VISUALIZATION OF AIRSPACE COMPLEXITY BASED ON AIR TRAFFIC CONTROL DIFFICULTY

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Abstract

The prediction of airspace complexity is of great interest for Air Traffic Management (ATM). Airspace complexity based on traffic situation prediction affects short- and medium-term trajectory management strategies and also affects the capacity of Air Traffic Control (ATC) operations. Our research group is developing a "difficulty index" of ATC to represent the degree of airspace complexity. The index is based on a metric that reflects the three-dimensional proximities between pairs of aircraft, and is intended to assess the complexity of airspace volumes containing multiple aircraft. In this paper, we apply the difficulty index to simulated flight trajectories based on actual flight plan data to assess its applicability to realistic traffic situations. We also report the results of attempting to visualize the difficulty on a map and illustrate its possible application to a future Trajectory-Based Operations (TBO) environment.

1 Introduction

The prediction and visualization of airspace complexity are of great interest for ATM. Airspace complexity affects the capacity of ATC operational processes as a result of increasing the number and complexity of tasks controllers have to perform for each aircraft. Excessive complexity therefore has the potential to degrade the safety of ATC.

A variety of indices to express the complexity of airspace have been studied over many years [1–3], most of which are based on the geometric positions of aircraft. A common aim of these studies has been to create an index of airspace complexity that can be used effectively for the assessment of new procedures and airspace designs.

Our research team is aiming to develop an ATC difficulty index that can represent the degree of airspace complexity by improving on the concept of Resilience suggested by the EUROCONTROL INTEGRA project [4]. Our new index is based on a metric that reflects the three-dimensional proximities between pairs of aircraft [5], and is intended to assess airspace volumes containing multiple aircraft [6]. Up until now, this difficulty index has been evaluated analytically using simple test cases. However, the calculation employs a number of free parameters which must be adjusted to give reasonable results. As an attempt to do better than *ad hoc* tuning, we propose a method of parameter tuning using the judgement of experts, that is, air traffic controllers. Specifically, we posit that the events of controller recognition of a conflict in a scenario and intervention to resolve the conflict are loosely correlated with values of the difficulty index. By extracting the timing of these judgements from controllers, we can adjust the index parameters to fit the data.

This paper describes the theory of adjustment of ATC difficulty index parameters based on air traffic controller judgements, and presents a case study example from a preliminary air traffic controller evaluation. Section 2 briefly describes the ATC difficulty index and its parameters. Section 3 then describes our parameter tuning hypothesis, a preliminary evaluation trial involving air traffic controllers, and presents an example of parameter extraction. In section 4, we attempt to show the reasonableness by using it to visualize simulated flight trajectories, and illustrate how it could be used in a trajectory-based operations environment. In section 5, we discuss the application of the index to future TBO and conclude the paper.

2 Air Traffic Control Difficulty Index

In current ATM in Japan, ATC sector demand is predicted based on the total radio telephony (R/T) communication time required to handle the traffic in a given time interval. If this demand exceeds a capacity limit, Air Traffic Flow Management (ATFM) measures are imposed such as pre-departure delay (holding aircraft at the gate) for flights from Japanese airports. In this way, ATC task processing time is strongly associated with airspace capacity.

This paper uses the ATC difficulty index proposed by our research group whereby ATC difficulty increases as available processing time becomes shorter [5, 6].

First the index is calculated for pairs of aircraft, and is then applied to a volume of airspace that contains multiple aircraft. Details of the index calculation have already been described in refs. 5 and 6, so only the essentials are shown here.

2.1 Aircraft Pairwise Difficulty Metric

The aircraft pairwise difficulty metric basically considers the predicted proximity situations of pairs of aircraft based on their relative motions, and closest point of approach (CPA).

The difficulty index $\mathrm{D}(t)$ for a pair of aircraft at a time t is calculated from the relative position vector $\vec{R} = (x, y, z)$ and relative velocity vector $\vec{V} = (v_x, v_y, v_z)$ as follows.

$$\mathrm{D}(t) = \max_{t_p \geq 0}\left(exp\left(-U(t_p)\right)\right) \quad (1)$$

Here, $\mathrm{U}(t_p)$ is an evaluation function to obtain a look-ahead time t_p.

$$\mathrm{U}(t_p) = \left(\frac{d_H(t_p)}{\lambda_H}\right)^2 + \left(\frac{d_z(t_p)}{\lambda_z}\right)^2 + \left(\frac{t_p}{\lambda_t}\right)^2 \quad (2)$$

where

$$d_H(t_p) = \sqrt{\left(x + v_x t_p\right)^2 + \left(y + v_y t_p\right)^2} \quad (3)$$

$$d_z(t_p) = \sqrt{\left(z + v_z t_p\right)^2} \quad (4)$$

t_p is found to minimize U after the present time $(t_p \geq 0)$. Then $\mathrm{D}(t)$ is calculated.

By using a product of exponential functions, the value of the metric is made to increase as time or distance to CPA decreases. These exponential functions are scaled by parameters in each dimension: λ_H for horizontal, λ_z for vertical and λ_t for time.

The resulting index $\mathrm{D}(t)$ is a value in the interval [0, 1], where 1 represents the greatest difficulty. There should be a threshold value of the index α above which the difficulty can be said to be “of concern”. We could say that a pairs of aircraft at close to the minimum separation distance applicable to the airspace, either lateral or vertical, should give resulting an index value of 0.5, or that the index value should reach 0.5 at a certain time before CPA.

For each dimension, we then set a parameter u_α such that the value of the corresponding exponential component will be 0.5 when u_α is attained. The λ values are then derived as follows.

$$\lambda = {u_\alpha}/{k} \quad (5)$$

k is a coefficient related to the shape of the exponential curves. We use value of $\alpha = 0.5$ $(D(t) = 0.5)$ and $k = 0.833$ in this paper. See refs. 5 and 6 for further details.

2.2 Airspace Difficulty Index

The pairwise proximity model is used to derive an ATC difficulty index for an airspace volume containing multiple aircraft. When the pairwise difficulty metric of a pair of aircraft i at a certain time t is $D_i(t)$, the overall ATC difficulty $D_{all}(t)$ of an airspace volume containing pairs of aircraft is expressed by the following equation.

$$D_{all}(t) = 1 - \prod_{i=1}^{N_{pair}}\left(1 - D_i(t)\right) \quad (6)$$

Again, the value of the airspace difficulty index is in the interval [0, 1].

3 Parameter Tuning by Controller Evaluation

Section 2 developed a mathematical model for expressing air traffic control difficulty contains free parameters which require tuning. In this section we formulate a concept by which expert judgement could be used for parameter tuning instead of more *ad hoc* methods such as trial-and-error, and describe part of a preliminary trial using air traffic controllers.

3.1 Concept

Suppose that a controller monitors an air traffic situation that contains a future proximity situation between a pair of aircraft. As the situation develops, the controller first recognizes that a potential loss of separation (a “conflict”) exists at a time T_{cog}, and then later decides to make an intervention to resolve the conflict at a time T_{dc}. These situations might correspond to certain values of difficulty index D_{cog} and D_{dc} respectively, which we can assign to values, say $D_{cog} = 0.2$ and $D_{dc} = 0.5$.

In our tuning method, we use trials with a number of controllers observing traffic scenarios to acquire values of T_{cog} and T_{dc} and then attempt to adjust the value λ_t to fit the time history of difficulty index curves to the data. See Fig. 1.

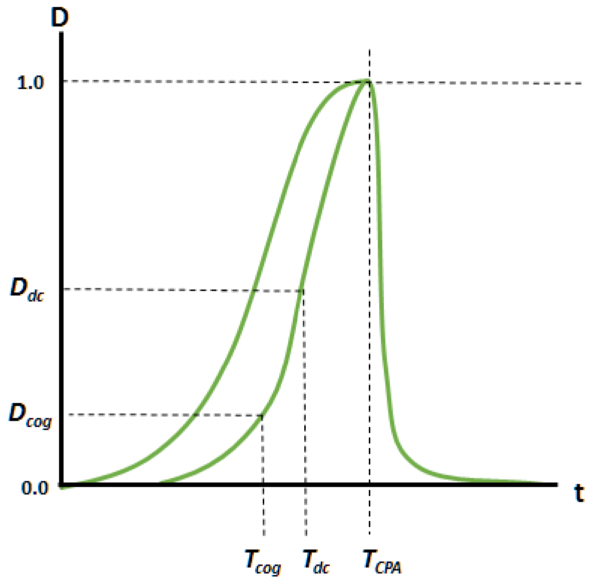

Fig. 1 Concept of Parameter Tuning for λ_t

3.2 Controller Trials

3.2.1 Scenarios

A real-world en-route radar controlled sector shown in Fig. 2 (the Kii sector) was selected as the target airspace volume. This sector contains crossing airways, so allows for realistic scenarios that contain crossing conflicts. There are also a few airports in the vicinity of the sector allowing conflicts involving climbing and descending traffic to be evaluated also.

Flight trajectories were created using the AirTOp fast time ATM simulator based on real-world fight plan information but modified to cause near conflicts.

Five 20-minute scenarios with between 3 and 6 aircraft flying along airways were created for the preliminary evaluation.

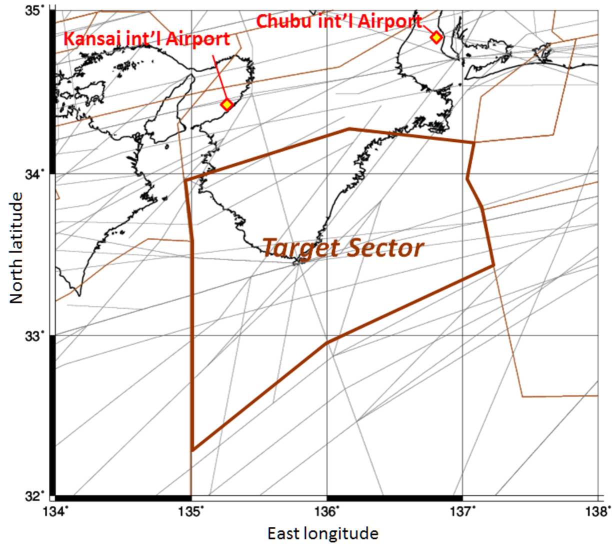

Fig. 2 Outline of the target sector (the Kii sector at Tokyo Area Control Center)

3.2.2 Method of Evaluation

Subject controllers were presented with replays of the scenarios on a radar like display as shown in Fig. 3 and were instructed to pause the replay, note the time and identify the related traffic when the following two situations occurred: (a) when a potential conflict situation that might require future intervention was first recognized (at time T_{cog}), and (b) when the subject felt that intervention was required to resolve the conflict (at time T_{dc}).

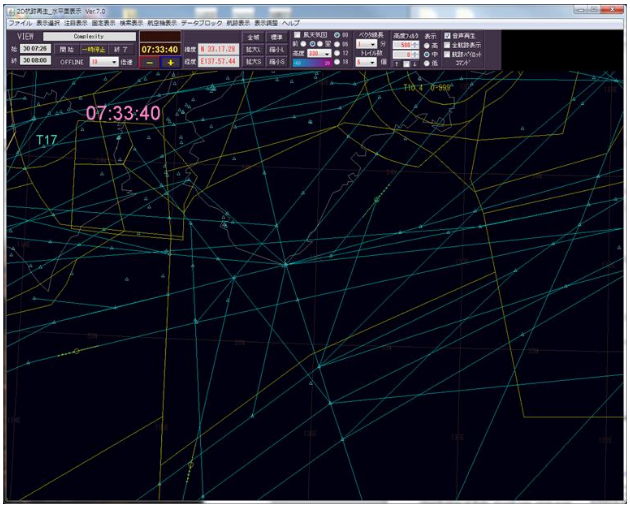

Fig.3 Radar screen-like display

3.2.3 Subjects

The subjects who participated in the preliminary study were 12 active air traffic controllers who had control experience of the target sector for between 3 and 15 years.

3.3 Tuning Examples

As part of this preliminary study, we consider a single scenario (Test 1) and the tuning of λ_t. For this scenario, the values of λ_H and λ_z were fixed as 9.6 NM and 840 feet respectively.

The Test 1 scenario had two aircraft, Aircraft A and Aircraft B flying at the same altitude on airways that crossed as shown in Fig. 4. The Test 1 scenario also contained other non-conflicting traffic.

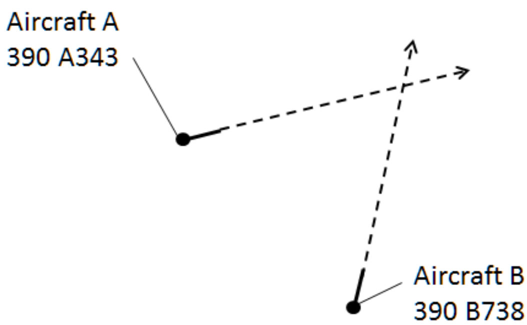

Fig. 4 Test 1 Scenario: crossing traffic

Fig. 5 shows the time histories of lateral and vertical separations between Aircraft A and B. Because they fly at the same altitude, vertical separation is a constant zero. The minimum lateral separation, which occurred at the CPA was 1.6 NM.

T_{cog} and T_{dc} were acquired from 11 controllers. (One controller's results had to be discarded due to a data gathering failure). The means and standard deviations of T_{cog} and T_{dc} for the 11 cases are shown in Table 1.

Fig. 6 shows time histories of the difficulty index D calculated using three different values of the tuning parameter λ_t: 216 sec., 360 sec. and 576 sec. These λ values were chosen such that the difficulty value of 0.5 was attained when the time to CPA between the two aircraft was 3 min., 5 min. and 8 min. respectively. The values of T_{cog} and T_{dc} for each controller and their mean values are also plotted in Fig. 6 for reference. The λ_t determines the shape (particularly the steepness) of the difficulty-time curve as the CPA is approached.

For the λ_t = 360 sec. case the difficulty curve fits well with the mean value T_{dc}. when the difficulty index value corresponding to controller intervention is set at 0.5. The difficulty index value corresponding to the mean of T_{cog} is 0.2 in this case. We set λ_t is 360 sec. for the remainder of the discussion in this paper.

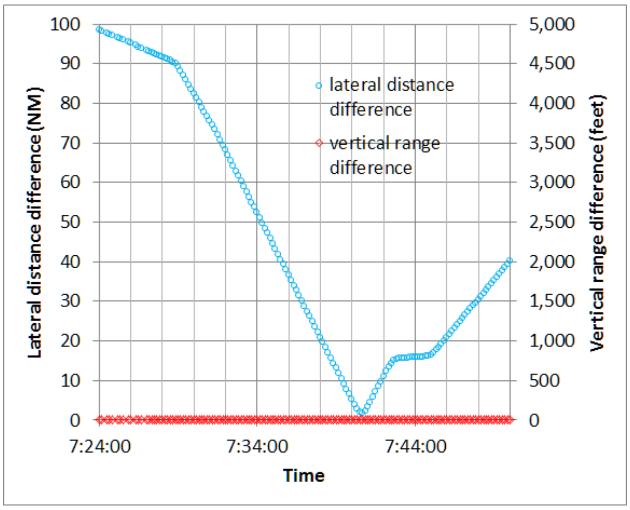

Fig. 5 Lateral and vertical separations between aircraft A and B

Table 1 Statistic values of T_{cog} and T_{dc}

Number of Sample 11

	Mean (hh:mm:ss)	SD (hh:mm:ss)
T_{cog}	07:33:23	00:02:32
T_{dc}	07:36:01	00:01:16

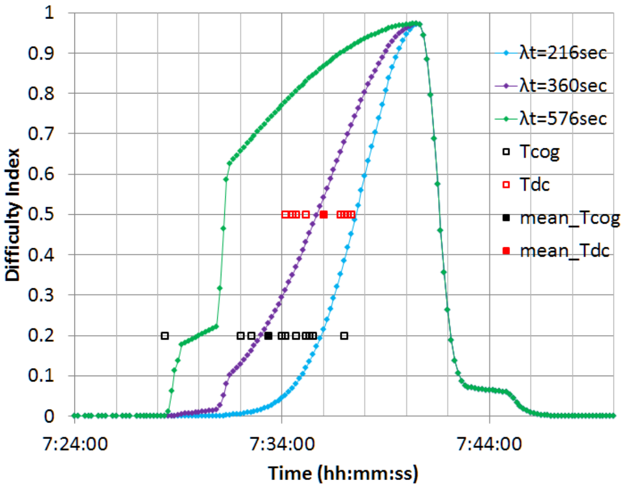

Fig. 6 Fitting of different difficulty index time histories to experiment data by varying λ_t.

4 Visualization of Difficulty

To demonstrate the applicability of the tuned difficulty index, we now visualize areas of high difficulty using a heat map based on realistic simulated traffic scenarios.

4.1 Heat Map Generation

Generally, the prescribed minimum lateral separation between aircraft in en route radar controlled airspace is 5 NM, so the difficulty index value was evaluated over a 0.1 degree (approximately 6 NM) square grid by equation (6) for successive time intervals. Grid squares were colored according to the maximum value of difficulty value in that grid square during that time interval as shown in Fig. 7.

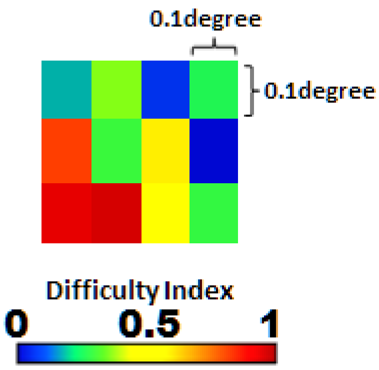

Fig. 7 Color coding of difficulty index in a grid

4.2 Changing of Difficulties in the Process of TBO

In future TBO, aircraft will attempt to adhere to the planned trajectory coordinated between the concerned parties such as the crew, aircraft operator and air navigation service providers (ANSPs). During flight, the actual and predicted trajectories are periodically updated. As a potential application of the ATC difficulty index, we assume the index supports the judgment of the coordination of the trajectories by allowing complexity “hot spots” to be identified based on planned and predicted trajectories. That is, areas of high complexity can be identified ahead of time, and coordination can be carried out as necessary to reduce excessive complexity.

Here, we created three patterns of heat-map which assume a coordination process in future TBO.

4.2.1 Traffic Scenarios

Traffic scenarios for three types of route pattern were prepared for the visualization from a real-world traffic sample for which actual flight plan and surveillance data from ARSRs (Air Route Surveillance Radar) were available. These data were provided by the Japan Civil Aviation Bureau.

- FP: The route of each aircraft was set as the actual filed flight planned route which follows the current Air Traffic Services route structures. Cruise altitude set to the highest recorded altitude in the radar track. FP trajectories correspond to planned trajectories submitted by the aircraft’s operator or crew for coordination in a TBO environment.
- RD: The route of each aircraft was set to follow the track actually flown based on surveillance radar data, with the cruise altitude set as same as FP. RD trajectories represent in-flight trajectory predictions based on planned trajectories which have been partially deconflicted (to the extent possible given prediction uncertainty) and optimized to reduce flight distance as the result of pre-departure coordination.
- Actual: Trajectory derived from ARSR radar track data. These represent trajectories that have additional constraints to resolve

conflicts detected between predicted trajectories during flight and are therefore conflict-free.

In the FP and RD cases, each aircraft's route was set and its trajectory was calculated by the AirTOp fast-time ATM simulator using the EUROCONTROL BADA version 3 performance model, as was used to create the scenarios in section 3. The departure time was set as Actual Time of Departure (ATD; that is take-off time) obtained from the FDPS (Flight Data Processing Systems), and the cruise altitude was set as the highest altitude recorded in the ARSR radar tracks.

4.2.2 Creation of Heat-Maps

"Free routing" is starting to be introduced in high altitude airspaces in Europe and elsewhere, and is planned to be introduced in Japan in the near future. Because there is little climbing and descending traffic in upper airspace, we examined visualizing our ATC difficulty index by a hat map using the parameter tuning in section 3 assumed conflicts between aircraft in cruise at constant altitude. Therefore, portions of the flight trajectories at or above FLL290 [1] were therefore taken and applied to the visualization.

Each trajectory's position and altitude were linearly interpolated at 10-second intervals and the difficulty index value was calculated when other aircraft existed within a lateral proximity of 100 NM. Then, the calculated difficulty index values were integrated for each square of the 0.1-degree grid. The heat maps were created for four one-four intervals over an area of approximately 240 NM square centered at 33°0'0"N 136°0'0" E.

4.2.3 Changing of Difficulties in the Process of TBO

Fig. 8 shows the heat maps corresponding to each scenario.

For the FP case (pre-coordination operator-requested trajectory), there are some areas of high ATC difficulty shown in red, such as at a trajectory crossing point in the 03:00Z map and also along airways in the 04:00Z, 05:00Z and 06:00Z maps.

For the RD case (prediction from post-coordinated trajectory) the high difficulty area at the 03:00Z time has been eliminated by coordination, but other high difficulty areas following airways remain.

For the Actual trajectories case, most of the high difficulty areas have been eliminated.

5 Discussion and Conclusions

Strategic management of aircraft operations will improve the overall efficiency and safety in the future ATM environment. We propose ATC difficulty as one of the indices that could be used in management of traffic flows, and in this study we have tried to show how it could be practically applied in a TBO environment by visualizing changes to ATC difficulty index in an airspace with time.

Our index uses some parameters which must be adjusted. For this purpose, we conducted a study with 12 actual air traffic controllers in which a time reference parameter λ_t was set such that the difficulty index of 0.5 corresponded to the mean value of $T_{dc,}$ the mean time at which controllers decided that conflict avoidance intervention was necessary. We only adjusted the time reference parameters in a simple co-altitude merging conflict case.

Although this paper reported only the results of parameter tuning for one simple conflict case, our scenarios contained other types of conflict which revealed some interesting issues. Our index incorporates separate adjustment parameters for the vertical horizontal and temporal dimensions. However, the difficulty of perceiving an actual conflict may depend on features of human judgement that are not so easily reflected in this formulation. For example, the prediction of three-dimensional spatial separation is difficult from a plan-view display when vertical manoeuvers are involved. Thus, in a case when

[1] Flight Level (FL): Aircraft altitude in hundreds of feet assuming an altimeter setting datum of 1013.35 hPa / 29.92 mmHg, i.e. International Standard Atmosphere sea-level pressure.

tracks cross but one aircraft of the pair is ascending or descending, even if vertical speed is constant controllers are less certain of whether a conflict will actually occur and so typically instruct the climbing or descending aircraft to level off until the aircraft gave crossed to guarantee vertical separation.

Regarding correlation with time, the variability of T_{dc} could reflect differences in controller strategy which could be both individual and workload-dependent. We infer there are at least two strategies affecting T_{dc}: (a) attempting to reduce overall workload by intervening to remove potential conflicts as early as possible (early T_{dc}), and (b) noting that a potential conflict exists but continue to monitor the situation until greater certainty of the conflict is achieved before intervening (late T_{dc}). Notwithstanding experience and preferred style, a busy controller will probably tend towards strategy (a) to create time for other tasks, while in a low workload situation the same controller may adopt strategy (b) to reduce unnecessary intervention.

How to handle different conflict cases involving hard-to-judge patterns, and how to treat variations in controller strategy, will be considered in our future study.

We examined visualizing our ATC difficulty index by a hat map assuming future "Free routing" using the parameter adjusted in this study to show how it might be applied in a future TBO environment. We will continue to improve the ATC difficulty index model so that it will be usable as an index for trajectory-based traffic management in the future.

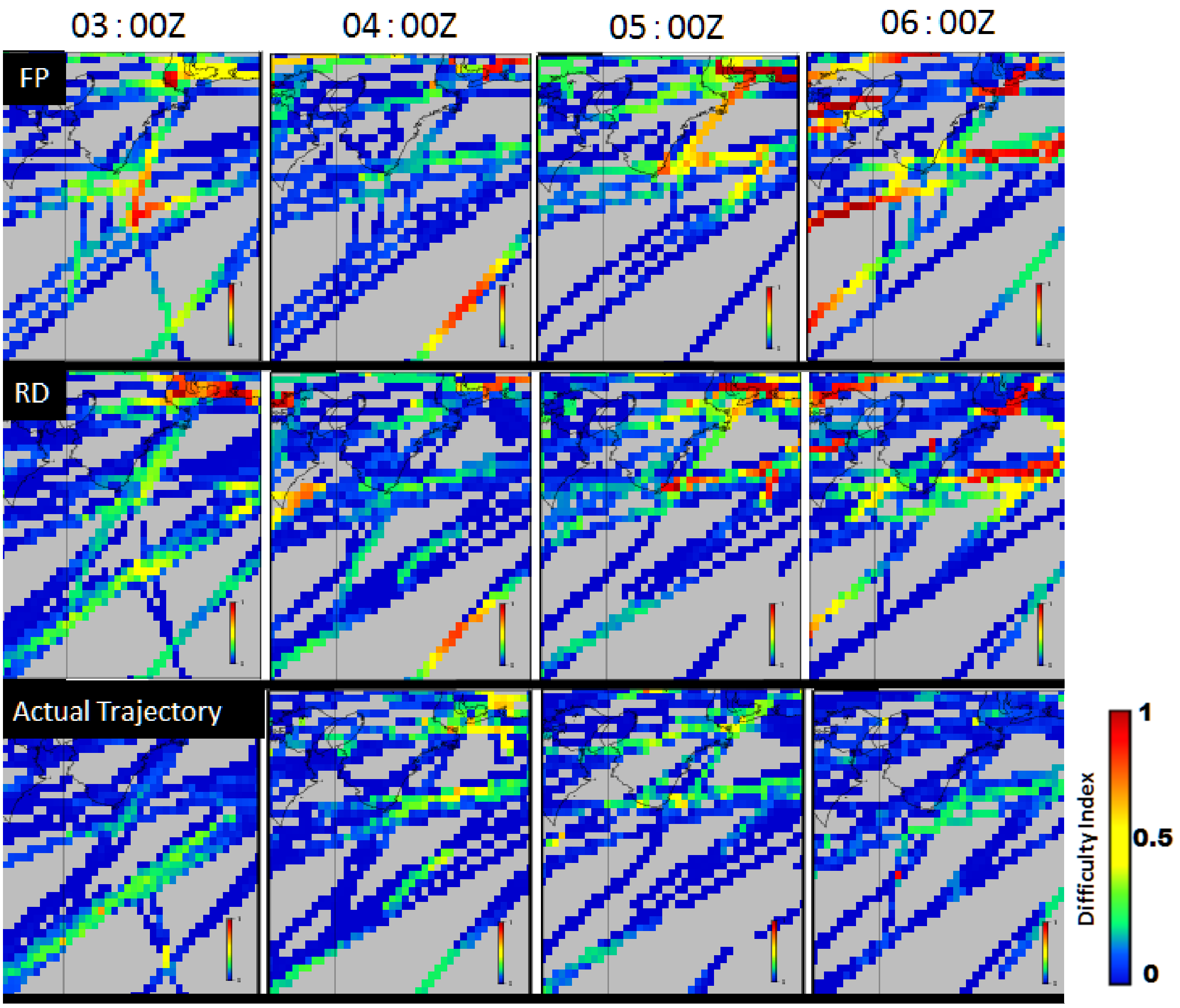

Fig. 8 Three route patterns of heat-maps

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