Dynamic Route Optimization Based on Adverse Weather Data

Christina Schilke, Peter Hecker
Institute of Flight Guidance
Technical University Braunschweig
Braunschweig, Germany

***Abstract*—As air traffic remains a growth market despite the economic recession in summer 2008 and current forecasts still predict an increase in the air traffic worldwide, it becomes necessary to change current traffic procedures and to integrate innovative ATM technologies in order to meet future requirements. The air transportation system is a highly complex system with innumerable influencing factors. One of the main goals is to preserve or even improve the current safety level, however environmental and economic aspects become more and more important.**

This paper describes an aircraft-based trajectory optimization system that generates efficient flight paths around convective weather. These flight paths are based on regularly updated weather radar data from which a nowcast is established.

Nowadays, the flight crew is provided with weather forecasts for the planned route and its surroundings before the flight. Within this research concept it is assumed that in the near future regular updates are transmitted via data link to the aircraft. Through an early optimization of the flight path, an ecological efficient route planning can be achieved which allows a minimization of detours and a reduction of fuel burn at the same time.

Keywords-adverse weather conditions; radar data; nowcast; trajectory optimization

I. Introduction

In future ATM concepts it is targeted to introduce four-dimensional business trajectories so that aircraft are able to organize their flight path from A to B more efficiently and safely than it is possible nowadays [1,2]. The four dimensions comprise all three space dimensions as well as the time.

In principle, the airline will be responsible for generating such a four-dimensional business trajectory before the aircraft takes off whereas updates during flight will be executed autonomously onboard. Subsequently, the determined trajectories will be transmitted to air traffic control where it will be analyzed if the trajectory leads to conflicts with trajectories of other participants in airspace. If conflicts are detected, the trajectories have to be redetermined in consideration of further boundary conditions.

In order to plan such four-dimensional trajectories, several types of advice are necessary. Information about the weather along the flight route is essential for the flight planning [3] and flight execution. Another one is information about noise protection areas. These are urban areas which should be not flown through due to noise minimization. This is in accordance with the ecological ambitions of future ATM concepts [4]. Another important data source concerns the traffic situation and the Notices to Airmen (NOTAMs) [2]. However, in this first concept only horizontal regions of adverse weather are considered. A concept for a route optimization application has been developed which will be validated in future in order to show the possibility of reducing detours during the existence of convective weather. This is one contribution to the ecological and economic ambitions in the future supporting the 4D-trajectory management under adverse weather conditions.

For the storage and the handling of the different types of data during flight in an aircraft, an on-board database has been set up. Through this database it is possible to store, to update, and to continue processing the necessary data before the flight and during each flight phase. This database should then comprise different types of data with which the route can be optimized. Within this study, only radar data has been analyzed, decoded, and stored in the database yet as mainly areas of high convective activity have been considered for the route optimization. For future applications it is possible to extend the database with several other types of data which are relevant for a safe and efficient flight execution.

From this radar data which are regularly transmitted via data link, nowcasts are generated during the flight providing information on the direction and the speed of the moving convective cells. Based on this information it is possible to estimate the position of the convective cells in the near future and to adapt the flight path in an efficient way so that detours can be minimized. The flight path is adapted during flight on board with all necessary information which are stored in the on-board database and then negotiated by Air Traffic Control (ATC) via the future data link.

II. Background

A. The Influence of Adverse Weather on Flight Performance and Safety

Severe weather such as e.g. thunderstorms affects both safety and efficiency of air traffic [5].

In 2013, adverse weather conditions were with about 22,000 occurrences from about 85,000 within the top 10 of contributors to aviation occurrences within the EASA member states [6] (see Fig. 1). The main causes were severe turbulences, icing, wind shear, and thunderstorms. Occurrences can be accidents, incidents, or occurrences without safety effect.

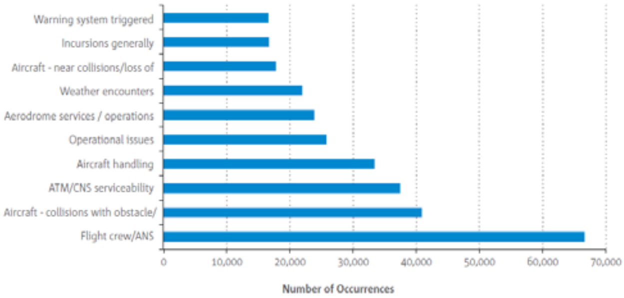

Figure 1. Top 10 Aircraft-Operation-Related Occurrences in the ECR [6]

Not only occurrences, but also delays can be caused by severe weather. According to [7] weather was with about 0.4 minutes average delay per flight of 10 minutes one of the main contributors to flight delays in 2012. Mainly, the weather-related delay is influenced by the decrease of the capacity of airports during adverse weather conditions rather than by the need to change flight routes.

B. Cumulonimbus Clouds/ Thunderstorm

Cumulonimbus clouds (CBs) cause several weather phenomena that induce risks for the air traffic. CBs are massive and thick clouds with a high vertical dimension that occur in a vertically unstable humid atmospheric layering. In extreme cases they extend up to the tropopause which is in average almost 40,000 ft high [8]. A CB often comes along with a thunderstorm.

Generally, there are different types of precipitation during a thunderstorm, such as rain, hail, snow pellets, and/or snow [9]. Due to the vertically unstable layering, there are heavy turbulences in a CB. The strong vertical movements are one cause for the heavy precipitation. Besides heavy precipitation and turbulence, also icing and lightning can occur in a CB [9].

The heavy precipitation can lead to an engine failure and the hail can damage the structure of the aircraft. Outside the cloud, shear turbulence is encountered several thousand feet above and up to 20 NM laterally from a severe storm [10]. Below and within the cloud, there are strong winds, especially up and downdrafts. In the upwind zone which normally expands from the atmospheric boundary layer in vertical direction up to the tropopause there are upwind speeds up to +13,000 ft/min (i.e. +65 m/s) [9]. This upwind is caused by thermic instability, i.e. convection. The downdraft zone is located between medium heights and the ground. The wind speed within the downdraft zone is with -5,000 ft/min (i.e. -25 m/s) regarding the absolute value a little bit less than in the upwind zone [9].

C. State of the Art – Navigation around Convective Cells

Nowadays, the pilots get the briefing package from their dispatcher before flight. The briefing package contains weather forecast, NOTAM, and navigational information as well as information of significant weather on the planned flight route, etc. [11]. The flight route is planned under consideration of the weather forecast. Forecasted convective cells are avoided regarding the route planning. However, flight route planning cannot always consider convective areas, e.g. as the forecast is imprecise and misses convective cells or as the convective weather covers a large area. In those cases the minimum time track is planned.

During the flight, pilots obtain supplemental weather information in order to determine whether the flight can be executed as planned or if modifications to the future flight route must be implemented due to hazardous weather conditions. However, in most cases the flight crew only gets restricted information on weather en route. Mainly, they get information on areas of high reflectivity from their on-board weather radar, information on lightning strikes from their stormscope, and additional information on the weather situation at several airports (METARs), and reports from other pilots (PIREPs). Little by little, the flight crews have Electronic Flight Bags (EFBs) and an internet connection on board where they can get current weather information.

If the flight crew has to rely on their on-board weather radar as they do not have updated precise external weather information, they navigate with a lateral distance of several nautical miles around the convective cells. There are different international rules concerning the distance to keep for circumnavigating a storm cell. The Federal Aviation Administration differs between the intensity of a storm cell. If it is a severe storm, the flight crew should avoid the cell by at least 20 NM [12]. Though a lateral safety distance to thunderstorms is mandatory, in [13] a study is described where it was found that other factors such as the storm growth or decay, the direction of storm motion, or characteristics that the pilot sees, e.g. the presence of thunderstorm turrets, and also personal factors such as the pilot’s risk tolerance are likely to play a part in pilot decision making in how far they keep a safety distance. Besides, there is a huge difference between cargo carriers and private business jets. Most cargo pilots are much more prepared to take a risk than pilots of private business jets who are much more cautious due to passenger comfort.

When using the on-board weather radar, there are some limitations such as the restricted range and angle of beam. The flight crew only can see cells in front of them with a maximum distance of about 160 NM. According to [14] the pilot flying

(PF) should set a range of 80 NM and the pilot not flying (PNF) a range of 160 NM. The aperture of an on-board weather radar is 115° [15]. In some cases the instrument has a vertical tilt option up to +/- 20° so that the field of view of the radar expands to a spherical rectangle [15].

Sometimes the flight crew also gets weather information from ATC who might have access to data of a ground weather radar system. Before the flight crew changes the current heading they have to contact ATC in order to get the clearance for the route change request and to ensure that the new route is free from traffic conflicts. In general, many heading changes are avoided as the communication should be kept to a minimum [16].

D. Problems Associated with the Current Situation and Research

Pilots suffer from different problems nowadays, such as high mental workload, a lack of reports, and a lack of weather information during flight. This is explained in detail in this chapter.

1) High Mental Workload

First of all, they get a vast amount of weather information before and during the flight which are graphical weather charts, textual weather, and weather information via voice radio. Then, they have to use and to interpret the obtained information correctly, as well as to select all important information. Finally, they have to integrate all those pieces of information mentally in order to get an overview picture of the complete weather situation. In other words, they have to accomplish much workload to be aware of the situation.

2) Lack of Reports

Another problem is that during flight, there is only little weather information available. Pilots are urged to volunteer reports of weather conditions which are called PIREPs. They are to help pilots to avoid areas of severe weather conditions and to determine escape routes. However, the problem is that those reports are not evenly distributed in either time or space [18]. Furthermore, there are only a few pilots that report good weather conditions, although that would be helpful in order to determine escape routes.

3) Imprecise Forecasts, little Current Weather Information, and few Heading Changes during Flight

Sometimes the forecasts are not precise enough in order to plan the shortest path around an area of convective weather, or the convective area is too huge in order to plan a flight path around this area. In both cases, the flight crew has to fly unnecessary detours as they do not have the whole picture of the weather situation, but only have the little extract of it from their on-board weather radar. The fact that they probably do not fly the shortest path may result in delays and extra fuel burn.

Another problem that contributes to the detours is that the flight crew has to contact ATC for each route change request. This results in less few as possible heading changes, so that they do not fly the absolutely shortest route.

III. Concept for Route Optimization

In order to enable an optimized tactical flight planning as well as an optimized adaptation of the flight paths due to unexpectedly occurring weather phenomena during the flight, a new holistic approach has been considered which supports the 4D-trajectory management in the frame of SESAR Joint Undertaking and its counterpart in the U.S.A. NEXTGEN.

The overall research concept envisages a route optimization regarding a minimization of detours under consideration of the current and nowcasted weather situation.

A. Overview of the Concept

The overall concept foresees that all necessary weather and operational data are uploaded into the on-board database and there are processed.

The pre-flight planning within the analyzed concept is similar as today. Before the aircraft takes off several types of information can be stored in the on-board database and provided to the flight crew, such as:

- weather forecasts
- information on significant weather phenomena, such as e.g. turbulence and icing (SIGMETs)
- information on volcanic ash clouds (ASHTAMs)
- notices that are filed with an aviation authority in order to alert flight crews of potential hazards that could affect the safety of the flight en route or also at the departure, alternate, or destination airport (NOTAMs)
- data on noise protection areas which should not be flown through
- and navigational information on the initially planned route.

This study focusses on the airborne flight planning considering dynamic in-flight weather information. The concept envisages that the flight crew regularly receives current radar data from ground radar stations (in general all 5-15 min) via data link during flight, which provide detailed meteorological information on areas of high reflectivity. Of course, for the future, it is also necessary to consider NOTAMs and SIGMETs which are issued during flight, as well as updated wind fields for the in-flight route adaptation and optimization.

From these radar data, the weather hazards, i.e. the convective areas, are marked as polygons. From the movement of the polygons over time, a nowcast can be generated and the route can be optimized under consideration of the nowcasted convective areas. For the optimization, a flexible trajectory generation is considered. That means, the aircraft stays at the current altitude, but flexibly changes the heading. In general, pilots prefer horizontal circumnavigations of thunderstorms to vertical maneuvers in order to save fuel and time and for safety reasons. The flexible trajectory planning is in accordance with future concepts with existing data links. The planned trajectories will then be sent via data link to ATC so that the clearance of the requested trajectory can be negotiated.

This study considers a presentation of adverse weather in a combined manner so that all hazards are depicted in a three dimensional way, i.e. the horizontal two dimensional areal expansion as well as the projected position of the weather hazard in the future. Thus, there is no need for interpretation of the image on board required by the pilot. Additionally, as the route is planned and optimized under consideration of the location of the adverse weather in the near future, it will be analyzed if delays can be minimized. For a future application, it is also necessary to consider other flight route limitations as e.g. other meteorological constraints, restricted airspaces, and other traffic. It is also possible to benefit from wind fields in order to save fuel.

B. System Architecture

The route optimization application is composed of three main components:

- The database management system (DBMS)
- The nowcast algorithm
- And the route planning and optimization algorithms.

In the DBMS there are dynamic radar data stored that are regularly (every 5 or 15 min – depending on the radar data product type) updated. For the future, the database can be extended with the other above-mentioned relevant data for a safe and efficient execution of the flight.

The radar data are processed by the nowcast function which consists of different algorithms in order to extrapolate a future weather pattern. As soon as new radar data are in the database, the extrapolation function uses the new ones. The weather cell extrapolation function itself is based on a time interval of the radar data of 15 min and predicts the location of adverse weather for the following hour.

The route planning and optimization function regularly calculates an optimized route from the start position of the aircraft to the destination with consideration of the nowcasted areas of significant weather. In a later development, the route planning and optimization function could also consider other meteorological data, other traffic, restricted areas, and noise protection areas for the route optimization.

The system architecture is depicted in Fig. 2 and the different components of the system are explained in detail in the next sections.

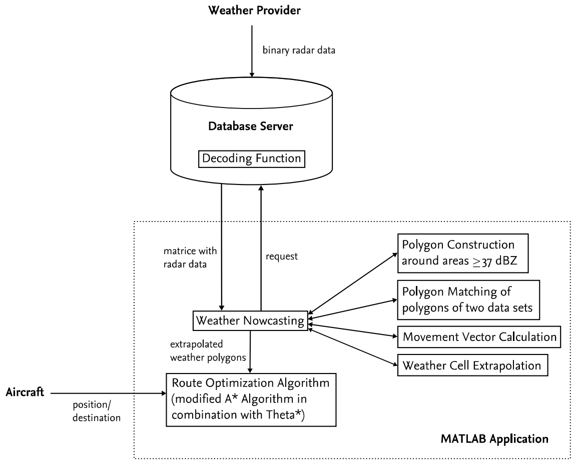

Figure 2. System Architecture of Route Optimization System

C. Database

The database is generated with PostgreSQL and mainly contains volume composite radar data from the German Weather Service (DWD).

Composite radar data are generated from the output of several weather radar stations and depict large-scale precipitation areas. This type of radar product utilizes all elevation scans during each volume scan to create the image. It is composed of the highest reflectivity from any elevation angle of the radar. Thus, it is a two dimensional depiction without any height information.

A thunderstorm can be detected with weather radars as the reflectivity in such areas is very high due to thick wet clouds. The thicker and wetter the clouds are the higher is the radar reflectivity. The unit within the composite radar products is dBZ which is a degree of reflectivity.

The spatial resolution of the composite radar data from the DWD is either a 2x2 km or 4x4 km square grid (depending on the product type) of Germany which is based on the polar stereographic coordinate system. The image is recalculated every 5 min or 15 min, respectively.

Besides the radar data there are several small functions in order to decode the binary radar data and to store them in the database. The database is built up in a modular way that extensions are easily possible.

D. Nowcast Function

For this initial study with the purpose to show the possibility of reducing detours, all algorithms of the route optimization application are written in MATLAB.

The first algorithms of the nowcast function create polygons around areas of adverse weather, then the following ones track the polygons from the two different radar datasets, and finally they match the polygons and create a movement vector from the position of both polygons which is used in order to predict the future position of the storm cell.

1) Creation of Polygons

For modelling purposes, thunderstorms can be understood as impermeable objects which therefore have to be circumnavigated. For convective weather one can assume the reflectivity threshold of 37 dBZ which is categorized as a moderate thunderstorm according to [18]. Is the reflectivity value ≥ 37 dBZ, there is in most cases heavy precipitation, severe turbulence, hail, and lightning. In addition, experience has shown that pilots often avoid flying through areas of reflectivity ≥ 37 dBZ [19].

Thus, the algorithm creating the polygons around areas of high reflectivity takes 37 dBZ as threshold. That means, every grid point which is ≥ 37 dBZ is within a polygon marking a no-go area. The polygons are created by a contour function.

As all thunderstorms create potentially hazardous turbulence around the cell area, a safety zone has to be implemented around those polygons marking the adverse weather region. However, in this initial study, the lateral safety zone has not been implemented yet because this zone has no effect on the validation later as the polygons in the reference scenario will not have such a safety zone, either.

Finally, the polygon creation algorithm calculates the centroid and the surface area of each polygon.

2) Tracking of Polygons

There are several possibilities of analyzing the movement of a convective area. In [20] there are different methods of tracking described which are presented in the following part.

One of the first attempts to extrapolate radar echoes in order to predict storm movements has been accomplished in 1953 by Ligda. Between 1960 and 1980 research was going on in order to develop and test extrapolation techniques. In principle, the following two techniques have been established.

On the one hand, there is the area tracker described by Kessler in 1966 where radar reflectivity images from different times have been cross correlated in order to determine the motion vector for the entire precipitation field. Later, this technique was improved by Rinehardt who obtained differential motions within the echo field.

The cell tracker developed by Barkley and Wilk in 1970 identified individual storms and then determined the motion of each cell centroid. Dixon and Wiener improved this method in 1993 as they developed a cell tracker who also considered the splitting and merging of storms.

In this research the cell tracker who follows the centroids of the contours marking areas equal and higher than the determined threshold of 37 dBZ has been chosen for implementation. It examines the movement of storm cells by matching those found in the current scan to those found in the previous scan. This algorithm identifies individual cells within a convective storm instead of regarding the movement of the entire storm.

In order to match the polygons several characteristics of the current and the previous scan are compared. As a convective cell typically moves with maximal 2 km/min [21], the matching centroid is searched within a threshold radius concerning a defined time span between both scans. For information, typically, many atmospheric phenomena, such as storms, move with a lesser speed of about 10 m/s, which is 0.6 km/min [15]. This equals in general the background wind speed at 500 hPa. Thus, for a given time interval of 15 min between both radar scans the speed of the horizontal displacement of weather leads to corresponding travel distances of maximal 30 km (and on an average of 9 km). As well as the searching radius of the centroid is limited, there is also a limit concerning the area difference of the polygons of both scans if the cell does not merge with or split into other cells. The last characteristic concerning the current and the previous scan is the overlap. If one polygon from the current scan highly overlaps or contains the other from the previous scan, it is probable that the polygons are the same ones [22].

According to [23], two or more convective storms merge quite frequently to form a single storm, and a little less frequently a single storm splits into two or more storms. These merging and splitting are also considered in this study as well as the generation of new cells. Concerning merging and splitting at least one track is extended if the above mentioned conditions are fulfilled. If the above mentioned conditions are not fulfilled or a new cell has been developed, a new track is created for the unmatched storm cell which will be explained in the next section. The generation of new storm cells cannot be nowcasted with an extrapolation algorithm. However, they are followed as soon as they have been detected. That means that new developed cells which are existent in the latest radar scan are further considered for extrapolation even if they could not be tracked from both radar scans.

3) Vector Calculation

For the nowcast, vectors describing the movement of the cells are calculated. From the vector the direction and the speed of the movement can be defined. Every polygon from the current scan is associated to a polygon from the previous scan if possible. So, the movement vector can be calculated from the dislocation of the centroids. The speed is then the length of the vector in relation to the time span between both radar scans.

If a polygon from the current scan cannot be matched with another polygon from the previous scan, a vector from the mean value of all vectors in the area is calculated so that for each cell such a movement vector is calculated.

4) Nowcasting

Concerning the nowcasting, only the motion of the storm cells is considered. That means that the geometrical form and the size of the different cells stay the same as in the current radar scan. For the nowcast calculation, the current positions of all centroids are projected in the future with the calculated motion vectors.

In this study, the nowcasting time has been limited to one hour as in most cases the extrapolation accuracy decreases with time – depending on the considered type of weather phenomenon. For individual convective storms, extrapolation nowcasting decreases very rapidly with time as storm evolution cannot be mathematically described by the extrapolation algorithm. Thus, nowcasting times for convective storms are in most cases only useful up to 30 min [20]. However, the extrapolation method may be useful for forecasting the movement of supercell type storms, squall lines, or storm complexes for periods up to several hours [20]. According to [24] echo extrapolation techniques may be accurate out to 6 h for large-scale precipitation systems that are primarily stratiform.

E. Route Optimization Function

Concerning the route optimization, at first the shortest path from A to B is calculated without consideration of possible weather hazards along the route. If the flight time for the considered route exceeds one hour, the route has to be split into different route segments as the nowcast is in a lot of cases only useful for prediction times less than one hour.

The path optimization itself is composed of a modified A* search algorithm in combination with a Theta* algorithm. The pathfinding is based on the composite radar grid of the DWD.

The A* algorithm finds a least-cost path from a given initial node to one goal node. It follows a path of the lowest expected total cost. The disadvantage of A* is that only movements from one node to one of the 8 neighbor nodes are allowed so that the path headings are artificially constrained by the grid. Thus, the A* with this octile heuristic creates unrealistic looking paths. Therefore, Theta*, a variant of A*, has been implemented in this study in order to allow diagonal movements at any angles as long as both vertices have line-of-sight to each other.

In this study the cost values to fly through an area of convective weather are set very high so that the A*/Theta* algorithm avoids planning the route through such areas. In the case the extrapolation algorithm is not predicting the exact position of the convective area which can be the case during the evolution of storm cells, the path can be nevertheless finished – even if the start point for the next optimization is located in a thunderstorm area. In a realistic flight operation, the flight crew has besides this assistant system also a weather radar on board as a safety net with which they can detect new developed convective cells and circumnavigate around them. For further development within the framework of SESAR it is also possible to replace the extrapolation algorithms with nowcasts based on numerical weather models which are being developed by meteorological institutes. As those numerical models require much more computing time, such nowcasts cannot be generated on board of an aircraft as the possible computing capacity there is limited. Thus, they would have to be generated on ground and the calculated routes have to be uplinked to each aircraft.

Concerning the path optimization function of this research study, at a first step, an initial extrapolation and route calculation is done from the two input radar data sets which depict the weather situation at different times (see Fig. 3 and Fig. 4). All grid points where the radar reflectivity is ≥ 37 dBZ are inside red polygons marking the no-go areas. The first route proposition is marked with a green line.

The initial route calculation is a first approach to the generation of the flight path that could be flown. The shortest distance from the starting point to each grid point is calculated. Then a constant flight velocity is assumed and based on this the imaginary flight time to each grid point is calculated. For each grid point, a calculation of the extrapolation function is done in order to find out how the meteorological situation will be at the time the aircraft passes this point.

However, this initial calculation assumes the direct and shortest path to the target point, which maybe cannot be flown due to weather hazards on the shortest track. Therefore, several optimizing calculations are done in defined distance steps (see Fig. 5). Every distance step, the extrapolation is recalculated and the flight path is optimized again. The smaller the distance steps are, the more precise is the flight path optimization. However, this demands high computing time. Thus, it is important to find trade-off between the computing time and the accuracy.

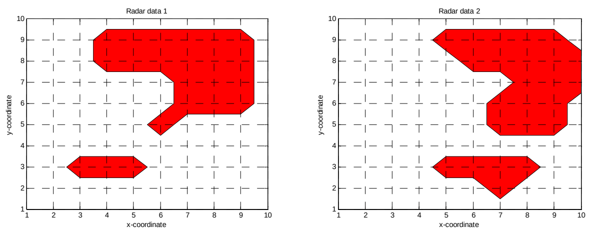

Figure 3. Provided Radar Data Sets at Different Times

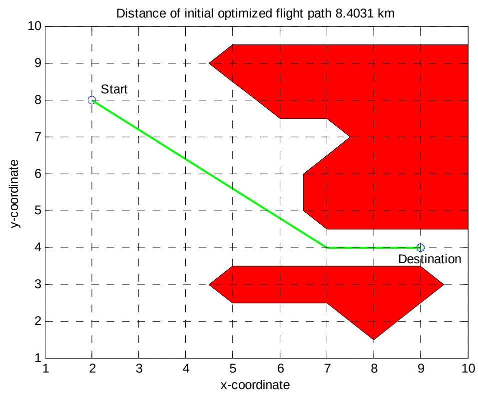

Figure 4. Initial Optimized Flight Path for the Flight Path Optimization

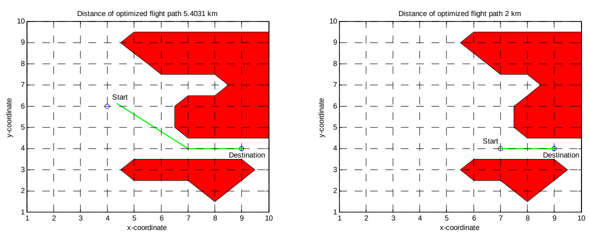

Figure 5. The Different Optimizing Steps for the Flight Path Optimization

IV. Conclusion and Perspectives

An aircraft-based trajectory automation system that regularly analyzes flight paths in en route airspace in order to find time- and fuel-saving corrections to existing weather hazards has been developed. There are several limitations of the system as it is an initial study in order to evaluate the potential distance saving that could be achieved with this concept. These limitations and associated enhancements for future developments are discussed in section A.

For the validation, it is planned to calculate the flight routes on the one hand with a reference scenario which simulates a scenario similar to the current weather avoidance procedures and on the other hand with the presented route optimization algorithm. This reference scenario is described in section B.

A. Limitations of the System and Future Work

Concerning the input data, there are limitations associated with radar composite images such as shading by mountainous barriers, shading behind major thunderstorms and convective cells, ground clutter, etc. In order to avoid these problems, a combination of radar data with satellite data could be used as input data for the creation of the no-go areas of severe weather phenomena.

At the moment, the nowcast algorithm is based on a simple extrapolation function in order to keep the computing time low. However, for the future a nowcast algorithm based on numerical weather prediction models could be integrated for the purpose of a ground-based trajectory automation system. Additionally, more flight-relevant data could be integrated, such as other meteorological information, information on restricted and noise protection airspaces, and traffic information.

For this first approach trajectories of constant speed and with no limitation on the turn rates are created. Thus, the aircraft performance is not considered at the moment. For the future, an implementation of an aircraft performance model and a limitation of the heading change would be useful.

As already mentioned, a lateral safety zone around the weather hazards has not been implemented yet because this zone has no effect on the validation later as the reference polygons will not have such a safety zone, either. However, for a safe flight execution, pilots have to consider a lateral safety zone around the cells.

B. Validation with Reference Scenario

The reference scenario for the validation of the system is loosely based on the current way of circumnavigating around weather hazards.

Concerning this reference scenario, a case where flown distance could be saved will be considered. This means, a case where pilots cannot strategically plan the flight route around a storm area, but where they have to tactically avoid convective cells with on-board weather radar support will be examined. This means that the simulated flight crew only can react to weather hazard areas within the field of view and, consequently, the generated trajectory also avoids only those.

In this study we assume a radar field of view with a horizontal circular sector described by the two parameters aperture and range. These parameters may be adjusted to simulate a given constellation. This means, the study will be accomplished with ranges of 80 and 160 NM in order to simulate the PFs and the PNFs field of view. Furthermore, the aperture may be varied from 115° to 360°. The latter represents a full view. Thus, during a flight through adverse weather, step by step new hazardous areas move into the field of view of the simulated flight crew.

Additionally to the field of view, a flexible trajectory concept will be presumed and the safety distance to keep to the storm cell will be neglected for two reasons. On the one hand, both scenarios should be comparable to each other, and on the other hand, if the reference scenario is based on the current situation, the safety distances kept by individual pilots depend on several parameters mentioned before that cannot be integrated in the simulation.

As the weather hazards, i.e. the storm cells are moving during flight, the radar scans have to be regularly updated. The stepwise dynamic radar scan update generates a similar stepwise response of the route adaptation. Consequently, the route adaptation will be smoother if the update rates are higher or a continuous space-time interpolation of both radar scans is done between the two time steps.

Concerning the route calculation, first of all, the shortest path neglecting all areas of adverse weather is planned. During the flight, this initial planned route will be manually changed as soon as an area of severe weather crosses it. It will be simulated that pilots can tactically plan for the range and the aperture of a radar with different configurations. As soon as the track crosses a convective weather cell, the obstacle avoidance maneuver will be simulated. Obstacles will be avoided in that way that the flight crew circumnavigates around the side where the additional distance seems to be shorter. After every defined distance or rather time, the algorithm will recalculate if there is an obstacle in form of a weather hazard crossing the flight path. If so, the avoidance algorithm will calculate a circumnavigation of this area. After each obstacle avoidance calculation, the diversion route becomes the planned route.

The case that there is no conflict route to the destination possible so that the aircraft has to land on an alternate airport or even to return to the home base will initially not be considered in this study – neither for the reference scenario nor for the proposed scenario.

C. Summary

The goal of this study is to create an application with which detours can be reduced. The database with the necessary data has already been set up. Furthermore, the combination of the nowcast algorithm with the route optimization algorithm has been created. The development of the reference scenario is ongoing.

The output will be a deviation route for each flight from A to B if there are weather hazards, i.e. thunderstorms with a reflectivity of ≥ 37 dBZ, along the flight path. For the validation this deviation routes are calculated for the two scenarios for different weather situations and different radar configurations in the reference scenario.

Finally, the distances of the deviation routes of the developed concept are compared to those ones of the reference scenario in order to analyze in how far detours can be reduced with the developed application within this research study.

This application only makes proposals for storm-cell-related circumnavigation. Thus, other weather conflicts as well as traffic conflicts or operational and airspace restrictions have not been considered so far.

Concerning the philosophy of SESAR, this research provides a first approach to the 4D-trajectory planning considering adverse weather conditions.

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