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PILOT CONVECTIVE WEATHER DECISION MAKING IN EN ROUTE AIRSPACE

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Abstract

The present research investigates characteristics exhibited in pilot convective weather decision making in en route airspace. In a part-task study, pilots performed weather avoidance under various encounter scenarios. Results showed that the margins of safety that pilots maintain from storms are as fluid as deviation decisions themselves.

1 Introduction

Weather related disruptions account for about seventy percent of the delays in the U.S. National Airspace System (NAS) [1]. The presence of convective weather hazards reduces traffic flows in impacted airspace and forces planes to deviate from planned trajectories. In today's operation, strategic weather avoidance reroutes (defined here as 2-6 hours time frame) are generated based on weather forecasts provided by the Collaborative Convective Forecast Product (CCFP) and implemented at the FAA Air Traffic Control System Command Center (ATCSCC) according to the National Severe Weather Playbook (NSWP) [2]. Tactical weather avoidance reroutes (defined here as 0-2 hours time frame) are generated by pilots in the air and submitted as requests to air traffic controllers, who vet the requested reroutes against conflicts with surrounding traffic. Reroutes free of conflicts can be readily approved and implemented; those that create potential conflicts will need to be modified through further negotiations between the pilot and controller. Handling pilot requests for deviations in the event of thunderstorms further burdens controllers at a time when they are already confronted with increased workload owing to increased traffic density and complexity created by constricted operable airspace [3]. As controller workload is a major determinant of airspace capacity, how to ease the demand on controllers when managing traffic through thunderstorms is a pressing issue in realizing the visions of the Next Generation Air Transportation System (NextGen).

Like most recent advances in airspace operations, solutions to reducing controller workload in managing traffic through thunderstorms involve automation. Specifically, research has focused on developing automated algorithms for generating conflict-free reroutes [4–8] around identified hazardous regions [9–13]. While the generated reroutes meet the requirement from a traffic management standpoint, they do not necessarily reflect how pilots deviate for weather. As such, further negotiations likely will still be needed before reaching resolutions satisfying both the pilot and controller. To date there has been little research examining the strategic aspects of pilot weather avoidance in en route airspace. The present research aims to shed some light on the process.

1.1 Automated Weather Avoidance for Traffic Management

While pilots bear the responsibility for deviating around hazardous weather, controllers oversee the weather avoidance decisions made by individual pilots to maintain separation assurance and ensure efficient use of available airports, airspace, and other resources as part of their Traffic Flow Management (TFM) responsibilities [14]. Various automated algorithms for weather avoidance have been developed under these premises for controllers [4–8]. The algorithms reroute aircraft around weather by first identifying whether their planned trajectories penetrate storm cells, which are typically represented computationally as polygons. If penetration occurs, the algorithms search for the most efficient reroutes around the storm cells. Refinements to the algorithms have included taking into account the unreliability of weather forecasts and periodically issuing new routes based on updated forecasts [4] and allowing users to add custom constraints, or wiggle room, to the reroutes [7].

Other refinements to automated weather avoidance have involved developing more elaborated descriptions of the obstructing storm cells. For example, Avijan and colleagues attempted to describe weather hazards as 4D grid-based weather avoidance hazard volumes instead of polygons [9–11]. The 4D description acknowledges the dynamic and time-variant nature of weather phenomena while data coded in a grid system make them more conducive to be manipulated mathematically.

DeLaura and colleagues took a further step beyond describing storm impacted regions based on the attributes of the weather activities by taking into account how pilots behaved when they were confronted with storms of similar attributes in the past [12], [13]. They analyzed real aircraft convective weather encounters and identified meteorological factors that best predicted pilots' decisions given specific weather conditions. The end result of their effort is the Convective Weather Avoidance Model (CWAM), a statistical model of pilot weather avoidance behavior in en route airspace. Outputs of the CWAM models specify impacted regions that pilots deviate to avoid and the associated probabilities (e.g. regions that 90%, 80%, etc. will avoid). Validations of CWAM model predictions of deviations and non-deviations against observed ones showed that prediction errors are around 25% [15–17].

1.2 Pilot Weather Avoidance Decisions: Situated and Opportunistic

The effectiveness of most of the aforementioned algorithms has only been demonstrated in fast-time simulations. In the few instances where comparisons were made between algorithm decisions and pilot decisions based on actual weather data, pilot decisions were found to match algorithm decisions to a large extent but differ in small and interesting ways. In comparing actual pilot decisions with CWAM outputs, Chan and colleagues found 3% of instances where pilots stayed on their flight plans without encountering a CWAM polygon as would be predicted by CWAM outputs [18]. Chan and colleagues speculated that those pilots waited until getting closer to the storms to determine whether the flight paths were acceptable. In addition, pilots were also frequently found to skirt or clip the edges of the CWAM polygons.

Discrepancies between CWAM outputs and actual pilot behaviors were also observed by DeLaura and Evans, who noted a case where the pilot made a large deviation around a region of weather whose intensity would be considered benign and thus penetrable according to CWAM predictions [12]. Crowe, DeLaura, and Matthews speculate that the discrepancies could be due to differences in weather information available to the flight deck and to ground-based CWAM [17]. Information discrepancies notwithstanding, Crowe et al. acknowledge that some deviation decisions are likely strategic, reflecting influences from opportunities present in a particular encounter; for instance, pilots may trade off comfort for efficiency, or vice versa, under different circumstances.

1.3 Present Research

The present research aims to systematically examine the strategic aspect of pilot weather decision making in the tactical time frame (0-2 hours) in en route airspace. In a part-task study, we presented pilots with weather encounter scenarios that varied in distance to encounter and point of approach, with the goal of manipulating urgency and opportunity, respectively. Predicted weather forecasts up to 40 minutes were provided; the prediction was assumed to be 100% accurate. Pilots were asked to find a safe and efficient route around weather within the shortest amount of time using the provided onboard tools to evaluate and implement alternative trajectories. We evaluated the type of maneuvers pilots took to deviate for weather and the safety margins they maintained from storms.

2 Method

2.1 Participants

Eighteen transport pilots with 1000 to over 5000 hours of commercial flight experience participated in the study and were compensated $25/hr. The majority of them had experience using the Cockpit Situation Display (CSD) from participating in previous studies in the lab but none had experience with the predicted weather display interfaces.

2.2 Apparatus

The study was conducted using an IBM-compatible personal computer (PC) equipped with a 30” LCD display. Pilots manipulated the CSD using a computer mouse.

The platform on which nowcast and forecasted predicted weather information was presented was the CSD, an extension of a Cockpit Display of Traffic Information (CDTI) (Fig. 1). The CSD is an interactive display prototype that has been in development in the Flight Deck Display Research Laboratory at NASA Ames Research Center for over a decade, for the purpose of implementing and testing future aviation concepts. The CSD supports both traditional 2D and advanced 3D perspective visualization models, and depicts the 4D interrelationship of traffic, terrain, and weather using a cylindrical volume metaphor.

As part of a capability supporting trajectory-based operations (TBO), the CSD also includes the Route Assessment Tool (RAT), which integrates with the aircraft’s Flight Management System (FMS) and allows for in-flight trajectory replanning. A standard computer mouse serves as the input device for use with the CSD. The RAT adopts the principle of a direct manipulation interface [19–22] providing the functionality to create and visualize in-flight route modifications, downlink proposed route modifications to Air Traffic Control (ATC), receive route modifications from ATC, and execute modifications. The RAT supports the addition of waypoints at arbitrary latitudes- longitudes, and deletion of waypoints, through both clicking and dragging-and-dropping mouse operations. For each waypoint, pilots can also adjust an associated flight altitude and speed, thus enabling 4D trajectory in-flight planning.

Fig. 1. A screenshot of the CSD and RAT. The weather scenario shown here is the Middle type.

2.3 Design

On each trial, pilots were presented with a weather encounter scenario in en route environments and asked to modify the planned trajectory if they found it unsafe according to predicted weather forecasts. We manipulated the distance between the starting location of ownship to the location on the initial trajectory where ownship was expected to reach the closest point of approach (CPA) to weather. These distances could be either 40 nm (~5 min) or 80 nm (~10 min). At either of the distances, ownship could encounter hazardous weather in one of four ways:

- Middle: On these trials, the existing 3D ownship trajectory, and the 4D forecast ownship trajectory, penetrated one of the storm cells near the center of a storm front. It was designed such that it would be very inefficient to take a large detour and bypass all of the storm cells so that pilots would be more tempted to find an alternative route through the gaps between storm cells.
- Initially clearing gap: On these trials, the existing 3D ownship trajectory was initially clear of the given line of storm cells, passing through a gap in the current weather depiction. However the forecast 4D trajectory was predicted to penetrate the storm cells.
- Initially clearing edge: On these trials, the existing 3D ownship trajectory appeared to clear the leading or trailing edge of a line of storm cells in current weather depictions, but the forecast 4D trajectory was predicted to penetrate the storm cells.
- Clear later: On these trials, the existing 3D ownship trajectory penetrated storm cells in current weather depictions, but the forecast 4D trajectory was predicted to be clear of weather.

A total of 144 unique trial scenarios were generated, with 36 trials in each of the encounter types. The 36 trials varied between the two distances conditions.

2.4 Procedure

Each trial began with a crosshair fixed at the center of a blank CSD display. After a variable amount of time, between 2-4 seconds, the trial display appeared with ownship in the center. The display range was preset to 160 nm (160 nm in front and behind ownship), with the trajectory extending upward ahead of ownship to the edge of the display. Storm cells were located at a distance specified by the trial condition ahead of ownship in the upper half of the display. Pilots were asked to determine if a given flight trajectory was safe and, if the trajectory was determined to be unsafe, find a safe and efficient re-route around weather using the shortest amount of time. They were instructed to use their company's standard operation procedure (SOP) for avoiding hazardous weather. Each trial ended when the pilot executed the modified flight trajectory using the RAT. On trials where pilots determined that no modification was necessary, they activated the RAT and executed the existing trajectory to terminate the trial. Following the end of a trial, a dialog box appeared in the center of the display with an OK button. As soon as the pilot clicked the OK button, the next trial began.

The 144 trials were divided into three blocks, one for each weather viewing method (for details, see [23]). The order of the blocks was counterbalanced between pilots. Pilots received the corresponding training for a particular method right before that block of trials.

On all trials the altitude of ownship was preset to 33000 feet; and the ground speed was preset to around 464 knots. Because it was assumed that the type of weather avoidance being studied here takes place en route, pilots were instructed to view the display in 2D and perform only lateral maneuvers even though CSD and RAT support 3D operations. No wind information was provided; pilots were instructed to infer wind direction based on the forecasted movement of the storm cells.

3 Results

The part-task study on which this paper is based was designed to evaluate usability and preference for three prototype methods for displaying predicted weather forecasts [23]. Results reported here are based on new analyses of the same set of data collapsed across the three methods which were assumed to not affect weather decisions differently.

3.1 Evaluation Times

Evaluation times (i.e., elapsed time between the beginning of a trial and activating the RAT) provide a gross index of the difficulty in making deviation decisions. We have previously evaluated evaluation times according to encounter type and distance to weather [23]. The results showed that pilots spent slightly less time evaluating weather and proceeded quickly to modify the trajectory using the RAT when the distance to encounter was close (10.0 sec at 40 nm and 10.8 sec at 80 nm). Pilots also spent more time on evaluation when the given trajectory was projected to go through the middle of a line of storms (11.3 sec) than when the given trajectory cleared the edge of the line of storms (9.2 sec).

3.2 Deviation Decisions

Deviation decisions were classified into one of four categories: no change, flying through gaps between storm cells, and flying around the leading or trailing edges. Fig. 2 plots the percentage distribution of deviation decisions by encounter type. As expected, different encounter scenarios elicited different mixtures of deviation decisions, and the particular mixtures reflected the opportunities afforded by the scenarios. For example, for scenario types with the initial trajectory flying through the middle of storms (middle and initially clearing gap), pilots mostly (about 80% time) chose to maneuver between gaps of storm cells as their initial course would have taken. In the remaining cases where pilots decided to fly around the storms, they mostly did so by flying around the trailing edge of the storms rather than the leading edge.

The preference for pilots to fly around the trailing than leading edge of storms given choices is perfectly understandable: flying around the trailing edge means that the storm is moving away as the flight progresses. However, this preference can be put aside when the initial trajectory is closer to the leading edge of a line of storms, such as the scenarios of the initially clearing edge encounter type. On those trials, pilots overwhelmingly (over 90% time) deviated for the weather by moving the trajectory further out from the leading edge of the storm.

Trajectories in the clear later type of scenarios were designed so that if left unmodified they would have remained safe around weather. However, Fig. 1 shows that about 45% of time pilots still made modifications. We examined conditions under which pilots chose to modify the trajectories by analyzing their deviation decisions with respect to how the trajectories would have avoided weather. Among the 36 clear later trial, there were 24 trials with trajectories that would have avoided weather by flying through gaps, 1 trial with a trajectory that would have avoided weather by flying around the leading edge, and 11 trials with trajectories that would have avoided weather by flying around the trailing edge. Fig. 3 shows the percentages of routing decisions as a function of how the trajectories would have avoided weather if left unchanged within each category. In general, for those trajectories that were modified, the distribution of deviation decisions seen in Fig. 2 reflected

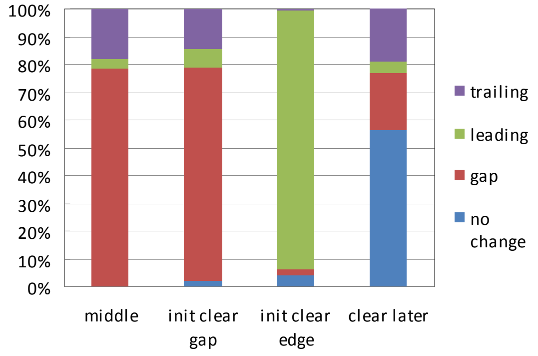

Fig. 2. Percentage distributions of deviation decisions under different weather encounter types

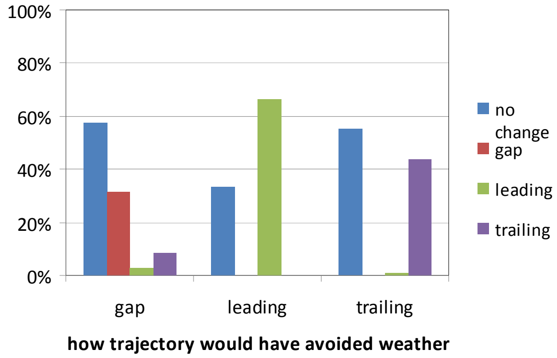

Fig. 3. Percentages of deviation decisions by the relation between initial trajectories and weather in the clear later type scenarios

the distribution of how the given trajectories would have avoided weather.

3.3 Closest Point of Approach (CPA) to Weather

While the types of encounter are expected to dictate deviation decisions to some extent, ideally they should not affect the maintenance of adequate safety margins from weather, which is 20 nm off any radar echo according to FAA guidelines [24]. We analyzed the distance between ownship trajectory and its closest point of approach (CPA) to weather for trials with middle and clear later types of encounters (Fig. 4). These data show that, under both encounter types, the average CPAs varied significantly by deviation decisions, and in most cases fell below the FAA guidance; $F(2,14) = 42.55$, $p < .0001$ for middle type of encounters, $F(3,21) = 44.45$, $p < .0001$ for clear later type of encounters. For the middle type of encounter scenarios, where "shooting the gap" was far and away the most efficient strategy, pilots mainly chose to fly through the gaps although this resulted in very small margins (~6 nm). However, for the clear later type of scenarios where the original trajectories were already designed to clear weather by a margin around 6 nm, pilots chose to modify the trajectories 40% of the time to increase the margin whenever possible.

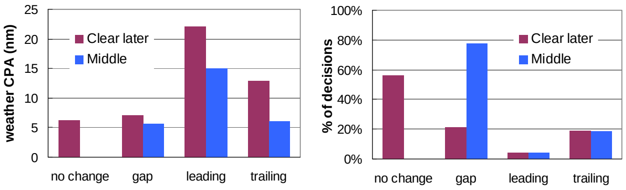

Fig. 4. Weather CPA and decision distributions by deviation decision type

4 Discussion

While the limited set of encounter scenarios may not capture all possible conditions under which weather avoidance occurs in en route airspace, certain patterns of pilot weather avoidance decisions emerge from these results. The most significant one is that pilots do not always adhere to the FAA guidelines on the safety margin to be maintained from hazardous weather. It appears that pilots do make an effort in maintaining a safe distance from weather when the encounter circumstances make it easy to achieve, such as when the initial trajectories were at the boundaries of the leading or trailing edges of the storms. When the encounter circumstances make it inefficient to fly around the hazardous region altogether, such as when the initial trajectories take them through the middle of a line of storm cells, pilots would be more willing to fly closer to the storms to trade off comfort for efficiency.

The current findings shed light on the observation by DeLaura and Evans where the pilot made a large deviation around weather conditions considered benign by CWAM [12]. According to the CPA results shown in Fig. 4, what DeLaura and Evans described as "an unclear deviation strategy" appears to be what pilots do whenever possible, stretching their routes further away from storms when the other side of the airspace is completely clear.

The current findings have practical implications for the development of automated weather avoidance algorithms. One suggestion for making the algorithms more tailored to pilot needs is to take into account opportunities present in the encounter circumstances, such as open airspace. Another suggestion is to incorporate a trade-off function between comfort and efficiency. In principle such a function could be derived from empirical observations of actual pilot decisions.

5 References

[1] Federal Aviation Administration, "Fact Sheet – Next Generation Air Transportation System," 27-May-2010. [Online]. Available: http://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=10261. [Accessed: 07-Jun-2012].

[2] Federal Aviation Administration, "National Severe Weather Playbook." [Online]. Available: http://www.fly.faa.gov/PLAYBOOK/pbindex.html. [Accessed: 27-Mar-2012].

[3] F. T. Durso and C. A. Manning, "Air Traffic Control," *Reviews of Human Factors and Ergonomics*, vol. 4, no. 1, pp. 195–244, Oct. 2008.

[4] R. Windhorst, M. Refai, and S. Karahan, “Convective weather avoidance with uncertain weather forecasts,” in *Digital Avionics Systems Conference, 2009. DASC’09. IEEE/AIAA 28th*, 2009, p. 3–D.

[5] J. F. Love, W. N. Chan, and C. H. Lee, “Analysis of Automated Aircraft Conflict Resolution and Weather Avoidance,” presented at the 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS), Hilton Head, SC, 2009, vol. AIAA-2009–6995.

[6] H. Erzberger, T. Lauderdale, and Y. Chu, “Automated conflict resolution, arrival management and weather avoidance for ATM,” in *27th International Congress of the Aeronautical Sciences, Nice, France*, 2010.

[7] V. Polishchuk, A. Pääkkö, J. S. . Mitchell, and J. Krozel, “Planning Routes with Wiggle Room in En Route Weather-Impacted Airspaces,” presented at the AIAA Guidance, Navigation, and Control Conference, Chicago, IL, 2009.

[8] H. K. Ng, S. Grabbe, and A. Mukherjee, “Design and Evaluation of a Dynamic Programming Flight Routing Algorithm Using the Convective Weather Avoidance Model,” presented at the AIAA Guidance, Navigation, and Control Conference, Chicago, IL, 2009, vol. AIAA 2009–5862.

[9] R. M. Avjian and J. Stobie, “Strategies for air traffic management integration of hazardous weather,” presented at the 54th Air Traffic Control Association Annual Conference, Washington, DC, 2009.

[10] R. M. Avjian, J. Dehn, and J. Stobie, “NextGen Trajectory-Based Integration of Grid-Based Weather Avoidance Fields,” presented at the 91st American Meteorological Society Annual Meeting, Second Aviation, Range and Aerospace Meteorology Special Symposium on Weather-Air Traffic Management Integration, 2011.

[11] R. M. Avjian and J. Dehn, “Trajectory-Based Integration of Aircraft Conflict Detection and Weather Avoidance Fields,” presented at the 92nd American Meteorological Society Annual Meeting, Third Aviation, Range and Aerospace Meteorology Special Symposium on Weather-Air Traffic Management Integration, 2012.

[12] R. DeLaura and J. Evans, “An exploratory study of modeling enroute pilot convective storm flight deviation behavior,” in *12th Conference on Aviation Range and Aerospace Meteorology*, 2006.

[13] R. DeLaura, M. Robinson, M. Pawlak, and J. Evans, “Modeling convective weather avoidance in enroute airspace,” in *13th Conference on Aviation, Range, and Aerospace Meteorology, AMS, New Orleans, LA*, 2008.

[14] B. Sridhar, S. R. Grabbe, and A. Mukherjee, “Modeling and optimization in traffic flow management,” *Proceedings of the IEEE*, vol. 96, no. 12, pp. 2060 –2080, Dec. 2008.

[15] R. DeLaura, B. Crowe, R. Ferris, J. Love, and W. Chan, “Comparing convective Weather Avoidance Models and Aircraft-based Data,” in *89th Annual Meeting of the American Meteorological Society: Aviation, Range and Aerospace Meteorology Special Symposium on Weather–Air Traffic Impacts, Phoenix, AZ*, 2009.

[16] M. P. Matthews and R. DeLaura, “Evaluation of Enroute Convective Weather Avoidance Models Based on Planned and Observed Flights,” in *14th Conference on Aviation, Range, and Aerospace Meteorology*, Atlanta, GA, 2010.

[17] B. Crowe, R. DeLaura, and M. Matthews, “Use of aircraft-based data to evaluate factors in pilot decision making in enroute airspace,” in *14th Conference on Aviation, Range, and Aerospace Meteorology*, 2010.

[18] W. Chan, M. Rafai, and R. DeLaura, “An Approach to Verify a Model for Translating Convective Weather Information to Air Traffic Management Impact,” in *AIAA Aviation Technology, Integration, and Operations Conf*, 2007.

[19] J. Rasmussen and K. J. Vicente, “Coping with human errors through system design: implications for ecological interface design,” *International Journal of Man-Machine Studies*, vol. 31, no. 5, pp. 517–534, 1989.

[20] K. J. Vicente and J. Rasmussen, “Ecological interface design: Theoretical foundations,” *Systems, Man and Cybernetics, IEEE Transactions on*, vol. 22, no. 4, pp. 589–606, 1992.

[21] K. J. Vicente, “Ecological interface design: Progress and challenges,” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, vol. 44, no. 1, p. 62, 2002.

[22] K. J. Vicente and J. Rasmussen, “The ecology of human-machine systems II: Mediating ‘direct perception’ in complex work domains,” *Ecological Psychology*, vol. 2, no. 3, pp. 207–249, 1990.

[23] S. C. Wu, C. G. Duong, R. W. Koteskey, and W. W. Johnson, “Designing a flight deck predictive weather forecast interface supporting trajectory-based operations,” presented at the Ninth USA/Europe Air Traffic Management Research and Development Seminars (ATM2011), Berlin, Germany, 2011.

[24] Federal Aviation Administration, “Aeronautical Information Manual: Official Guide to Basic Flight Information and ATC Procedures.” 09-Feb-2012.

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