TEMPORAL DISPLACEMENT OF TAKE-OFF TIMES IF VOLCANIC ASH CLOSED THE AIRPORT

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Abstract

The eruption of Eyjafjallajökull in 2010 caused airport closures and thus delayed and cancelled flights. The necessary time shift to resolve airport related conflicts with volcanic ash zones is investigated in simulations. One day of remodeled volcanic ash data, representing the minimal predicted concentration, is used as volcanic ash advisories in the six hour interval operationally used yet. The targeted air traffic demand is chosen as a given demand for the volcanic ash scenario day. In different scenario trials the maximum allowed time shift for temporal conflict resolution is increased hourly until all conflicts are resolved. For the chosen scenario day and targeted air traffic demand all flights could be resolved with a mean of three hour time shifts.

1. INTRODUCTION

Within the DLR's project VolcATS (Volcanic ash impact on the Air Transportation System) the eruption of Eyjafjallajökull in April 2010 is reprocessed. One of the project's goals is to minimize the impact on air traffic.

In the event of an eruption the responsible volcanic ash advisory center will issue volcanic ash advisories. Operationally distributed volcanic ash advisory forecasts cover a six hour period and the area in which ash particles are moving during this time. Once a zone of volcanic ash (VA) is forecasted for an airport, that airport is inaccessible for the entire six hours. Flights planned within this time frame cannot take off or land inside the VA zones. For Eyjafjallajökull 2010, up to 80% of all cancellations were necessary due to inaccessible departure or arrival airports according to performed simulation [1]. These are about 14 800 flights for a worst-case simulation day. For Grimsvötn 2011, up to 62% of all cancelled flights were unable to depart and 30% were unable to reach their arrival airport for a single simulation day [2]. In case of Grimsvötn, there is no difference between a six hour period and an advanced one hour period volcanic ash forecast. The high number of cancelations is caused by the extensive ash clouds. A reduction of affected flights especially for take-off and landing may be possible by displacement of the take-off times. A classification of ash conflicts indicates that the departure and arrival phase of flights are the most affected ones [1].

Since the eruption in 2010 some more recommendations were made – or refined – concerning volcanic ash. Section 2 describes these valid recommendations and regulations. The performed simulations take into account the possibility to plan through forecasted VA zones of low concentration.

In case of volcanic ash forecasts flights can be pre- or postponed by several hours until the airport is free of ash. If these flights fit into the surrounding air traffic on the simulation day more flights can take place. Different time shifts were investigated for one day of air traffic and VA forecasts to identify the smallest necessary time span. The simulation approach used and results are described in section 4.

2. RULES AND RECOMMENDATIONS TO FLY WITH VOLCANIC ASH

Ever since the eruption of volcano Eyjafjallajökull in 2010, the severe influence of volcanic ash for air traffic is known worldwide. However, the issue has been taken into account earlier. The volcanic eruption in 2010 intensified work in this area.

Airspace zones were defined in May 2010 by EUROCONTROL to support the decision making process of member states [3]. The four introduced zones are the no-fly zone, the enhanced procedures zones (a) and (b) and the normal zone. One year later these zones were revised to the three zone model of volcanic ash concentrations distinguishing between low, medium and high concentrations [4].

In 2010 the ICAO [5] introduced the possibility to carry out a safety risk assessment (SRA) prior to flight operations in areas of forecasted volcanic ash contamination. Every air carrier needs its own SRA taking into account air operator specific procedures. The SRA is valid for each airline individually. EASA adopted the SRA in 2011 for Europe [4]. Simultaneously EASA recommended to '… avoid operation in visible VA or, where visibility of ash is impaired, avoid operation in discernible volcanic ash'.

The regulations in the member states differ from these recommendations. For example, operation in medium and high contaminated airspace is forbidden for the German airspace even if an SRA for high concentration is present [6] [7]. However, operation in low contaminated airspace is allowed. This regulation is used in the simulations globally; medium and high concentration zones are avoided.

3. SCENARIO DESCRIPTION

Simulations have been performed to determine the necessary time shift allowing avoidance of forecasted volcanic ash at take-off. One day of the eruption of Eyjafjallajökull in 2010 is simulated with focus on flights having airport related conflicts with forecasted volcanic ash clouds.

3.1. Scenario Day

Day of simulation is April 17th, 2010. This particular day was influenced most by volcanic ash, evident by a significant difference between demanded flights and performed flights [8]. Only about 5 100 flights took place while 17 200 flights have been canceled due to the forecasted volcanic ash regions, summing up in a demand of 22 300 flights.

3.2. Air Traffic Data

The real air traffic data for April 17th, 2010 does not contain flights that start in a forecasted volcanic ash cloud. A typical air traffic demand is necessary for the simulation. Looking at the same day of the week, both, one week earlier and one week later would be suitable as traffic demand [8]. According to [8], the traffic on the 24th was '… almost back to normal', which is why this day is used as the air traffic demand reference.

Air traffic data was downloaded from the demand data repository (DDR) of EUROCONTROL [9]. Round trips and flights shorter than 22 NM (these flights will not reach relevant cruise altitudes) are excluded. The considered time frame starts at 9:00 pm the day before, and end at 3:00 am the next day. The resulting scenario contains a demand of 21 506 flights.

3.3. Volcanic Ash Data

The forecast information of volcanic ash is provided by the DLR Institute of Atmospheric Physics. It uses the three zone model distinguishing between

- low (0.2–2 mg/m³),
- medium (between 2-4 mg/m³) and
- high (more than 4 mg/m³)

concentration, as specified by the Volcanic Ash Advisory Center London [10]. The output region covers 30° west to 35° east and 35° to 75° north. The ash forecast is divided into three altitude ranges:

- from ground to FL200,
- FL200 to FL350, and
- FL350 to FL490.

The upper height boundary differs from the operationally defined FL550 in [11] section 3.4.5 caused by the upper limit of the calculation model used. Detected or modelled volcanic ash between these specified height boundaries will cause a zone over the full interval. The remodeled VA data results in a sequence of nowcasts every three hours covering one day. To generate the region in which volcanic ash is moving – like VA forecasts – every nowcast is valid from T-3 to T+3 hours depending on its timestamp T. Thus, the different VA nowcasts overlap in time. As an illustration, Figure 1 shows a detail of the volcanic ash data at midnight (left) and at 3:00 am (right). From midnight VA zones $A_{1\text{-}2}$ and $B_{1\text{-}2}$ are active until 3:00 am while VA zones $B_{1\text{-}2}$ stay active and C became active.

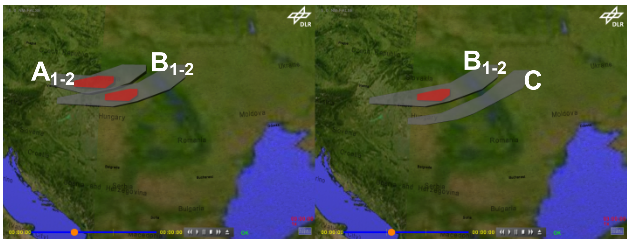

Figure 1 Moving VA zones covering six hours at midnight left and at 3:00 am right.

Following two different versions of VA nowcasts are provided:

- high-emission scenario, these nowcasts take the *maximum* calculated concentration from five different distribution models respectively.
- low-emission scenario, these nowcasts represent the model with the *lowest* calculated concentration in sum of the same five distribution models respectively.

It is assumed that the real amount of volcanic ash is between these two scenarios. Comparing the forecasts from 2010 with real world data in retrospect, the low-emission scenarios turn out to be more realistic. Therefore, the low-emission scenario is used.

In line with the regulations in section 2 for the German airspace, the simulations plan flights through forecasted VA zones of low concentration. VA zones of medium and high concentration are no-fly zones.

The corresponding nowcasts of the low-emission scenario with medium and high concentration zones are shown in Figure 2.

Figure 2 Medium (gray) and high (red) concentration zones of the low-emission scenario. Situation at midnight, 3:00 am and 6 am from left to right

4. TEMPORAL DISPLACEMENT OF TAKE-OFF TIMES

Because volcanic ash forecasts may cover whole airports, take-off and landing is not possible and can only be solved by shifting flights in time. For determining the necessary time shifts for flights with airport related conflicts with volcanic ash zones, these flights will be separated from the air traffic data (demand) into the set F_{airp}, as shown in Figure 3. A conflict exists if a defined separation minimum is violated. Two different types of conflicts are defined as follows:

- Different trajectories are separated if they have either a vertical distance of at least 1 000 feet, or a lateral distance of at least 5 NM (3 NM below FL100).
- Trajectories are separated from 4D-volumes like VA zones if they do not penetrate them.

In detail, conflicts are categories by the flight phase of involved aircraft. An airport related conflict does not start later than two minutes after take-off or does not end earlier than two minutes before touch-down.

The air traffic demand contains 21 506 flights is divided into the two sets F_{airp} and F_r as shown in Figure 3 below. From 21 506 flights (demand) 323 flights have an airport related conflict and are assigned to set F_{airp}, see Table 1. The remaining 21 183 flights are assigned to the set F_r. In F_r 381 flights are in conflict with medium or high VA concentration at climb, cruise or descent phase of flight. In total, 704 flights (3.27%) from 21 506 flights are in conflict with VA zones. Thus, the air traffic is only slightly affected by VA zones in this scenario.

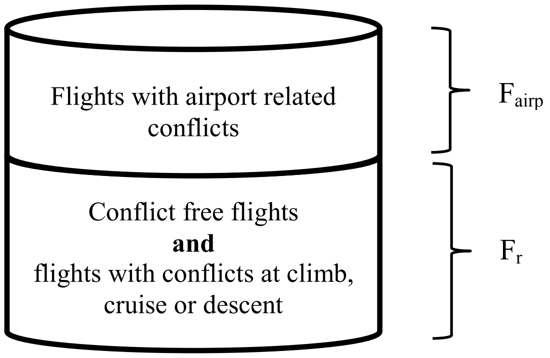

Figure 3 Distribution of air traffic demand into sets depending on conflicts with volcanic ash zones

Table 1 Number of flights in F_{airp} and F_r

	Flights	*Conflicting flights*
F_{airp}	323	323
F_r	21 183	381
All	21 506	704

The set F_{airp}, consisting of flights with airport related VA conflicts, is used to examine temporal resolutions to avoid conflicts between trajectories and volcanic ash zones. For the first approximation, only conflicts between trajectories and VA zones are considered. In the second stage, conflicts between trajectories are also considered in addition to the VA zones conflicts. The second stage causes an additional temporal shift of take-off times. Each stage resolves conflicts in the following order of conflict solving strategies:

1. Temporal resolution (no more than a given maximum of time $\pm t_{max}$ in hours)
2. Lateral and vertical resolution (utilizes the smallest deviation possible)
3. Temporal resolution of no more than 30 minutes to solve conflicts resulting from lateral or vertical resolutions
4. Remaining conflicts are resolved by cancelling flights which are still in conflict.

Since runway position and elevation are fixed, the lateral and vertical resolution strategies are not suitable to solve departure and arrival conflicts. Therefore, lateral and vertical changes were only implemented for non-airport-related conflicts.

The output region for the VA data, from 30° west to 35° east and 35° to 75° north, is available for flights between 9:00 pm the day before until 3:00 am the day after the selected scenario day, resulting in a 30 hours observation timeframe. To avoid shifting flights into uncovered areas, beyond this timeframe the output region is not available for flights.

4.1. Determine the necessary time shift value for flights in F_{airp}

In this section, only the flights with airport related conflicts, F_{airp}, are under consideration. Different values for t_{max} are examined to solve the airport related VA conflicts by shifting the take-off time. If only VA conflicts are considered than the value of time shift should be half of the timespan of the VA forecasts in worst case, here three hours. However, conflict resolution becomes more complex considering multi-polygon conflicts taking also into account newly generated conflicts further downstream. To solve all trajectory-conflicts, it is assumed that more than three hours are necessary for the conflict-free scenario (stage two).

$$t_{max} = i \, , \ \ i > 3$$

Thus, for the first attempt t_{max} is set to four hours and is increased by steps of one hour until all flights in F_{airp} are resolved.

For the low-emission scenario 323 demanded flights are in F_{airp}. Following the previously described four steps to solve conflicts, t_{max} is increased until all flights are free of conflicts with VA zones. The number of solved flights depending on t_{max} is shown in Figure 3. The scenario trial with $t_{max} = 4$ solved 293 flights of demanded flights. 30 flights need to be cancelled in the fourth solving step. Number and kind of conflicts are shown in Table 2. Most of the remaining conflicts are airport related conflicts evoking the cancellations.
With $t_{max} = 6$ hours, only one flight is still in conflict. Analysis of this specific flight shows that it departs at Paris Charles-de-Gaulle. The airport Charles-de-Gaulle is covered by VA zones from the low-emission scenario

Figure 4 Number of conflict free flights depending on probed t_{max}

Table 2 Number of conflicts with volcanic ash depending on phase of flight and t_{max}

t_{max}	Climb	Descent	Departure or arrival
4	10	2	29
5	4	2	9
6	1	0	0

starting at 3:00 am until 9:00 am. The VA zones of medium concentration (see Figure 2) move slowly from north-east to south-west nearby and over the airport Charles-de-Gaulle. In addition to airport related conflicts, this causes conflicts of the departure and arrival routes of the demanded air traffic. As mentioned, departure and arrival routes are not handled by the selected conflict solving strategies. Thus, this particular Charles-de-Gaulle departure can only be solved by a higher t_{max}. In this case $t_{max} = 7{:}15$ hours solves all conflicts with VA zones.

When considering only VA conflicts and disregarding conflicts between aircraft, the algorithm shifts the take-offs and landings just after or before a VA zone covering an airport. This generates conflicts between trajectories as exemplarily shown in Figure 5.

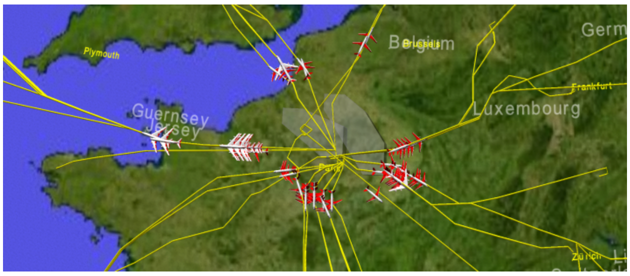

Figure 5 Generated trajectory conflicts by shifting take-off directly before VA zones cover an airport

Trajectory conflicts will be considered in the second stage. Therefore, another run performing all four steps and taking into account trajectory conflicts generates the final conflict-free scenario by using $t_{max} = 7{:}15$ hours. The number of airborne flights for both stages is shown in Figure 6 for flights in F_{airp}. Peaks at three and nine am – while Paris is covered by VA zones – are smoothed by the algorithm for the conflict-free solution.

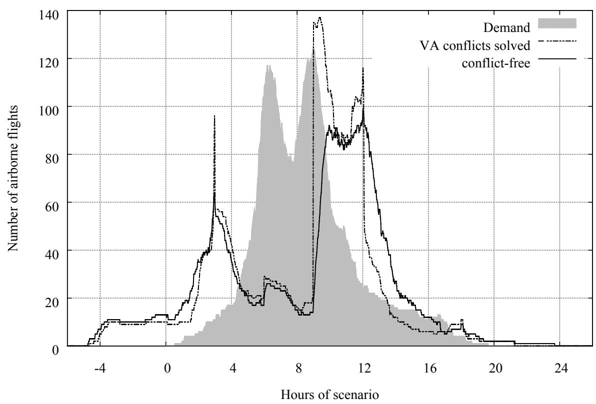

Figure 6 Airborne aircrafts in F_{airp}, the result if VA conflicts are solved only and the result if trajectory conflicts are solved too.

For each trial, the signed mean and absolute mean of time shifts with standard deviation is plotted in Figure 7. In absolute mean, VA conflicts were solved by a time shift with less than three hours. This is half of the VA forecast time. Since aircraft might fly into VA after take-off, the algorithm scheduled more flights later than scheduling them earlier. As plotted in Figure 6, the air traffic demand rises significantly after 3:00 am, when VA covers Paris completely, causing the tendency to delay flights. The conflict-free scenario results in an absolute mean of time shifts of 3:27 hours. This increased both the signed and absolute mean of take-off time shifts.

According to Table 2, a maximum time shift of $t_{max} = 6$ hours would be sufficient solving all airport related conflicts. However, one aircraft climbing out of Paris still penetrates a volcanic ash zone and a lateral detour may be preferred to increasing the time-shift to 7:15 hours.

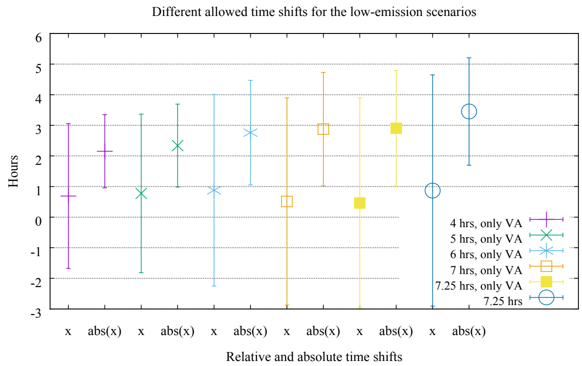

Figure 7 Mean and standard deviation of time shifts for low-emission scenario

4.2. Resolve F_r against VA

The previous section shows that when considering only flights with airport related VA conflicts a conflict-free scenario is possible with a maximum time shift of 7:15 hours. To get back to the complete scenario the remaining 21 183 flights in F_r must be solved considering the VA scenario first. Therefore, the four steps to resolve conflicts are implemented with $t_{max} = 2$ hours. In addition, conflicts between trajectories are considered to reach the conflict-free result directly.
The VA zones of medium and high concentration cause 455 conflicts with 381 different flights in F_r. These conflicts are categorized in Table 3. Conflicts with VA zones in climb and descent phase predominate.

Table 3 Categorized number of conflicts of flights in F_r with the VA scenario

	VA conflicts		
Total	Climb	Cruise	Descent
455	180	21	254

By the four-step solution process all these conflicts are solved without cancelling any flight. Therefore 232 flights were altered. In mean, flights were shifted by 11 minutes with a standard deviation of 42.49 minutes.

4.3. Combined solutions

In the previous sections, both the airport related conflicts with VA (F_{airp}) and the remaining flights of the global air traffic demand (F_r) were solved. If the resolved flights are schedulable together in a global scenario investigations in this section will show.

Both conflict-free sub-scenarios are merged into one global scenario. Trajectories changed by the separated solving process in one sub-scenario may now be in conflict with the resolved trajectories of the other sub-scenario. Two trajectories can have a conflict while one is in arrival and the other is in departure phase of flight referred as ‘Arr/Dep’. Trajectory conflicts not in departure or arrival phase of flight are combined in the category referred as ‘other’ like climb/descent and cruise/cruise. For the merged scenario, the number of conflicts is 590. These conflicts are categorized in Table 4.

Table 4 Categorized number of conflicts of merged air traffic scenario (solved F_{airp} and F_r)

Arrival	*Departure*	*Arr/Dep*	*Other*
85	118	53	334

Again all conflicts are solvable within the first three steps with t_{max} = 0.5 hours. Thus, there is no need to cancel further flights. Comparison of the air traffic demand and the resulting, conflict-free air traffic shows that 873 flight plans were altered. The absolute time shift of these flights is 1:28 hours with a standard deviation of 1:54 hour. The maximum time shift is 7:25 hour, caused by the one particular flight that climbs into a zone of forecasted volcanic ash directly after departure. A lateral adaptation of the departure route would be preferable. The minimum time shift of the altered flight plans is ten seconds. The resulting number of airborne flights is plotted in Figure 8.

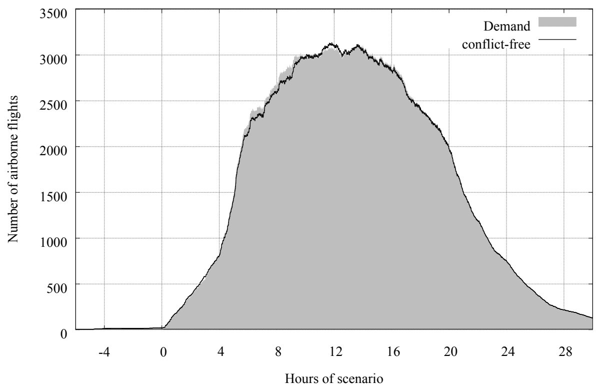

Figure 8 Airborne flights of the resulting conflict-free air traffic scenario

5. CONCLUSION

The volcanic ash scenario under investigation has conflicts between 704 different trajectories (3.27% of demanded air traffic) and zones of medium or high VA concentration. The experiments carried out show what time shift is necessary to solve airport related conflicts of trajectories with VA zones and what time shift is necessary to arrange a completely conflict-free air traffic scenario.

As expected, the time shift is in mean nearly half of the timespan of the VA forecasts, here three hours. However this value is not sufficient for the maximum allowed timespan for shifting the take-off time. Apart from just one flight, all flights can be solved with a maximum allowed time shift of six hours. This is the period of validity of the VA forecasts used. If this statement would be generally valid, then a higher time-based resolution would reduce the necessary shift time until the motion of ash is modeled with a sufficient precision. To confirm this statement for other periods of validity further tests are necessary.

Only less than 4% of the demanded air traffic is affected by medium or high contaminated zones of the low-emission VA scenario used. No flights have to be cancelled for the resulting conflict-free scenario. In a more severe scenario which has 35% conflicting flights, canceling the flights with airport related conflicts would not reduce the number of flights in a conflict-free air traffic scenario caused by unresolvable trajectory or VA conflicts [12]. The modifications carried out here do not lead to significant changes in traffic flow.

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