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A critical element of situation awareness and sensemaking support for humans in complex environments is the ability to access, detect, and integrate environmental elements to recognize and project the state of the world. Some past research has suggested that new weather technology capabilities in general aviation (GA) flight settings could help improve pilot decision making and reduce accidents such as unintentional transitions from visual flight rules (VFR) to marginal VFR or even instrument meteorological conditions (IMC). This paper addresses an ongoing Federal Aviation Administration (FAA) funded research project investigating the effect of transmission delays and update latencies in presentations of weather information to pilots in the GA environment. Across a range of fixed-install, portable, and handheld (i.e. tablet, smartphone) weather information technologies, latencies of up to 15-20 minutes can be identified. These latencies may affect the use of information regarding dangerous weather conditions and timelines of pilot planning activities during VFR-to-IMC transitions.

Introduction

In General Aviation (GA) flight, pilots obtain a weather briefing before flights in what is described by the Federal Aviation Regulations (Title 14 Code of Federal Regulations) as 'preflight action' in the section Subpart B - Flight Rules. Specifically, the language in Part 91.103 includes a requirement that each pilot in command "become familiar with all available information…" including "weather reports and forecasts, fuel requirements, alternatives available if the planned flight cannot be completed" for flights "not in the vicinity of an airport" (FAA, 2014).

Traditionally, this requirement was met by the pilot in command telephoning 1-800-WXBrief and asking for a standard briefing from a Flight Service Station (FSS) weather briefer. The briefer provides in-depth weather briefing information to the pilot and records the pilot's name, aircraft N number and other pertinent information so that the specific standard briefing is retained for a period of X days. The pilot listens to the briefer, asks and answers questions, and writes down on paper the information transmitted. Recent research indicates an increase in the direct use of web-based weather products for flight preparation by GA pilots (Casner, et al., 2012; Knecht, 2011). Anecdotal evidence also indicates the proliferation of mobile aviation weather information products and tools with access to the internet while airborne has led to a reliance of web-based products and tools for enroute weather updates.

Advances in technology allow easy access to weather information elements (such as METAR, TAF, AIRMET/SIGMET, or FA), provided not only by the Federal Aviation Administration and the National Oceanic and Atmospheric Administration, but also by a number of commercial organizations, in a variety of web-based mobile devices. It is not surprising that "Pilots seem to be transitioning from a traditional means of assisted weather briefing to self-briefing" (Casner et al., 2012). This raises the question - to what extent do GA pilots actually *make use of and effectively use* the weather services that are available for them?

Results of a study of weather-related GA occurrences (Batt, 2005) identified 280 incidents out of 491 occurrences (57%). Pilots made VFR into IMC decisions while other pilots avoided bad weather only in 151 cases (30.8%), and made precautionary landings even more rarely - in 60 cases (12.2%). These results confirmed the idea that decisions made by pilots play a leading role in weather-related incident or accident outcomes.

Pilots' decisions can be affected by the timeliness of weather information presented by the technology (Bailey, 2007). For example, NEXRAD radar data and images, which can represent weather information in graphical form that could decrease workload on a pilot, cannot keep up with rapidly changing weather due to limits in data aggregation and dissemination. Pilots using software apps that display NEXRAD images can receive outdated information that decrease the accuracy or validity of pilot decision making in degrading or rapidly changing weather conditions (Bustamante, et al., 2007). These factors, combined with sometimes rapidly changing weather conditions and widely varying pilot experience, represent major concerns to the potential safety of the GA flying community.

Weather Technology in the Cockpit (WTIC)

As part of its efforts to address the future of air traffic in the United States, the Federal Aviation Administration (FAA) has requested research in the area of GA pilot decision making and behavior, including how pilot decisions are affected by new weather information tools available to and used by the pilot. This paper addresses ongoing work being conducted by researchers in the FAA Center of Excellence for General Aviation Research, known as the Partnership to Enhance General Aviation Safety, Accessibility and Sustainability (PEGASAS). The research presented in this paper is conducted as part of the PEGASAS Project 4 in Support of the Weather Technology in the Cockpit Program, or "PEGASAS WTIC". Of the four teams involved in this effort, the authors of this paper (representing PEGASAS Team 4D) were tasked to focus on technology integration factors that affect how and when weather information is presented to the GA pilot.

Original Research Questions and Gaps

Discussions during the initial stages of collaboration between PEGASAS researchers and FAA WTIC Program leadership emphasized the range of FAA-approved weather information technology systems suitable for installation and use in GA aircraft. However, there is a growing use among GA pilots of mobile devices and software applications for accessing weather information products. The initial organization of research tasks for PEGASAS Team 4D was based on the following "primary GAP":

GAP 0: There is a limited understanding of how FAA-authorized weather information sources, as presented / displayed in the range of available tools (including mobile devices and software applications), influences pilot interaction with and use of weather information in degrading weather conditions.

While conducting PEGASAS Project 4 efforts throughout 2014, it has became apparent that structuring research efforts and discussions around GAPs, as opposed to research deliverables, can substantially improve the value of the research findings for use by the FAA and the GA community. Summaries of Team 4D progress during 2014 continue to describe effort in terms of tasks and deliverables presented in this document. However, the description of GAPs provides better integration of key findings and research priorities for integration across PEGASAS activity.

Weather Information Tools and Systems Studied

The general aim of weather technology tools and products in the cockpit is to enable pilots to obtain an updated weather briefing and current conditions for a selected flight plan. The research tasks and deliverables addressed by Team 4D are intended to examine a range of available hardware device and software applications (including the proliferation of mobile devices), beyond the expected uses of certified devices only referencing authorized MET information products. Using a set of popular and varied available systems, Team 4D tasks examined pilot activity to obtain current weather information (including an updated weather briefing) for a selected flight plan, and pertinent issues that arise from efforts to obtain the updated brief.

Cataloging Weather Information Systems

The tools currently used to provide weather information to GA pilots were classified as either hardware or software, based on the following criteria. Hardware tools were taken to include handheld or dashboard-mounted devices and installed devices designed specifically for providing weather (and/or navigation) information to pilots. Software tools represent applications available on general purpose devices (such as tablets or smartphones), including those that make use of an associated hardware project (e.g., Stratus ADS-B receiver). Team 4D evaluated nine hardware tools and 55 software tools (25 Android and 30 IOS) were identified and inventoried for consideration. Weather briefing and information update capabilities were benchmarked against the FAA 1-800-WXBRIEF Flight Service Station (FSS) service, including pilots calling FSS via radio while in-flight. It is important to note that Team 4D also considered technologically possible uses, even if they are not recommended or even subject to degraded performance (such as use of cellular network service signals above 5,000' altitude). A total of eight systems have been selected and included for additional analysis, including the web-based www.1800wxbrief.com software tool.

Goal-Directed Task Analysis and Tool Comparison

Cognitive Work Analysis and Goal-Directed Task Analysis (GDTA) tools have been previously identified by FAA as relevant HF tools for aviation task evaluations (FAA, n.d.). Consistent with the scope of this project, the primary GDTA pilot activity is to obtain an updated weather briefing for a selected flight plan. Team 4D findings were subject to how different use patterns among the range of mobile devices and software applications can affect pilot planning tasks and use of appropriate weather information sources. Differences in weather information available to pilots during pre-flight and in-flight conditions, combined with the variety of mobile device and software applications in common use, highlights additional GAPs identified by Team 4D:

GAP 1: The effectiveness of available mobile device and software application tools is affected in unknown ways due to feature availability and use of weather information sources based on device / application and relevant phase of flight.

GAP 2: Information presentation and interface design in some mobile devices and software applications may limit or prevent pilot planning activity in potentially degrading ways during adverse or degrading weather conditions.

Issues from Task Analysis Regarding Weather Information

The use of software applications and mobile devices in the GA cockpit is subject to a number of human factors and ergonomics (HFE) considerations that are more formally addressed in fixed-installation multi-function displays. However, detailed HFE of glare, vibration, or other issues was outside of the scope of Team 4D analysis. More critical elements of study included task analysis steps required to obtain information, as well as the demand on working memory or situation awareness (SA) associated with obtaining required information to support pilot decision making.

Effective weather information systems should provide information that depicts, in unambiguous ways, the important features relevant to the pilot's ability to select a proper course of action (Shattuck and Miller, 2006). Past work has clearly identified that the "picture" of the weather that the pilot develops from accessing and assessing weather information that is presented will affect pilot decision making (McAdaragh, 2002). Understanding developed about the weather situation during any phase of flight is limited by the amount of **uncertainty** associated with the weather information, the **reliability/validity** of the weather information, and the **time stress** and **task load** (Latorella et al., 2002) during the phase of flight:

- Uncertainty associated with the weather information presented to the pilot may be the level of *spatial* or *temporal* uncertainty contained in the information, which require additional mental workload to interpret.
- The reliability/validity of the weather information presented to the pilot concerns its source, which must deliver *accurate* and *complete* information as well as the *availability* of the information, which may be impacted by the type of data link used.
- Time stress and task load are interconnected and impact pilot cognitive workload and the time available to process information, make a decision and take action.

Weather Event Triggers, Latency, and SA

The interplay between information presentation and dynamic weather factors is critical during flights in or around adverse weather, where action must be taken to avoid the potential for transitioning from VMC to IMC, or dangerous exposure to severe weather events. Naturalistic decision-making dominates under situations with uncertainty and high time stress (Wiggins and O'Hare, 1995, Elgin and Thomas, 2004). In these conditions, decision-making tasks and resulting actions are more likely to be automatic, executed intuitively rather than analytically (Caldwell, 2008). The general model of SA describes the pilot's awareness being comprised of *perceiving* the components of the weather-relevant enviroment (Level 1 SA), *integrating / comprehending* those components (Level 2 SA), and *projecting* those components into the future (Level 3 SA) (Endsley, 2000). Specifically, relevant weather event components were identified in Team 4D based on interviews with seven experienced aviation weather and flight instructors. Results of the interviews highlighted the following weather transitions, which are shown in Table 1. For the purposes of the PEGASAS WTIC research, these components influencing pilot SA can be described as "weather event triggers". Note that these findings replicate a number of past research studies regarding critical weather event triggers that should (but do not always) cause pilots to consider alternate flight path / diversion / return activities (Johnson and Wiegmann, 2011).

Table 1.
Results of seven interviews regarding possible Weather Event Triggers (# reporting trigger)

On the Ground (# reporting)	In the Air (# reporting)
Thunderstorms (3)	Clouds below form a CIG (1)
MVFR or close (2)	Descending clouds (3)
Clouds (night) (1)	Thunderstorms (3)
High winds (2)	Lowering visibility (2)
Snow (1)	Shapes of clouds (1)
General bad, don't go (1)	Precipitation (2)
Convective outlook (1)	Tall buildups in clouds (2)
Visbility dropping (1)	Convection (1)
Advisories from FSS (1)	Wind shear (2)
	Moderate / greater turbulence (2)
	Icing (1)
	High winds (1)
	Advisories from FSS (1)
	ATIS / ASOS reports (1)

Planning, near-term, and immediate decision-making activities are influenced by the level of time stress of the situation the pilot faces (Elgin and Thomas, 2004); guidelines indicate separations into planning (> 20 minutes), near-term (3-20 minutes) and immediate (< 3 minutes) decision-making regimes (FAA, 2014; RTCA SC-206, 2014). Pilot SA is maintained by two forms of environmental data: "out-the-window" (OTW) input and the instrument input. OTW input provides a clear and contemporary, yet limited, view of what the conditions are directly outside the aircraft. Instrument input provides other types of information in the general vicinity, certainly beyond the immediately visible range. However, due to the technology capabilities of collecting, integrating, and broadcasting NEXRAD data, "real time" NEXRAD information regarding potentially dangerous and fast moving event triggers (e.g., convection, thunderstorm fronts) are subject to considerable delays. Members of Team 4D collected NEXRAD latency data using a fixed-installation Garmin 1000 hardware system in an actual SR-20 GA aircraft on the flight line at the Purdue University Airport. After initial loading, "time now" and the screen "time stamp" were recorded every minute using the aircraft clock to indicate "time now" and G1000 XM weather screen time as "time stamp". The "time stamp" doesn't include the time it took for the image to be generated and sent to Sirius XM, but is an estimate of the latency from satellite upload to image appearance on the G1000. The latencies presented in Table 2 below are confirmed by similar intervals reported in AC 00-63A (FAA, 2014). Additional investigation suggests that NEXRAD latency may actually be an additional 2 or 3 minutes from when the image was taken to satellite upload.

These findings, plus additional Team 4D investigations of flight simulator display capabilities, identified two additional GAPs focused on weather information presentation latencies.

*GAP 3: **Reported** aviation weather update capabilities and use of FAA-approved weather information sources differ in latency or availability from **achieved** updates presented to the GA pilot during actual flight.*

GAP 4: Identification of adverse weather event triggers (and impact on pilot planning efforts) differs between out the window and mobile device / software application presentations of weather conditions; differences in awareness of trigger severity and potential impact affects pilot planning task and time sequences.

Table 2.
Tools by Latencies and Refresh Rates

Tool	Latencies (min)	Refresh Rates (min)
NEXRAD	2 – 7 minutes	4 – 5 minutes
Echo Top	1 – 16 minutes	7 – 9 minutes
Cloud Top	4 – 21 minutes	11 – 13 minutes
XM Lightning	0 – 7 minutes	3 – 7 minutes

Note: Cell Movement presentation experienced no additional latencies beyond 2 minutes

Popular commercial aviation training device simulators (ATDs) available by December 2014 are not capable of presenting weather information to weather displays that are not synchronized to the computer-generated "out the window" (OTW) display. Team 4D team efforts during Phase I determined that modifications of existing ATDs are infeasible to demonstrate NEXRAD latencies of 10-20 minutes in a General Aviation (GA) operational scenario. Previous research, as well as Team 4D empirical data, has demonstrated that such latencies are characteristic of actual GA operations (NTSB, 2012). Discrepancies in OTW and radar-based presentations of environmental components represent major challenges to developing and maintaining SA, in either individual or team-based performance scenarios; even minor shifts in information presentation modality could severly degrade task coordination performance (Caldwell and Everhart, 1998).

Ongoing Research Questions and Gap Resolutions

Based on the GAPs identified, and tasks completed, by the PEGASAS WTIC Team 4D in 2014, a number of additional research and technology development activities are planned for Phase II work in 2015. These activities include:

Select and use of existing PEGASAS Phase I weather event scenarios, and generate additional scenarios, to examine influence of information latencies on planning capabilities and diversion activities

The outcomes of this activity will be used to empirically test available GA pilot planning capabilities in low- and high-fidelity aviation simulation environments, as affected by weather information presentation latencies.

Determine feasibility of PC-based GA aviation training simulator prototypes integrating realistic (up to 20 minute) weather information presentation latencies

If a potential PC-based aviation training device (PC-ATD) is feasible and can be developed with realistic presentations of weather information presentation latencies, such a device could provide substantial education and training benefits to the GA community.

Comparative testing of weather information latency effects on pilot planning capabilities and tasks in both low-fidelity (PC prototype) and high-fidelity aviation simulator environments

The use of experimenter-controlled weather information presentation latencies can help identify and quantify the effects of those latencies on pilot immediate (0-3 minute) and near-term (3-20 minute) planning capabilities. If similar experimental conditions can be run in both the low-fidelity and high fidelity contexts, and directly compared, additional benefits can be obtained.

As part of the PEGASAS Project 4 in support of the WTIC Program, we believe that the creation of suitable PC-ATD capabilities (with suitable latencies) and sentinel weather event scenarios can be an important contribution to pilot education and knowledge development to increase awareness and reduce risks of dangerous decision making currently affecting the GA pilot community.

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