A HUMAN FACTORS APPROACH TO THE DEVELOPMENT AND EVALUATION OF THE GRAPHICAL WEATHER SERVICE*

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ABSTRACT

With the sponsorship of the Federal Aviation Administration, MIT Lincoln Laboratory is developing the Graphical Weather Service (GWS), a data link application that provides near-real-time ground-based weather information to pilots. Through the use of GWS, the pilot will be able to access both graphical and text weather information for any location in the contiguous United States. In-cockpit access to near-real-time weather information may substantially affect the situational awareness and subsequent decision making of pilots. In developing and evaluating this service, a human factors approach has been taken. This paper is an overview of the human factors activities performed in the development and evaluation of GWS.

INTRODUCTION

The basic concept of the Graphical Weather Service (GWS) is that ground-based graphical weather information is compressed and then transmitted to aircraft on a request-reply basis via digital data link. Throughout the development and evaluation process of this service, an emphasis has been placed on the application of human factors techniques to ensure that the service meets the needs and requirements of the user, i.e., the General Aviation (GA) pilot.

This paper begins with a brief explanation of why graphical weather information is needed in the cockpit, then describes what GWS is and how it is provided to the pilot. The main body of the paper provides a description of the human factors work accomplished thus far, including a description of: the methodology and results of two controlled experimental studies, design of the avionics user interface, and plans for the field evaluation of GWS. As mentioned above, this paper is an overview of these activities. Throughout the paper, the reader is referred to other sources of documentation that provide detail on each activity.

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THE NEED FOR IN-COCKPIT GRAPHICAL WEATHER INFORMATION

In a recent Aviation Weather Users Forum [1], pilots were asked to identify the types of information that they do not currently have in the cockpit, but that they believe are necessary and would like to have. The number one need identified was the need for the graphical depiction of weather.

Currently, during flight, most GA pilots access weather information via radio contact with Air Traffic Control (ATC) or weather dissemination personnel at a Flight Service Station (FSS). The GA pilot has to split his or her attention among the tasks of flying, navigating, and communicating. To obtain weather information, the pilot must query ground-based personnel and try to construct a mental image of the weather situation described. This can be a very difficult and time-consuming process, sometimes resulting in a very limited view of the weather situation. A GA pilot could receive weather information via airborne weather radar. However, this equipment is quite costly and, therefore, not an option for many pilots. In addition, the information provided is limited to weather ahead of the aircraft. Airborne weather radar cannot display weather at extended range, e.g., the aircraft's destination.

The Federal Aviation Administration (FAA) Data Link Integrated Products Team has tasked MIT Lincoln Laboratory to develop GWS and other Mode S data link applications to meet the needs of pilots. The goal of GWS is to provide accurate and timely graphical weather information that can be both easily interpreted and easily accessed by pilots. On a very practical note, the service must be made available at an affordable price to ensure that it will be within the financial reach of GA pilots.

THE GRAPHICAL WEATHER SERVICE

The initial GWS product is a composite precipitation image derived from a mosaic of ground-based weather radars. The radar mosaic is a commercial product provided by WSI Corporation, and is a nationwide image of the six National Weather Service precipitation levels with a resolution of 2 kilometer x 2 kilometer (km). It is a product that is familiar to pilots and is easily interpretable. In its current implementation, GWS uses three colors to depict intensity levels: green for weak, yellow for moderate, and red for strong to extreme precipitation.

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A typical weather graphics image may consist of several hundreds of thousands of bits and would require considerably more data link bandwidth for transmission than is available with any practical data link implementation. Because of the large number of aircraft that would request this information and the increasing number of aviation-oriented graphical weather products that will become available on the ground, some means must be employed to decrease the bandwidth required to transmit weather graphics images.

With support from the FAA, MIT Lincoln Laboratory has developed an image compression algorithm that is applicable to data link transmission of weather graphics. The Polygon-Ellipse algorithm [2,3] is based upon the underlying geometric structure of weather phenomena and operates by coding the graphical image as a set of polygons and ellipses (see Figure 1).

To use the GWS application, the aircraft must be equipped with the appropriate data link avionics (see Figure 2) . In general, this consists of a data link "modem" such as a Mode S transponder or a VHF data radio that transmits and receives the data link messages. In addition, a Control and Display Unit (CDU) is required to allow the pilot to request data link services and display the results. It is estimated that the data link avionics suite for a typical general aviation aircraft will cost approximately $5000 to $8000 [4]. This cost is attractive when compared to either airborne weather radar or lightning detection equipment. The same avionics that support GWS may also be used for the display of data-link provided traffic information, text weather products, Air Traffic Control communications, and other data link applications.

HUMAN FACTORS ACTIVITIES

The use of the Polygon-Ellipse algorithm made the transmission of graphical weather images to the cockpit possible, despite the limited bandwidth of data link. From this point, the development and evaluation of GWS progressed via a series of human factors activities, including: two controlled experimental studies to examine the overall effect of GWS on pilot decision making and the specific effect of compression-induced distortion on pilot decision making, design of the avionics user interface, and plans for the field evaluation of GWS. These activities are described below.

Human Factors Experiments - Phase I and II

The availability of near-real-time graphical weather information via data link will significantly affect pilot decision making. Two human factors studies were conducted to assess this effect. The Phase I study addressed the issue of how does GWS affect decision making. Phase I was seen as a first step in validating the need for GWS and as a proof of concept. Once Phase I findings validated that GWS had a substantial positive effect on pilot decision making, then we proceeded to Phase II testing. Since these complex images need to be compressed due to limited bandwidth, the resulting image is somewhat altered from the original image. Therefore, the key issue in Phase II was the determination of how much image compression, and associated distortion, is considered acceptable for transmission of weather images to the aircraft and at what point is the level of compression no longer acceptable.

Both phases were conducted in an office setting. GWS images were displayed on a Macintosh personal computer. All of the weather information and images used were constructed from actual recorded data, made available by WSI Corporation.

In both phases, the pilot-subjects were told that the aircraft flown in these hypothetical flights is a light, single engine aircraft, such as a Cessna 172. They were told to assume that they have full fuel for the flight and could assume that they are planning to travel with one passenger who is not a pilot.

To enlist the subject-participation of a pool of pilots from the community, an advertisement was placed in a local aviation newspaper. Twenty volunteer instrument-rated pilots participated in each phase. Pilot-subjects had a range of flight time of 500 to over 27,000 hours, and a range of actual instrument time of 35 to over 2,000 hours. The following two sections provide a summary of the two phases of human factor study. For detailed documentation of both phases, the reader is referred to references 5, 6, and 7.

Phase I - The Proof of Concept Study. Phase I tested the effect of GWS on decision making during hypothetical flights in challenging weather conditions. Each subject participated in four flights (two with GWS and two without GWS). For each flight, half of the pilot-subjects had access to GWS and half of the pilot-subjects did not. This design enabled the testing of the effect of GWS.

Prior to each hypothetical flight, the subject received a prepared flight plan, relevant navigational charts and weather briefing materials. The subject was questioned at each of three decision points within the flight: prior to departure, in the cruise portion of the flight, and near the destination. Since the subject did not have the benefit of the sensory experience of flight, the experimenter told the subject what the pilot would be experiencing, e.g., ride quality, visibility, and precipitation. The subject was then asked what action he would take. The subject could respond immediately or could seek additional information using GWS (in the GWS Condition) or via queries to Air Traffic Control (ATC) or Flight Watch (FW) (in the GWS and No GWS Condition). An experimenter, sitting in the room with the subject, played the role of ATC and FW personnel and provided pre-scripted answers.

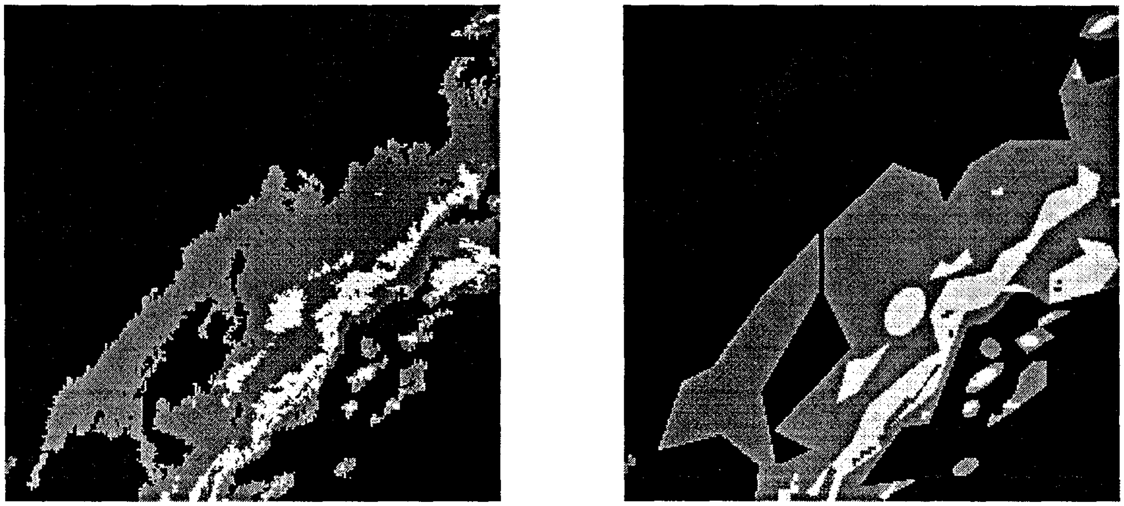

Figure 1. Uncompressed and Compressed Weather Images. Without data compression, the 256x256 km image on the left would require 131,000 bits to transmit. The image on the right has been compressed to 2413 bits using the Polygon-Ellipse algorithms. The compressed image can be transmitted to the aircraft by Mode S data link in approximately 10 seconds.

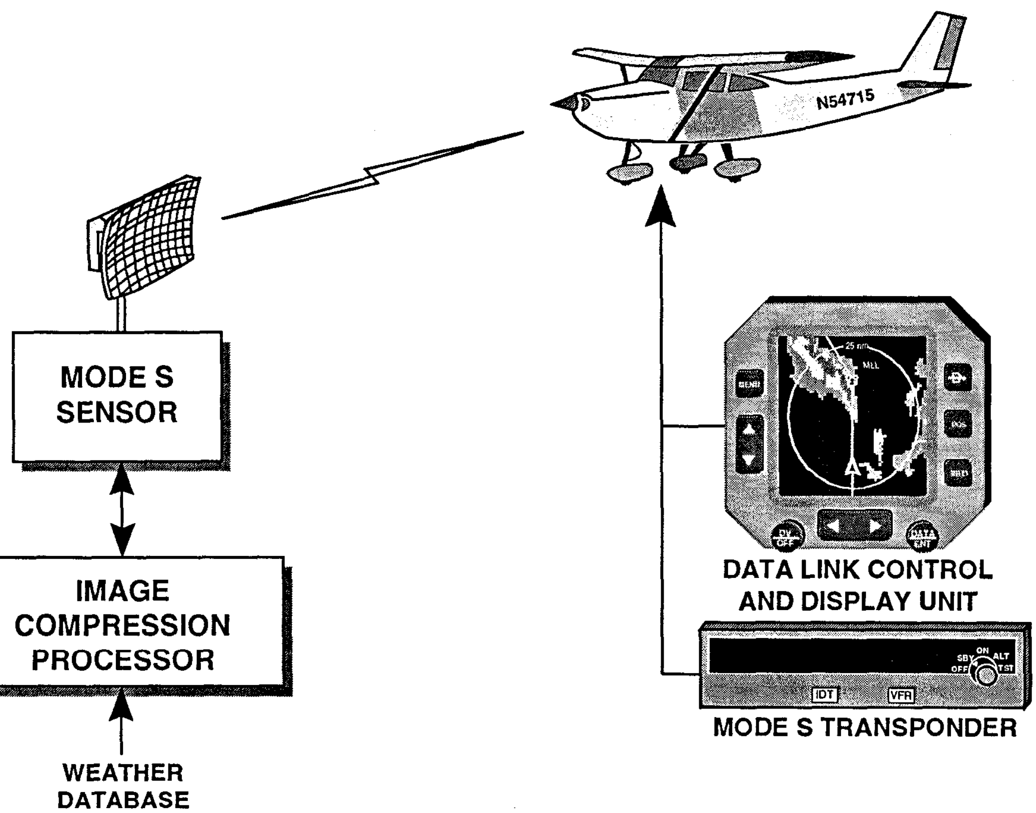

Figure 2. Mode S data link components. The Mode S surveillance sensor provides a connection to ground-based data link services. The aircraft is equipped with a data link Mode S transponder and a control and display unit.

For each decision point in which the subject had GWS, experimental images could be accessed for four locations (present position, departure, destination, alternate), at four different ranges (25, 50, 100, 200-nautical mile radius). The subject was asked to "think aloud" throughout the experimental sessions. Verbal requests for information from ATC and FW, choices of GWS images, comments and actions taken at each decision point were recorded. Actions taken included go and no-go decisions and, decisions to deviate or to proceed on course, decisions to go to destination or alternate. Subjective ratings of pilot confidence in his ability to assess the weather and subjective ratings of the usefulness of GWS were also taken.

Results indicated that, by using GWS, pilot-subjects were able to make decisions based on an improved awareness of the actual weather situation. This was true for go / no-go decisions, as well as actions taken throughout the hypothetical flights. For example, in one flight, there was forecast to be a chance of embedded thunderstorms in the area. Pilot-subjects with GWS were able to see that none of them were pertinent to the planned route of flight. As a result, all pilot-subjects with GWS decided to go on this flight, while half of the pilot-subjects without GWS decided not to go.

It was found that when pilot-subjects had GWS, they made significantly fewer verbal requests for weather information. Pilot-subjects commented that with GWS they had a picture of the weather right there "in the cockpit" and so often it was not necessary to contact ATC or FW. When fewer calls for weather information are made, there is the potential benefit of decreased workload for both pilot and controller.

Pilot ratings of their confidence in assessing the weather situation were significantly higher when GWS was used. GWS was rated as being more than moderately useful to very useful (rated on a scale of (1) Not at all Useful to (5) Very Useful). This approval of GWS was substantiated by subject comments made throughout the study. In addition, when pilot-subjects were asked if they would purchase the equipage necessary for receipt of data link services, the answer was overwhelmingly positive.

The main conclusion from Phase I is that GWS had a substantial positive effect on the weather-related decisions made by the pilot-subjects. Knowing this, and knowing that pilots were enthusiastic about receipt of GWS services we proceeded to Phase II testing.

Phase II - The Compression Study. Given the fact that these complex weather images need to be compressed and that with compression there can be accompanying distortion, Phase II was designed and conducted. Phase II tested the effect of various levels of compression of GWS images on pilot perception of distortion, opinion of acceptability and performance on a route selection task. The main objective of this phase was to determine what amount of compression would be acceptable for transmission of images to an aircraft.

Twenty images were compressed to three compression levels, representing high, moderate, and low compression. These images where used in the two parts of this phase which are described below. As mentioned earlier, twenty instrument-rated pilots participated in the study.

Part I of the study consisted of two subjective rating tasks: a distortion rating task and an acceptability rating task. For both tasks, pilot-subjects saw a series of pairs of GWS weather images. Each pair contained an uncompressed image and a compressed image. In the distortion rating task, the subject judged the degree to which the compressed image had been distorted relative to the uncompressed image. The rating was based on the quantitative amount of distortion of the compressed image. In the acceptability task, the subject rated the functionality of images for use in the flight task, regardless of the degree of image distortion.

Part II of the study consisted of a route selection task. The subject saw a series of single GWS weather images. Each image was either an uncompressed image or a compressed image at high, moderate, or low compression (no designation of compression level was made to the subject). The subject was asked to draw a route of flight from one designated point to another designated point, indicated on the screen as point "A" and "B". The route was drawn by using the mouse and clicking to indicate waypoints.

Results of the distortion task indicated that pilot-subjects were in general agreement in their perception of amount of distortion in the images. However, pilot-subjects tended to differ on how many of the most distorted images they were willing to call acceptable, ranging from a subject who accepted only 50% to one subject who accepted 100%.

Pilot-subjects found images compressed to low to moderate levels to be acceptable, while highly compressed images were considered to be generally unacceptable. Subject comments indicated the main objection to the highly compressed images was that detail was lacking, and the configuration of the weather was too greatly distorted. When images are highly compressed the Polygon-Ellipse algorithm tends to convert areas of precipitation to elliptical shapes. Pilot comments indicated a general dislike for elliptical shapes since reportedly they did not adequately represent the actual weather as seen in the raw images.

Pilot performance, as measured by the route selection task, was not significantly affected when compression was moderate or low. When compression was high, pilots tended to draw their routes further from Level 1 (weak precipitation intensity) as compared to routes drawn in response to low and moderately compressed images. Pilot comments indicated that the presence of ellipses in the highly compressed images caused them to distrust the image and want to keep their distance from ellipses.

What do the findings of Phase II mean to the implementation of GWS? As a result of Phase II, it became clear that, when the Polygon-Ellipse algorithm was used to compress complex weather images, highly compressed images (approximately 2,500 bits or less) were considered by the subject-pilots to be generally unacceptable. Since it is desirable to use high levels of compression while maintaining the acceptability of the image, the use of another method for compressing images needed to be explored.

The Improved Weather-Huffman Algorithm. Both of the experiments that have been discussed here used images that were compressed using the Polygon-Ellipse method of compression. In this method, the software starts the compression process by tracing the outline of each region of weather. If the region is approximately an ellipse, then the parameters of the ellipse are encoded. Otherwise the region is encoded as a polygon by sending each of the vertices that define the region. The encoding is iterative with the acceptable errors being gradually increased until the acceptable number of bits is reached. The problem with this approach is that many of the pilot-subjects found that the elliptical representation of images was not realistic, and was therefore unacceptable.

In order to remedy this problem, a new compression algorithm was developed. The Improved Weather-Huffman method of compression is a type of run length encoding. As weather tends to form in regions, it uses a Hilbert scan rather than a standard row-by-row raster scan. If this initial scan does not meet the bit limit then several different steps are taken in different combinations. The program can reduce the resolution of the image, using a pixel averaging technique. It may then throw short runs of lower level weather away. Finally if it is able to reach the bit limit, but has extra bits available, then these are used to increase the resolution of specific small areas that will most benefit. Finally when the image is decompressed the neighboring pixels are used to help expand each pixel appropriately. The effect of this is that the images appear to be much more natural, as seen in Figure 3.

Avionics Interface Design

Following the completion of the above human factors studies, work began on the development of the user interface. Human factors principals were used in the development of the interface. The interface was designed considering: the capabilities of current technology, the limited space available in a GA aircraft instrument panel, and the constraints in system use inherent in single-pilot operation in a GA environment. The interface was designed to integrate access to the graphical weather product, as well as, other data link services including traffic information and text weather. For full details on the design of the interface the reader is referred to reference 8.

The design of the interface was heavily influenced by the choice of the CDU. Because the services are expected to be deployed in the near term (i.e., over the next 2 to 5 years), it was important to choose a CDU that was commercial-off-the-shelf, panel-mount avionics equipment. The unit chosen was the ARNAV MFD 5100, a color CRT that is driven by a 486 SLC CPU with a math co-processor. The test avionics set consisting of a Mode S transponder, CDU, and processor is described fully in reference 9.

Once the interface was designed and functioning, the next step was to make GWS, as well as other data link services, available to a community of GA pilots.

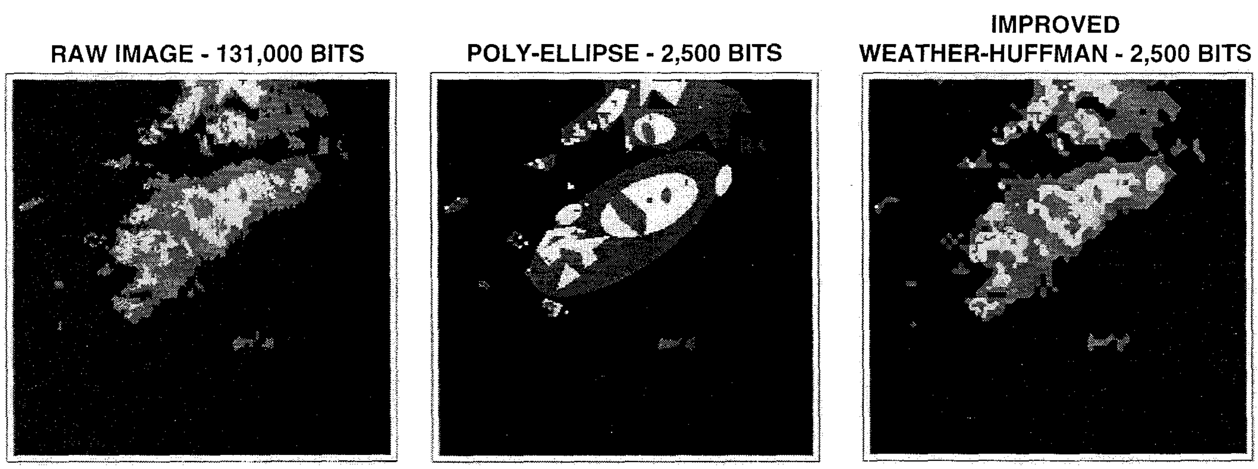

Figure 3. Comparison of uncompressed image to image compressed by Polygon-Ellipse algorithm and Improved Weather-Huffman algorithm.

Field Evaluation of Data Link Services for General Aviation

After the successful completion of the human factors studies and interface design work, GWS has reached a field evaluation stage. In the field evaluation, the Dulles Mode S sensor, as well as the ground station installed at Frederick, MD, are providing the service. A number of general aviation aircraft are now, or will soon be, equipped with the avionics necessary for data link. A detailed description of the field evaluation is contained in reference 9.

Briefly summarized, the main purpose of the field evaluation is to gain feedback on the operational suitability and utility of the data link services from pilots who are familiar with the needs of the GA community. During a six-month period, users with a range of general aviation flying experience will serve as evaluators. Pilots from the Aircraft Owners and Pilots Association (AOPA) Air Safety Foundation will take the lead in evaluating services and the user interface.

The system will be used both in routine flights and in structured evaluation flights. The pilots will be able to request graphical weather, as well as text weather, and traffic information. The pilots will assess the utility of GWS and the need for training on use of the interface. They will also assess the usability of services for single-pilot operations.

SUMMARY AND CONCLUSIONS

To aid in the design and evaluation of GWS, a human factors approach was taken. The first experimental study, Phase I, was conducted to assess the overall effect of GWS on pilot decision making. It was seen as a first step in validating the need for GWS and as a proof of concept. Once Phase I findings validated that GWS is useful and effective, then we proceeded to the second experimental study, Phase II, to determine the effect of compression-induced distortion on pilot decision making. These data were needed to determine what amount of compression would be acceptable for transmission of images to aircraft. It was determined that images compressed to a low to moderate level through use of the Polygon-Ellipse method were considered to be acceptable. However, pilot-subjects considered highly-compressed complex images generally unacceptable since they tended to look elliptical did not adequately represent the actual precipitation map. The findings lead to the development of the Improved Weather-Huffman algorithm which enables complex images to be highly compressed and yet maintains the fidelity of image representation. Following the completion of the human factors studies, the avionics interface was designed. With the results obtained from the two experimental studies in hand and user interface developed, we were then able to proceed to a field evaluation of GWS.

Additional human factors experiments are planned. Pilot reaction to images generated through use of the Improved Weather Huffman Algorithm will be assessed. In addition, members of the air transport community have expressed interest in applying the technology developed for GA to the air transport environment. This area will be explored.

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