IDENTIFYING POTENTIAL CONFLICTS AND CORRESPONDING RESOLUTIONS IN THE UPPER AIRSPACE FROM HISTORICAL AIR TRAFFIC DATA

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Abstract

There is currently a shortage of air traffic controllers (ATCO), while air traffic volumes are projected to increase in the future. To ensure that ATCOs can manage this growing demand, it is necessary to develop supportive solutions. One widely explored approach is the development of decision-support tools that can assist ATCOs in their daily operations. For these systems to provide efficient support, their advisories need to be tailored to the ATCOs' preferences and the strategies they employ to accomplish their tasks. This poses the challenge of first analyzing what these strategies look like. A core responsibility of ATCOs is to ensure conflict-free trajectories and to intervene when potential conflicts between aircraft may arise. Designing a system that provides conflict resolution advisories that align with the strategies of ATCOs therefore requires an analysis of established processes. Since no dataset currently exists that would allow such an analysis, this work introduces an approach to generate one based on the Swedish Civil Air Traffic Control (SCAT) dataset. The proposed approach leverages the ADS-B data, flight plans, and issued clearances provided in the dataset to predict the trajectories of aircraft if they had not been issued clearance, whether this would have resulted in potential conflicts, and whether these interventions from ATCOs resolved these potential conflicts.

Using this approach, overall 135 potential conflicts that were resolved by heading clearances and 3,720 that were resolved by flight level clearances could be found. The resulting data can be used in future research to study ATCO strategies and to design systems that provide conflict resolution advisories that are adapted to the way ATCOs work.

Keywords

Air Traffic Control, Conflict Resolution, Human-Computer Interaction

NOMENCLATURE

Units

ft	feet
NM	Nautical Mile

Acronyms

ADS-B	Automatic Dependent Surveillance-Broadcast
ATCO	Air Traffic Controller
ATM	Air Traffic Management
SCAT	Swedish Civil Air Traffic Control

1. INTRODUCTION

Currently, air traffic management (ATM) systems are under significant stress due to a widespread shortage of air traffic controllers (ATCO) leading to delays all over Europe [1, 2]. With air traffic volumes projected to increase there is a need to explore methods to enhance the operational capacity of ATCOs [3]. One promising approach to address this challenge is the integration of digital assistants into ATM systems to reduce the workload of ATCOs by either completely take over routine tasks or provide decision support for complex tasks such as planning conflict free trajectories and avoiding potential conflicts [4, 5].

A conflict occurs when two or more aircraft come closer than the prescribed minimum separation which depend on various factors [6]. Typical thresholds for en-route separation are 5 NM horizontally and 1,000 ft vertically [7]. Fig. 1 illustrates an example of a situation that could lead to such a conflict.

Planning conflict free trajectories and therefore preventing conflicts is a core task of ATCOs. Consequently, numerous papers have focused on developing systems that can provide ATCOs with suggestions on how to resolve emerging potential conflicts [8]. It is essential that such suggestions are well understood and accepted by ATCOs. One promising way to increase their acceptance is through personalization,

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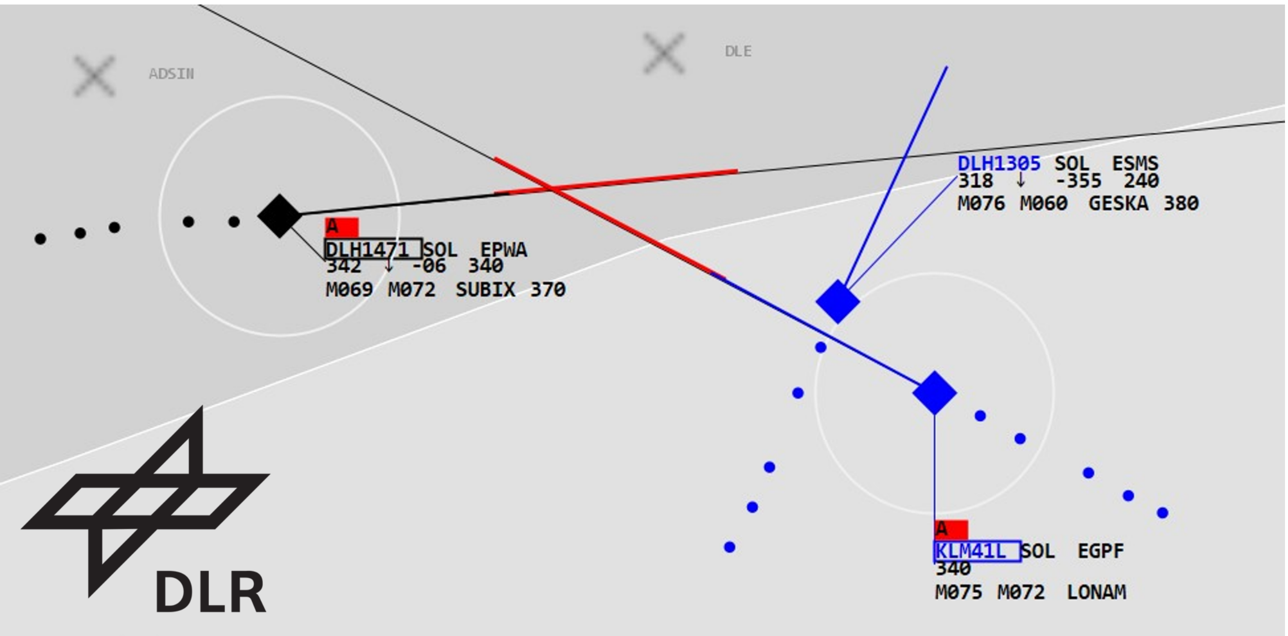


FIG 1. The radar display shows a potential conflict between two aircraft. Aircraft are represented by diamonds, and their trajectories are shown as lines. The black diamond represents an aircraft currently within the ATCO's sector, while the blue ones indicate aircraft approaching the sector. The red segments highlight portions of the trajectories where the separation between the aircraft becomes insufficient.

i.e., adapting the suggestions to reflect the behavior and decision-making patterns of ATCOs [9]. To achieve this, it is necessary to analyze the behavior of ATCOs and to understand how potential conflicts are actually prevented or resolved in practice. However, no suitable dataset is currently available for this purpose, meaning that this data usually have to be generated in simulation scenarios which is a time- and cost-intensive procedure. To address this problem, this paper introduces an approach for identifying situations in which ATCOs issued clearances to prevent these potential conflicts in the Swedish Civil Air Traffic Control (SCAT) dataset [10]. This dataset was selected as the foundation because it is publicly available and free of charge. It contains 13 weeks of traffic data recorded between October 2016 and September 2017.

The proposed method identifies heading and flight level changes resulting from ATC instructions. These situations are then analyzed to determine whether a potential conflict would have arisen had the aircraft continued along its original trajectory. If the analysis indicates that the ATC-issued clearance successfully prevented a potential conflict, it is classified as a conflict resolving action. The resulting samples are collected and ultimately constitute the processed dataset, which contains 135 heading clearances and 3,720 flight level clearances to avoid potential conflicts.

The remainder of the paper is structured as follows: First, related work and efforts to create similar datasets are discussed in Section 2. Section 3 describes the methodology used to identify potential conflicts and corresponding solutions. The results are presented and discussed in Section 4, followed by a discussion of potential research directions using this data in Section 5. Finally, the paper concludes with a short summary in Section 6.

2. RELATED WORK

Several datasets and approaches are currently available that provide information on aircraft interactions and conflict-resolution actions [11, 12]. One such approach was developed by Gaume et al. [11], who focused on aircraft flying above 20,000 ft in French airspace. Their method was implemented using data from OpenSky [13], combined with corresponding flight plans. The approach identifies situations in which an aircraft deviates from its assigned flight plan and then analyzes whether a conflict would have occurred with other aircraft in the airspace had the aircraft continued to follow its original plan.

The method is straightforward to implement; however, the flight plans required are not always openly available and need to be matched to the data. Aside from this limitation, the approach could be applied to any dataset that provides both Automatic Dependent Surveillance–Broadcast (ADS-B) data and complete flight plans. Consequently, it could also be applied to the SCAT dataset used in this study. Moreover, since SCAT provides additional information, such as clearances issued by ATCOs and predicted trajectories, it enables the development of an even more reliable approach. Another limitation of Gaume et al.'s method is that it is restricted to lateral changes. By contrast, the approach proposed in this paper can also be applied to vertical and speed changes, although this study focuses on vertical and heading changes, as these are the most common and preferred strategies for resolving potential conflicts [14].

López-Martín and Zanin [12] provide a dataset that was created by analyzing trajectories, both planned and executed, that describes aircraft interactions over Europe. This dataset does not specifically focus on actions conducted to resolve potential conflicts, but provides data that could be used to analyze situations leading up to potential conflicts and typical interactions between aircraft giving insights into the strategies of ATCOs.

3. METHOD

In the following sections, the approach used to identify clearances in the SCAT dataset that may have been issued to prevent potential conflicts is described. First, the dataset and the preprocessing steps are outlined, followed by the method used to filter for clearances associated with conflict resolving actions.

3.1. Dataset

This study uses the SCAT as its foundation, since it is publicly available and freely accessible [10]. The dataset contains detailed information on aircraft movements, flight plans, and timestamped clearances issued by ATCOs. It also includes regularly updated trajectory predictions and weather data, although the latter is not used in this study. In total, SCAT covers 13 weeks of traffic recorded between October 2016 and September 2017, excluding military and private flights [10].

3.2. Preprocessing

Since air traffic is typically denser around airports, and aircraft perform more frequent turns and vertical maneuvers during climbs and approaches, this study focuses on the upper airspace. Accordingly, only aircraft flying above flight level 200 are considered.

To identify relevant clearances, coherent rows describing executed maneuvers must first be identified for all maneuvers conducted during each flight. The SCAT dataset provides indicators to easily distinguish between horizontal maneuvers (straight flight (0), right turns (1), left turns (2)) and vertical maneuvers (no vertical movement (0), climbs (1) and descents (2)) [10]. Consecutive entries with the same indicator were grouped together to form continuous maneuvers, and the start and end points of each sequence were stored for further analysis.

In addition, the dataset was standardized to ensure consistency across variables. Altitude information is provided in mixed units (ft or flight levels) and needs to be standardized, and timestamps must be reformatted into a consistent structure.

3.3. Identifying Relevant Clearances

The first step in identifying clearances that may have been issued to resolve a potential conflict is to examine for each maneuver (turn or vertical change) whether a corresponding clearance was issued beforehand. This process is described by Alg. 1.

For heading clearances, all turns identified during data preprocessing are examined. For each detected turn, it is verified whether a clearance was issued beforehand (within a predefined time window) and whether this clearance corresponds to the executed maneuver. Correspondence is validated by comparing the post-turn heading to the assigned heading.

The identification of relevant flight level clearances follows the same logic. For each climb or descent, it is checked whether a clearance was issued beforehand and whether the resulting flight level corresponds to the assigned clearance. Vertical events are only considered if they start from level flight, to exclude cases where the aircraft was already climbing or descending when the event began. The process is guided by several predefined parameters:

- Time window: the period prior to a maneuver during which a clearance is considered relevant. Wüstenbecker et al. [15] found that the interval between the issuance of a clearance and the pilot's initiation of the corresponding action is typically no more than 30 seconds for heading clearances and 100 seconds for flight level clearances. Accordingly, this parameter was set to 30 seconds for heading changes and 100 seconds for flight level changes.
- Heading or flight level tolerance: the maximum deviation allowed for a maneuver to be considered a valid response to a clearance. Set to 20 degrees for heading changes and 5 FL for flight level changes.
- Averaging window: the time interval after a maneuver used to calculate the average heading and validate correspondence with the clearance. Set to 20 seconds after the maneuver ends.
- Minimum heading or flight level change: the minimum deviation required for a maneuver to be classified as an actual turn or climb/descent. Set to 5 degrees for turns and 5 FL for flight level changes. This may imply that certain actions aimed at preventing conflicts in the longer term are excluded. However, as outlined later in the paper, the analysis is limited to 10 minutes following a clearance, which means the focus is primarily on conflicts resolved in the short to medium term.
- Maximum flight level change: all flight level changes greater than 50 FL were excluded, as larger descents or climbs are typically issued not solely for conflict resolution.

3.4. Identifying Potential Conflicts

A conflict is defined as any situation in which predefined thresholds are not satisfied. Since the predicted route is not perfectly accurate, a relatively large buffer was applied. In addition, an evaluation function was implemented to further assess the identified scenarios and corresponding actions. The conflict detection used the following parameters:

Algorithm 1: MatchingManeuversToClearances

Input: flights, detected_maneuvers (turns or vertical changes), clearances, minimum_threshold, averaging_window, time_window, tolerance
Output: maneuver_clearance_pairs, relevant_clearances
maneuver_clearance_pairs $\leftarrow$ empty set;
relevant_clearances $\leftarrow$ empty set;
foreach *flight f in flights* **do**
    foreach *maneuver m in detected_maneuvers of f* **do**
        Identify start time t_{start} and end time t_{end};
        Compute maneuver magnitude Δ (heading change or flight level change);
        if $\Delta <$ *minimum_threshold* **then**
            skip this maneuver;
        if *vertical maneuver and not starting from level flight* **then**
            skip this maneuver;
        Compute post-maneuver average value (heading or flight level) over $[t_{end}, t_{end}+$ averaging_window$]$;
        Find clearance c in clearances issued before t_{start} within the time_window;
        if *no such clearance exists* **then**
            skip this maneuver;
        if *actual value after $m \approx$ assigned value of c (within tolerance)* **then**
            Add m and c to maneuver_clearance_pairs;
            Add c to relevant_clearances;
return maneuver_clearance_pairs, relevant_clearances

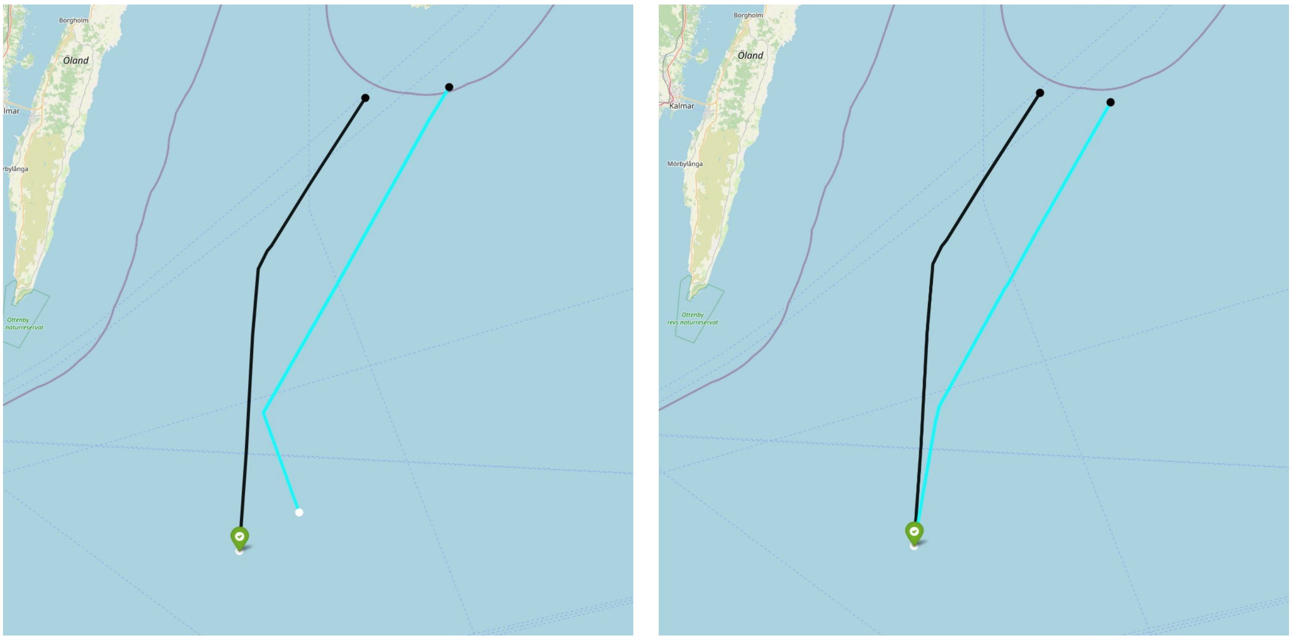
- Lateral threshold: the minimum horizontal separation used for conflict detection. Set to 10 NM.
- Vertical threshold: the minimum vertical separation used for conflict detection. Set to 1200 ft.
- Time horizon: the forward-looking period used for conflict detection. Set to 600 seconds.
- Point tolerance: the time window compensating for mismatches between the timestamps of potential conflict locations and predicted trajectories. Set to 10 seconds.
- Step size: the temporal resolution at which the projected trajectory is sampled. Set to 5 seconds.

To assess whether a potential conflict would have occurred without the ATCO's intervention, it is necessary to predict the trajectory the aircraft would have flown in the absence of such intervention. This predicted trajectory then serves as the basis for identifying potential conflicts. The prediction is made immediately before the ATCO's clearance was issued, as it most closely reflects the trajectory that would likely have been flown without intervention. The following section outlines how this trajectory was determined for heading and flight level changes, and how potential conflicts were subsequently identified.

3.4.1. Identifying Conflicts Potentially Resolved by Heading Changes

The SCAT dataset provides predictions of aircraft trajectories at various points in time. These predictions are generated at irregular intervals of approximately 30 seconds to 2 minutes and include, among other parameters, the predicted position and altitude of the aircraft at a corresponding timestamp. To address the irregularity, the predictions were linearly interpolated to obtain position and altitude values at uniform 5-second intervals. However, there is another issue with the predicted trajectories. Even when a new prediction is available, the predicted position of the aircraft at or close to the timestamp of the prediction often does not match the aircraft's actual position. This effect is illustrated in Fig. 2a. The cyan line represents the prediction immediately prior to the clearance indicated by the green marker and predicted location at the time of the clearance already deviates from the aircraft's actual position indicated by the black line.

To address this problem, an alternative prediction was generated to replace the predicted trajectory provided in the SCAT dataset. Since the dataset also contains information on flight plans, the custom prediction is based on the provided flight plans. Specifically, whenever a relevant heading clearance is issued, the flight plan is examined to identify the next waypoint likely to be approached. A predicted trajectory is then constructed under the assumption that this waypoint will be flown to directly. The altitude at the time of clearance serves as the reference altitude, and the ground speed at clearance time is used to propagate positions along the predicted path. Predicted positions are sampled at 5-second intervals up to a 10-minute horizon, and to account for possible timing offsets intruding aircraft are matched within a small time window of $\pm$10 seconds. Only the closest approach per pair of aircraft is retained. The procedure is outlined in the pseudocode shown in Alg. 2. This trajectory prediction



(a) Predicted trajectory extracted from the SCAT dataset.

(b) Flight plan based prediction used in this paper.

FIG 2. Comparison of the projected trajectory based on the prediction stored in the SCAT dataset shown in (a) and the manually created prediction based on the flight plans shown in (b). The black line indicates the actual trajectory, the cyan line the projected trajectory and the green marker shows the location of the aircraft at the time a heading clearance was issued. The white dot highlights the start point, the black dot the end point after 10 minutes. The shown flight has flight ID 101029 in the SCAT dataset.

is very similar to the approach described by Gaume et al. [11] and is used for the remainder of this paper. A side-by-side comparison of both the prediction from the SCAT dataset and the manually generated trajectory can be seen in Fig. 2.
Using this trajectory, potential conflicts were identified by checking for other aircraft whose separation from the aircraft under consideration would have fallen below the defined thresholds if it had remained on its projected path. This process is described by Alg. 3.

3.4.2. Identifying Conflicts Potentially Resolved by Flight Level Changes

The procedure for predicting the trajectory in the absence of a flight level clearance is comparatively straightforward. For each such case, a projected trajectory was constructed by combining the aircraft's actually flown lateral path with a fixed altitude corresponding to the flight level at the start of the vertical event. Only clearances issued while the aircraft was in level flight were considered. Potential conflicts were then identified after the clearance, over a fixed time horizon, by sampling the trajectory at regular intervals and checking nearby aircraft within a small temporal tolerance against lateral and vertical separation thresholds. The process of checking for such conflicts is analogous to the procedure described in Sec. 3.4.1.

3.5. Evaluating Conflicts and Corresponding Resolutions

A dedicated function was implemented for both heading and flight level clearances to determine whether they actually represent interventions to prevent a potential conflict. For heading clearances, the lateral separation resulting from the projected trajectory is compared to that of the actual flown trajectory. For flight level clearances, the vertical separation resulting from the projected trajectory is compared to that of the actual flown altitudes. If the separation achieved by the actual trajectory exceeds that of the projected trajectory, the situation is considered as a potential conflict resolved by the corresponding clearance and included in the dataset. An example of a potential conflict resolved by a heading clearance is shown in Fig. 3, while Fig. 4 illustrates a potential conflict resolved by a flight level clearance.

4. RESULTS & DISCUSSION

In total, 877 relevant turns and 12,382 flight level changes with corresponding clearances were identified and analyzed. From these, the initial screening revealed 161 potential conflicts that might have been resolved through heading changes and 4,803 potential conflicts that might have been mitigated through flight level adjustments. Upon closer evaluation, 135 heading clearances were confirmed to increase the distance between aircraft, suggesting they were likely intended to resolve the potential conflicts. Similarly, 3,720 flight level clearances improved the situation

Algorithm 2: BuildProjectedPathFromNextWaypoints

Input: flight_ID, clearance_time, flight_plans, waypoints, traffic, horizon H, time step Δt
Output: projected_trajectory or None
Find last flight_plan before clearance;
if *no flight_plan found or route missing* **then**
  return None
Decode the ICAO route into a list of waypoint coordinates;
if *fewer than 2 waypoints* **then**
  return None
Get the aircraft's actual position at clearance_time;
if *position not found* **then**
  return None
Select the next waypoint to target based on current position and route;
if *no suitable waypoint* **then**
  return None
Build polyline = [current position] + [remaining waypoints];
Get ground speed and altitude at clearance time;
Resample polyline into trajectory points (every Δt seconds, up to horizon H);
if *resampling fails* **then**
  return None
Assign constant altitude from clearance to all points;
return projected_trajectory;

Algorithm 3: CheckConflictsOnProjectedPath

Input: heading_actions, flight_plans, waypoints, traffic, thresholds (distance, altitude), horizon H, time tolerance τ, time step Δt
Output: Set of projected conflicts
conflicts $\leftarrow$ empty set;
foreach *action in heading_actions* **do**
  flight_ID $\leftarrow$ action.flight_id;
  clearance_time $\leftarrow$ action.clearance_timestamp;
  projected_path $\leftarrow$ BuildProjectedPathFromNextWaypoints(...);
  if *projected_path is None* **then**
    continue
  intruders $\leftarrow$ all other flights in traffic;
  foreach *point in projected_path* **do**
    Search intruders within $[t - \tau, t + \tau]$;
    foreach *intruder in nearby set* **do**
      Compute lateral_distance (NM);
      Compute vertical_separation (ft);
      if *lateral_distance < threshold AND vertical_separation < threshold* **then**
        Add to conflicts: (flight ID, intruder ID, clearance time, conflict time, distance, vertical separation);
if *Conflicts = empty* **then**
  return None
For each (flight_ID, intruder_ID) pair, keep only the conflict with smallest distance;
return Conflicts;

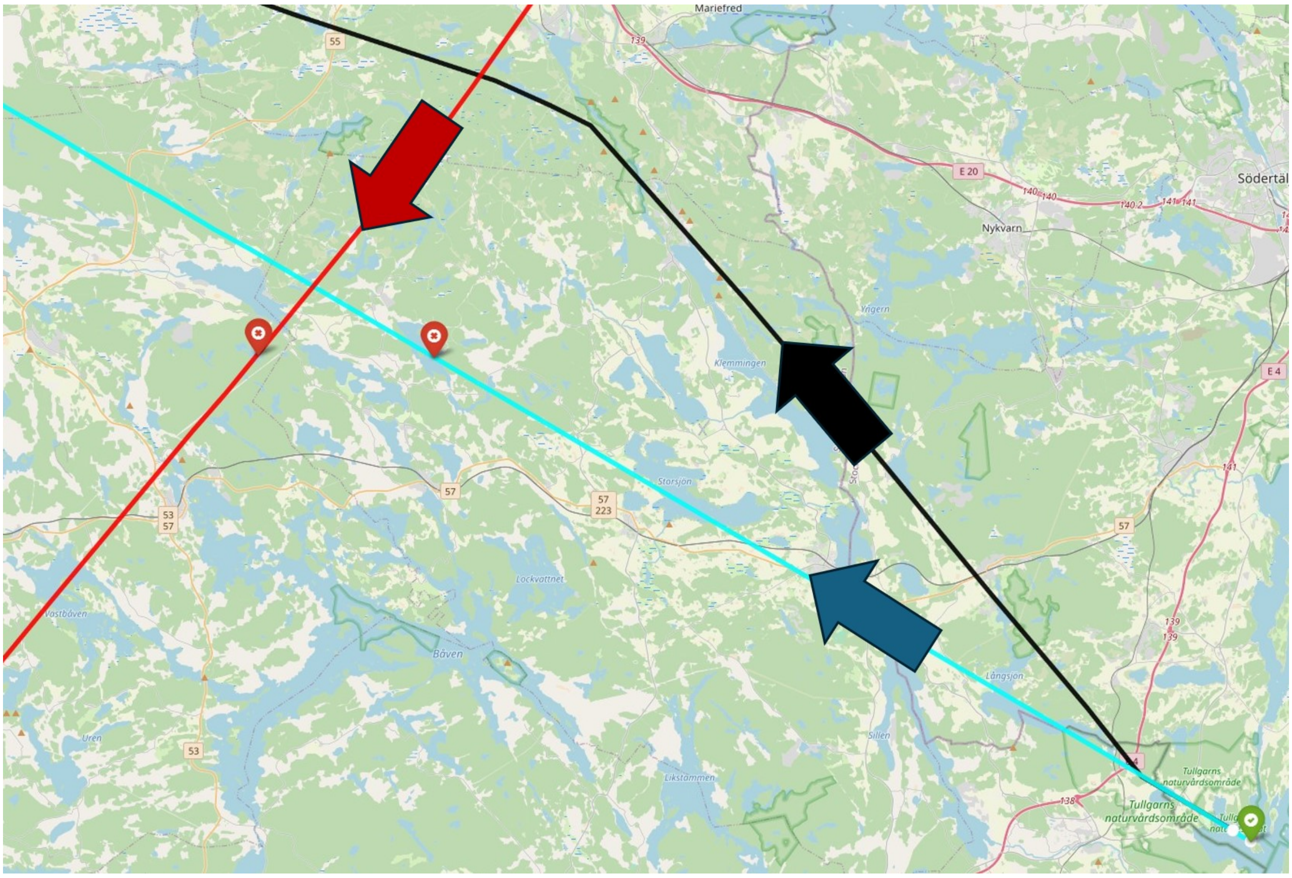


FIG 3. **The figure shows a potential conflict that is resolved by a heading clearance. The red line shows the trajectory of the conflicting aircraft (flight ID 103724), the cyan line the projected trajectory based on the flight plan and the black line the actual path of the aircraft (flight ID 10407). The green marker on the bottom right of the figure indicate the location of the aircraft when the clearance was issued. The red markers indicate the positions of the aircraft at their closest point.**

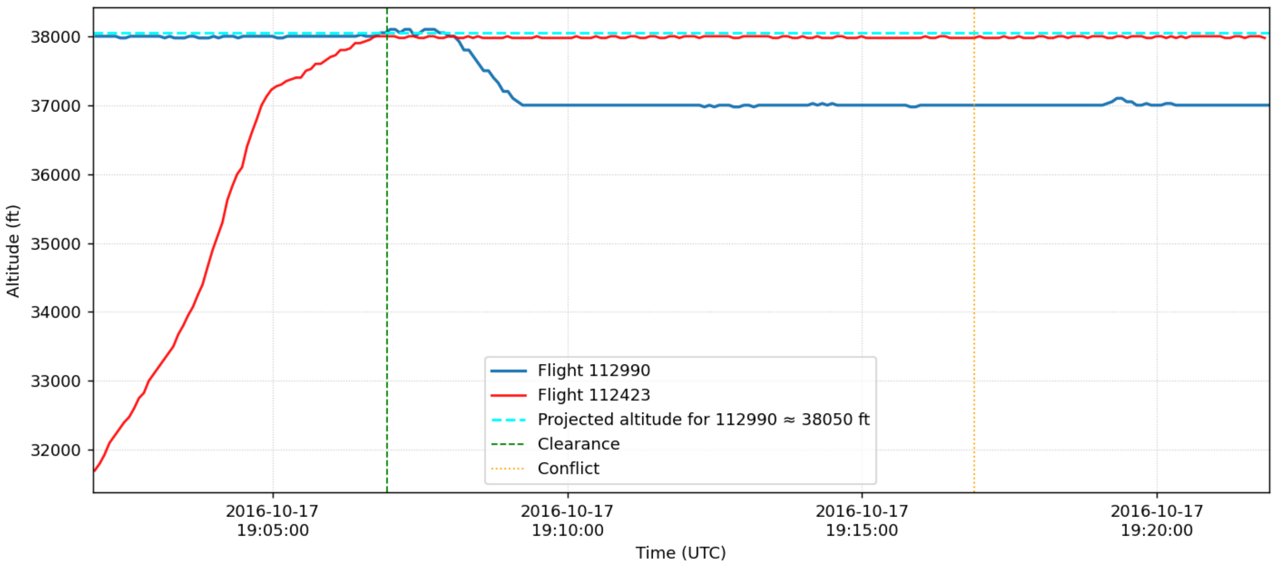


FIG 4. **The figure shows a flight level change to avoid a potential conflict between flight 112990 and flight 112423. The the blue line shows the flight level of the aircraft that received a clearance to decent and the dotted cyan line represents the projected flight level if no clearance would have been given to that aircraft. The red line indicates the flight level of the conflicting aircraft. The yellow line indicates the point at which the lateral distance between the aircraft was small enough so that a conflict would have occurred.**

and can therefore be interpreted as conflict-resolution measures. Notably, a substantially larger number of situations were resolved through flight level changes compared to heading adjustments. This is plausible, as in relatively low-traffic airspace it might be more efficient to assign an aircraft to a less occupied flight level than to issue a heading change, particularly given that the required lateral separation standards are greater than the corresponding vertical minima.
Considering the fact, that the SCAT dataset consists of data from 167,547 flights, relatively few situations were extracted from the dataset. In comparison, Gaume et al. [11] obtained 4,950 different situations in 78,316 flights. A key reason for this is that, due to its geographical location, Sweden experiences comparatively lower traffic volumes than central Europe. As a result, there are fewer potential conflicts and fewer required interventions compared to the French airspace analyzed by Gaume et al. Furthermore, in the approach by Gaume et al., it remains unclear whether each deviation from the flight plan was preceded by a clearance, i.e., an intervention by ATC, or whether the deviation occurred for other reasons. By contrast, the approach proposed in this paper requires an ATC-issued clearance as a prerequisite for considering a situation in the analysis.
Furthermore, only vertical changes that are not part of an ongoing climb or descent are considered. The current prediction model assumes that the aircraft will maintain its present flight level. However, the dataset also includes climb and descent rates as well as the selected altitude. This would allow for an improved predicted trajectory that incorporates this additional information, but such functionality has not yet been implemented.
Additionally, often only a portion of each flight is included in the dataset, typically the segment within Swedish airspace, since the dataset is limited to this region. This makes it difficult to assess the full trajectory of a flight in the broader context of European traffic. Also, currently only 600 seconds after the clearance are checked for potential conflicts.
Moreover, for aircraft that received a potentially relevant clearance, a projected trajectory is calculated, while for all other aircraft that are potential conflict candidates, the actual flown routes are considered. However, it would also be reasonable to check whether these other aircraft received clearances as well, which may have caused them to deviate from their original routes. Otherwise, potential conflicts might be overlooked in cases where clearances were issued to both aircraft involved.

5. POTENTIAL RESEARCH DIRECTIONS

As mentioned earlier, it would be valuable to apply this approach to busier airspaces. Unfortunately, no suitable datasets from other regions are currently available. The main limitation is that clearances are typically not included. However, the AI-based approach introduced in the author's previous work [16] could be used to label publicly available ADS-B data with clearances, thereby enabling the application of the method presented in this paper to other airspaces.
Previous research has shown that ATCOs are more likely to accept advisories from decision-support systems when these recommendations align with the solutions they would naturally choose themselves [17]. Consequently, considerable effort has been devoted to developing personalized recommendation systems tailored to the ATCOs preferences [9]. However, personalization comes with the drawback of requiring large amounts of individually recorded data from each ATCO [18]. Collecting, processing, and analyzing such data is both resource-intensive and time-consuming. Given these challenges, it is therefore practical to investigate whether generalized, universally applicable strategies can be identified across ATCOs. Such strategies could significantly accelerate the implementation of personalized systems: an initial model could be trained on these general strategies, requiring only limited fine-tuning to adapt the system to a specific ATCO. This would reduce the dependence on extensive user-specific data collection.
Furthermore, the dataset could be used to test and benchmark algorithms designed to generate conflict-free trajectories. The filtered scenarios provide examples that can be used to assess whether an algorithm performs compared to an ATCO and to test whether its outputs align with the typical decisions made by them.

6. CONCLUSION

Using the proposed approach, 135 potential conflicts resolved through heading clearances and 3,720 resolved through flight level clearances were identified in the SCAT dataset. Compared to the results of Gaume et al. [11], this number appears relatively small; however, it must be considered that Swedish airspace is less busy than the French airspace analyzed in their study. Moreover, the parameters used to filter for conflicts in this study can be adjusted and fine-tuned to meet different requirements, allowing for the inclusion of more or fewer potentially relevant scenarios. Future work should focus on improving the evaluation of identified potential conflicts to ensure that all scenarios are relevant. Ultimately, the resulting data will be used to analyze ATCO strategies for resolving potential conflicts, with the goal of developing support systems tailored to the specific needs and preferences of individual ATCOs.

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