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TRAJECTORY-BASED PERFORMANCE ASSESSMENT OF AVIATION WEATHER INFORMATION

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1. INTRODUCTION

Adverse weather has a major impact on aviation safety and efficiency (National Research Council, 1995). In order to mitigate the impact of adverse weather on flight operations, several efforts are under way to help improve the weather information available to the key aviation decision-makers, including pilots, air traffic controllers and airline dispatchers. These efforts address a variety of adverse weather phenomena (e.g., convective weather, icing, turbulence, widespread low visibility, volcanic ash, etc.). They also support the development of new forecast products, graphical and integrated cockpit weather displays, improved capabilities for weather data link, as well as enhanced interfaces and tools for the dissemination of weather information (Stough, 1999). In order to best support these efforts, it is important to understand users' information needs so as to provide adequate information products and decision-support tools.

2. WEATHER INFORMATION NEEDS

From an analysis of pilots' user needs for operating in icing conditions (Vigeant-Langlois & Hansman, 1999), it has been found that the key decisions related to operating in potentially hazardous weather conditions include:

- Go/no-go, or the decision to launch or delay a flight;
- Route selection;
- Tactical adverse weather avoidance;
- Tactical escape from adverse weather conditions;
- Aircraft systems management.

2.1 Generalized Weather Information Needs

For each decision identified above, information needs relate to assessing how potential aircraft trajectories will interact with the potentially hazardous weather field. The generalized weather information needs of aviation users include:

- The spatial distribution of the weather field along the planned and alternate aircraft trajectories;
- The potential for hazardous conditions and hazard-free zones along the planned and alternate aircraft trajectories;
- The potential for at least one path free of hazardous conditions;
- The location of hazard-free zones along the planned and alternate aircraft trajectories.

In all cases, information is needed about the spatial distribution of the weather field at locations along or near the planned or alternate aircraft trajectories, *at times in the future when the aircraft would be at these locations*.

Figure 1 displays how weather information fits in the aviation routing decision control loop. In operating aircraft in or near a potentially hazardous weather field, the situation that the pilot attempts to mitigate involves the interaction between an aircraft trajectory and the weather field. The means by which pilots are able to affect the situation is by controlling the aircraft trajectory and by the management of aircraft systems (e.g., ice protection system, engine thrust, seat-belt sign). Pilots learn about the state of the weather field by direct visual observations, measurements and weather forecasts. In a potentially undesirable way, pilots may also learn about the weather field through direct interaction with the hazardous conditions.

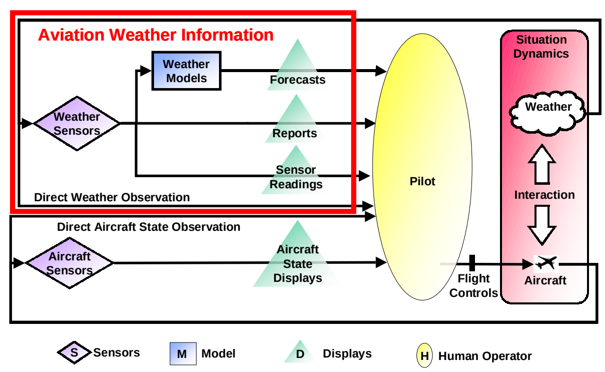

Figure 1: The role of weather information in influencing pilot's aircraft trajectory control and weather avoidance

Pilots have the final authority regarding aircraft routing around adverse weather. However the aircraft re-routing problems is truly a collaborative decision problem, involving air traffic controllers, airline dispatchers and flight crews. Also, as shown in Figure 2, the information which gets to the decision-makers is processed and interpreted by several other agents including forecasters, weather service providers and Flight Service Stations.

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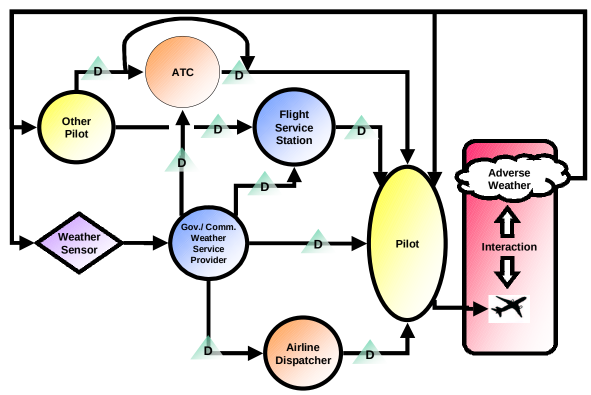

Figure 2: Weather information flow and aviation weather information users

2.2 Temporal Regimes of Weather Representation & Planning

The needs of aviation decision-makers are found to depend on the planning time horizon of the tasks they perform. For instance, as the decision time horizon decreases, the criticality of pilots' decisions increases (Haraldsdottir *et al.*, 1998). Fortunately, at the same time the uncertainty in the dynamics of the situation decreases, due to reduced uncertainty about the evolution of the weather field and in the aircraft's future trajectory. A representation of the different temporal regimes of planning and weather representation is illustrated in Figure 3.

Experienced users of weather information understand that the accuracy of weather forecasts degrades as the forecast horizons increase, and use a cognitive representation of the information that varies according to its forecast horizon. The temporal continuum of weather representation can be broken down into the following four regimes illustrated in Figure 3:

- Historical: In this regime, the weather representation acknowledges that the situation is in the past.
- Quasi-Constant: In this regime, the representation is approximated to be time-invariant. The time duration for which the Quasi-Constant representation is appropriate depends on the meteorological situation.
- Quasi-Deterministic: In this regime, weather conditions are represented to evolve in a manner which can be reasonably predicted (e.g., advection of convective weather);
- Non-Deterministic: In this regime, the weather dynamics cannot be deterministically represented due to either chaotic processes or lack of information. The representation is therefore non-deterministic and at best can be represented stochastically.

In a similar manner, the temporal continuum of the pilot's planning task regarding hazardous weather decisions can be broken down into three regimes:

- Reactive: In this regime, pilots simply react to the weather situation that they perceive and, if they encounter hazardous weather, are principally making decisions regarding escape.
- Tactical: In this regime, pilots are making short-term trajectory management decisions to avoid hazardous weather conditions.
- Strategic: In this regime, pilots are making long-term decisions regarding routing and flight planning which need to consider the potential for hazardous weather conditions.

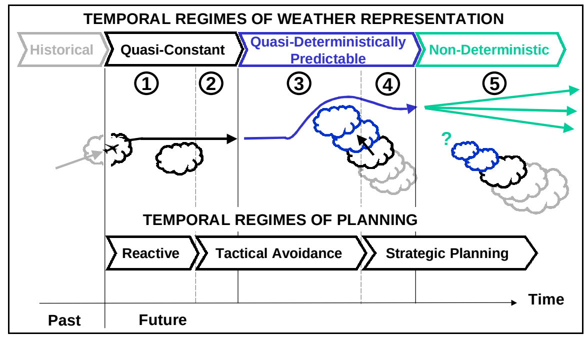

Figure 3: Temporal regimes of weather representation and planning

2.3 Temporal Regimes of Hazardous Weather Information Needs

The convolution of the different regimes of weather representation and decision-making result in the following five combinations of weather information needs identified in Figure 4:

- Temporal Regime (TR) 1: In this regime, pilots are making escape decisions in reaction to encounters with hazardous weather conditions based on a quasi-constant representation of the weather field;
- TR2: In this regime, pilots are making avoidance decisions around hazardous weather conditions based on a quasi-constant representation of the weather field;
- TR3: In this regime, pilots are making avoidance and route planning decisions based on the deterministic projection of the hazardous weather field;
- TR4: In this regime, pilots are making planning decisions based on a deterministic representation of the hazardous weather field;
- TR5: In this regime, pilots are making planning decisions based on non-deterministic representations of the weather field or no representation at all. This is also the regime in which air traffic controllers and airline dispatchers make strategic decisions regarding flight routing and cancellation decisions (Evans, 2001)

3. TRAJECTORY-CENTRIC FRAMEWORK

At a fundamental level, the aviation weather problem can be reduced to the assessment of the interaction of one or more four-dimensional trajectories with a weather field. The key elements of this abstraction are discussed below. Figure 4 shows a simplified representation of a weather encounter scenario, where the temporal aspect is not fully represented.

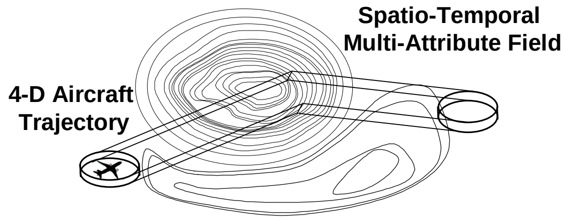

Figure 4: Simplified representation of the key elements of a weather encounter scenario
(Note: The Temporal Aspect is Not Represented in this Figure)

Aircraft Trajectory: The planned or alternative aircraft trajectory can be represented by a four-dimensional (4-D) *hypertube*, corresponding to a three-dimensional (3-D) volume of the airspace required to protect the aircraft. The fourth dimension is added to represent the temporal evolution of the aircraft trajectories. Note that in Figure 4, the aircraft protected airspace is represented by a cylinder which features different characteristic dimensions along the vertical and lateral directions that correspond to distinct weather separation needs due to aircraft maneuvering dynamics. The 4-D trajectory *hypertube* can be thought of as either the deterministic *hypertube* which represents a specific planned aircraft trajectory, and simply has the dimension of the aircraft protected airspace, or as a stochastic *hypertube* which includes uncertainty in the aircraft's future position and timing.

Weather Field: The weather field can be abstracted as a multi-attribute field distributed in space that can vary over time (e.g., wind, temperature, liquid water content). In the case of potentially hazardous weather conditions, it is often useful if the representation can be simplified to a single-attribute dichotomic threat field with discrete boundaries between hazardous and hazard-free zones that vary over time. The hazardous weather spaces are thus referred to as 4-D hazardous weather *hypervolumes*.

3.1 Four-Dimensional Intersection Testing

If aircraft trajectories can be modeled as 4-D *hypertubes* and the weather can be modeled as 4-D hazardous *hypervolumes*, then in the quasi-constant and quasi-deterministic regimes of weather representation, the aircraft-weather interaction can be evaluated using 4-D intersection testing. This test is essentially equivalent to the aircraft collision detection and alerting problem and can serve to decide whether to accept or reject trajectories, and also to generate conflict-free paths.

To visualize this abstraction, consider the example of an aircraft protected zone transiting through an airspace which also contains a hazardous weather region (see Figure 5). To simplify the visualization, in this example, the hazardous weather space is modeled as a cube. For a given interval of time Δt, the location of the two volumes is propagated in the 3-D space. As can be seen in Figure 4, an apparent intersection exists between the volumes swept by the aircraft protected airspace and the hazardous weather space, indicating the potential for an "unsafe" trajectory.

Assuming that the problem illustrated in Figure 4 can be resolved using only two spatial dimensions (latitude and longitude in this case), the aircraft protected zone is reduced to a circle and the hazardous weather zone is reduced to a square. With time represented on the third axis, the two-dimensional polygons sweep out hypervolumes in 3-D space-time that are shown in Figure 6. In this space-time domain, a hazardous weather encounter is anticipated if and only if the prisms intersect. Given this abstraction the literature emerging in relation to aircraft conflict detection and robotics can be used to solve the 4-D hyperspace intersection problem (Cameron,1990).

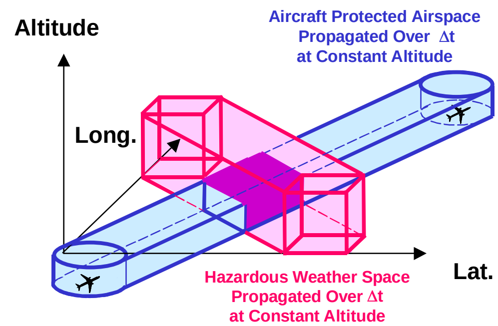

Figure 5: Illustration of 3-D volume swept by hazardous weather space and aircraft protected airspace over Δt

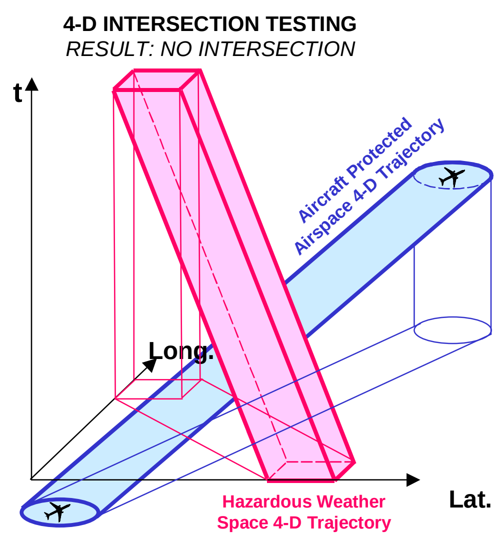

Figure 6 :Illustration of 3-D space-time hypervolumes that can be used for weather "collision" detection

3.3 Trajectory-Based Weather Forecast Performance Assessment

From the perspective of users of aviation weather information, an accurate forecast is one which is correct with respect to predicting the intersection between the aircraft 4-D *hypertubes* they are responsible for and hazardous weather *hypervolumes*. Based on this perspective, categorical dichotomic forecasts can be evaluated using the following contingencies:

- *Hit:* Occurrence in which a 4-D intersection between a protected aircraft *hypertube* and a hazardous weather *hypervolume* was predicted and did occur;
- *Miss:* Occurrence in which a 4-D intersection between a protected aircraft *hypertube* and a hazardous weather *hypervolume* was not predicted but did occur;
- *False Alarm:* Occurrence in which a 4-D intersection between a protected aircraft *hypertube* and a hazardous weather *hypervolume* was predicted but did not occur;
- *Correct Rejection:* Occurrence in which a 4-D intersection between a protected aircraft *hypertube* and a hazardous weather *hypervolume* was predicted to not occur and did not occur.

These definitions contrast with the traditional way in which weather forecasts are provided and verified. For example, forecasts of convective weather are typically provided for a specific geographical airspace over selected time intervals. The forecasts are normally assessed using verification statistics that are based on spatial grid-to-grid comparison of the forecast and observed fields (Doswell, 1986). Discrepancies between the two types of assessment methods are encountered for scenarios where intersections do exist between the 3-D volumes swept by aircraft protected airspace and hazardous weather spaces over time intervals (such as illustrated in Figure 5), and for which no intersection is found in the 4-D space-time domain (such as in Figure 6).

The difference in the perception of correctness between trajectory-based and area-based forecasts highlights an aspect of the difficulty in using pilot weather reports (PIREPs) for traditional forecast verification (Brown & Young, 2000). It is nevertheless desirable to consider the trajectory-based perspective of users in evaluating information needs and performance assessment. From this perspective may emerge new approaches to the development of promising weather information tools such as the Aviation Digital Data Service Flight Path Tool (Sherretz, 2000).

4. CONCLUSIONS

Based on an analysis of aviation decision-makers' time-related weather information needs, an abstraction of the aviation weather decision task was developed, that involves 4-D intersection testing between aircraft trajectory *hypertubes* and hazardous weather *hypervolumes*. The framework builds on the hypothesis that hazardous meteorological fields can be simplified using discrete boundaries of surrogate threat attributes. The abstractions developed in the framework may be useful in studying how to improve the performance of weather forecasts from the trajectory-centric perspective, as well as for developing useful visualization techniques of weather information.

5. ACKNOWLEDGEMENTS

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