Partnership for AiR Transportation
Noise and Emissions Reduction

Final Findings on the Development and Evaluation of an En-Route Fuel Optimal Conflict Resolution Algorithm to Support Strategic Decision-Making

PARTNER Project 5 final report

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Executive Summary

The novel strategic conflict-resolution algorithm for fuel minimization that is documented in this report provides air traffic controllers and/or pilots with fuel-optimal heading, speed, and altitude recommendations in the en route flight phase, thereby providing a possibility of reducing the fuel consumption and associated emissions from en route operations. This work is aligned with the goals of the NextGen initiative to minimize the environmental impact of increased traffic volumes while also improving the capacity and throughput of the en route airspace. It is also hoped that the results of this research will enable the future use of truly wind optimal routings and the possible creation of super-sectors to support these new routings.

The primary version of the algorithm is a Mixed-Integer Linear Programming (MILP) formulation with multiple constraints to ensure that the desired behavior of the aircraft during conflict resolution maneuvers (aircraft must retain their exit point, etc.) is achieved while at the same time minimizing the fuel used during conflict resolution (as estimated using data from the BADA Version 3.7 database). This version of the algorithm has been designed to expand on the capabilities of the prior version of the algorithm that was developed. This version, reported in PARTNER-COE-2008-001, showed promising results in terms of both reduced distance travelled and fuel burned, and thus environmental impacts; but had two significant shortcomings: 1) the aircraft that were maneuvered were not guaranteed to exit the sector where originally planned, thus causing a problem for handoffs at sector boundaries; and 2) the algorithm did not account for the transitioning aircraft to other flight levels as a way of resolving potential conflicts.

There were five objectives to this research effort: 1) extend the algorithm to multiple flight levels, 2) ensure that all aircraft exit the sector as originally planned; (3) ensure reasonable controller workload; (4) develop an interface and concept of operations to test the algorithm; (5) evaluate the algorithm with a human in the loop evaluation. The first three objectives were achieved through the design of the optimization algorithm. In a conflict avoidance maneuver, aircraft are allowed to undertake a lateral displacement (achieved by two heading changes and a third heading change to return to intended exit point); a vertical displacement (achieved by an altitude change that does not result in a conflict at the new flight level); or a combined lateral and vertical displacement. Three additional constraints were added to the primary algorithm to explicitly render algorithm solutions viable for controller usage. First, resolution maneuvers are temporally spaced no closer than 20 seconds. Second, resolution maneuvers are scheduled to occur long enough after maneuvers are presented to the controller so that he/she has sufficient time comprehend them and take appropriate action. Third, each aircraft may only be maneuvered once in each volume of airspace.

Overall, three different versions of the algorithm were created and tested: (1) a cooperative version where all the aircraft involved in a potential conflict are allowed to maneuver to resolve the conflict; (2) a non-cooperative version where only one aircraft involved in a potential conflict is allowed to maneuver to resolve the conflict; and (3) a no-speed-change version where potential conflicts are resolved without aircraft changing their speeds, i.e. with heading and altitude changes only.

The algorithm was evaluated in two phases. In the first phase, algorithm-level evaluation was conducted within the scope of the algorithm process, where the results from the algorithm were checked by a conflict

detection routine. In the second phase, scenario-level evaluation was conducted on the output (specifically the time history of the output) of the algorithm. This latter phase of testing was needed because of the greater-than-expected stochasticity in real-world radar data that became evident once the traffic simulation engine provided by the FAA Technical Center, i.e. the Target Generation Facility (TGF), was employed. The TGF is a simulation in which the various uncertainties and stochastic phenomenon associated with aircraft dynamics and radar monitoring are modeled. Simulated radar returns was provided to the algorithm via the Common Message Set (CMS), the mechanism used in the NAS to feed data from the En Route computer system to Air Traffic Management applications, such as Traffic Management Advisor and Traffic Flow Management.

The evaluation yielded four key observations: (1) The optimal solution of the algorithm is often cooperative, that is, both aircraft involved in a conflict are maneuvered; (2) non-cooperative solution can be enforced at the cost of a higher fuel burn (on an average ~3%); (3) when speed changes are disallowed, more altitude changes are observed, but fewer of solutions are cooperative; and (4) restricting speed changes results in recommendations with a higher fuel burn than those provided by the primary (general) version of the algorithm that allows for speed changes.

Note that it had been hoped that the algorithm would be evaluated in a human-in-the-loop (HITL) simulation study but this was ultimately not possible in the given time frame, as more time than originally budgeted was needed to adapt the algorithm to deal with the real-world uncertainties encountered during the first two phases of the evaluation. Before returning to the IIF at the FAA's Technical Center, two additional evaluations should be performed on the algorithm. First, the algorithm's buffer size must be determined based on a parametric examination of the buffer size, scenario complexity and miss distance uncertainty. Second, the algorithm with optimized buffer size should be tested using the TGF simulation and some visualization tool by ab-initio controllers at Georgia Tech to determine appropriate settings for additional parameters in the ERFO algorithm. After successfully completing these two evaluations, it would be appropriate to complete the remainder of the HITL evaluation at the FAA's Technical Center. Only at the FAA's Technical Center would it be possible to fully quantify the benefits of the algorithm, and to identify any additional improvements that would be necessary to deal with the impacts of weather and restricted airspace on the feasible space for conflict resolutions.

A HITL simulation study was, however, conducted based on developed scenarios in order to establish a baseline against which the algorithms under consideration, or even other approaches, can be measured. This simulation study was required because there was no historical data readily available to serve as a baseline as the proposed concept of operations when the algorithm is employed is very different from current standard operating procedures. Baseline data was collected for future comparison and includes: air traffic management clearances given, controller workload and situation awareness measures, and time and distance flown. In this evaluation 4 controllers performed en route air traffic control (ATC) simulations at two traffic levels corresponding to low (average of 18 aircraft per super sector and 14 conflicts) or high (average of 28 aircraft per sector and 20 conflicts). Controllers were given an evolved version of the NAS where aircraft were given wind-optimal routings (straight line) and a large but flat airspace consisting of 4 flight levels over a horizontal area covering 3 Memphis En Route Sectors: 20, 34, and 44. Over the course of 3 consecutive days of testing, a baseline evaluation of the nine developed scenarios was performed. For clarity, this HITL baseline evaluation was performed without live runs of the algorithm.

The HITL results provided insight into the relative difficulty of the different scenarios, the impact of scenario characteristics on controller workload, situation awareness, actions, performance and perceptions. Of the four scenarios designed to be "easy", the results indicate that only two were statistically easier than the other scenarios. The remainder of the scenarios was statistically similar in terms of controller perception and measured workload. The average number of aircraft in the sector correlated with most measures of workload, time and distance savings increased, and inversely correlated with the controller's confidence in his ability to maintain the mental picture of air traffic and handle the level of traffic. The number of expected conflicts over the course of the scenario was correlated with increased workload, situation awareness, decreases in time and distance savings, and inversely correlated with the controller's confidence in his ability to maintain the mental picture of air traffic and handle the level of traffic. Both the number of aircraft and the number of expected conflicts correlated significantly with the total number of clearances, number of heading changes and number of repeated clearances. Neither of these correlated with the number of altitude changes (which were limited due to the instructions given to the controllers to use altitude changes for traffic management only as a last resort). Speed changes were used more frequently in cases with higher numbers of aircraft and were independent of the number of expected conflicts.

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1 INTRODUCTION

Air traffic delays in the National Airspace System (NAS) are a source of significant additional operating costs to the aviation industry and to the passengers and shippers that utilize the air transportation system. For example, during the year 2007, these additional and unnecessary costs summed to approximately $41 billion: $19 billion in direct airline operating costs, $12 billion in the value of passenger time, and $10 billion in indirect cost of delays to other industries [1]. These very significant delays are of particular concern because they are an indication that the current air traffic control infrastructure is not able to handle current traffic levels when faced with weather related capacity reductions – the major cause of delays in the NAS – which thus suggests that existing infrastructure will not support the considerably higher forecasted traffic demand.

Significant reduction in en route fuel burn could be achieved if aircraft were allowed to fly their fuel optimal trajectories, and when they must deviate from these trajectories for conflict resolution purposes, such deviations are also fuel optimal (the additional fuel required is minimized). The rational for this supposition is that aircraft must often deviate from their fuel optimal trajectories to "fit in" to the underlying static en route structure that has been designed, albeit with consideration of the most popular traffic flow directions, to provide predictable intersections between traffic flows as opposed to purely enabling fuel optimal flight. In fact, aircraft are often forced to fly less direct routes, or far from their fuel optimal cruise altitude and speed. In addition to the obvious economic cost, the delays and limitations imposed by the route structure have an environmental cost, as sub-optimal trajectories result in unnecessary gaseous emission that give rise to environmental concerns.

It is therefore desirable to have a strategic approach to conflict resolution where the deviations from the optimal trajectories are small and the economic and environmental costs of resolving conflicts are minimized. The strategic conflict-resolution algorithm described in this report provides air traffic controllers and/or pilots with a tool to determine the desired set of fuel-optimal heading, speed, and altitude changes for aircraft during their en route phase of flight. The evaluation of this algorithm is documented herein. Also documented is a human-in-the-loop (HITL) simulation study that was conducted to establish a baseline against which the algorithm under consideration or other similar approaches can be compared. This baseline is required because this concept of allowing aircraft to fly their fuel optimal trajectories is sufficiently different than current standard operating procedures; no historical data was readily available to serve as a baseline.

1.1 Relevance to NextGen and Environment

The Next Generation of Air Transportation System (NextGen) initiative is a wide-ranging effort to transform the NAS and is most widely characterized as a move from a ground-based system of air traffic control to a satellite-based system of air traffic management. The transformation is being made to not only accommodate the growing demand for air traffic, but also to improve efficiency and enhance mobility while minimizing the environmental impacts of aviation. When fully implemented, NextGen will allow more aircraft to safely fly closer together on more direct routes, reducing delays and providing unprecedented benefits for the environment and the economy through reductions in carbon emissions, fuel consumption and noise.

The FAA Office of Environment and Energy (AEE) is interested in reducing the environmental impacts of civil aviation. The strategic conflict-resolution algorithm described in this report supports this effort because it provides fuel-optimal heading, speed, and altitude recommendations for aircraft during the en route phase of flight, which is where much of the fuel that is used by aircraft is expended. Utilization of such a strategic conflict-resolution algorithm is a potentially promising approach for reducing fuel consumption and associated carbon emissions from en route operations. The results of this research could also enable more use of wind optimal routings and the possible creation of super-sectors to support these new routings.

1.2 NextGen Project Level Agreement (PLA) Requirement

This document is intended to provide the findings required for the System Development - Environment and Energy Milestone #10, which is titled "Demonstration of control algorithms for environmentally and energy favorable en-route operational procedures". Specific details of the requirements of this item are shown in Table 1 below. Note that these requirements have been updated after an interim project status briefing in January 2011.

Table 1: PLA Requirement – Environment and Energy Milestone #10

Analyses and demonstration of environmental control algorithms for en route procedures			
10.2	A white paper describing: a) en route mitigation algorithm development in FY09 and b) approach to conduct fast-time computer based simulations and demonstration of real-time human in the loop simulations, and anticipated results.	May 17, 2010	T+3
10.3a	An interim findings report on fast-time computer based simulations and demonstration of real-time human in the loop simulations	February 15, 2011	T+12
10.3b	A final findings report which expands on the interim report	January 17, 2012	T+23

1.3 Prior Work

This research has its genesis in an optimization-based automated tactical controller, which was previously developed for the routing of aircraft at a single, given fight level within an Air Route Traffic Control Center (ARTCC) [2]. The core of the automated tactical controller was a mixed integer linear program (MILP) that recommends heading and speed changes for large groups of aircraft such that the total additional fuel burn to achieve conflict-free linear trajectories with respect to all other aircraft and weather systems is minimized.

The performance of the automated tactical controller was evaluated through fast-time simulation. The scenarios for the fast-time simulations studies were created using historical traffic data for aircraft traversing the Cleveland Center – one of the seven choke points identified by the FAA in 2001 – at 37000 feet nominal pressure altitude or flight-level (FL370). The benefit of the automated controller was then determined by comparing the fuel burn and emissions estimates from the fast-time simulation to estimates of the fuel burn and emissions computed using the observed trajectories as flown historically on the existing route structure with existing control actions.

As hoped, use of the automated controller resulted in significant improvements. For example, all aircraft traveled a shorter distance under the command of the automated controller with the average distance traveled through Cleveland Center reduced by 9 nautical miles. Furthermore, the cruise speeds suggested by the automated controller were closer to the optimal speeds for the aircraft. Hence, almost all aircraft traveled on or very near their optimal trajectory, illustrating the utility of the underlying algorithms in terms of fuel savings and emissions reductions. The minimum expected fuel savings for the automated tactical controller was 1.4%. When considering that aircraft in the observed data set might operate at 10% to 15% below optimum speeds the potential fuel savings increased to anywhere between 3.37% and 6.13% [2].

One shortcoming of this prior algorithm (i.e. automated controller) was that the resolution of a conflict resulted in a set of straight-line trajectories that are conflict free for "all time." While this is clearly not a shortcoming from a conflict resolution perspective – no new conflict can be created while resolving existing conflicts – it is a shortcoming from the perspective of aircraft handoffs because aircraft that deviate from their original trajectories will, by definition, not exit the airspace at their originally planned exit points. Given the importance, from a system perspective, of having all aircraft exit each distinct volumes of airspace at their planned location, where human and automation handoff issues are minimized if there are no changes to the handoff location, a heuristic algorithm was developed for determining when each aircraft was free of all conflicts and could navigate towards its intended exit point. Alternately, the optimal trajectories between entry and exit points could be approximated by repeatedly solving the MILP until each aircraft has a conflict-free trajectory to its intended exit location. In the conflict resolution algorithm, the cost of returning all aircraft to their intended exits are approximated and accounted for. Therefore, the algorithm would create trajectories that are as close as possible to their intended exit locations. However, there are limitations to the utility of both approaches. Truly optimal trajectories cannot be guaranteed because only the cost of returning to the exit is approximated after a deviation has occurred. Additionally, very large weather systems can cause deviations that are so large in angle that they invalidate many of the assumptions that were made to achieve tractability. Notwithstanding, this algorithm aims to provide a significant improvement over the existing situation where aircraft must follow prescribed routings that vary from their optimal trajectory.

Another shortcoming of the original fuel-optimal conflict resolution algorithm that was previously developed is that it was a conflict-free solution for a single flight level, i.e. included heading and speed changes only. This is a common feature of most existing conflict resolution algorithms, as documented in the comprehensive review of previous conflict resolution algorithms by Kuchar [3] that identified a need for an increased focus on conflict resolution over arbitrary paths of extended lengths that may include altitude changes. A realm of focus that has thus far been limited, as most conflict resolution algorithms only provide resolutions in a plane (i.e. a single flight level) and only focus on solving short-term or imminent conflicts.

1.4 Research Objectives and Scope of Work

The present research effort has been conducted to address shortcomings and expand the capabilities of the aforementioned algorithm. The primary goal of the present research effort was to develop a fuel-optimal, multi-level, conflict resolution algorithm that could be used to identify potential conflicts strategically, and recommend assignments with fuel-optimal cruise altitudes, headings, and speeds. A second goal was to investigate and quantify the environmental benefits of fuel-optimal aircraft trajectories.

These were achieved by enhancing prior research efforts in the following areas:

1) Extend the algorithm to multi-level: The previous algorithm only considered conflict-free solutions for a single flight level. In other words, the conflict resolution maneuvers included only heading and speed changes. With multi-level capability, the current work extends the algorithm ability to also change altitude as part of the overall conflict resolution strategy. The basic idea behind the multi-level algorithm is illustrated in Figure 1, in which the dotted path represents the original path of the aircraft, and the solid lines the altered path of the aircraft.

2) Incorporate exit point information: It is considered that the turn back maneuver is part of the overall optimization scheme. In particular, an aircraft that performs a lateral separation (by two heading changes) in order to avoid a conflict, will then perform a third heading change in order to track to its originally intended exit location. This is illustrated in Figure 1(a).

3) Ensuring reasonable controller workload: Controller workload generally increases as the number of conflict resolution maneuvers increases (i.e. as the number of maneuvers that the controller has to instruct the pilot to perform increases) and as the time between maneuvers decreases (i.e. as the "downtime" between bursts of instructions decreases and ultimately disappears). The former because each individual has a given cognitive capacity and must, in addition to expending capacity on each task, use some of their cognitive capacity to manage the transition between tasks. The latter because there is a lower limit to the time in which instructions can be given and acknowledged by pilots. Thus, to maintain a reasonable controller workload, it is reasonable to assume that an upper bound must be set on the number of conflict resolution maneuvers used to resolve conflicts. With no prior studies to rely on, we exercised our expert judgment in determining that each aircraft be allowed to make at most three heading, and/or one altitude change. A stand-alone speed change may occur once, otherwise speed changes may occur only with a heading or altitude change. Furthermore, we space the maneuvers in time because preliminary testing revealed that each maneuver took approximately 10s to verbalize clearances and receive acknowledgment.

4) Developing an interface for testing the algorithm: The algorithm is integrated with an interface, in order to test the algorithm. The interface intends to provide air traffic controllers with an automated tool to de-conflict en route traffic in an optimal way. Specifically, the algorithm interface would provide the following capabilities: 1) data management, 2) algorithm initiation, 3) data collection, and 4) controller interaction.

5) Human-In-The-Loop Testing: A baseline performance estimate (i.e. an estimate of the performance of the system without the algorithm) was developed via real-time HITL simulations were performed at the FAA William J Hughes Technical Center (WJHTC). Should it be determined that a HITL evaluation of

the algorithm is possible, this baseline performance estimate will be the basis for determining the improvement provided by the algorithm in the most realistic simulation setting.

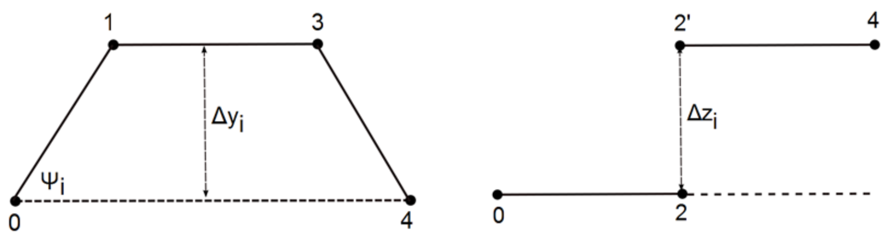


Figure 1: Proposed Conflict Resolution Scheme: (a) Horizontal Plane, (b) Vertical Plane

2 EN ROUTE FUEL-OPTIMAL CONFLICT RESOLUTION ALGORITHM

The problem of fuel optimal multi-level conflict resolution problem can be stated as follows: Given a set of aircraft at different altitude levels, along with their current position and velocity information, determine the control actions (heading, speed, and altitude changes) such that the aircraft fly conflict-free trajectories while expending minimum fuel. Conflict-free trajectories imply that all aircraft pairs at the same altitude maintain at least 5 Nautical Miles (nm) separation at all times during their flight through the airspace.

In this section, a multi-level conflict resolution algorithm based on our proposed conflict resolution scheme is outlined. Also discussed are methods for validating the developed algorithm and the different restricted versions of the algorithm that have been developed dependent on the choice of control actions. Finally, the various tests that have been performed using the algorithm are discussed.

For the purposes of validation, the objective is to de-conflict aircraft flying through the airspace at four flight levels: FL360 (equivalent to an altitude of 36,000 ft. on a standard day); FL370 (equivalent to an altitude of 37,000 ft. on a standard day); FL380 (equivalent to an altitude of 38,000 ft. on a standard day); and FL390 (equivalent to an altitude of 39,000 ft. on a standard day). The aircraft at FL370 and FL380 are controllable (unless specified to be restricted), that is, they can change heading, speed, and altitude in order to avoid conflicts. The aircraft originally flying in FL360 and FL390 are restricted and cannot be maneuvered. Hence, all aircraft in FL360 and FL390 are assumed to be conflict-free originally. Furthermore, it is considered that a controllable aircraft from FL370 can change altitude only to FL390 (ascend), while an aircraft in FL380 can only change altitude to FL 360 (descend).

2.1 Description of Algorithm

The following describes the underlying conflict resolution scheme on which the algorithm is built, and provides the specifics related to the optimization problem.

2.1.1 *Conflict Resolution Scheme*

The following conflict resolution scheme is considered: In order to resolve a potential conflict at a time $t > 0$, an aircraft is allowed to undertake one or both of the following conflict avoidance maneuvers: (1) A lateral displacement Δy_i achieved by two heading changes, followed by a third heading change to turn the aircraft back to its intended exit location, (2) A vertical displacement Δz_i achieved by an altitude change, without creating conflicts at that level. In both of these cases, speed is considered to be constant over a linear segment of the path, that is, speed may change with a heading or an altitude change. Of course, our conjecture is that there exists a control strategy (with three heading changes and/or a vertical displacement for every aircraft, and any associated speed changes) that resolves all conflicts in a reasonable amount of time. Furthermore, we assume that the time to perform a heading change or an altitude change is small compared to the time of flight of the aircraft through the airspace. In other words, the control actions are considered instantaneous in the problem formulation of the algorithm conflict resolution scheme. This is illustrated in Figure 1.

2.1.2 *Consideration of Controller Workload*

As already mentioned, conflict resolution maneuvers must be reasonably spaced temporally to ensure reasonable controller workload. Also, controllers must be given comprehension time during which no maneuvers can be recommended. Furthermore, the number of conflict avoidance maneuvers that can be made by an aircraft may also be restricted to reduce the workload or pilots. For example, an aircraft that has been previously maneuvered may be restricted from subsequent maneuvers.

Taking all these into consideration, a MILP formulation was developed for the multi-level conflict resolution problem. The advantage of a MILP formulation is that there are several commercial software programs available to solve such problems efficiently. Among all such software packages, CPLEX [4] is a well-known and established solver for optimization problems. Thus, for the conflict resolution problem in this work, CPLEX is used to solve the MILP.

2.1.3 *Decision Variables*

For every aircraft that is not restricted, continuous and binary decision variables are utilized. The continuous variables include the lengths and times of the legs of the altered route. Whether an aircraft may change altitude is designated by a binary variable. Also, only a discrete set of heading changes for each aircraft is allowed, and the optimization problem therefore has discrete variables. No decision variable is associated with a restricted aircraft because it cannot be maneuvered.

2.1.4 *Constraints*

Conflict avoidance constraints are set up for each aircraft pair in appropriate levels. For instance, all aircraft pairs at FL 370 must satisfy the conflict avoidance constraints between them. If an aircraft at FL 370 changes altitude, then it must also satisfy conflict avoidance constraints with all aircraft at FL 390. All conflict avoidance constraints are formulated for parallel and non-parallel (intersecting) aircraft pair, at least one of which must be controllable. These constraints ensure that the feasible space of solutions yield conflict-free trajectories. Furthermore, other constrains such as speed and specific geometry of the altered routes, are also considered.

2.1.5 Cost function

Any aircraft that has to deviate from its original intended route in order to avoid a conflict will expend more fuel than if it had flown a direct route at its optimal speed. Hence, our goal is to resolve all conflicts by expending the minimum additional fuel during the conflict avoidance maneuvers. The Base of Aircraft Data (BADA)Version 3.7 model [5] is used to obtain the fuel burn curves for an aircraft and thereby calculate the fuel expended by each aircraft during their flight. A fuel burn curve is a convex function of speed, and is approximated as a piecewise linear function. For cost calculations due to airspeed, heading and altitude changes for an aircraft, it is assumed that the cost for each aircraft is the percent deviation in fuel burn, when compared to the optimal flight (direct route at its optimal speed) of the aircraft. The sum of additional fuel burn over all aircraft yields the cost function.

2.2 Algorithm Versions

The primary version of the algorithm recommends speed, heading, and altitude changes for the set of aircraft in consideration. This *general* or *full* version of the algorithm is a cooperative conflict resolution algorithm, as both aircraft involved in a potential conflict may be maneuvered to prevent the conflict. Users are also allowed to place additional constraints on the control actions that can be chosen. Specifically, a limited or restricted version of the algorithm can be formulated.

For instance, the second version of the algorithm that has specifically been developed is the "*No Speed Change"* version, which allows for altitude and heading changes only. However, the conflict resolution maneuvers are allowed to be cooperative. This version was created by modifying the speed constraints so that the speeds on individual legs are fixed. This version was created because it was observed that an aircraft often did not follow the speed (in TGF simulations) recommended by the algorithm.

The third version of the algorithm is the *Non-Cooperative* version. This version discourages cooperative conflict resolution and was created to help better understand the relationship between fuel burn savings and controller workload, by comparing against the full version of the algorithm. There are two motivations for developing this version:

- Cooperative conflict resolution means more aircraft may be maneuvered, and hence likely to increase the workload of a controller.

- A non-cooperative version will only move one of two aircraft involved in a conflict, and the other aircraft can always be maneuvered later on to correct for an inexact resolution in the presence of uncertainties. Note that this is not possible in the case of a cooperative conflict resolution because both aircraft that have been maneuvered are restricted, and thereby exempted from additional maneuvering.

2.3 *Algorithm Integration*

The algorithm communicates with an interface by means of input-output files. The input-output files are xml based files. The algorithm uses the following input files:

- Configuration file containing the set of all files required by the algorithm
- Flight information files, that provide information about aircraft IDs, type, current position, intended exit locations, and restriction (if any) on the aircraft
- Simulation parameters file, containing various parameters pertaining to scenario runs, e.g. controller comprehension time, algorithm run time, etc.
- Previous resolutions file in case it is not the first iteration, containing information about trajectories of aircraft that have been maneuvered previously

After the input files are read, the data is processed. The *input data processor* block of the algorithm performs the following tasks: (1) converts aircraft positions from lat-long to state space variables, using Lambert's canonical transformation, (2) checks whether an aircraft is within the sector, and rejects the aircraft if it is not, (3) checks whether an aircraft has been maneuvered previously, and obtains information about its path (way-points), (4) propagates all aircraft trajectories by the controller comprehension time, and rejects any aircraft that is outside the sector at the end of the controller comprehension time, (5) checks for existing separation violations at the initial time and at the end of controller comprehension time (flagging such a violation is necessary, because the algorithm would fail to find a feasible solution comprising of a conflict-free path connecting the current position with the exit position). Once the input data has been processed, the algorithm constructs the MILP in the format required by CPLEX. This primarily involves establishing all the constraints, decision variables and the cost function associated with the MILP formulation of the problem.

Once completed, the algorithm then checks for the feasibility of the problem, and extracts the CPLEX solution in the cases where the problem is feasible. Conflict-free trajectories of the aircraft are constructed by (1) reading the CPLEX solution and checking for heading, speed, and/or altitude changes for each controllable aircraft, and (2) obtaining associated variables for the new trajectories of all maneuvered aircraft. The trajectories of all maneuvered aircraft are constructed by specifying the four way-points and times to apply the control action. The algorithm then converts all aircraft way-point positions from state-space to latitude and longitude, using the inverse Lambert transformation.

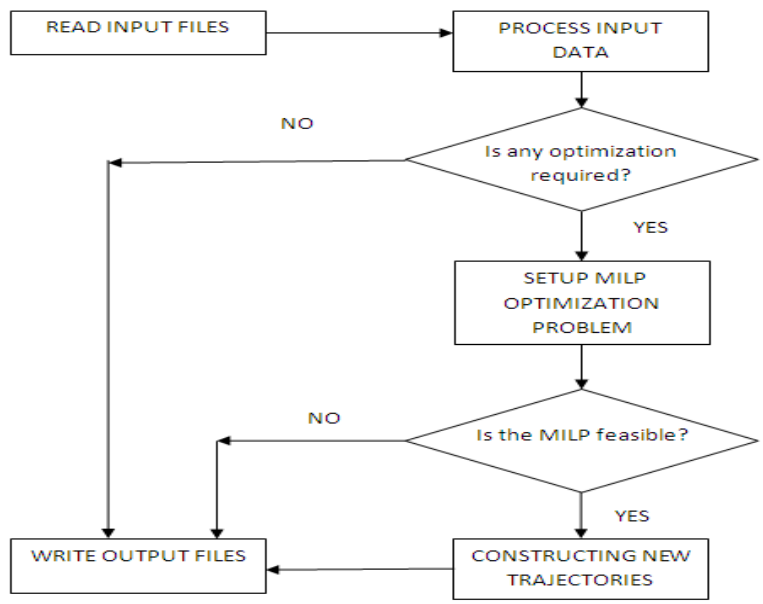


Figure 2: Algorithm Flow-chart

Finally, the algorithm writes the following output files:

- Algorithm recommendations
- Information about trajectories of all maneuvered aircraft to be used in future iterations

The overall algorithm flowchart is depicted in Figure 2.

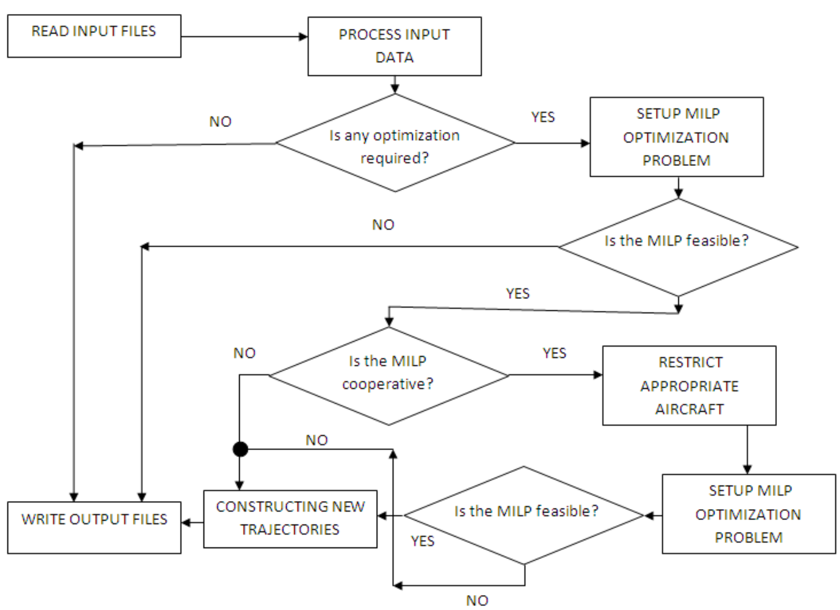


Figure 3: Algorithm Flow-chart (Non-Cooperative version).

The non-cooperative version of the algorithm is more complex than the general version of the algorithm, because it is not possible to determine beforehand which pairs of aircraft will engage in a cooperative conflict resolution. Hence, the generation of a non-cooperative solution is a two-step process. Firstly, a solution is generated in the usual way and checked to determine if it is cooperative. If cooperative, then one aircraft in every cooperative pair is restricted, and the optimization repeated. If feasible, this restricted version of the algorithm will yield a non-cooperative solution. The overall algorithm flow is illustrated in the Figure 3. Note that the no speed version has the same flow as the primary algorithm (only some variables and constraints of the MILP changes) and hence no separate flowchart is presented for the "no speed version" of the algorithm.

3 HUMAN-IN-THE-LOOP (HITL) SIMULATION STUDY

3.1 Overview

The HITL simulation study provided an assessment of the scenarios designed for the investigation of the effectiveness of a new En-Route Fuel Optimization (ERFO) algorithm and associated interface to reduce emissions and trip time in the en-route environment while keeping controller workload within acceptable tolerances. While the algorithm was not part of the HITL simulation study, this portion of the project provided baseline data to be compared with future simulation studies involving the algorithm and its interface in terms of air traffic management and time and distance flown. In this simulation study 4 controllers performed en-route air traffic control (ATC) simulations at two traffic levels corresponding to low: average of 18 aircraft per super sector and 14 conflicts and high: average of 28 aircraft per sector and 20 conflicts. The controllers were presented with an evolved version of the NAS where aircraft were given wind-optimal routings (straight line) and a large but flat airspace consisting of 4 flight levels over a horizontal area covering 3 Memphis en route sectors (20, 34, and 44). Controllers worked individually. Over the course of 3 consecutive days of testing, a series of baseline simulation studies of the developed scenarios were performed.

3.2 Scenarios

Airspace Organization

The ERFO concept of operation continues to organize airspace using the ARTCC and sector model. Here however, sectors would be combined to form super sectors comprised approximately of the area included in 2 to 4 present day sectors, but include fewer flight levels. For scenarios in this study, the ERFO sectors were designed to have only four flight levels. Specifically, the ERFO sector evaluated was the equivalent of Memphis Center (ZME) sectors 20, 34, and 44 as shown in Figure 25, with an altitude range of FL 360-370. The use of this combined sector, or super-sector, provided more lateral area to resolve potential conflicts with relatively small lateral deviations from the desired trajectory, making the solution closer to a global optimum. Moreover, the super-sector was also designed to show scalability of the algorithm and also a controller's ability to manage more airspace via such an algorithm.

Route Structure

Presently, flight plans most often utilize the current fixed route structure that consists of a series of Jet Routes (or Victor Airways depending on altitude) which connect ground based navigation aids. Routes provide a convenient method of specifying flight plans as the common link in affecting system wide communication and situational awareness, and they serve as a mechanism to control airspace complexity and enhance the application of separation. Sector geometry has been designed to take advantage of the existing route structure such that each sector has defined junctions at which traffic flows intersect. Consequently, controllers are trained specifically on the geometry, aircraft flows, and other attributes unique to each sector they are responsible for. It would be significantly more difficult or even impossible during heavy traffic to manage aircraft if all, or a majority of aircraft, were allowed to fly flight plans that deviated from this established route structure.

As aircraft operators have only limited ability to file direct or wind optimal flight plans, this causes significant inefficiencies in the NAS. Aircraft must often travel non-optimal paths to their destinations to remain on the route assigned to them, unnecessarily burning hundreds of tons of fuel every year. In order for the operators that wish to take advantage of winds by deviating from the established route structure, they must file in accordance with the National Route Program (NRP).

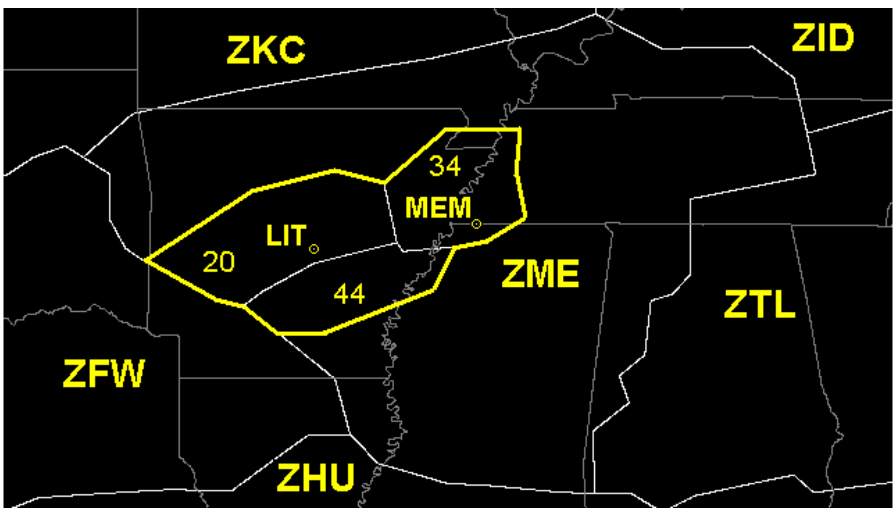


Figure 25: Super-sector to be utilized by the ERFO Algorithm

Data for Scenarios

Nine scenarios were created for this simulation study. The scenarios were derived from historical data provided by ATAC Corporation. The scenarios consisted of four flight levels (FL360-FL390); two primary flight levels (FL370 and FL380) and two secondary flight levels (FL360 and FL390). All conflicts were constrained to the two primary flight levels, and accordingly the secondary flight levels were free of conflicts. The scenarios were designed to have between 0-7 conflicts and to have between 60-160 aircraft in the super sector in each six minute period. Data for the scenarios are from the two good weather days (April 30, 2008 and October 30, 2008). The 45-minute time periods that define each of the scenarios are identified by analyzing the cumulative flight counts in a rolling 45-minute window.

3.3 Baseline Simulation Study

Participants in the HITL simulations

Four recently retired en-route controllers participated in the experiment. The participants' average experience was 26.25 years (Standard Deviation = 1.5). To maintain a homogenous participant pool, participants were recruited from ARTCCs other than Memphis Center (ZME). The majority came from New York Center (ZNY), Boston Center (ZBW), and Washington Center (ZDC). All had been previously certified on the Display System Replacement (DSR) including the User Request Evaluation Tool (URET) and many were presently employed as ARTCC instructors.

Experimental Staff
Georgia Tech and Metron Aviation staff, which included an ATC Subject Matter Expert (SME), conducted the simulations at the FAA William J. Hughes Technical Center in Atlantic City, NJ with the help of the FAA's Integration and Interoperability Facility (IIF) staff. Metron Aviation in conjunction with the IIF staff created the scenarios from historical data and the Georgia Tech and Metron Aviation personnel conducted the experiments and collected the data.

Simulation Pilots
Four simulation pilots were used in this simulation study. Two were assigned to each super sector.

Role of the Controller and Pilot
Presently, the pilot retains ultimate responsibility for the safety of the aircraft. However, within the limits of safety, the air traffic controller, has primary responsibility for maintaining safe separation among the aircraft within their operational jurisdiction. Pilots are required by Federal Aviation Regulations (FARs) to follow their cleared flight plan and any amendments to this clearance must be approved by ATC, except during emergencies.

The ERFO concept of operation would not alter this distribution of responsibility. Instead, it would serve as a guidance tool for air traffic controllers for traffic de-confliction in which the controller would need to approve and relay to pilots. The ERFO interface is designed so that suggested flight plan changes can be entered into the HOST system. HOST is a National Airspace System (NAS) component that provides automation for control of En Route Air Traffic across the United States. The Integration and Interoperability Facility at the FAA Technical Center in Atlantic City, NJ operates an instance of the HOST component, in conjunction with several simulation engines, to provide a high fidelity Air Traffic simulation environment. However, it does not assume that Controller Pilot Data Link Communication (CPDLC) is available to the flight deck; consequently all clearances must be verbally relayed to the pilot. In the future, the ERFO interface may interact directly with the En-Route Automation Modernization (ERAM) system and provide CPDLC to equipped aircraft.

Target Generation
Modeled airspace and scenarios were prepared for the training sessions in the high-fidelity ATC simulator at the IIF. An integrated system including the Target Generation Facility (TGF) [6] was used to generate radar tracks for the HOST software to interpret.

Controller Environment
Controllers in the IIF were equipped with a standard setup consisting of an R-side (the radar controller) controller's full-sized DSR monitor and a D-side (the assist controller) controller's URET display. Controllers were provided with the standard input devices; a DSR keyboard and trackball. Above the controller's seat were duplicate sets of video cameras for recording. These were located on each side of a row of controller stations. The atmosphere mimicked an ARTCC environment with dimmed lighting and an air-conditioned environment.

Communication Equipment

The controllers used either headsets provided by the IIF or personal headsets. Foot pedals for the radio transmissions were also available. The transmissions from the controllers' headsets were connected with the simulation pilots' headsets. The experiment's moderators were also connected to the system enabling them to inject situational awareness (SA) questions.

All of the equipment was connected to a computer that recorded all voice communication between the pilots and controllers and between the moderators and controllers.

Video Camera and Video Recording Configuration

One camera was provided for each of the two stations. These cameras were supported by extension arms and positioned just over the controllers to minimize distraction. Since the primary goal was to have recordings of what the controllers were seeing as they were providing instructions to the pilots, the cameras were focused on the DSR display, and the controllers were not in their field of view. Both cameras were connected to a computer that was able to record video simultaneously.

Independent Variables

The only independent variable manipulated in this study was scenario difficulty. Each scenario was classified as either high or low workload, which was defined by the average number of aircraft in the sector, the maximum number of aircraft in the sector, and the total numbers of conflicts that were originally designed into the scenarios. The scenario classifications are shown in Table 2.

Table 2: Scenario Summary

	Scenario								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Average AC in Sector	25	20	27	28	33	13	24	20	13
Max AC in Sector	33	28	36	38	45	16	28	26	17
No. Conflicts Total	22	17	20	16	21	7	16	17	13
Classification	High	Low	High	High	High	Low	Low	Low	Low

Dependent Variables

Table 3 below summarizes the primary measures of data collected during the study. The focus was primarily controller workload as it related to their performance in response to resolving conflicts and maintaining aircraft separation.

Table 3: Dependent Variable Summary

Dependent Variable	Frequency / Duration	Measurement / Recording Method
Workload Rating	Every 6-minute intervals	Workload assessment keypad
Situation Awareness	Every 6-minute intervals	Direct inquiry via radio & paper
Aircraft data (heading, altitude, speed)	Entire scenario	Computer
Controller instructions	Event-based	Audio recording
Pilot / Aircraft response	Event-based	Audio recording & aircraft data
Questionnaire response	At end of scenario & end of experiment	Paper

After the aircraft were loaded on the DSR display, workload ratings were collected at 6 minute intervals from the touch-screen communications panel below the DSR display, where a workload rating application prompted the controllers to provide their assessment. Situation awareness questions were included starting at 7 minutes into the scenarios.

Extensive data on aircraft were collected; their location, altitude, entry points, and exit points associated with time. The questionnaire response included NASA Task Load Index (TLX) rating and subjective measures of the experimental runs.

3.4 Workload Ratings

Two measures were taken to measure workload. The first was taken using a Workload Assessment Keypad (WAK) device [7] which was integrated into the radio control panel located at the base of the radar scope. The WAK device consists of 10 keys numbered 1 through 10. When the controller was probed to give a workload assessment the WAK would illuminate, blink and sound an audio ping. These measures were taken every 6 minutes throughout the scenario. The second measure of workload used the NASA TLX workload index subscales administered after the completion of each session.

3.5 Situation Awareness

Situation awareness was measured throughout each of the sessions, with 6 questions per scenario for each controller. The questions were asked via party line radio, in which the moderators were connected to the controllers using standard controller radio equipment. At 6 minute intervals, the moderators "called" the controllers using the radio control panel with the WAK device. The time to answer the call (TAC) was recorded. The moderators asked the controller a situation awareness question, and the controllers provided the moderators with the appropriate answers via radio. The time to answer the question (TAQ) was then recorded. The situation awareness questions for each scenario are listed in Appendix B.

3.6 Controller Instructions

Controllers managed the air traffic at their discretion, using a variety of commands sent to the simulation pilots via radio. Commands included lateral, speed, and vertical changes to aircraft. These voice commands were recorded, along with any other communication via radio. From the recordings, the number of these commands, their type, and the number of repetition of the commands were extracted. Controllers were instructed to use altitude clearances only when absolutely necessary.

3.7 Questionnaire Response

At the end of each scenario run, the participants individually provided feedback of the session with a survey. Both the TLX rating and the subjective workload level assessment were performed on paper. The TLX collected subjective measurements in six areas: mental demand, physical demand, temporal demand, effort, performance, and frustration. The workload level assessment included the following statements in which the participants indicated their level of agreement.

- I felt I had sufficient control of the air traffic.
- I was able to maintain my mental picture of the air traffic.
- I was able to handle this level of traffic.
- My workload for this simulation run was sustainable over an entire shift.
- I was able to handle this number of flight levels.
- I was able to anticipate likely conflict points.

- How difficult was this scenario?

At the end of the testing on the 3rd day, participants were gathered for a final debriefing, where they shared their thoughts about the project, testing, and the future of air traffic.

3.8 Results

The results are calculated using three different statistical techniques: partial correlations, repeated measure Analysis of Variance (ANOVA) and general linear models. The partial correlations calculate the correlation coefficient for the requested variables while controlling the effects of the individual differences of the controllers. The repeated measures ANOVA calculate the impact of the different scenarios on the various dependent variables. In association with the repeated measures ANOVA, we conducted post hoc paired-comparisons via the commonly used Tukey Honestly Significant Difference (HSD) test to determine which scenarios are significantly different from other scenarios [8]. Unless otherwise stated all assumptions associated with repeated measures ANOVA have been met. General linear models were used to calculate the impact of the two independent variables: total number of aircraft per scenario and the total number of conflicts expected on the dependent variables. The two independent variables and the participants were included in the model as random effects. The significance value was set at $\alpha = 0.05$. The data from the experiments was analyzed to draw inferences regarding the difficulty of the scenario and the impact of the scenario characteristics on the data collected.

3.8.1 Are the easy and hard categorizations of scenarios appropriate?

The scenarios have been roughly classified as “easy” and “hard”. Quantification of these subjective measures may add another dimension for further tests. Using a repeated measures ANOVA followed by a paired comparison, it was found that the “easy” scenarios 2 and 6-9, were not universally distinct from the “hard” scenarios 1, 3, 4, and 5. Instead it appears that scenarios 2 and 9 were easier than the rest of the scenarios. Scenarios 7 and 8 were not as simple as planned and should be made easier if they are to be similar to scenario 6 and 9.

3.8.2 How do scenario characteristics (number of aircraft, expected conflicts) affect controller workload, situation awareness and controller actions?

While most measures of workload were found to positively correlate with increases in the number of aircraft in each scenario along with the expected number of conflicts, the expected number of conflicts was found to be a stronger predictor of workload. Similarly, the number of expected conflicts was found to be a significant predictor of situation awareness (operationalized here as the time to answer the query), while the number of aircraft in the scenario was not. Both the number of aircraft and the number of expected conflicts correlated significantly with the total number of clearances, number of heading changes and number of repeated clearances. However neither of them correlated with the number of altitude changes (which were limited due to the instructions given to the controllers to use altitude changes only as a last resort). Speed changes were used more frequently in cases with higher numbers of aircraft and were independent of the number of expected conflicts.

3.8.3 How do scenario characteristics (number of aircraft, expected conflicts) affect controller performance?

Overall controllers were able to create significant time and distances savings from the wind-optimal routes by shortening the distances flown through the super sector. This is most likely inadvertent as controllers often told the aircraft to resume planned navigation after re-routing them for traffic and were unaware of the implications on time and distance. As additional aircraft were included in the scenario both time and distance savings increased, but as conflicts were increased the time and distance savings decreased.

3.8.4 How do scenario characteristics (number of aircraft, expected conflicts) affect controller perceptions?

Overall, the controllers indicated confidence in their ability to grasp the situation and handle the traffic in each situation. Confidence seemed slightly higher in easier scenarios, and slightly lower in harder scenarios, with the notable exception when asked if their workload was sustainable over an entire shift. Both the number of aircraft in the scenario and the number of expected conflicts were significantly correlated to the controller's ability to maintain a mental picture of air traffic and handle the level of traffic, and inversely correlated to how difficult the scenario was.

3.8.5 How are the number and type of commands issued by a controller related to the scenario characteristics and controller's situational awareness?

The number of aircraft included in a scenario was significantly correlated to both the total number of clearances and the number of heading, speed and repeated clearances and accordingly to the number of total clearances issued. The number of expected conflicts was significantly correlated to only the number of heading changes and the number of repeated clearances. Additionally a significant correlation was found between the number of speed changes and the controller's situation awareness.

3.9 Impact of Algorithm Performance Issues on HITL Simulation Study Schedule

Initially, the project research plan consisted of 4 weeks of HITL simulation study with algorithm runs. Preparations were complete; however the persistence of algorithm performance issues caused delays and forced re-planning. As a result, the HITL baseline simulation study without algorithm, described earlier in section 3, was performed. The HITL simulation study using the live algorithm runs was delayed and ultimately cancelled indefinitely due to the aforementioned significant algorithm performance issues.

4 SIMULATION ENGINES

4.1 Target Generation Facility (TGF)

The TGF provides a stochastic environment to run fast-time simulations with the algorithm and analyze the algorithm behavior for validation. The stochasticity observed in the simulations are the result of the following:

1) *Un-modeled dynamics*: The TGF considers aircraft dynamics, and hence any un-modeled dynamics and approximations of data for maneuvered aircraft within the algorithm are a source of uncertainty.
2) *Approximation errors*: Owing to controller requirements, some of the output data from the algorithm are approximated. For instance, every speed change is approximated to the nearest multiple of 5 knots, and every heading change is in multiples of 10 degrees. These approximations were necessary to mimic the regular day-to-day instructions currently given by air traffic controllers to the pilots of aircraft. Note here that this error, although present in the simulations, is not a limitation of TGF because it would be possible to run the algorithm with TGF (with no controllers or pilots in the loop) with more precise increments.
3) *Navigation Errors:* Owing to approximation errors in 3D to 2D projections, and navigational errors when aircraft trajectories are propagated through the airspace, additional uncertainties are introduced in the output of TGF simulations. TGF's point to point navigation uses Rhumb lines (Mercator Projection) for point to point guidance, using constant desired heading to move from fix to fix on its route. This is an accurate method of depicting real world aircraft behavior. However, JPVD (and most ATC systems) displays route data using a Stereographic projection. The "route" lines shown in the figures are stereographic projections of lines between two points. This line contains inaccuracies, because there will always be a difference between a line drawn as a straight line on the stereographic projection and the actual path taken by an aircraft flying a Rhumb line to the next fix. Differences will change based on the length of the leg of route drawn as well as the routes relation to the Stereographic Point of Tangency.

A few samples are now considered to illustrate the stochasticity of the TGF environment. The effect of inherent uncertainties (3) can be particularly noticed for aircraft that have not been issued any maneuvering recommendation or that have been given only an altitude or speed change. In such a case, an aircraft is observed to deviate from its path, producing a lateral bias with respect to its intended route. Although some of the observed lateral bias is small and may be considered negligible, in some cases the deviations are quite large. For instance, as shown in Figure 9, AAL705 deviated laterally from its original route (direct route shown in yellow in the figure) although no maneuvering recommendations were received.

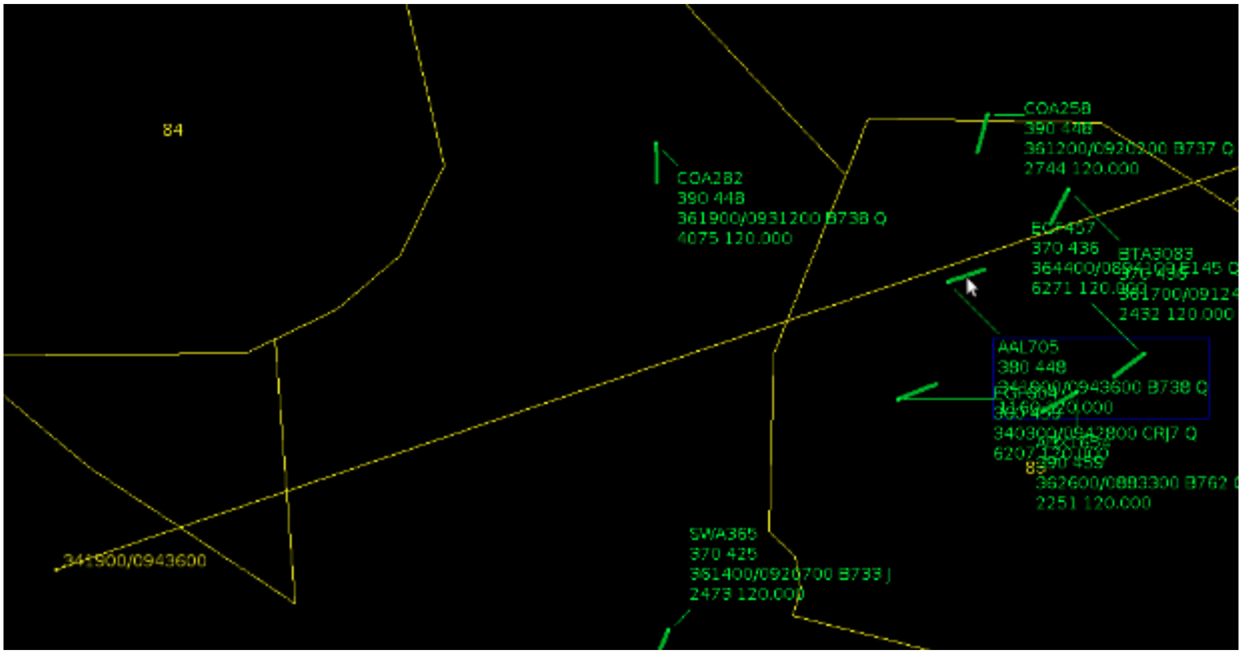


Figure 9: Lateral bias developed in TGF by an aircraft receiving no recommendation.

As depicted in Figure 10, AAL342 received an altitude change recommendation from the algorithm to climb from flight level FL370 to FL390. At FL390, the aircraft's intent was to follow the original direct route shown by the straight yellow line; however, a large lateral bias from its intended route resulted as shown in the figure.

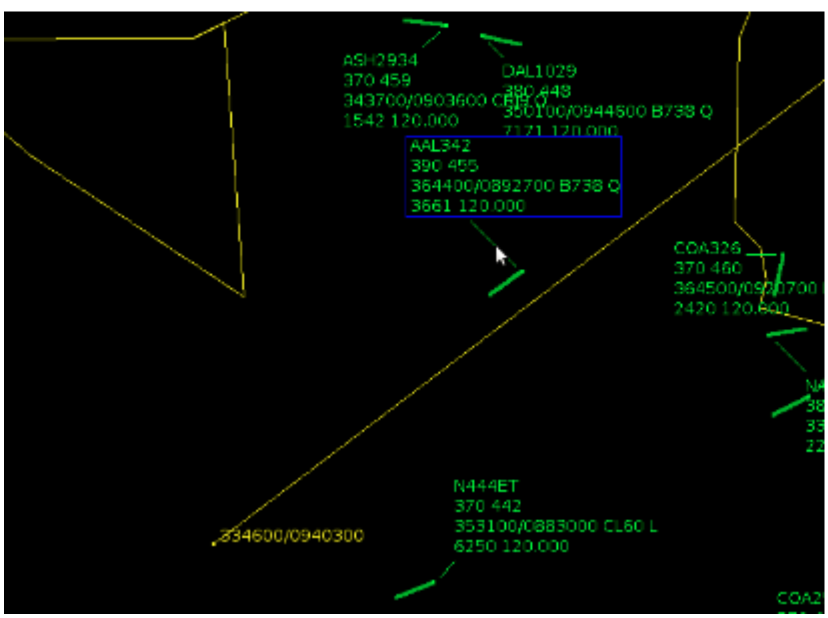


Figure 10: Lateral bias developed in TGF by an aircraft undergoing altitude change.

The lateral bias depicted in Figures 9 and 10 is due to the inherent stochasticity of the TGF environment. The effect of all sources of uncertainty can be seen for aircraft receiving re-routing recommendations from the algorithm. Figure 3 depicts a lateral bias for EJA320 that had received a re-routing recommendation from the algorithm.

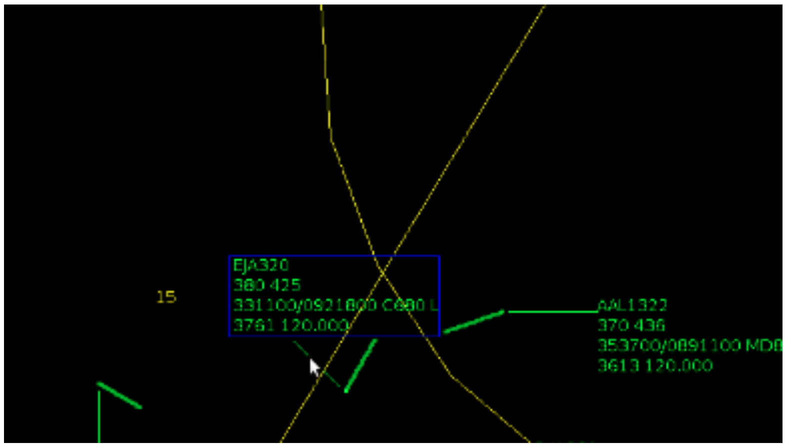


Figure 11: Lateral bias developed in TGF by a re-routed aircraft.

Such lateral biases to intended routes do not necessarily occur for every flight; it is quite random and there are several instances when flights transit the airspace with negligible or no lateral deviation to their intended routes. For instance, as shown in Figure 12, the flight receives a re-routing recommendation from the algorithm, and continued with negligible lateral bias.

Figure 12: Negligible lateral bias in TGF for a re-routed aircraft.

There are also rare instances, when a flight could be classified as wayward due to the large bias. For example, as shown in Figure 13, COA1092 received only an altitude change recommendation and then continues with a large lateral bias.

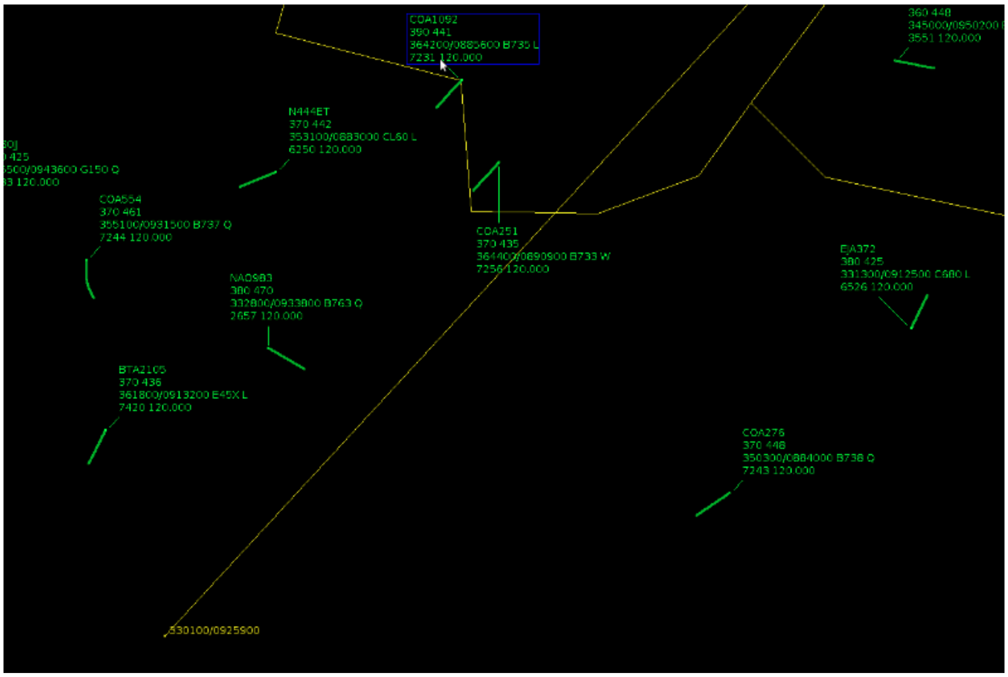


Figure 13: Huge lateral bias in TGF for an aircraft receiving only altitude change.

In general, with the exception of the wayward behavior shown in Figure 13, the lateral bias can be up to 2 nm. Due to the uncertainties described above, the algorithm was modified in order to accommodate lateral track bias of up to 2 nm. It should be noted that such a modification results in a reduction in the feasible space of solutions from an algorithmic viewpoint, and has the following implications:

1) Increased risk of infeasible solutions; although this risk was increased, after including the modification, no infeasibility was observed even for a high-traffic scenario such as sim5.
2) Sub-optimal solutions; the cost of increasing the buffer is a higher fuel burn.

Note that the algorithm modification to contend with a large lateral bias will result in an increased number of conflict detections when compared to the interim algorithm. This in itself is an interesting area of study that is beyond the scope of this study.

4.2 Target Generation Facility with Common Message Set Data Stream (TGF-CMS)

The Target Generation Facility provided an excellent opportunity, to some extent, to run a scenario by capturing the stochasticity of the simulation environment. The TGF only runs provided a level of uncertainty arising due to un-modeled dynamics, and approximation errors while communicating the output (e.g. speed rounded off to the nearest multiple of 5 knots, way-points reported in hours and minutes ignoring the seconds, etc.). For the Conflict3 scenario, TGF runs have been completed and compared with the results of the deterministic setup. Furthermore, several runs were made in order to test if the results were reproducible under the uncertainties provided by the TGF environment. It was found that results (recommendations) were similar in nature for the different simulation runs. Also, the results were reproducible in terms of not only which aircraft are maneuvered but how they were maneuvered. The stochastic-level runs (*TGF Simulation with CMS data stream)* were also been found to be consistent and conflict-free.

4.3 Implementation Challenges

The majority of algorithm performance issues were realized after migrating from the deterministic to the stochastic-level evaluation at the WJHTC. Specifically, it was discovered that the algorithm was extremely sensitive to its evaluation environment and input, and its robustness required major improvements to perform properly in the stochastic (realistic) evaluation environment setup at the WJHTC. In particular, the key challenges encountered were:

(1) Infeasible solutions occurred when the algorithm could not construct alternate routing for aircraft in conflict; this inability was due to a variety of issues including algorithm logic errors and/or system uncertainties.
(2) Algorithm hanging/freezing occurred due to unforeseen coding, logic, and other errors.
(3) Inconsistent results were observed when comparing deterministic and stochastic runs with identical initial conditions. These inconsistencies were mainly due to unknown uncertainties.
(4) Speed fluctuations in input data provided to the algorithm from the WJHTC systems impacted algorithm performance in terms of both function and results.
(5) The algorithm required updating and testing to convert from continuous heading and speed variable recommendations to integer inputs based on best-practice minimum increments identified by controllers and pilots.
(6) Sector exit and timing mismatches due to various errors and aforementioned issues.
(7) Input/output connection issues between the algorithm interface and the Tech Center systems were a significant challenge.
(8) The non-cooperative version was not truly non-cooperative in the presence of uncertainties; so changes had to be made.

These issues are the most significant of the challenges encountered, and it should be noted that many were inter-dependent. A significant effort was required for identification of these issues, and resolving them proved challenging. Addressing the uncertainties of the TGF environment was the biggest challenge because it was not known a priori that some of the deviations could be as large as 2 nm. It was found through several simulation runs, and scanning the data of the simulation runs, that for some aircraft, the deviations were too large. The algorithm was not originally designed to handle such large perturbations, and had to be modified to address such fluctuations. It should be noted that the obvious effect of the large perturbations was a compromise on the optimality of the simulations. Chances of infeasible solutions also increase when adjusting for high fluctuations; however, a heavy-traffic scenario like sim5 has run without any uncertainty.

5 ALGORITHM EVALUATION

Given a set of aircraft at four altitude levels, the algorithm provides a set of flight plan change recommendations for one or more aircraft. A question that naturally arises is whether the conflict resolution maneuvers, suggested by the algorithm, indeed result in conflict-free trajectories for the set of aircraft. The answer to this question is provided below in the form of a sequence of evaluations that were conducted: (1) at the Algorithm-Level, where performance is accessed solely on the output of the algorithm (code); (2) at the Encounter-Level, where performance is accessed in terms of how well a single repeated encounter is resolved; (3) at the Scenario-Level, where performance is accessed in terms of how well the various encounters in a scenario are resolved.

5.1 Algorithm-Level Evaluation

Algorithm-level validation can be performed by augmenting the algorithm with a conflict detection scheme, separate from the optimization process. Note that the optimization process attempts to create a set of feasible (conflict-free) trajectories for all aircraft in consideration. The originally planned trajectories can be sent to a conflict detector to determine whether any conflicts exist. Similarly, when the optimization problem is solved; the new trajectories (including the conflict resolution maneuvers) for the set of aircraft can be routed to the same conflict detector to determine whether there are any conflicts. By comparing the results for the old and new trajectories, it can be easily verified whether the algorithm does result in a conflict-free trajectories. This is illustrated in the Figure 4.

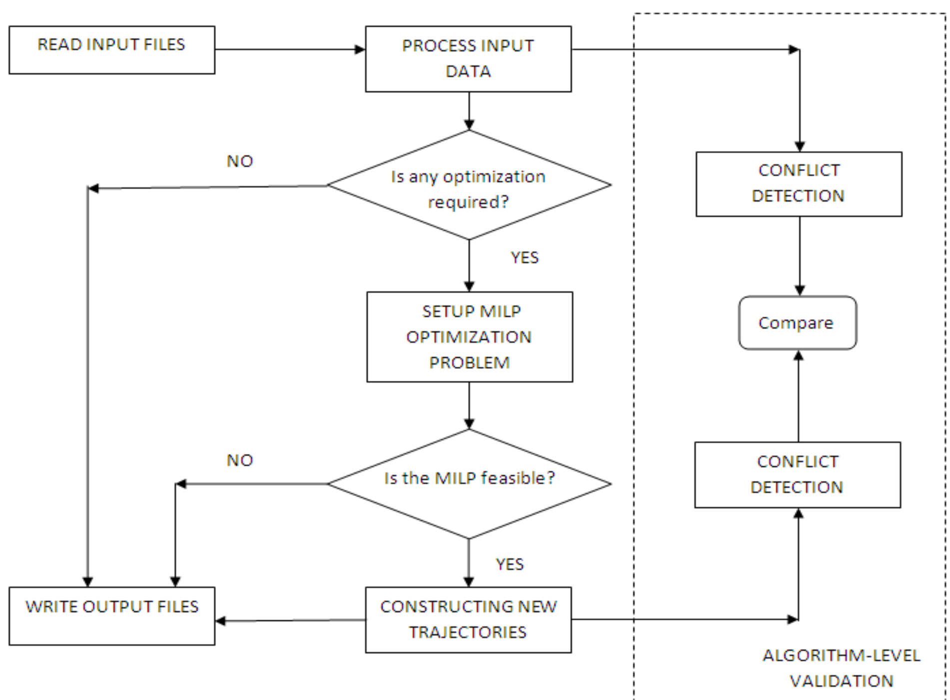


Figure 4: Algorithm Flow-chart including the algorithm-level validation

An algorithm-level validation is necessary, but is not sufficient to guarantee conflict-free paths. It would have been sufficient in the case of a deterministic world, where aircraft would have followed the exact trajectories as computed by the algorithm. However, in a real world, this is not possible due to the presence of uncertainties. These uncertainties may be caused by factors such as un-modeled dynamics, approximations introduced to maintain specific output format, and noise in the input data provided to the algorithm. While the first factor causes aircraft to deviate from their predicted trajectories, the latter two factors cause the resolutions to be inexact.

One common way to generate conflict-free trajectories in the presence of uncertainties is to make the conflict resolution algorithm more conservative. That is, using buffers that would absorb any deviation from the projected aircraft trajectories. Furthermore, in our case, it is known a priori that aircraft speed information is more accurate than aircraft position information. This knowledge can be utilized in a more accurate conflict resolution by relying on speed information wherever possible.

Whether the algorithm can work in the presence of these uncertainties can only be determined by performing encounter-level and scenario-level validations.

5.2 Encounter-Level Evaluation

The WJHTC has (over the years) developed air traffic simulations of what they refer to as "encounter geometries." In these simulations, aircraft come into conflict with each other at repeated intervals. The number of aircraft and geometries being considered are less, and thereby allows tracking for each aircraft over its path through the airspace. This aids in the understanding of the algorithm behavior, and provides a platform for comparison of the results for the different simulation environments mentioned above.

These encounter geometries were evaluated with the following two simulation engines:

1. Deterministic Simulation Engine
2. TGF Simulation Engine

5.2.1 Encounter-Level Deterministic Evaluation

A deterministic evaluation was performed at Georgia Tech, using a set up that does not consider any of the sources of uncertainties discussed in Sec. 4.1 previously. In this evaluation, the algorithm is used in a cyclic manner. First, the algorithm develops solutions to conflicts and selects the fuel-optimal routes during the Algorithm Run Period (ARP) based on the current location and flight plan of each aircraft. The optimized solution consists of a series of aircraft deviation suggestions. These suggestions are presented to the Air Traffic Controller responsible for that sector of airspace. Air traffic controllers are given time to review the recommendations and decide whether the suggested course changes are appropriate during the Controller Comprehension Period (CCP). The recommended changes are restricted to fall within the time interval between the end of the CCP and the beginning of the next APR. Once the agreed-upon recommendations are approved, the controller is responsible for implementing these actions at the advised time of action, as indicated in Figure 5.

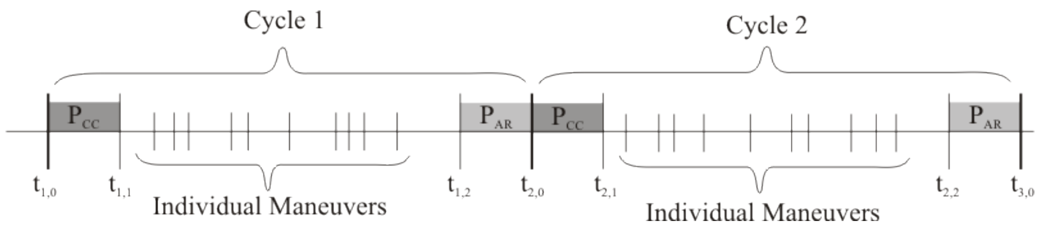


Figure 5: Algorithm Cycle

Now, referencing Figure 1, step-by-step details are discussed regarding how the algorithm works in a deterministic setting. All iterations (executions of the algorithm) are detailed for the encounter geometry simulation entitled "Conflict3" which it is easy to monitor how each aircraft traverses the airspace. It is also shown how the solution of the general algorithm compares with the non-cooperative version of the algorithm.

<u>Iteration 1 (t = 0 min)</u> No flight is present; hence no action recommended by the algorithm.

<u>Iteration 2 (t = 2 min)</u> Only 1 aircraft present, hence no action recommended by the algorithm.

<u>Iteration 3 (t = 4 min)</u> No new aircraft has entered the airspace, hence no action recommended by the algorithm.

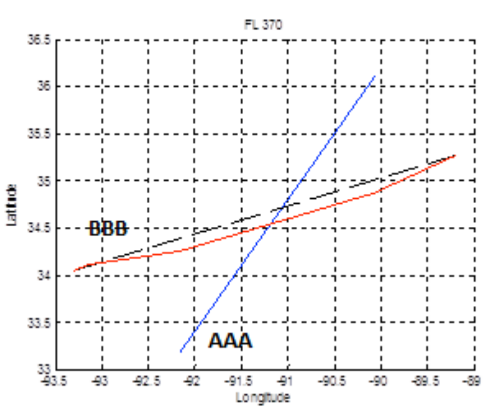
Figure 6 depicts iterations 4 to 9. The x-axis represents West-East direction, while y-axis represents South-North direction. If the trajectory of an aircraft is altered by the algorithm, then the projected route of that aircraft is denoted in red.

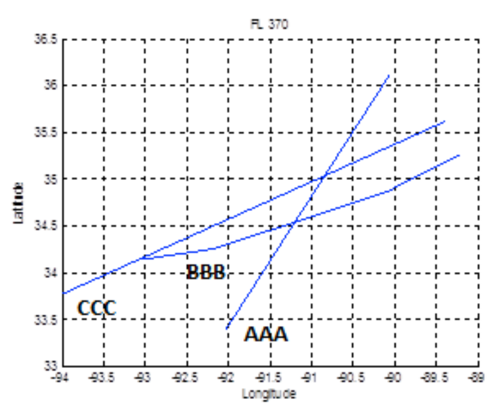
<u>Iteration 4 (t = 6 min)</u> Aircraft AAA (ELO001_100) and BBB (EHI001_000) are in potential conflict. The point of intersection between the two trajectories is 113.385 nm ahead of AAA, and 117.066 nm ahead of BBB. AAA arrives at the point in 14.7405 minutes, while BBB arrives at the same point in 14.8344 minutes, since this is less than the minimum required threshold value the algorithm issues recommendations. Aircraft BBB receives a recommendation for speed and heading changes. The altered route of the aircraft is trapezoidal in nature (recall Figure 1) with the three solid legs comprising three sides of the trapezoid. The original route completes the trapezoid shape. In the altered route, the length of the legs are d12 = 49.4689, d23 = 112.155, and d34 = 49.4689 nm respectively (d12, d23, and d34 are the lengths of the three legs of the trapezoidal path followed by the aircraft that has changed heading). The aircraft takes a time of t12 = 6.40387, t23 = 13.9181, and t34 = 6.13897 minutes over these three legs. Aircraft AAA receives speed changes. Overall, the total fuel burn of the two aircraft is 0.33% more than were planned to burn on their original route. In their altered routes, aircraft AAA and BBB are non-parallel with point of conflict at: 96.8444 NM ahead of AAA and 96.089 nm ahead of BBB in their respective paths. The time of arrival at the conflict point is 13.4185 minutes and 12.296 minutes respectively for the two aircraft, a difference that is greater than the required threshold of 0.872599 minutes (note that the threshold represents the minimum time required to maintain separation of the aircraft trajectories as the two aircraft traverse the airspace.) Hence, the conflict has been resolved between the aircraft pair. If aircraft AAA is restricted, then the algorithm is forced to have a non-cooperative solution, in which only BBB can maneuver in order to resolve the conflict. In this case, the conflict pair burns 0.51% more fuel in order to resolve the conflict. Similarly, if aircraft BBB is restricted the algorithm is forced to have a non-cooperative solution, in which only AAA can maneuver in order to

resolve the conflict. In this case, the conflict pair burns 1.4% more fuel in order to resolve the conflict. Hence, both of the non-cooperative conflict resolutions are costlier (in terms of fuel) than the optimal cooperative maneuver. However, the cooperative conflict resolution may require additional controller to pilot clearances, thereby increasing the controller workload.

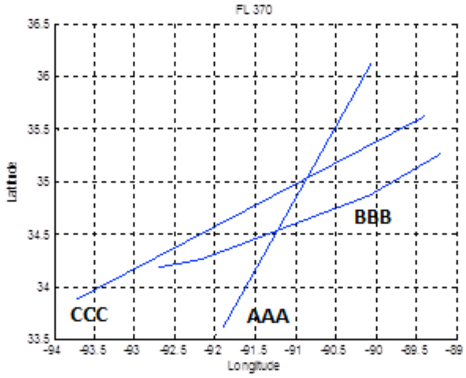
Iteration 5 (t = 8 min) New aircraft CCC (EHI002_200) has entered the airspace but is not in conflict with the other two aircraft; hence no action is recommended by the algorithm.

Iteration 6 (t = 10 min) No new aircraft have entered the airspace thus no conflict exists; hence, there is no recommendation from the algorithm.

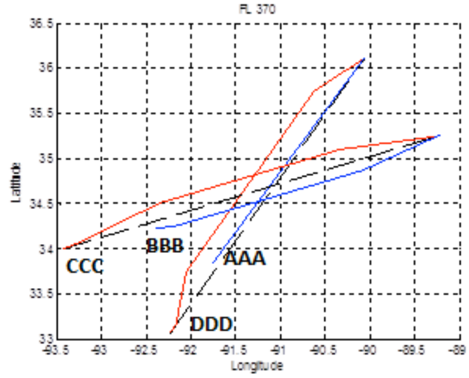




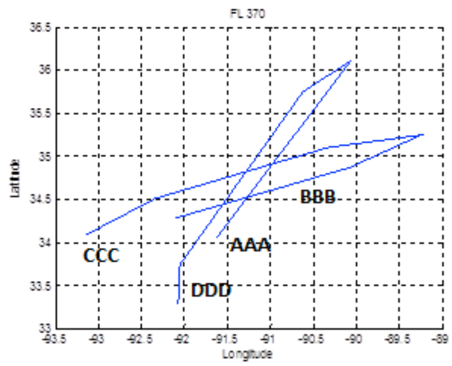
Iteration 4



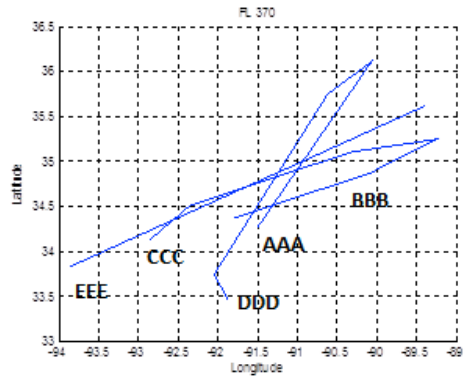
Iteration 5



Iteration 6



Iteration 7



Iteration 8

Iteration 9

Figure 6: Aircraft Trajectories for Conflict3 (Iterations 4 to 9).

Iteration 7 (t = 12 min) Aircraft DDD (ELO002_300) has entered the airspace. Aircraft DDD and CCC are non-parallel with a point of intersection 121.526 nm ahead of DDD, and 124.302 nm ahead of CCC. Their times of arrival at the conflict point are 15.7926 minutes and 15.7381 minutes respectively. Hence, there is a potential conflict between the two aircraft. Both aircraft DDD and CCC receive heading and speed change recommendations. For the altered route of aircraft DDD, the length of leg 1 is d12 = 35.4449, leg 2 is d23 = 139.725, and leg 3 is d34 = 35.4449. The time taken by the aircraft over these legs are t12 = 4.70813, t23 = 17.7727, and t34 = 4.50851 minutes respectively. On their new trajectories, aircraft DDD and CCC are non-parallel with point of intersection at: 103.659 nm ahead of DDD and 103.091 nm ahead of CCC, with arrival times at the conflict point: 14.3495 minutes and 13.4796 minutes respectively, a difference greater than the threshold of 0.872599 minutes, therefore the conflict has been resolved between the aircraft pair. Overall, the total fuel burn of the two aircraft increases by 0.72% in order to resolve the conflict. If aircraft DDD is restricted then it will force the algorithm to have a non-cooperative solution, in which only CCC can maneuver in order to resolve the conflict. In this case, the conflict pair burns 1.61% more fuel in order to resolve the conflict. Similarly, if aircraft CCC is restricted then the algorithm is forced to have a non-cooperative solution, in which only DDD can maneuver in order to resolve the conflict. In this case, the pair burns 0.82% more fuel in order to resolve the conflict.

Hence, both of the non-cooperative conflict resolutions are costlier (in terms of fuel) than the optimal cooperative maneuver.

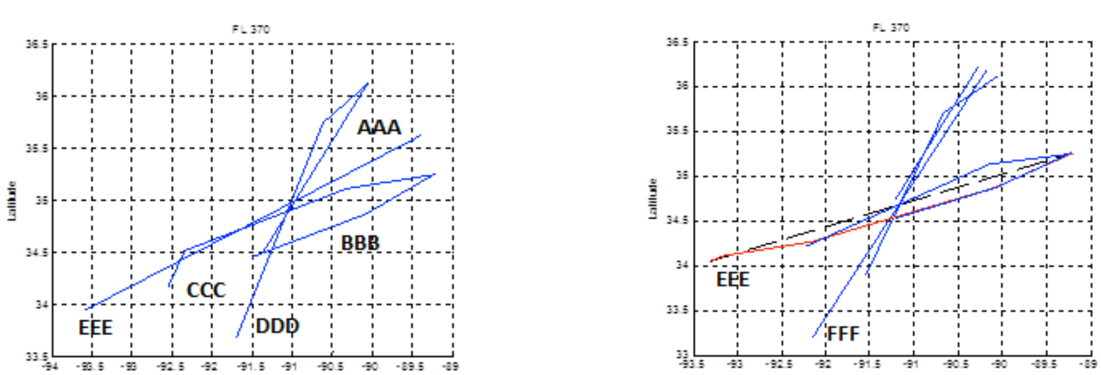
Iteration 8 (t = 14 min) No new aircraft in the airspace, hence no action is recommended by the algorithm.

Iteration 9 (t = 16 min) A new aircraft EEE (EHI003_400) enters the airspace but there is no potential conflict, and hence no action is recommended by the algorithm.

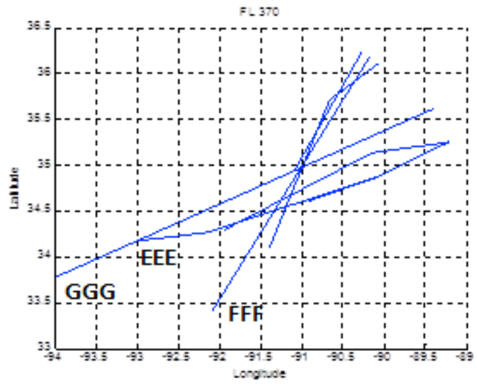
Figure 7 depicts the projected aircraft paths as computed by the algorithm during iterations 10-15. As before, the x-axis represents West-East direction, while the y-axis represents South-North direction. If the trajectory of an aircraft is altered by the algorithm, then the projected route of that aircraft is marked in red.

Iteration 10 (t = 18 min) No new aircraft have entered the airspace, hence no recommendation from the algorithm.

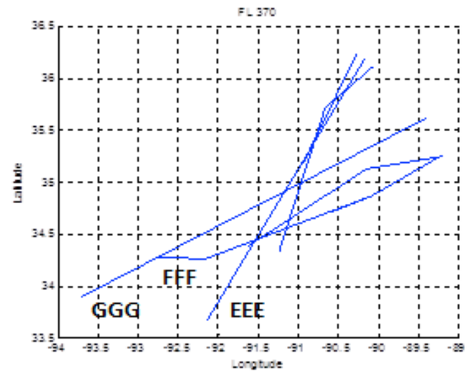
Iteration 11 (t = 20 min) A new aircraft FFF (ELO003_500) has entered the airspace. Aircraft FFF and EEE are non-parallel with a point of intersection at 113.066 nm with respect to FFF and 117.213 nm with respect to EEE. The arrival times for the aircraft at the point of intersection are 14.7082 minutes and 14.8654 minutes, respectively, therefore there is a potential conflict and both FFF and EEE receive recommendations: EEE received a heading and speed change recommendation, while FFF received only a speed change recommendation. Overall, the aircraft burn 0.41% more fuel in order to resolve the conflict. Aircraft FFF and EEE are non-parallel with point of intersection of 96.3909 nm ahead of EEE and 95.518 nm ahead of FFF, with the time of arrival at the conflict being 13.3637 minutes and 12.223 minutes respectively, and the required threshold of 0.872599 minutes, resolving the conflict. If aircraft FFF is restricted then the algorithm is forced to have a non-cooperative solution, in which only EEE can maneuver in order to resolve the conflict. In this case, the conflict pair burns 0.49% more fuel in order to resolve the conflict. Similarly, if aircraft EEE is restricted then the algorithm is forced to have a non-cooperative solution, in which only FFF can maneuver in order to resolve the conflict. In this case, the conflict pair burns 1.4% more fuel in order to resolve the conflict. Hence, both of the non-cooperative conflict resolutions are costlier (in terms of fuel) than the optimal cooperative maneuver.



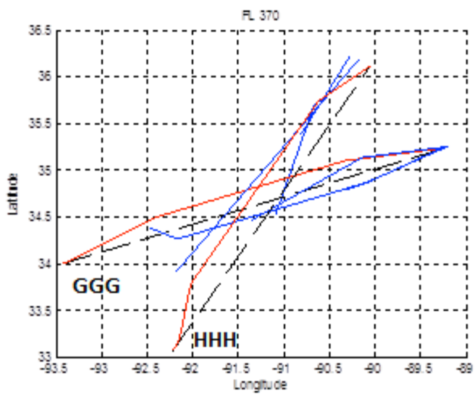
Iteration 10



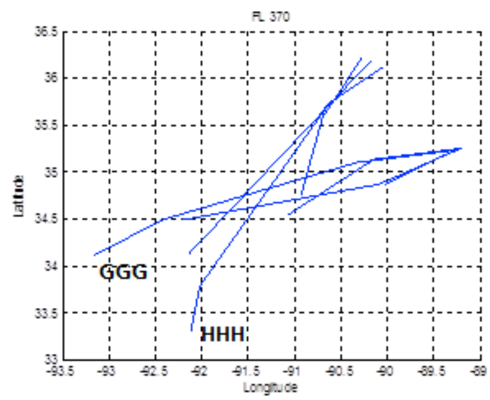
Iteration 11



Iteration 12



Iteration 13



Iteration 15

Iteration 14

Figure 7: Aircraft Trajectories for Conflict3 (Iterations 10 to 15).

Iteration 12 (t = 22 min) A new aircraft GGG (EHI004_600) has entered the airspace, but is not in conflict with any of the existing aircraft. Hence, no action is recommended.

Iteration 13 (t = 24 min) There is no new aircraft, no potential conflict, and hence no action is recommended.

Iteration 14 (t = 26 min) A new aircraft HHH (ELO004_700) enters the airspace. Aircraft GGG and HHH are non-parallel with point of intersection 124.332 nm ahead of GGG and 121.686 nm ahead of HHH. The times of arrival at the conflict point are 15.7631 minutes and 15.8248 minutes respectively, therefore, there is a potential conflict. Aircraft GGG receives a recommendation of speed and heading change. In the altered route, aircraft GGG travels a distance of d12 = 53.8575 nm over leg 1, d23 = 108.345 nm over leg 2, and d34 = 53.8575 nm over leg 3. Aircraft GGG requires a time of t12 = 6.68684, t23 = 13.4518, t34 = 6.68684 minutes to travel the three legs respectively. Aircraft HHH receives a recommendation of speed and heading change. In the altered route, aircraft HHH travels a distance of d12 = 36.0183 nm over leg 1, d23 = 138.867 nm over leg 2, and d34 = 36.0183 nm over leg 3. Aircraft HHH takes times t12 = 4.76995, t23 = 17.676, and t34 = 4.58468 minutes to travel over the three legs respectively. In their new trajectories, aircraft HHH and GGG are non-parallel with point of intersection 96.3909 nm ahead of HHH and 95.518 nm ahead of GGG with times of arrival at their conflict point of 13.3637 minutes and 12.223

minutes respectively. The time difference is greater than the required threshold of 0.872599 minutes; hence, the conflict has been resolved. If aircraft HHH is restricted, the algorithm is forced to have a non-cooperative solution, in which only GGG can be maneuvered in order to resolve the conflict. In this case, the conflict pair burn 0.85% more fuel in order to resolve the conflict. Similarly, if aircraft GGG is restricted, then the algorithm is forced to have a non-cooperative solution, in which only HHH can maneuver in order to resolve the conflict. In this case, the conflict pair burns 1.54% more fuel in order to resolve the conflict. Hence, both of the non-cooperative conflict resolutions are costlier (in terms of fuel) than the optimal cooperative maneuver (0.68%).

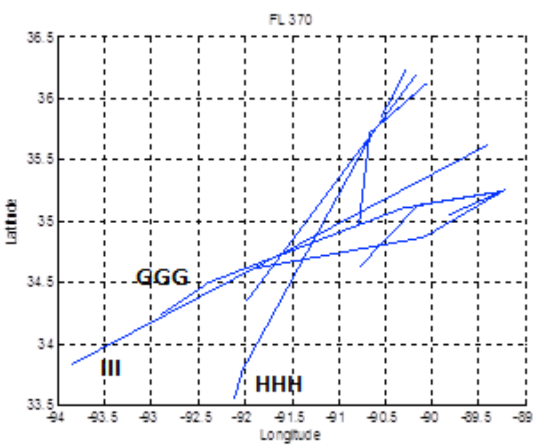
Iteration 15 (t = 28 min) No new aircraft, 8 aircraft flying in their restricted path, no conflict and no action taken.

Iteration 16 (t = 30 min) A total 9 aircraft are present in the airspace, including new aircraft III (EHI005_800). There is no conflict between any aircraft, and hence no action was taken.

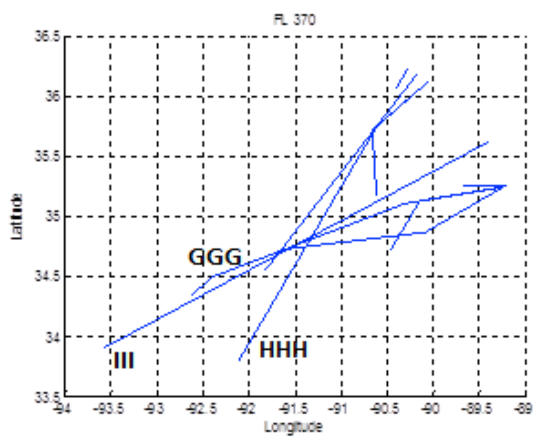
Iteration 17 (t = 32 min) No new aircraft has entered the airspace, and the same 9 aircraft are present. Hence, no conflict has been introduced and hence no action is taken.

Iteration 18 (t = 34 min) There are now 10 aircraft in the airspace with the entry of aircraft JJJ (ELO005_900). Aircraft III and JJJ are in conflict. The algorithm recommends heading and speed changes for III, and only a speed change for JJJ.

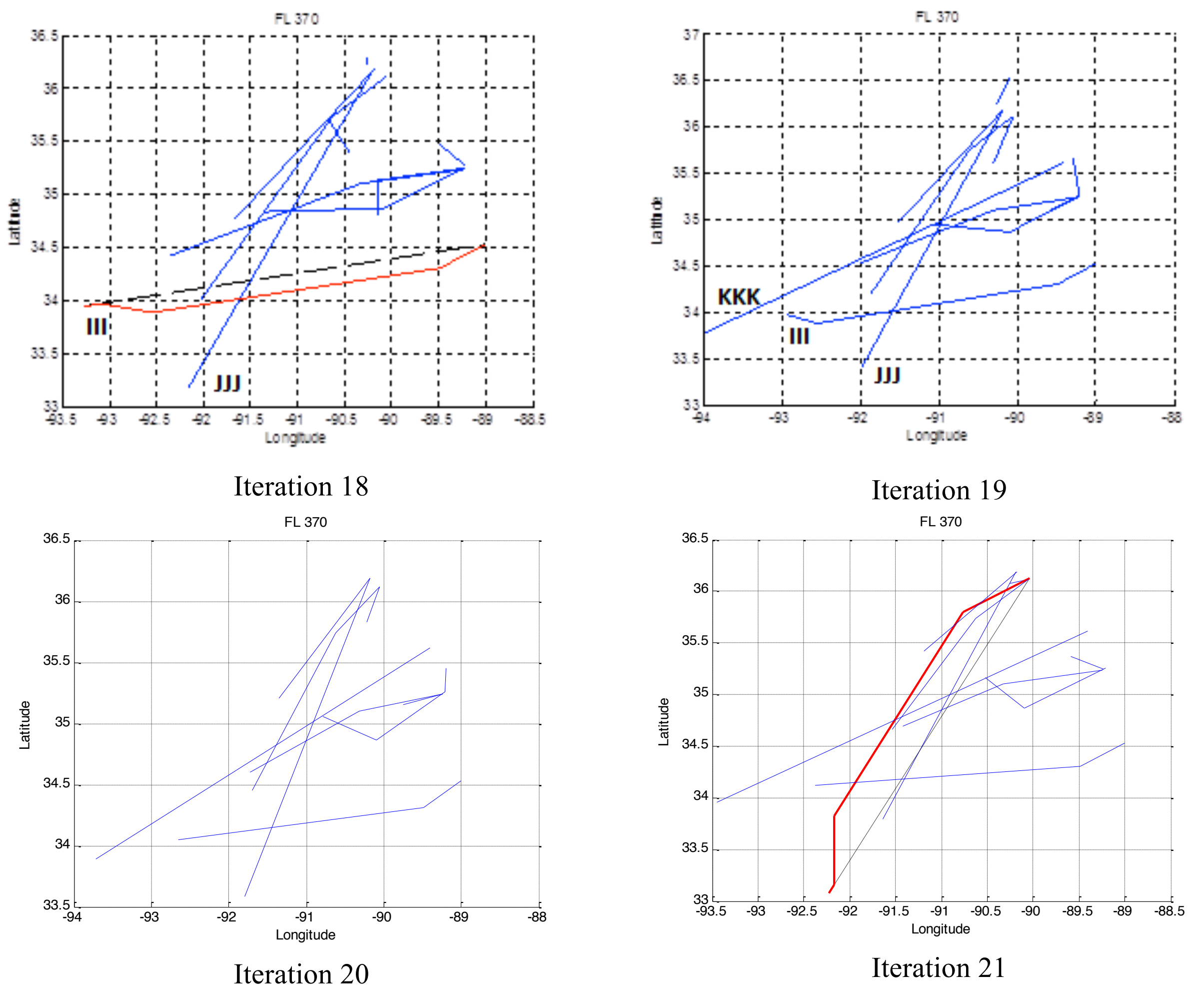
Similarly, the remaining iterations of the scenario are executed. Figure 8 depicts the projected aircraft paths as computed by the algorithm during iterations 16-21.



Iteration 16



Iteration 17



Iteration 18 Iteration 19

Iteration 20 Iteration 21

Figure 8: Aircraft Trajectories for Conflict3 (Iterations 16 to 21).

5.2.2 Encounter-Level TGF Evaluation

The output of the encounter-level algorithm validation using the TGF simulation for Conflict3 are provided and compared with the deterministic runs described previously. For the general version of the algorithm, the TGF results pretty much resemble the deterministic runs. The results may vary slightly in the length of the legs or the time of action if the simulation is run repeatedly, however, the recommendations are similar (same aircraft moved, with similar recommended route changes).

For the limited version of the algorithm forcing a non-cooperative version, there is a difference between the algorithm behavior in the deterministic environment, and the TGF simulation. For the first three iterations, the number of aircraft is less than 2 and hence there is no conflict. The algorithm therefore does not recommend any action. For the fourth iteration, a conflict is detected, and the algorithm recommends AAA to be moved. In iteration 5, no conflict is detected and hence no action is recommended. In iteration 6, BBB, which was in conflict with AAA, is recommended to alter its speed. Although the recommendation may not seem necessary because the projected trajectories of the aircraft will not violate the required separation criterion, the algorithm sees it to be necessary because the feasible set of solutions for the algorithm need to maintain a greater separation (required separation + buffer). The algorithm sees this 'greater separation' to be violated by the projected routes of the aircraft and therefore produces a recommendation. In fact, proceeding through the remaining iterations, results in both aircraft involved in the conflict to be maneuvered eventually. Most of the second recommendations issued to conflicting traffic are very small changes, and are usually speed changes.

5.3 Scenario-Level Evaluations

The scenario-level evaluations were conducted with the following two simulation engines:

1. TGF Simulation Engine
2. TGF Simulation Engine + CMS

5.3.1 Scenario-Level TGF Evaluation – Light-Traffic Scenario (sim8)

The scenario is initially run with a dummy algorithm (that recommends nothing) in order to detect the original conflicts that are in the scenario. Next, the scenario is run with the modified algorithm. Conflicts detected in the second run help identify the conflicts that are introduced in the scenario due to the algorithm recommendations. The detected conflicts in each case are tabulated in Appendix: Sim8. Note that in the first case, the conflicts are not being resolved; hence the same conflicts appear over a set of iterations during the simulation.

Originally, there are 18 conflicts in the scenario. 13 of these are actual conflicts based on a 5 nm separation; however, since a greater separation is included to account for the fluctuations of the TGF, the additional 5 conflicts result and are marked in red in the table. When the scenario is run with the proper algorithm so that conflicts are resolved, the re-routing of an aircraft affects future conflicts. In fact, we find that two original conflicts EJA320 x EGF403 (iteration 4) and AAL1231 x DAL981 (iteration 8) in the scenarios are no longer encountered because EJA320 is re-routed in iteration 3, and AAL1231 is re-routed in iteration 4. On the other hand, four new conflicts are introduced in the scenario owing to the re-routings: DAL1727 x EJA320 (iteration 3); DAL981 x EJA320 (iteration 8); DAL1727 x COA347 (iteration 9); and LXJ609 x SWA3604 (iteration 15). Therefore, when the algorithm runs, a total of 18-2+4 = 20 conflicts are encountered during the scenario run. These conflicts are resolved by maneuvering 17 aircraft. The summary of conflicts encountered and the resolution maneuvers recommended by the algorithm are given in the Appendix: Sim8.

Of the 17 recommendations, 2 include altitude changes, and the remaining 15 are re-routing recommendations using three heading changes. The conflict avoidance between various aircraft pairs are illustrated in Figures 14-22. Of these, Figures 14(a) and 21(a) depicts conflict avoidance by altitude changes; while the remaining figures demonstrate conflict avoidance by re-routing the aircraft. In most cases, the lateral bias from the intended trajectory can be seen in the Figures, and it can be observed that conflict is avoided in spite of the uncertainties.

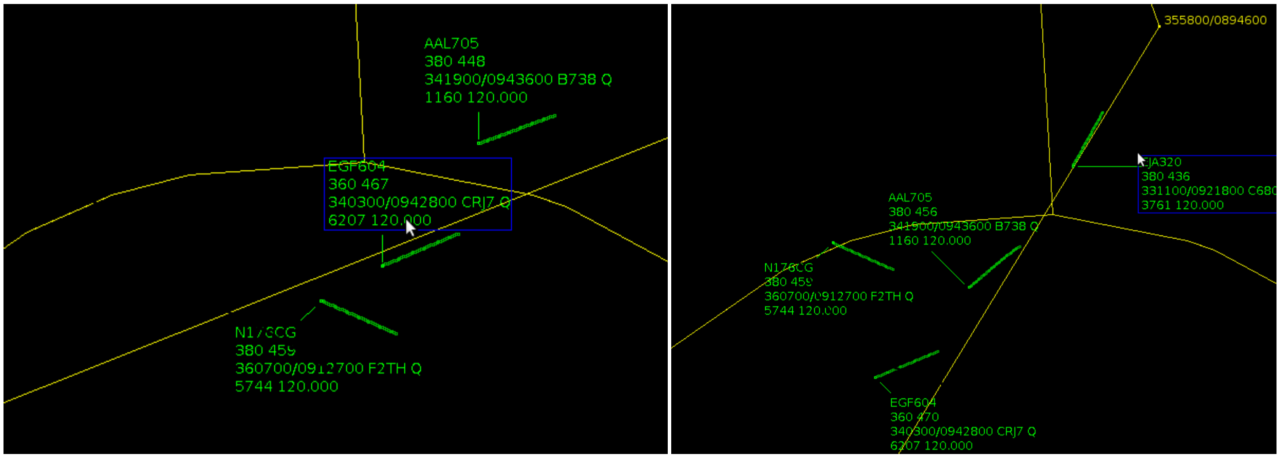


Figure 14: Conflict avoidance between (a) EGF604 x N176CG (b) EJA320 x AAL705 and N176CG

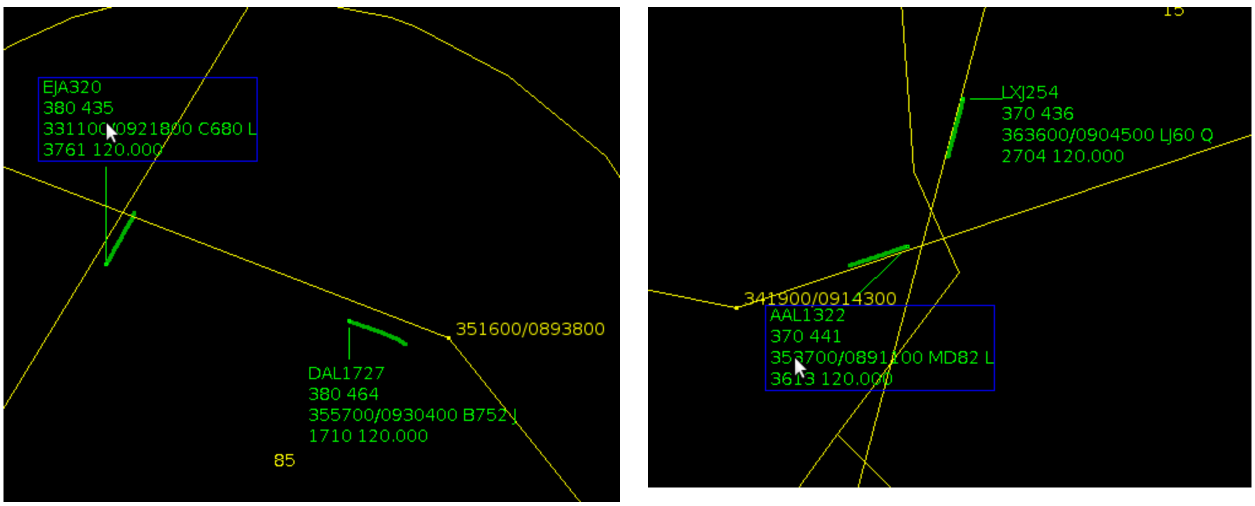


Figure 15: Conflict avoidance between (a) EJA320 x DAL1727 (b) AAL1322 x LXJ254

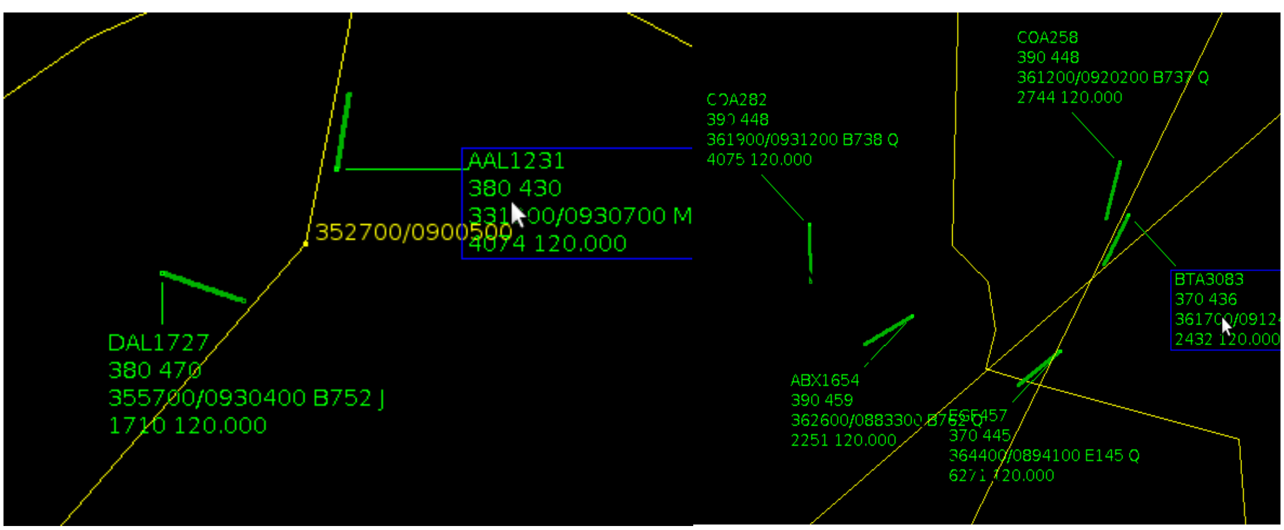


Figure 16: Conflict avoidance between (a) AAL1231 x DAL1727 (b) EGF457 x BTA3083

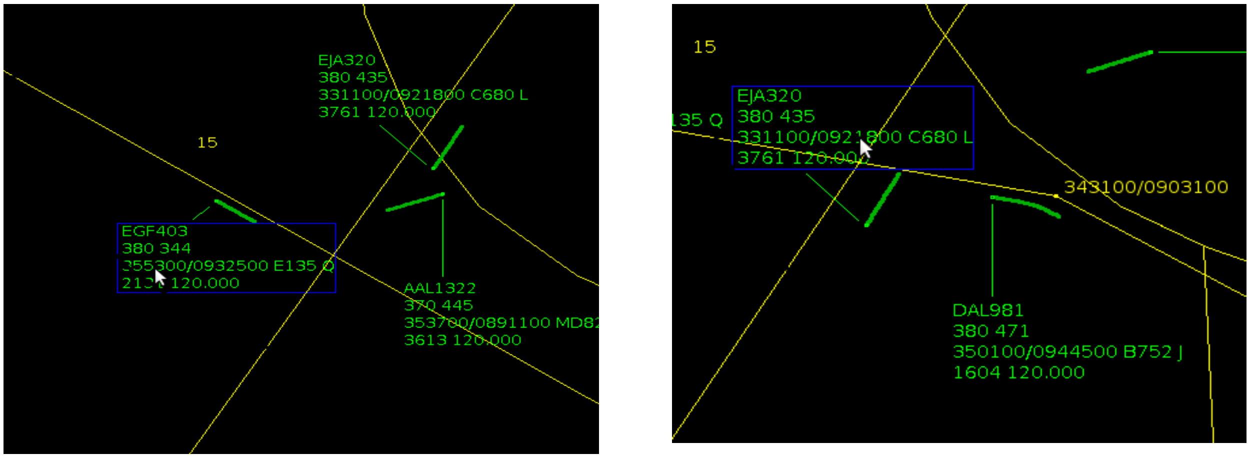


Figure 17: Conflict avoidance between (a) EGF403 x EJA320 (b) DAL981 x EJA320

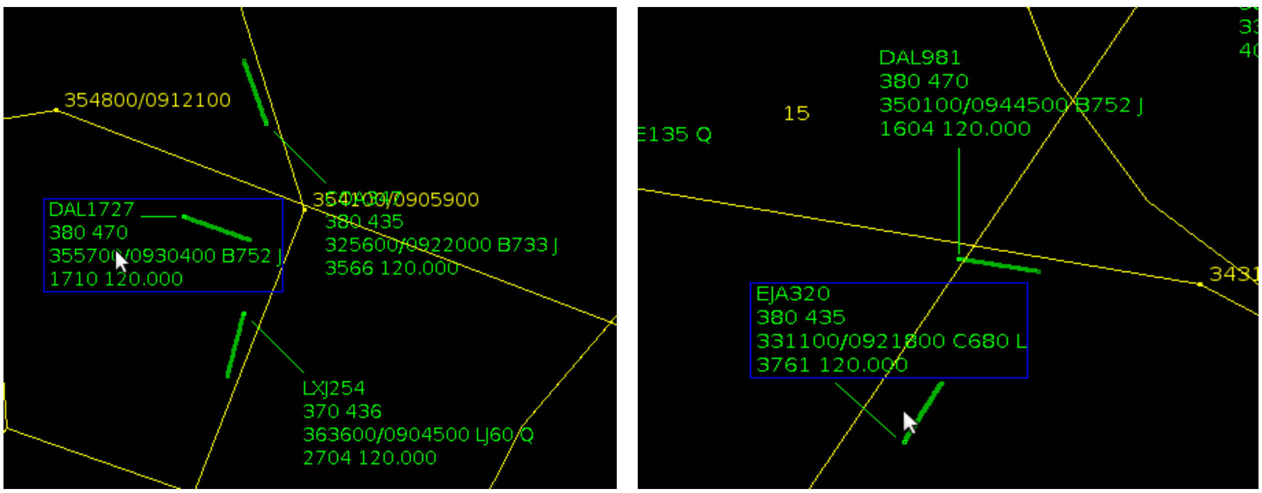


Figure 18: Conflict avoidance between (a) COA347 x DAL1727 (b) DAL981 x EJA320

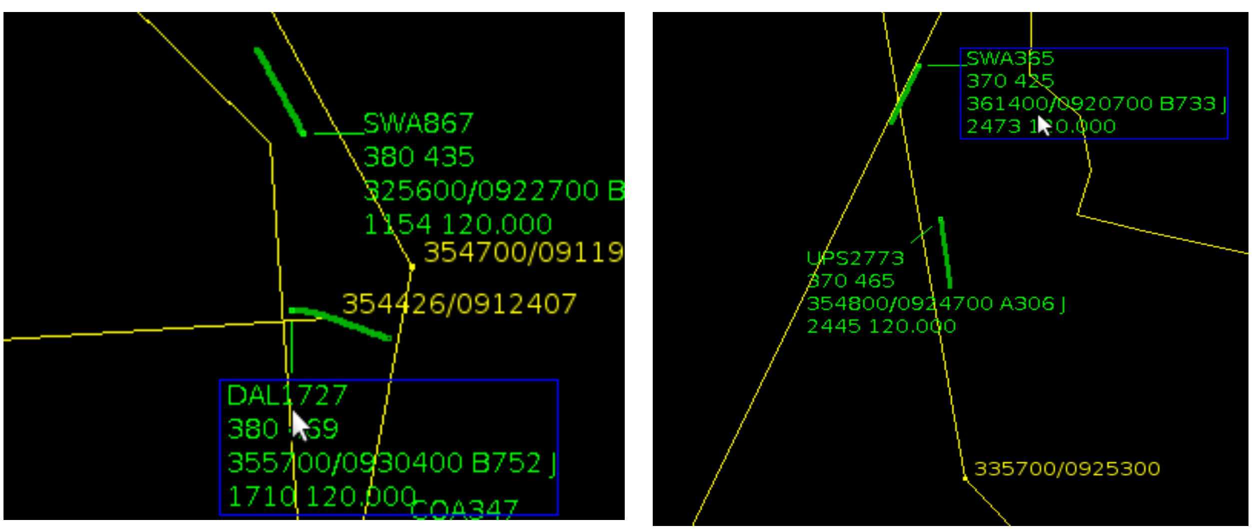


Figure 19: Conflict avoidance between (a) SWA867 x DAL1727 (b) UPS2773 x SWA365

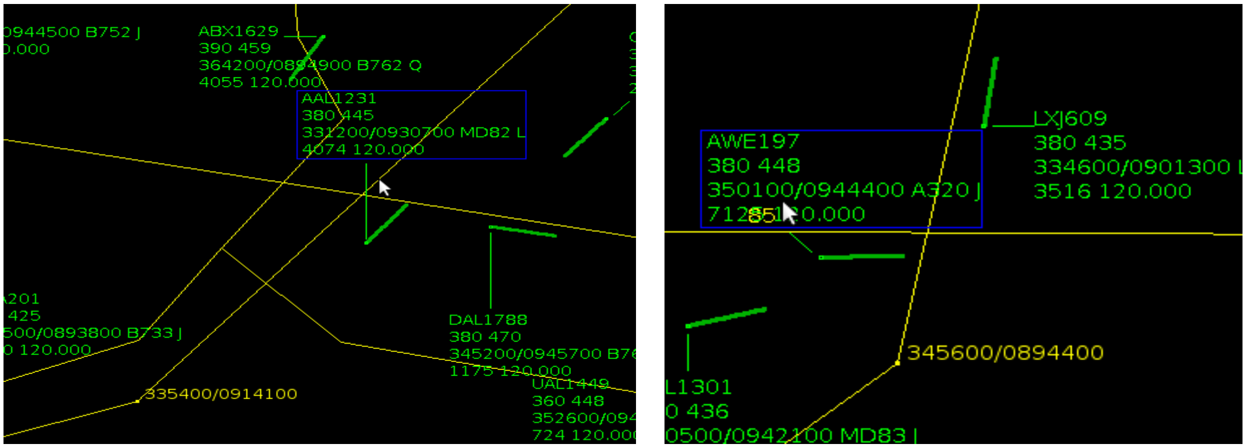


Figure 20: Conflict avoidance between (a) AAL1231 x DAL1788 (b) LXJ609 x AWE197

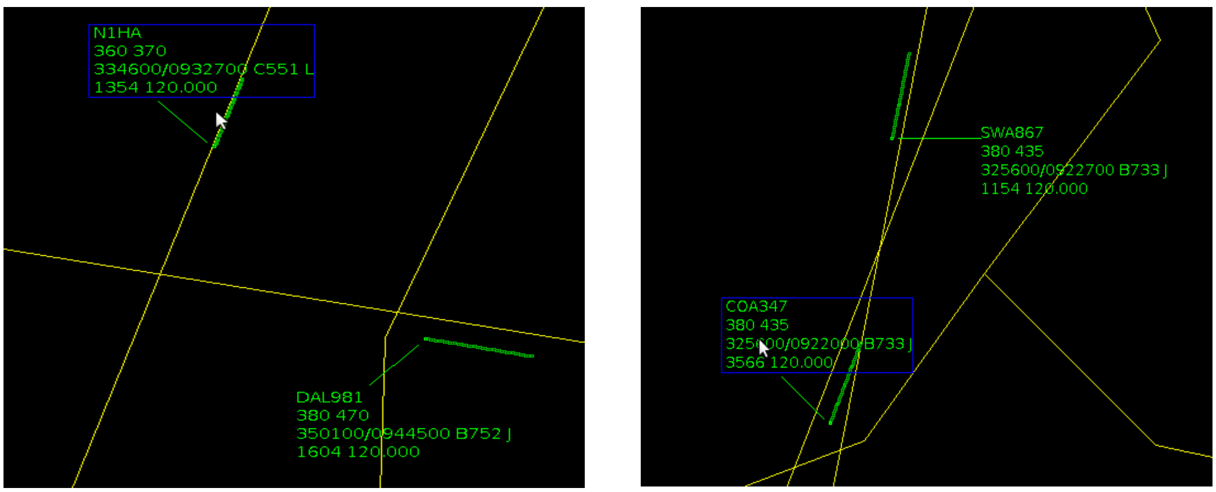


Figure 21: Conflict avoidance between (a) N1HA x DAL981 (b) COA347 x SWA867

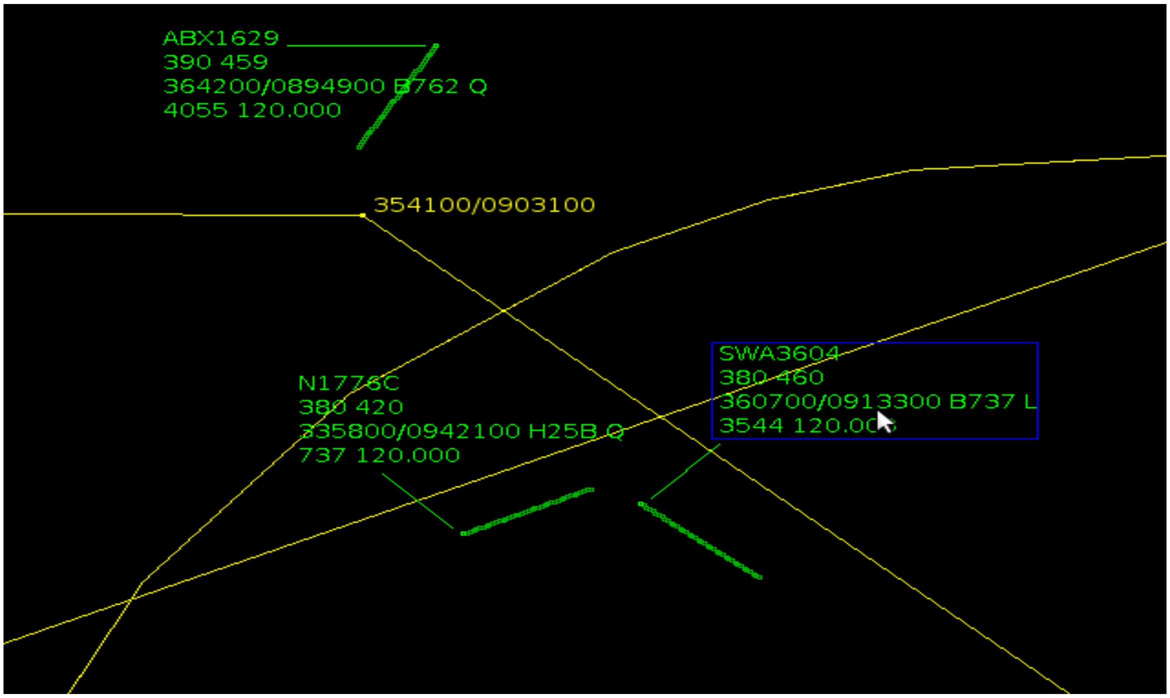


Figure 22: Conflict avoidance between N1776C x SWA3604

Figure 22 perhaps provides the best example of conflict avoidance under uncertainties. SWA3604 and N1776C both received recommendations from the algorithm, and are traversing the airspace with considerable lateral bias. In fact, the lateral drifts for both aircraft are such that it brings them closer to each other. In spite of this, the conflict has been avoided: N1776C crosses the path of SWA3604 long before the latter arrives even with the lateral bias shown.

The runtimes (in seconds) for different iterations of the TGF simulation are depicted in Figure 23. It can easily be verified that the higher algorithm runtimes correspond to the number of conflicts detected and not with increasing aircraft in the airspace. Although entry of new aircraft leads to more decision variables, restricting maneuvered aircraft removes some decision variables. This balance of decision variables results in consistent algorithm runtimes. Only when the addition of aircraft into the airspace produces several new conflicts does the algorithm runtime increase.

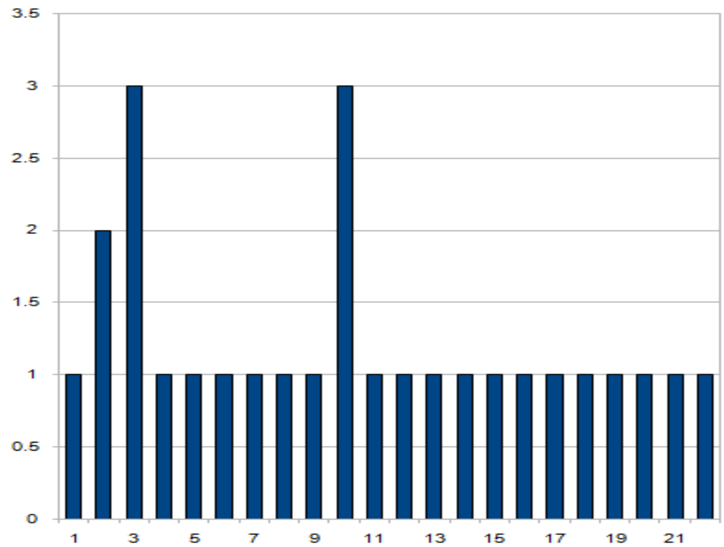


Figure 23: Algorithm Runtime (sec) for Different Iterations of sim8.

5.3.2 Scenario-Level TGF Evaluation – Heavy Traffic Scenario (sim5)

Similar to scenario sim8 run, scenario sim5 is initially run with a dummy algorithm (that recommends nothing) in order to detect the original conflicts within the scenario. Next, the scenario is run with the modified algorithm. The detected conflicts in each case are tabulated in Appendix: Sim5. Originally, there are 27 conflicts in the scenario. When the scenario is run with the proper algorithm resolving the conflicts, the re-routing of an aircraft affects future conflicts. Overall, 33 aircraft are maneuvered during the simulation run. The run resulted in no conflicts, and there was no infeasibility that was encountered.

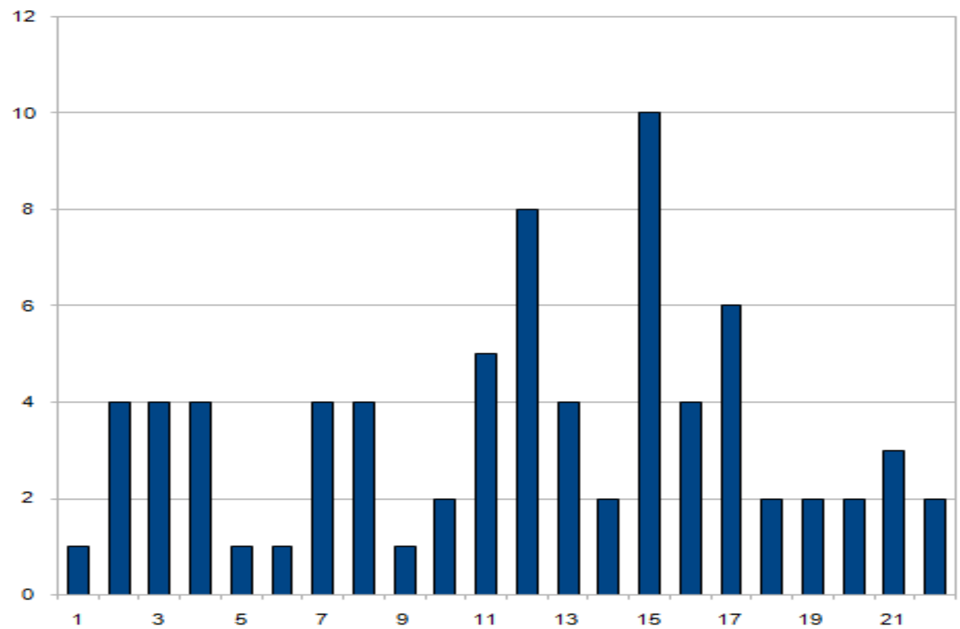


Figure 24: Algorithm Runtime (sec) for Different Iterations of sim5.

6 ANALYSIS

From a performance perspective, there are five question of great interest. These are:

1. What benefit does the algorithm provide?
2. How does this benefit change as a function of traffic level?
3. How does this benefit change if you restrict cooperation?
4. How does this benefit change if you restrict the speed of the aircraft?
5. How does this benefit change if you restrict the altitude of the aircraft?

The comparisons below provide answers to these questions. There are based on TGF simulation runs for 3 scenarios: sim8, sim9, and sim5. Of these, sim8 and sim9 are light-traffic scenarios, while sim5 is a heavy traffic scenario.

6.1 What benefit does the algorithm provide?

We computed the fuel burn benefit of the algorithm using trajectory data from the baseline simulation study and the scenario-level evaluations with the full implementation of the algorithm, and the methods and fuel burn data of BADA Version 3.7. While readers may obtain the details of the fuel burn computation process from BADA documentation [4], the computation involves the derivation of the thrust of the aircraft at a given point in time (defined by the time of a given radar return) from the position and time at prior and successive points in time (using the aircraft performance data in the BADA database) and then the conversion of the resulting thrust value into a fuel burn rate value using propulsion-to-fuel burn relationships (using the values for the relevant parameters in the BADA database). The net fuel burn is a time-based summation of the resulting series of fuel burn rates.

We found that across all scenarios the algorithm provided at least 1% reduction in fuel burn. Please note that we have chosen to report our results in terms of percentage changes because the BADA-based model for fuel burn prediction, like all models that rely on curve fits to data across various aircraft models, is more accurate in predicting trends as opposed to absolute values, and because all the goals and legislation associated with reduced fuel burn are given in terms of percentage changes.

6.2 How does this benefit change as a function of traffic level?

We also computed benefits as function of traffic level (because each scenario represents a different traffic level) by combining, in the case of the baseline data, the fuel burn for the different controllers into a single average number for each scenario, and then comparing the resulting values to their corresponding values in the scenario-level evaluation with the fully implemented algorithm. The results of this comparison are listed in the following table. As can be seen, the benefits of the algorithm increase with increasing traffic level, which is a very good result from a benefits perspective. While this might at first seem counter-intuitive, it is understandable given that the inefficiencies introduced by humans tends to grow as the traffic level rises and they approach their cognitive limits and start to make extremely gross actions.

Table 7: Benefits of Using Algorithm.

Scenario	Reduction in fuel burn
Sim8	1.029%
Sim9	1.145%
Sim5	1.217%

6.3 How does this benefit change if you restrict cooperation?

The optimal solution to the multi-level conflict resolution problem is often cooperative in nature. However, while the non-cooperative version moves fewer aircraft this solution is more costly when compared to the cooperative solution. The cost increases ranges between 1.7% and 3.8%. On an average, the non-cooperative version is costlier by approximately 3%. Among all scenario runs, it was observed in 3 cases that the non-cooperative solution is infeasible, so the result from the algorithm had to be chosen as cooperative. The reason for the infeasibility of the non-cooperative solution is the presence of other aircraft that restricts the movement of the aircraft in consideration. With this restriction on maneuvers, the conflict could only be avoided cooperatively.

6.4 How does this benefit change if you restrict the speed of the aircraft?

We found that the no-speed change version of the algorithm yields a higher cost than the general cooperative solution. This restricted version resulted in an increased number of altitude changes compared to the general version. This is most likely due to the lack of speed change allowance for this version.

6.5 How does this benefit change if you restrict the altitude of the aircraft?

We found that the introduction of an altitude constraint reduces the overall fuel burn required for conflict resolution. This is evidenced by the non-dimensional fuel burn values for the algorithm versions with and without an altitude constraint that are summarized in Table 4. Recall that in the version with an altitude constraint, aircraft will only receive recommendations for speed and heading changes, i.e. they will always while remaining at the same altitude. The fuel burn is expressed as a ratio of total fuel burn on a conflict-free aircraft path following algorithm recommendations to the total fuel burn that would have occurred had all aircraft followed direct routes that had no conflicts.

Table 4: Fuel Expenditure

Scenario	General Algorithm	No Altitude Change
Sim8	1.0156	1.0214
Sim9	1.0188	1.0188
Sim5	1.0213	1.0213

The number of maneuvered aircraft is listed in Table 5 for each scenario. A comparison of the of the two right-most columns reveals that the introduction of an altitude constraint results in fewer aircraft being maneuvered, which is perhaps beneficial from the point of view of controller workload.

Table 5: Number of Maneuvered Aircraft

Scenario	General Algorithm	No Altitude Change
Sim8	17	21
Sim9	18	19
Sim5	33	39

The average computational time per iteration is listed in Table 6 for the three scenarios. As can be seen, the computational time is more related to the number of conflicts than the number of aircraft in the airspace, and the addition of an altitude constraint had little effect on computation time.

Table 6: Average Computational Time (sec) per Iteration

Scenario	General Algorithm	No Altitude Change
Sim8	1.22	1.23
Sim9	3.45	3.52
Sim5	1.11	1.10

7 SUMMARY OF FINDINGS

The main observations from the algorithm simulation study are the following:

- The optimal solution of the algorithm is often cooperative because, in order to provide the most fuel savings, both aircraft involved in a conflict must be maneuvered.

- A non-cooperative solution can be enforced at the cost of a higher fuel burn (average ~ 3%).
- If no speed change is allowed, more altitude changes are observed, but fewer solutions are cooperative. Also the fuel burn is higher than the primary (general) version of the algorithm that allows for speed changes and cooperative maneuvers.
- Impact of uncertainties can be addressed, to an extent, by adding a buffer to the required separation criterion between two aircraft.

As stated in Section 3 above, initially, the project research plan consisted of 4 weeks of HITL simulation study with algorithm runs. Preparations were complete; however the persistence of algorithm performance issues caused delays and forced re-planning. As a result, the HITL baseline simulation study without algorithm, described earlier in section 3, was performed. The HITL simulation study using the live algorithm runs was delayed and ultimately cancelled indefinitely due to the aforementioned significant algorithm performance issues.

8 RECOMMENDATIONS FOR NEXT STEPS

Now that the algorithm is working in a stochastic environment and continues to demonstrate promising results, we recommend the following:

(1) TGF Simulations with CMS: Our simulations have only been performed using TGF. The obvious first step is to run the simulations using TGF + CMS configuration.

(2) *HITL Simulations:* Once all scenario runs in the TGF+CMS settings perform satisfactorily, we would like to perform the HITL simulations using the algorithm and its interface. The results from the HITL simulations can then be compared with the baseline simulations (that have already been performed) in order to evaluate the benefits provided by the algorithm.

(3) *Simulation Environment Modifications:* We have accounted for large fluctuations in the uncertain TGF environment by increasing the buffer size (too large to be called a buffer in realistic terms!). While increasing the buffer size helps in avoiding conflicts in presence of uncertainties, the downside is a reduced feasible space for the algorithm. At some point (based on a certain value of the buffer size), we will encounter infeasible solutions. Less than that particular value of the buffer size, we can obtain feasible solutions which will be less optimal compared to the case because of the reduced feasible space. In other words, the benefits can be truly captured if the large deviations in the simulation environment can be reduced before sending the data to the algorithm. Whether this can be done by adding some filter, or by using higher number of way-points in order to reduce deviation from the intended route, or by a more appropriate method, needs to be investigated.

(4) Algorithm Augmentation/Improvements: The HITL simulations using the algorithm may require additional capabilities that would be needed by the algorithm and the interface. This may come as a result of suggestions from air traffic controllers or as a result from the analysis of data from the HITL simulations. All necessary modifications/augmentation would need to be addressed. Furthermore, additional modifications may be introduced in the algorithm in order to augment airspace awareness to the tool. This would allow for aircraft maneuvers based on ownership.

(5) Effect of Weather: Current algorithm formulation allows for easy inclusion of weather within the multi-level conflict resolution scheme. A moving weather front can be perceived as a slowly moving aircraft (restricted, that is, cannot be maneuvered) with the distance of separation equaling the radius of the circle that circumscribes the area of the weather front. Algorithm and interface enhancements to demonstrate performance for weather scenarios is another important future step that needs to be addressed.

(6) Flight trial application: The final goal of the project is to apply for flight trials if benefits are demonstrated and proven by the HITL studies. The task would involve preparation of all documents necessary for flight trials.

References

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9 APPENDIX: ACRONYMS

AC	Aircraft
ANOVA	Analysis of Variance
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
CPDLC	Controller Pilot Data Link Communication
Df	Degree of Freedom
DME	Distance Measuring Equipment
DSR	Display System Replacement
DV	Dependent Variable
ERAM	En Route Automation Modernization
ERFO	En Route Fuel Optimization
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FL	Flight Level
HSD	Honestly Significant Difference
IAW	In Accordance With
IIF	Integration and Interoperability Facility
IV	Independent Variable
N_{AC}	Total Number of Aircraft
NAS	National Airspace System

NASA	National Aeronautics and Space Administration
N_C	Total Number of Conflicts
NDB	Non-Directional Beacon
NextGen	Next Generation of Air Transportation
NRP	National Route Program
PCA	Point of Closest Approach
SA	Situation Awareness
SD	Standard Deviation
SME	Subject Matter Expert
TAC	Time to Answer the Call
TACAN	Tactical Air Navigation
TAQ	Time to Answer the Question
TLX	Task Load Index
URET	User Request Evaluation Tool
VHF	Very High Frequency
VOR	VHF Omnidirectional Range
WAK	Workload Assessment Keypad
ZBW	Boston Center
ZDC	Washington Center
ZME	Memphis Center
ZNY	New York Center

10 APPENDIX: SIM8

Table 7:

Iter	Without Algorithm	With Algorithm	Maneuvered Aircraft
1	None.	None.	None.
2	**(1)AAL705_005 x N176CG_006** **(2)AAL705_005 x EJA320_004** **(3)N176CG_006 x EJA320_004** **(4)N176CG_006 x EGF604_003**	**(1)AAL705_005 x N176CG_006** **(2)AAL705_005 x EJA320_004** **(3)N176CG_006 x EJA320_004** **(4)N176CG_006 x EGF604_003**	1)EJA320_004 2)EGF604_003
3	**(5)BTA3083_013 x EGF457_012** **(6)LXJ254_008 x AAL1322_002** **(7)AAL1231_009 x DAL1727_010**	**(6)LXJ254_008 x AAL1322_002** **(5)BTA3083_013 x EGF457_012** **(19)DAL1727_010 x EJA320_004**	3)AAL1322_002 4)EGF457_012 5)DAL1727

	(1)AAL705_005 x N176CG_006 (2)AAL705_005 x EJA320_004 (3)N176CG_006 x EJA320_004 (4)N176CG_006 x EGF604_003	**(7)DAL1727_010 x AAL1231_009** (1)AAL705_005 x N176CG_006	6)AAL705_005
4	(5)BTA3083_013 x EGF457_012 (6)LXJ254_008 x AAL1322_002 **(8)AAL1231_009 x EGF403_015** (7)AAL1231_009 x DAL1727_010 (2)AAL705_005 x EJA320_004 (3)N176CG_006 x EJA320_004 **(9)EJA320_004 x EGF403_015**	**(8)EGF403_015 x AAL1231_009**	7)AAL1231_009
5	(5)BTA3083_013 x EGF457_012 (6)LXJ254_008 x AAL1322_002 (8)AAL1231_009 x EGF403_015 (7)AAL1231_009 x DAL1727_010 (2)AAL705_005 x EJA320_004 (9)EJA320_004 x EGF403_015	None.	None.
6	(5)BTA3083_013 x EGF457_012 (6)LXJ254_008 x AAL1322_002 (8)AAL1231_009 x EGF403_015 (7)AAL1231_009 x DAL1727_010 (9)EJA320_004 x EGF403_015	None.	None.
7	(5)BTA3083_013 x EGF457_012 (6)LXJ254_008 x AAL1322_002 (8)AAL1231_009 x EGF403_015 (7)AAL1231_009 x	None.	None.

	DAL1727_010 (9)EJA320_004 x EGF403_015		
8	(5)BTA3083_013 x EGF457_012 **(10)AAL1231_009 x DAL981_018** (8)AAL1231_009 x EGF403_015 (7)AAL1231_009 x DAL1727_010 (9)EJA320_004 x EGF403_015	**(20)DAL981_018 x EJA320_004**	8)DAL981_018
9	(5)BTA3083_013 x EGF457_012 (10)AAL1231_009 x DAL981_018 (8)AAL1231_009 x EGF403_015 (7)AAL1231_009 x DAL1727_010 (9)EJA320_004 x EGF403_015	**(21)DAL1727_010 x COA347_023**	9)COA347_023
10	(5)BTA3083_013 x EGF457_012 **(11)UPS2773_020 x SWA365_024** (10)AAL1231_009 x DAL981_018 (8)AAL1231_009 x EGF403_015 **(12)DAL1788_026 x COA347_023** **(13)DAL1788_026 x SWA867_027** **(14)SWA867_027 x EGF403_015** **(15)SWA867_027 x DAL1727_010**	**(11)UPS2773_020 x SWA365_024** **(15)DAL1727_010 x SWA867_026** **(13)SWA867_026 x DAL1788_027** **(14)SWA867_026 x EGF403_015**	10)UPS2773_020 11)SWA867_026 12)EGF403_015
11	(5)BTA3083_013 x EGF457_012 (11)UPS2773_020 x SWA365_024	**(12)COA347_023 x DAL1788_027** **(16)LXJ609_022 x AWE197_030**	13)LXJ609_022 14)DAL1788_027

	(16)LXJ609_022 x AWE197_030 (10)AAL1231_009 x DAL981_018 (8)AAL1231_009 x EGF403_015 (12)DAL1788_026 x COA347_023 (13)DAL1788_026 x SWA867_027 (14)SWA867_027 x EGF403_015 (15)SWA867_027 x DAL1727_010		
12	(11)UPS2773_020 x SWA365_024 (16)LXJ609_022 x AWE197_030 (10)AAL1231_009 x DAL981_018 (12)DAL1788_026 x COA347_023 (13)DAL1788_026 x SWA867_027 (14)SWA867_027 x EGF403_015	None.	None.
13	(11)UPS2773_020 x SWA365_024 (16)LXJ609_022 x AWE197_030 (10)AAL1231_009 x DAL981_018 (12)DAL1788_026 x COA347_023 (13)DAL1788_026 x SWA867_027 **(17)DAL981_018 x N1HA_031** (14)SWA867_027 x EGF403_015	**(17)DAL981_018 x N1HA_031**	15)N1HA_031
14	(11)UPS2773_020 x	None.	

	SWA365_024 (16)LXJ609_022 x AWE197_030 (12)DAL1788_026 x COA347_023 (13)DAL1788_026 x SWA867_027 (17)DAL981_018 x N1HA_031		
15	(11)UPS2773_020 x SWA365_024 (16)LXJ609_022 x AWE197_030 (12)DAL1788_026 x COA347_023 (13)DAL1788_026 x SWA867_027 **(18)SWA3604_036 x N1776C_034** (17)DAL981_018 x N1HA_031	**(22)LXJ609_022 x SWA3604_036** **(18)SWA3604_036 x N1776C_034**	16)SWA3604_036
16	(12)DAL1788_026 x COA347_023 (13)DAL1788_026 x SWA867_027 (18)SWA3604_036 x N1776C_034 (17)DAL981_018 x N1HA_031	(18)SWA3604_036 x N1776C_034	17)N1776C_034
17	(13)DAL1788_026 x SWA867_027 (18)SWA3604_036 x N1776C_034 (17)DAL981_018 x N1HA_031	None.	None.
18	(18)SWA3604_036 x N1776C_034 (17)DAL981_018 x N1HA_031	None.	None.

19	(18)SWA3604_036 x N1776C_034	None.	None.
20	(18)SWA3604_036 x N1776C_034	None.	None.
21	None	None.	None.

Table 8:

Iter	Without Algorithm	With Algorithm	Maneuvered Aircraft
1			
2	**(1)SIA62_004 x N924JE_005** **(2)SWA377_014 x NAO983_013** **(3)SWA1754_012 x N924JE_005**	NAO983_013 x SWA377_014 SWA1754_012 x N924JE_005 SIA62_006 x N924JE_005	NAO983_013 SIA62_006 N924JE_005
3	**(4)N54YR_015 x SWA397_007** **(5)N54YR_015 x N876H_003** (1)SIA62_004 x N924JE_005 (2)SWA377_014 x NAO983_013 (3)SWA1754_012 x N924JE_005 **(6)DAL1029_016 x BTA2647_008**	N54YR_015 x N876H_003 N54YR_015 x SWA397_007 BTA2647_009 x DAL1029_016	N876H_003 BTA2647_009 SWA397_007 SWA1754_012
4	(4)N54YR_015 x SWA397_007 (5)N54YR_015 x N876H_003 **(7)SKW28A_020 x BTA3082_011** **(8)AAL1216_017 x NWA1630_018** (1)SIA62_004 x N924JE_005 (2)SWA377_014 x NAO983_013 (3)SWA1754_012 x N924JE_005	SKW28A_020 x BTA3082_011 N54YR_015 x N876H_003 NWA1630_018 x AAL1216_017	BTA3082_011 N54YR_015 AAL1216_017

<table>
<tr><td></td><td>(6)DAL1029_016 x BTA2647_008</td><td></td><td></td></tr>
<tr><td>5</td><td>(4)N54YR_015 x SWA397_007
(5)N54YR_015 x N876H_003
(7)SKW28A_020 x BTA3082_011
(8)AAL1216_017 x NWA1630_018
(1)SIA62_004 x N924JE_005
(2)SWA377_014 x NAO983_013
(3)SWA1754_012 x N924JE_005
(6)DAL1029_016 x BTA2647_008</td><td></td><td></td></tr>
<tr><td>6</td><td>(5)N54YR_015 x N876H_003
(7)SKW28A_020 x BTA3082_011
(8)AAL1216_017 x NWA1630_018
(1)SIA62_004 x N924JE_005
(2)SWA377_014 x NAO983_013
(9)SWA377_014 x N631SF_023
(3)SWA1754_012 x N924JE_005
(6)DAL1029_016 x BTA2647_008
(10)N480JJ_009 x N631SF_023</td><td>SWA377_014 x N631SF_023
N631SF_023 x BTA2647_009
N631SF_023 x N480JJ_010</td><td>N631SF_023</td></tr>
<tr><td>7</td><td>(5)N54YR_015 x N876H_003
(7)SKW28A_020 x BTA3082_011
(8)AAL1216_017 x NWA1630_018
(11)BAW26E_026 x NWA703_027
(1)SIA62_004 x N924JE_005
(9)SWA377_014 x N631SF_023
(3)SWA1754_012 x N924JE_005
(12)NWA703_027 x N631SF_023
(6)DAL1029_016 x BTA2647_008</td><td>NWA703_027 x N631SF_023
NWA703_027 x BAW26E_026</td><td>NWA703_027</td></tr>
</table>

	(10)N480JJ_009 x N631SF_023		
8	**(13)COA482_031 x COA300_030** (7)SKW28A_020 x BTA3082_011 (8)AAL1216_017 x NWA1630_018 (11)BAW26E_026 x NWA703_027 (9)SWA377_014 x N631SF_023 (12)NWA703_027 x N631SF_023 (6)DAL1029_016 x BTA2647_008 (10)N480JJ_009 x N631SF_023	COA482_031 x COA300_030 BAW26E_026 x N924JE_005	COA482_031 BAW26E_026
9	(13)COA482_031 x COA300_030 (7)SKW28A_020 x BTA3082_011 (8)AAL1216_017 x NWA1630_018 (11)BAW26E_026 x NWA703_027 (9)SWA377_014 x N631SF_023 (12)NWA703_027 x N631SF_023 (10)N480JJ_009 x N631SF_023		
10	(13)COA482_031 x COA300_030 (7)SKW28A_020 x BTA3082_011 (8)AAL1216_017 x NWA1630_018 (11)BAW26E_026 x NWA703_027 (9)SWA377_014 x N631SF_023 (10)NWA703_027 x N631SF_023		
11	(13)COA482_031 x COA300_030 (8)AAL1216_017 x NWA1630_018 **(14)EGF3679_034 x COA326_033** (11)BAW26E_026 x NWA703_027	COA326_033 x EGF3679_034	EGF3679_034

	(9)SWA377_014 x N631SF_023 (10)NWA703_027 x N631SF_023		
12	(13)COA482_031 x COA300_030 **(15)RCH908_039 x AAL342_041** **(16)RCH908_039 x COA326_033** (8)AAL1216_017 x NWA1630_018 (14)EGF3679_034 x COA326_033 (11)BAW26E_026 x NWA703_027 **(17)SIA62_004 x SWA1754_012** **(18)DAL1477_038 x EJA372_019** (9)SWA377_014 x N631SF_023 (10)NWA703_027 x N631SF_023	AAL342_040 x RCH908_039 COA326_033 x RCH908_039 EJA372_019 x DAL1477_038	RCH908_039 COA326_033 DAL1477_038
13	(13)COA482_031 x COA300_030 **(19)COA251_043 x RCH908_039** **(20)RCH908_039 x COA1092_042** (15)RCH908_039 x AAL342_041 (16)RCH908_039 x COA326_033 (8)AAL1216_017 x NWA1630_018 (14)EGF3679_034 x COA326_033 (11)BAW26E_026 x NWA703_027 (17)SIA62_004 x SWA1754_012 (18)DAL1477_038 x EJA372_019 (10)NWA703_027 x N631SF_023	AAL342_040 x ASH2934_037 EJA372_019 x DAL1477_038	AAL342_040 EJA372_019
14	(13)COA482_031 x COA300_030 (19)COA251_043 x RCH908_039 (20)RCH908_039 x COA1092_042 (15)RCH908_039 x AAL342_041 (16)RCH908_039 x COA326_033	N444ET_049 x SWA648_053 NWA1066_050 x DLH440_048	SWA648_053 NWA1066_050

	(8)AAL1216_017 x NWA1630_018 (14)EGF3679_034 x COA326_033 (11)BAW26E_026 x NWA703_027 (17)SIA62_004 x SWA1754_012 (18)DAL1477_038 x EJA372_019 (10)NWA703_027 x N631SF_023		
15	(13)COA482_031 x COA300_030 (19)COA251_043 x RCH908_039 **(21)N444ET_049 x SWA648_053** (20)RCH908_039 x COA1092_042 (15)RCH908_039 x AAL342_041 (16)RCH908_039 x COA326_033 (8)AAL1216_017 x NWA1630_018 (14)EGF3679_034 x COA326_033 **(22)NWA1066_050 x DLH440_048** (11)BAW26E_026 x NWA703_027 (17)SIA62_004 x SWA1754_012 (10)NWA703_027 x N631SF_023	N444ET_049 x COA554_052	N444ET_049
16	(13)COA482_031 x COA300_030 (19)COA251_043 x RCH908_039 (21)N444ET_049 x SWA648_053 (20)RCH908_039 x COA1092_042 (15)RCH908_039 x AAL342_041 (16)RCH908_039 x COA326_033 (8)AAL1216_017 x NWA1630_018 (22)NWA1066_050 x DLH440_048 (11)BAW26E_026 x NWA703_027 (17)SIA62_004 x SWA1754_012	ASQ5199_044 x N490QS_056 LXJ619_058 x WDR260_055	ASQ5199_044 LXJ619_058

17	(21)N444ET_049 x SWA648_053 (19)COA251_043 x RCH908_039 (20)RCH908_039 x COA1092_042 (15)RCH908_039 x AAL342_041 (16)RCH908_039 x COA326_033 (22)NWA1066_050 x DLH440_048 **(23)ASQ5199_044 x N490QS_056** (11)BAW26E_026 x NWA703_027 **(24)LXJ619_058 x WDR260_055** (17)SIA62_004 x SWA1754_012		
18	(21)N444ET_049 x SWA648_053 (19)COA251_043 x RCH908_039 (20)RCH908_039 x COA1092_042 (15)RCH908_039 x AAL342_041 (22)NWA1066_050 x DLH440_048 (23)ASQ5199_044 x N490QS_056 (11)BAW26E_026 x NWA703_027 (24)LXJ619_058 x WDR260_055 (17)SIA62_004 x SWA1754_012		
19	(21)N444ET_049 x SWA648_053 (19)COA251_043 x RCH908_039 (20)RCH908_039 x COA1092_042 (15)RCH908_039 x AAL342_041 (22)NWA1066_050 x DLH440_048 (23)ASQ5199_044 x N490QS_056 (11)BAW26E_026 x NWA703_027 (24)LXJ619_058 x WDR260_055		

	(17)SIA62_004 x SWA1754_012		
20	(21)N444ET_049 x SWA648_053 (19)COA251_043 x RCH908_039 (20)RCH908_039 x COA1092_042 **(25)NWA1630_018x BTA3082_011** (23)ASQ5199_044 x N490QS_056 (11)BAW26E_026 x NWA703_027 (24)LXJ619_058 x WDR260_055 (17)SIA62_004 x SWA1754_012		
21	**(26)BTA2187_021x BTA3082_011** (21)N444ET_049 x SWA648_053 (19)COA251_043 x RCH908_039 (20)RCH908_039 x COA1092_042 **(27)COA1088_064x CHQ5850_062** (25)NWA1630_018x BTA3082_011 (23)ASQ5199_044 x N490QS_056 (11)BAW26E_026 x NWA703_027 (24)LXJ619_058 x WDR260_055 (17)SIA62_004 x SWA1754_012		