UTC, showing two weather objects at the FPL route. The aircraft's current position represented by the triangle is close to the northern object, heading along the given diversion route (green) until the FPL route will be rejoined. The actual flight (orange dots) is delayed by approximately 6 min. The performed routes of the latest five minutes are shown in the same colour as the current position. (b) implies that the intensity of the northern weather object might have weakened when the actual flight passes through the corresponding area at 15:21 UTC. The simulated flight is approaching its destination meanwhile.

been achieved with 5 NM safety margin (up to 8 NM less). At the same time the smallest deviations from the FPL have been achieved. It is worth pointing out that, fundamentally, conflicts with other approaches as well as the destination airport working to capacity may occur due to the earlier arrival time. The regulation of such problems is not taken into account in DIVMET or NAVSIM yet.

It remains to be emphasized that all simulated routes are shorter than the CPR route.

TABLE I
TRACK LENGTHS AND DEVIATIONS FROM FPL AND CPR ROUTE

route parameters	track length (NM)	deviation from FPL route (NM)	deviation from CPR route (NM)
FPL	358.0	0.0	-14.0
5 NM, fv	351.0	-7.0	-21.0
10 NM, fv	353.6	-4.4	-18.4
15 NM, fv	357.9	-0.1	-14.1
5 NM, pv	350.0	-8.0	-22.0
10 NM, pv	370.3	+12.3	-1.7
15 NM, pv	371.3	+13.3	-0.7
CPR	372.0	+14.1	0.0

V. Conclusion

The research in this paper is a part of the project MET4ATM, which deals with the air traffic over Austria on 17 July 2010. The aim is to optimize the routes in case of existing weather hazards in favour of a lower workload for the ATCO. The latter can be achieved in particular by means of appropriate weather information that leads to the benefit of keeping route modifications as low as possible. For this purpose, the planned routes are simulated by avoiding weather risks and evaluated in terms of deviations from the FPL and the actually flown route.

The results shown above are just the beginning of simulating a scenario which covers 1,800 flights in the airspace of interest on that day. The 2D weather diversion model DIVMET was coupled with the global 4D air traffic simulation model NAVSIM. The aircraft movement is realized by NAVSIM taking the aircraft performance into account. DIVMET calculates any necessary diversion routes to avoid the weather hazards and passes the data to NAVSIM.

The single aircraft treated in this paper is flight AUA131L with destination Frankfurt that started in Vienna at about 14:35 UTC. As the figures shown above reveal, this flight seems to be worth investigating since it deviated from its planned route and should therefore have caused additional communication with the ATC.

In the simulations, a return to the planned route was preferred as long as the heading change at the return point was not greater than 30°. The direct route to the destination would be another option for further studies which would come close to the SESAR vision of the 4D-trajectory based free-flight. The simulations described were performed in the pilot's view mode to get approximately real flight conditions based on the limited weather information of a pilot, which in particular is based on the on-board weather radar. Also the full view mode is used, which implies that all weather objects are detected at the same time. This suggests a data link into cockpit. For each of the two modes, three simulations were made with different safety margins to the weather objects. With 5 NM, the predetermined minimum distance of 10 NM (see [7]) was fallen below. With 10 NM and 15 NM, respectively, the threshold was taken into consideration.

The flown trajectory of the actual flight suggests that the relevant weather information was considered in the initial flight phase as the aircraft deviated from the FPL route to the north and thereby apparently complied the minimum safety distance to the risk areas. However, in the further course the pilot headed back to the FPL route and fell apparently below the stated minimum distance.

In the simulations taking into account this safety margin, the FPL route was rejoined only in the arrival section of the flight. The weather objects were flown around further north than the actual flight did. Nevertheless, there were differences with regard to the track lengths between pilot's view and full view mode. Owing to the limited field of view, not every hazard could be detected in the middle section of the planned route, so the possibility of early rejoining was considered. A few minutes later, however, this resulted in new weather conflict situations, so that finally a detour was taken compared to the case of full view, in which the path lengths were even shorter than the FPL route distance. The avoidance of delays, despite flying around weather risk areas, is therefore a first indication of the potential that a data link into the cockpit could entail with regard to the route optimization.

If the pilot's willingness to apply smaller safety margins is higher, deviations from FPL naturally are more rarely necessary. This is illustrated in the simulation with a safety margin of 5 NM. In the selected case, pilot's view and full view mode differ only minimally. The simulated routes were shorter (about 2 %) than the FPL route and even significantly shorter (6 %) than the actually flown route.

The fact that all simulated routes were shorter than the actually flown route illustrated the potential advantage the coupling of the models DIVMET and NAVSIM can bring for ATM and, not least, for the airlines. Nevertheless, for the simulated routes the deviations from the flight plan were markedly larger than for the actual flight. Moreover, other flights will certainly yield some different results as well. Although conflicts between aircraft are not resolved by these models so far, extensive simulation scenarios will allow numerously more evaluations and conclusions for the case of 17 July 2010 soon. The inclusion of sector capacities in these studies is planned as well.

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