IMPROVEMENTS FOR OPTIMUM PROFILE SCHEDULING OF USER PREFERRED TRAJECTORIES

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Abstract

The reduction of fuel usage in air travel industry is an important objective, for example through improvements in ATM processes. Studies have shown that about 5% fuel savings can be achieved with improved air traffic flow. This paper presents a mathematical methodology for co-operative air traffic optimization for total minimum fuel usage. At this stage only cruise flight in still air is considered. Each flight consists of several user-specified sectors and can be dynamically changed for example to account for air space closure, divert, etc. Optimisation variables are speed and altitude variation along the flight path. Constraints on minimum separation and aircraft performance limits using BADA as applied.

The pertinent improvements and additional functionality consist of three aspects. The first aspect refers to a procedural architecture that supports the update, reassessment, and reapplication, of air traffic fuel usage optimization. The second aspect refers to the four-dimensional discretisation of aircraft interaction so as to create mutually exclusive, and therefore separately optimized, air traffic clusters. The third aspect refers to alterations to trajectory control mechanisms that take advantage of the properties of reapplied optimization to reduce its computational requirements whilst still maintaining sufficient trajectory control fidelity to reach feasible fuel usage optimums. When combined, these aspects enable the optimum profile scheduling for air traffic over an entire continent.

1 Introduction

Various Air Traffic Management (ATM) reports and programmes have marked fuel usage reduction as an objective for both environmental and economic reasons [1, 2, 3, 4]. However, ATC primary task is maintaining minimum safe separation and they are not equipped to determine minimum fuel usage trajectories. This paper describes a mathematical framework for optimum profile scheduling for all aircraft in a given airspace, subject to minimum separation and aircraft performance constraints. Optimum profile scheduling of User Preferred Trajectories (UPT) refers to the mathematical optimization of aircraft flight profiles, ie. speed and altitude, that reduce the total fuel usage of all aircraft subject to minimum separation and aircraft performance constraints. The method of optimum profile scheduling integrates a fuel optimized Conflict Detection and Resolution (CDR) method [5], and a cruise altitude and speed allocation method [6], with an area discretized assessment of separation [7] and

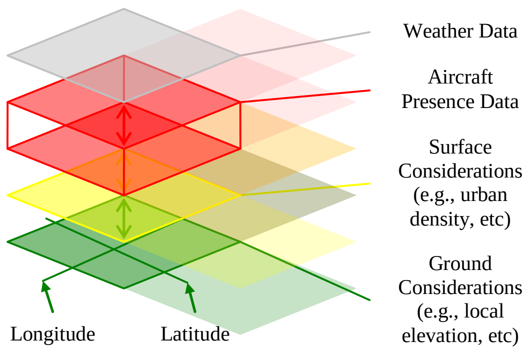

Fig. 1. Common unit for ATS data transfer.

environmental data [8] (Figure 1). The Base of Aircraft Data Base (BADA) was used to calculate [9] the fuel usage and operational constraints for each aircraft being optimized. Air traffic separation was simulated by adhering to the ICAO standards [10, 11]. The integration resulted in an optimum profile scheduling methodology that allowed a priori assessment of potential conflict so the size of the optimization problem can be reduced by excluding irrelevant parameters [12]. For example, aircraft with routes that do not intersect do not have to be checked for conflict. This methodology optimizes a scenario assuming that all aircraft follow their predetermined routes and assigned altitude and speed schedule. In practice, flight plans do vary due to unforeseen circumstances, such as weather, emergency, or simply a change of plans.

The second issue is that, like other current Air Traffic System (ATS) optimization methods that directly control CDR, this method can take long computing times, particularly when the amount of traffic increases. The fundamental difficulty with dealing with this is that any improvement in computation time can not come at the expense of the detail, accuracy, and robustness of methods that define and predict aircraft performance and separation. Improvements have to come from refinements to the way ATS is broken down and modeled before optimization. Therefore, the optimum profile scheduling methodology was designed to reduce the amount of computation time required.

2 Improvements to Optimum Profile Scheduling

The improvements to optimum profile scheduling have three aspects and each are discussed separately in the following subsections, ie:

- Dynamic re-optimisation refers to a procedural architecture that supports the update, reassessment, and reapplication, of air traffic fuel usage optimization, due to changes in the flight plans or aircraft not following their assigned altitude/speed profiles and moving off-track.
- Four-dimensional discretisation of aircraft interaction by creating isolated, and therefore separately optimized, air traffic clusters.
- Strategic placement of trajectory control nodes that take advantage of the properties of reapplied optimization to reduce its computational requirements whilst maintaining sufficient trajectory control fidelity.

2.1 Dynamic Re-Optimization

The process of updating air traffic trajectories to re-optimize their overall fuel usage is conceptually simple; i.e. whenever unpredictable events occur reapply optimization to the new situation. However given the ability of the optimizer to remove unnecessary variables a priori from the optimization process, it has to be checked if this is still valid for the new situation. The following list of steps defines how the optimizer architecture procedurally re-optimizes air traffic:

1) *Define Trajectories of Currently Flying Aircraft*
2) *Define New Entrants and Alterations to Currently Flying Aircraft*
3) *Define Unseparated Fuel Optimized Parameters for New or Altered Trajectories*
4) *Perform Initial Separation Assessment.*
5) *Perform Concerted Separation Optimization, if required.*
6) *Apply new trajectories, and wait for next event.*

The aim of the first step is to update all previously used data pertaining to air traffic, their trajectories and the environment itself. No new information is generated at this stage, and only traffic information that has already occurred and cannot affect any future actions, i.e. the actual and potential four dimensional positions of aircraft prior to the maximum time separation minima before the time of the unexpected event, is discarded.

The aim of the second step is to introduce changes caused by the unplanned event into a

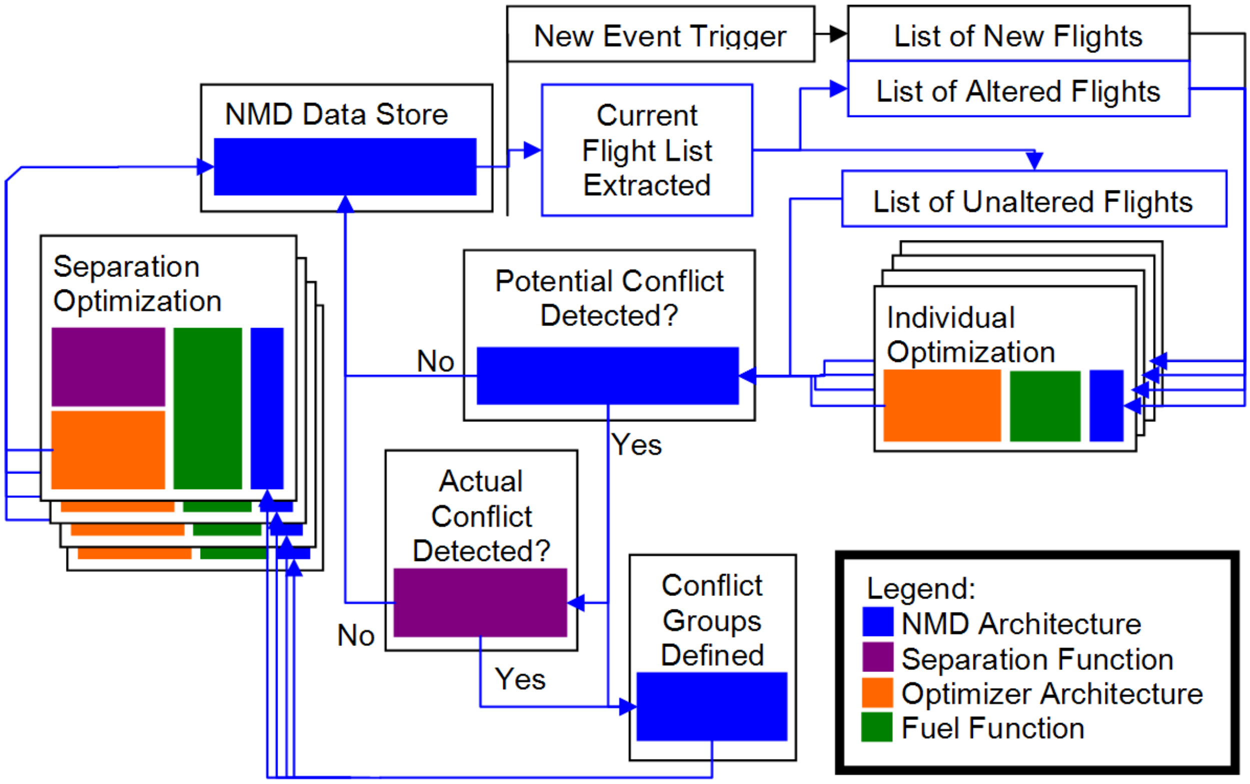

Fig. 2. Dynamic re-optimization architecture.

format that the optimizer can understand; i.e. direct changes to environmental data, the addition of aircraft routes belonging to aircraft that have just entered optimized airspace, as well as the replacement of previously intended routes with new routes as a result of the unplanned event. While unplanned events can take many forms, provided they can be defined in terms of a new desired route or destination, they can be optimized.

The purpose of the third step is to define an acceptable initial profile for aircraft that either do not have one, or had one that was rendered obsolete due to the unplanned event. This profile is merely a series of altitudes and velocities along a route which dictates the aircraft’s four dimensional position during its flight. Consequently, the scheduler is required to create an initial profile by optimizing a crude but viable profile for minimum fuel usage. This optimization is the same as the optimum profile scheduling used when optimizing all air traffic but without enforcing separation constraints. Thus, it will adhere to the same aircraft limits and preferences whilst ensuring that trajectory deviations resulting from later minimization of fuel usage of aircraft separation are as small as possible. New aircraft entering the airspace undergo the same process.

As mentioned previously, the optimum profile scheduler has the ability to determine aircraft pairs that have potential conflict. It does this by performing a separation assessment prior to optimization that considers the actual four-dimensional locations of aircraft during their flight. The locations between all aircraft can then be compared for overlap in order to cluster aircraft together if they have a potential conflict. Consequently it is possible to define clusters that have new aircraft entering the airspace, aircraft with changed flight plans, had an altered aircraft removed from the cluster, or did not experience any change at all.

In the fifth step, any aircraft clusters that encountered a new or altered aircraft, or have had one removed since the last global optimization, will undergo the process for finding an optimum profile schedule. This is to ensure that an optimum profile schedule is found in the former, and maintained in the latter. In the case of clusters that experience no new entrants or alterations, whoever is controlling the optimizer will have the option of optimizing or not optimizing the cluster; either option is safe, but provide different benefits. These are defined in section 2.3.

The sixth step is merely the transfer and application of the results of the optimization process. These can be through a variety of methods, however so long as they are appropriately reflected in the aircraft and environmental data, either as part of the aircrafts preferences or air traffic control limits, then this should occur according to the optimized result.

A flow diagram of the above steps as they are applied in the re-optimization architecture is shown in Figure 2. Things to note in the figure include: the consistent use of aircraft route definition, i.e. Nautical Minute Discretisation Architecture, to transfer data between steps; the assessment of separation both prior to and within optimum profile scheduling; and the use of the same fuel usage optimization process to reflect aircraft performance constraints with and without consideration of other traffic.

2.2 Aircraft Clustering for Optimization

This functionality defines which aircraft should be considered during each re-optimization stage. The understanding gained from this was that any attempt to include aircraft that were not yet in airspace would most likely lead to unnecessary trajectory changes in other aircraft if the new aircraft could not enter airspace at the scheduled time, e.g. due to delayed takeoff. Therefore, only aircraft that are present in the airspace were re-optimised. The difference it makes compared to including aircraft that have not yet entered airspace is significant. To visualize the difference, 2007 domestic flight statistics [13] were used to create an average day of air traffic for Australia; the number of trips between destinations averaged on a day then evenly distributed over 24 hours. An initial separation assessment, i.e. step 4 in section 2.1, including all planned aircraft yielded the aircraft cluster sizes and numbers shown at the top of Figure 3. The same data was then divided into five minute increments, with the initial separation assessment occurring at each increment and only including the aircraft in the airspace at the time; this yielded the cluster sizes and numbers shown at the bottom of Figure 3.

Figure 3 displays the total aircraft number being handled by the optimizer (vertical axis) at any point in time during the process (horizontal axis), with the different colours therein representing separate groups; the size of a

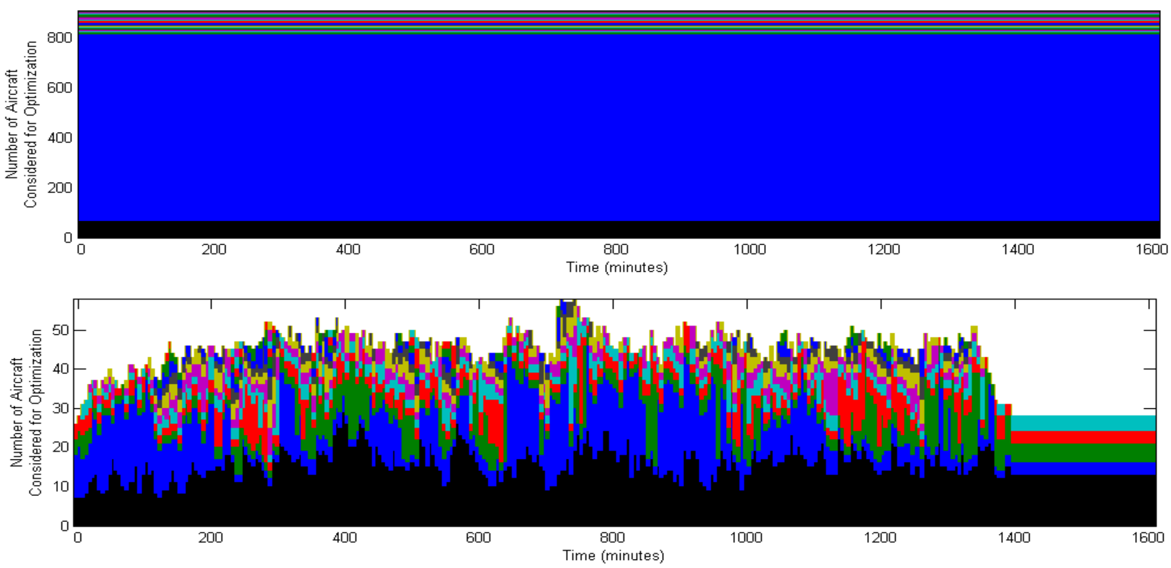

Fig. 3. Mutually Exclusive Group Distribution in a Day of Australian Domestic Travel including all planned aircraft (top) or only aircraft currently in optimized airspace (bottom).

colour band representing the number of aircraft in that group. The top of Figure 3 shows how a singular separation assessment combines the majority of the aircraft into the one blue group; with interactions in time causing spread out sequences of aircraft interactions to require simultaneous optimization. As it is only one optimization stage, the variation in cluster numbers and sizes remains constant. In contrast the bottom of Figure 3 presents considerable variation in the size and number of isolated aircraft clusters, with the size of any one optimization group being less than 35 aircraft. The difference in computational processing requirements between the two would therefore be very noticeable, and of considerable significance knowing that interaction between aircraft is not limited a by look ahead time, and considers the impact of interaction between aircraft at their destinations as well.

2.3 Strategic Control Node Placement

An additional feature is Strategic Control Node Placement which allows the user to influence the distribution of control nodes along the trajectory. As each control node is associated with two free variables, speed and altitude, reducing control nodes means a reduction in the number of free variables and thus computing time. For example, Figure 4a shows a typical trajectory with all control nodes evenly distributed. If it is required that the aircraft speed and altitude are not to be varied during the cruise phase, e.g. for passenger comfort and ease of ATC during high traffic regions, one can places tight bounds on the speed and altitude variables for that part of the trajectory. Although the free variables are restricted to move, they will be considered as free variables in the optimization process. Alternatively, the relevant control nodes can be removed, resulting in a significantly reduced number of free variables (Figure 4b). Alternate control node placements allow trajectories to have a minimal number of planned trajectory changes and consequently to force aircraft interactions during intersections to adhere to a constant climb or flight level. This minimal number of trajectory changes was achieved by allowing optimizer control nodes to exist only where trajectory changes were necessary; i.e. during initial climb and final descent. When applied in a constant altitude/speed scenario the resulting trajectories matched. However, when applied in a changing scenario, i.e. as in Figure 4c, an additional capability becomes apparent.

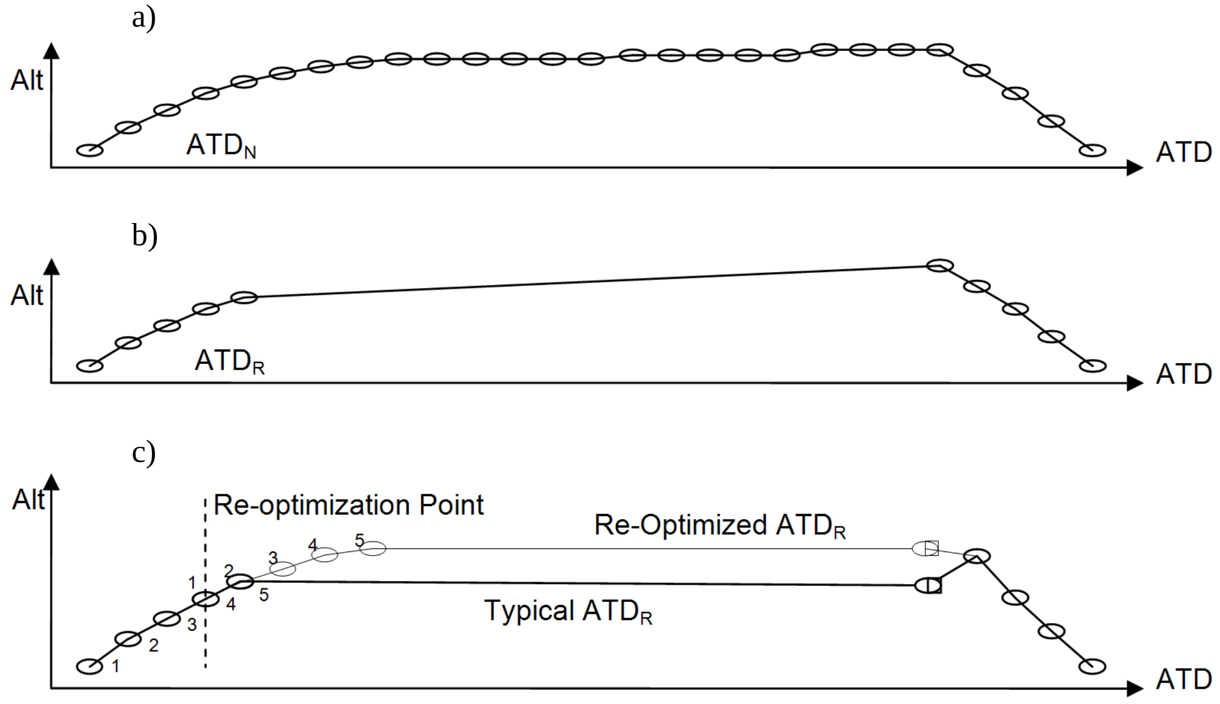

Fig. 4. Trajectory Control Node Placement with: (a) full, (b) reduced static, and (c) reduced dynamic, fidelity.

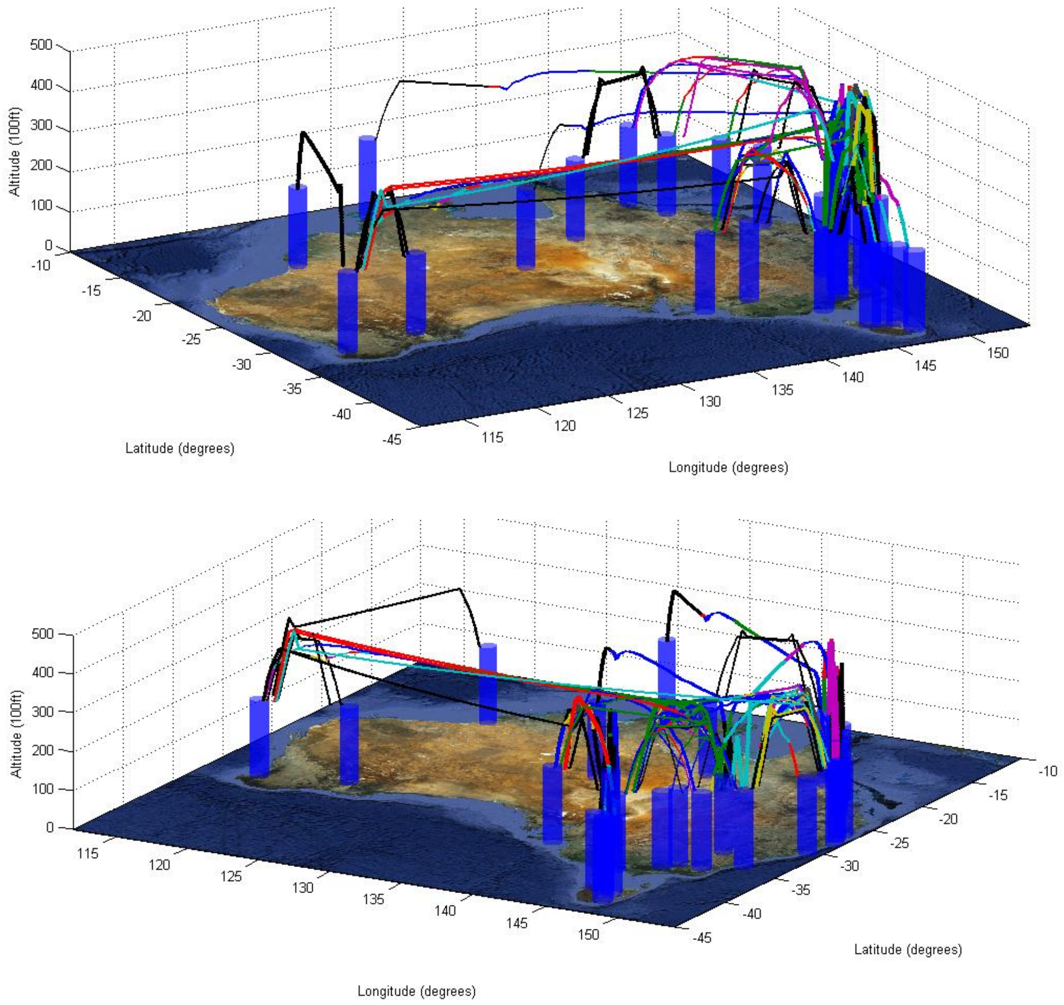

Fig. 5. Optimized Trajectories for 2 hours of Australian Domestic Air Traffic.

In re-optimizations for changing scenarios, the placement of control nodes must continually be reset, As a consequence, the nodes that enable trajectory variation in initial climb are reset to occur at the current position of the aircraft during re-optimization. This allows an increasing portion of the trajectory to be variable over the course of the flight, which in turn becomes optimized during each re-optimization. This allows a frequently re-optimized trajectory that uses a minimal number of control nodes to fly a trajectory that closely resembles one that had a complete set of control nodes. Because it is using a minimum number of control nodes, the process becomes considerably quicker as well. Obviously, this does counter the intended property of trajectory intersections with constant climb angle or flight level, however the process depends on whether or not re-optimizations occurs; this therefore gives ATC considerable control over a situation as they can choose between re-optimization and more optimal trajectories, or less frequent re-optimizations and stable trajectory intersections.

3 Simulation Results

While the usefulness of the three improvements to optimum profile scheduling are readily apparent, it is difficult to see their combined impact on the effectiveness of the scheduling method. For this reason a continental scale test of the method was performed. The resulting trajectories can be seen in Figure 5. This test used the first 2 hours of the same used in section 2.2. In terms of hardware, the test used one core of a AMD Quad Core Opteron™ 2.3ghz processor with 32GB of RAM and 1.2TB of scratch space. Twenty-four re-optimizations were processed with all trajectories being successfully optimized and re-optimized within an 84 hour time frame. Significant better performance can be achieved implementing the methodology on parallel computer architecture.

3 Conclusions

This paper described the development of three improvements to the process of optimizing air traffic flow. The first improvement created a procedural architecture that supported the update, reassessment, and reapplication, of air traffic fuel usage optimization. Further, it was created in such a way to allow other components inside the architecture to take advantage of the potential aircraft interaction assessment inherent in the original optimum profile scheduling process. The second improvement added another dimension to air traffic discretisation by allowing aircraft entrants to be removed from consideration completely. This caused isolated aircraft cluster groups to be localized in the time dimension which prevented the creation of extremely large aircraft clusters that were linked primarily through that dimension; consequently the and the amount of computation time was reduced. The third improvement was the increase in scheduling efficiency when used in dynamic re-optimization; the removal of profile variation at points in the trajectory where constant altitude and speed do not vary. Finally, a test trial of domestic trajectories over the continent of Australia was performed.

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