Cockpit Graphical Weather Information Shown to Enhance Efficiency, Safety, and Situation Awareness*

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INTRODUCTION

Today, in-flight weather information is typically found through specific requests made by the flight crew through Very High Frequency (VHF) voice radio or VHF data links. Pilots can have difficulty obtaining weather information in a timely manner, assimilating that information into a clear mental picture, and developing a good understanding of changing weather trends, all the while managing cockpit activity and control of the airplane. Incomplete weather situation awareness can result in the flight crew having difficulty making alternate route decisions or having encounters with adverse weather.

In an effort to address these problems, the National Aeronautics and Space Adsministration (NASA) Langley Research Center has begun a piloted simulation and flight test research program called Cockpit Weather Information (CWIN). The purpose of CWIN is to examine the benefits of appropriately combining and presenting various weather information obtained through multiple data link sources to aid crews with sound flight management.

The CWIN program envisions the use of multiple data link systems being developed and/or that are currently in place for general information transfer. Figure 1 illustrates this concept for a potential aviation weather data flow. A broadcast satellite system could be used to transmit the "Big Picture" of weather information that includes information of interest to all aircraft. Two-way data links, such as ACARS (ARINC, Aeronautical Radio Incorporated, Addressing, Communications, and Reporting System) and Mode-S, could furnish more detailed route-specific information on a request/reply basis. Terrestrial line-of-sight radios could broadcast local weather information such as micro burst and wind shear information.

Piloted simulation tests have been completed in the NASA Transport System Research Vehicle (TSRV) simulator to evaluate a graphical presentation of weather information for use in the cockpit. For these tests, a touch-sensitive panel was overlaid on a color Cathode Ray Tube (CRT), located on the instrument panel, for selection and observation of weather information. Both graphical and textual information was available to the flight crews. CWIN weather information included surface observations, terminal forecasts, national radar mosaics, and lightning data. This information was color-coded and presented on the CWIN CRT.

During this test, 14 airline transport flight crews evaluated the CWIN weather graphics system in the NASA TSRV simulator. Comparisons were made with and without the use of the CWIN graphical weather system during typical airline flights in which adverse weather conditions were encountered. This report describes the results of this test.

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SYMBOLS AND ABBREVIATIONS

ACARS	ARINC Communications, Addressing, and Reporting System
ARINC	Aeronautical Radio Incorporated
CDU	Control Display Unit
CRT	Cathode Ray Tube
CWIN	Cockpit Weather Information
FMC	Flight Management Computer
GDS	Geomet Data Services
IMC	Instrument Meteorological Conditions
NASA	National Aeronautics and Space Administration
ND	Navigation Display
PFD	Primary Flight Display
TCAS	Traffic Collision Avoidance System
TM	Technical Memorandum
TSRV	Transport Systems Research Vehicle
VFR	Visual Flight Rules
VHF	Very High Frequency
WDC	Weather Data Computer
WX	Weather

TEST SYSTEM DESCRIPTION

TSRV SIMULATOR: The TSRV simulator, figure 2, is a fixed-base flight-deck simulation facility that is controlled through a central computer system operating in a real-time mode at 32 computations, cycles, per second. The airplane model represents the NASA TSRV B-737-100 airplane. The flight deck is a two-crew member arrangement with similar instrumentation in both flight stations. An out-the-window visual scene is provided by computer-generated imagery.

The TSRV simulator represents an "all glass" flight deck, in that the flight instrumentation is depicted on eight ARINC size D CRTs mounted in the flight deck front panel. Each pilot has a primary flight display (PFD) and a navigation display (ND) directly in front of each seat. There are four CRTs in the center-panel that are used for engine instrumentation, flight limitations, control surface deflection, data link messages, and the CWIN display system. The lower two center-panel CRTs have a touch screen overlay which is used for the data link and CWIN operations.

Each pilot has a control display unit (CDU) in front of him that is used as a terminal to the flight management computer (FMC). Each CDU has a keyboard that is used for textual input to the FMC, data link, and CWIN systems. The CDUs are standard aircraft units similar to those in current generation airliners.

The TSRV simulator has a digital electronic flight control system. This system may be operated in an automatic flight mode or manually flown in either an attitude control stick steering mode or in a velocity vector control stick mode. Manually controlled flight is done through a fly-by-wire side stick controller. Each crew member has his own side stick. The side sticks are hydraulically connected and may be adjusted to provide desired stick forces. Pilot tactical feedback is achieved by programming the sticks with a “strongest man wins” algorithm.

An airborne radar was developed that displays returns overlaid on the ND. The radar system has the ability to simulate echo attenuation due to distance and blockage by heavy weather cells. The radar has a fixed elevation and an adjustable range.

WEATHER DATA COMPUTER SYSTEM: A Weather Data Computer (WDC) system was developed at the NASA Langley Research Center to furnish "Big Picture" and ACARS type weather information for CWIN tests. The WDC system utilizes multiple computers, networks, and telecommunications sources to access and deliver aviation weather information from multiple sources. National radar mosaics were purchased from WSI Corporation, Billerica, Massachusetts, via a dial-up telephone connection every 15 minutes. Surface observations and terminal forecasts were received via satellite from Alden Electronics, Westborough, Massachusetts. Air-to-ground lightning strike data were received from Geomet Data Services, Tucson, Arizona, through a dial-up telephone connection. A request-reply weather data base, similar to weather information utilized by some major airlines through the ACARS data link, was replicated by connecting to the CompuServe, Columbus, Ohio, aviation weather data base on another dial-up telephone connection.

The WDC system can furnish both live and recorded weather information to the TSRV simulation facilities. For the purposes of the tests, actual weather conditions were recorded during 4 days of adverse weather in 1993. This recorded information was then used to provide the same test scenarios to each of the test subject flight crews. Live and recorded weather was used on the WDC system during pilot training and system demonstrations.

CWIN PILOT SYSTEM: The graphical CWIN weather system is designed to satisfy pilot requests to "give me the information that I need when I need it and don't bother me at other times". The CWIN system receives weather information and stores that data in memory for retrieval when needed or desired by the flight crew. Pilots can monitor any map by displaying the desired map which is updated as new data is received. The system is an interactive mobile weather information system designed to be user friendly and easy to learn.

The bottom two center CRTs in figure 2 are used for the CWIN display. Bezel buttons around the edge of the display allow the flight crew to position the CWIN display on either the right-hand or left-hand bottom center CRTs. Other bezel buttons offer a “panning” feature for moving the viewing area around the displayed map.

The CWIN system is integrated with the ATC (Air Traffic Control)/Dispatch/ ACARS two-way data link system sharing the same CRT display. The data link system is described in reference 2 and has been modified to incorporate the CWIN graphical weather features. Clearance routes received via data link from ATC are graphed on the CWIN display, thus allowing the flight crew the ability to examine routes in relationship to weather before acceptance.

Four different weather maps were available for flight crew selection during the simulation test. These were the national radar mosaic, air-to-ground lightning strike map, the Category map, and the Ceiling and Visibility map.

Figure 3 illustrates the national radar mosaic map and general features found on all the weather maps. Weather data, route information, and airplane position and heading are overlaid on a map of the United States. The MAP button access the weather maps by traversing the circular queue of maps when activated. The HIST (history) button activates a “play-back” feature where the last five weather maps are displayed for 0.5 second in chronological order, pausing at the current map. The SCALE button gives the flight crew the ability to “zoom-in” or “zoom-out” on the currently displayed map. Activating the APT (airport) button will display identifiers of airports in the data base and give access to a textual display of the last five surface observations and terminal forecast for each airport. The MAIN button changes the display to the Main Menu page of the Data Link system as described in reference 2. Rectangles at the lower right of the display are colored green, amber, and red illustrating a color spectrum of the weather coding scheme. The color spectrum is touch-sensitive and, when activated, will change the display to a color key for weather in the CWIN system. The time stamp above the color spectrum is the time that the displayed data were observed.

The national radar mosaic data are purchased from WSI Corporation. These data are a composite summary of the 128 National Weather Service radar images time correlated on the quarter hour. WSI builds the composite, filters out ground clutter and anomalous propagation, and then has a meteorologist review and correct the mosaic before it is delivered to customers. This product goes through five quality control steps prior to delivery. The final national radar mosaic is about 14 minutes old when it is received by the airplane.

The Lightning map of the CWIN system displays air-to-ground lightning strike data. Every time a lightning bolt strikes the ground, Geomet Data Service (GDS) sends information about that strike to the WDC within about 9 seconds. The WDC collects five minutes of lightning strike data (latitude and longitude of each strike) during a time period centered around the quarter hour. This lightning strike data are then transmitted to the aircraft and displayed on the lightning map of the CWIN system. At the time of reception by the airplane, lightning strike data are current data representing lightning strikes that have occured within the last five minutes.

The Category map is a graphical depiction of the current visual or instrument meteorological conditions of all the airports that are displayed. Color-coded circular disks centered at each airport give the flight crew the category of the last surface observation at that airport. Green is used for visual meteorological conditions, amber for instrument meteorological conditions, and red for category two and three meteorological conditions. As soon as a new surface observation, including special reports, are received, the color of the disk is changed to reflect the latest category.

The Ceiling and Visibility map is a further detailed presentation of the Category map. Each airport is represented by a square that is divided into an upper and a lower region. The upper region is color-coded to represent the ceiling and the lower region is coded to represent the visibility. A flashing "H" is displayed to the side of the square if a flight hazard is present in the observation and a "P" is displayed if precipitation is reported. If the surface winds are in excess of 30 knots, a white bar between the regions will flash. This format gives the flight crew a quick view of ceilings, visibilities, percipitations, flight hazards, and excess winds at all airports in the map.

Active routes and route modifications in the FMC are graphed on the CWIN display (see figure 3). These features allow the flight crew to make flight reroute decisions based on weather conditions much farther away from the airplane than can be sensed by airborne radar. An arrowhead-shaped figure representing the current position and heading of the airplane is also displayed on this map.

Each colored disk of the Category and Ceiling and Visibility maps is touch-sensitive and when activated, will change the display to a textual display of the last five surface observations and the current terminal forecast for the airport represented. The textual information also is colored-coded to represent the category of the surface observation and terminal forecast. The last five surface observations are vertically aligned so that the flight crew can search for chronological patterns in weather information, such as trends in ceiling, visibility, temperature dew point spread, winds, etc.

ATC/DISPATCH/PSEUDO-PILOT WORK STATIONS: Other facilities used to support these tests included include simulation capabilities for air traffic control (ATC), company dispatch, and "other traffic" communications. The ATC workstation included a sector suite display of aircraft positional information, a two-way intercom for audio communications with the flight crew, and access to a data link computer for digital communications with the simulator. The dispatch station had a CWIN display system identical to the cockpit system, as well as intercom and data link communications identical to the ATC workstation.

Retired air traffic controllers were hired to simulate ATC and dispatch. Both voice radio and data link were used for air/ground communications during these tests. ATC and dispatch personnel also functioned as “other traffic”, pseudo-pilots, over the voice radio to simulate “party line” information.

TEST DESIGN

GENERAL: The simulation test was designed with the help of a pilot advisory panel of pilots from United Airlines, US Air, American Airlines, Emery Riddle Aeronautical University, and NASA. This panel suggested test scenarios including route structure, adverse weather, and other test parameters.

The simulation test was designed so that each test flight crew would fly 4 different test scenarios. Each test scenario was designed to represent a typical airline flight between city pairs. All of the test scenarios contained adverse weather conditions along the planned route of flight. During two of the test scenarios, the test crew had the use of the CWIN system and during the other two they did not. Comparisons were made between the crews decisions when the CWIN system was available and when it was not.

Basic inflight weather information available to all the test scenarios included textual information on a dispatch release, voice information from ATC and dispatch, textual information obtained over the simulated ACARS data link, and airborne radar depiction. The basic ACARS weather offered surface observations, terminal forecasts, winds and temperature aloft, sigmets, notams, and pilot reports. Dispatch offered the same information except by voice radio. ATC generally advised the crew to contact their company dispatch.

The testing period lasted two and one half days. The first day was spent on pretest questionnaires, familiarization, and crew training. On the second day, three test scenarios were flown. On the third day, the last test scenario was flown, then a post-test questionnaire was completed and an oral debriefing was held.

TEST OBJECTIVES: There were four basic test objectives:

1) Determine the effect that the CWIN system had on the long-range enroute decisions made by the flight crew to avoid adverse weather during flight.

2) Determine the effect that the CWIN system had on the flight crew's situational awareness of adverse weather.

3) Determine the benefits that the CWIN system had in aiding the flight crew to make quick, logical, and safe rerouting decisions.

4) Determine flight crew acceptance and utilization of the CWIN system.

TEST SCENARIOS: Four different test scenarios were flown by each of the test flight crews. Each scenario contained an approximate two-hour flight between a city pair. The city pairs used for these tests included Denver, CO to Reno, NV; Denver, CO to St. Louis, MO; and Denver, CO to Dallas, TX.

Each test scenario began with the issuance of a flight dispatch release. This release included weather information along the route of flight, the filed route of flight, notices to airmen, pilot reports, weight and balance information, and fuel on board. This dispatch release was similar to those used by major airlines.

Each of the flight tests began with the airplane on the taxiway for runway 35L at Stapleton International Airport in Denver. The test crew would request and obtain their pre departure enroute instrument clearance through the data link, and then use the voice VHF radio to request their take-off clearance. Departure weather was VFR with a visibility of 8 miles and a layer of clouds 2000 feet above the airport. After the take-off, the aircraft remained in the clouds until on short final approach to landing at the destination airport.

During the flight, if the flight crew flew too close to any of thunderstorm cells, the out-the-window scene would darken and lightning would begin.

The Captain and First Officer alternated pilot flying duties. This gave each test subject the opportunity to fly the simulator and use the CWIN system. The pilot not flying was in charge of communications and weather monitoring. The Captain was asked to make all major decisions.

TEST SUBJECTS: Fourteen flight crews were used as test subjects. These crews represented United Airlines, US Air, America West, Northwest Airlines, Boeing, and Honeywell. Each crew had a Captain and First Officer. All test subjects had recent experience in an “all glass” airline transport cockpit.

TEST CREW TRAINING: The first day was devoted mostly to crew training on the TSRV FMC, flight guidance and mode control panel, and flight control system. Training on the CWIN system took less than one hour. Each pilot was given the opportunity to fly the simulator for two training flight scenarios.

RECORDED DATA: The recorded data included pilot questionnaires, pilot comments, subjective workload measures, researcher notes, real-time flight variables, and video and audio recordings.

RESULTS AND DISCUSSION

PILOT ACCEPTANCE: All of the test pilots liked the CWIN system. Pilot comments included: “CWIN graphical weather is a big step forward in giving the flight crew data (real-time) to better plan and execute their flight. Also reduces [perceived] cockpit work load in critical phases of flight. Hope it can be sold to the industry. Not a nice-to-have but definitely a need-to-have in today's 2-man glass cockpit.” “The graphical display is great and very helpful." "The graphical WX [weather] is far superior to anything I have seen or used in the past to reduce [perceived] pilot workload and increase aircraft operational efficiency." "The graphical was very nice and allowed a big picture decision to be made easier than trying to figure out the big picture from a bunch of text messages." "Graphic WX [weather] display allows a much better display and much more current information which enhances our situation awareness and enroute planning." "Pictures (Lightning and Radar depiction) are worth much more than words. Overlaid on the route/destination or proposed routes/alternates extremely valuable." "CWIN graphical is one of the great improvements in aviation. I believe it will be received better than TCAS, which is well liked. CWIN will save $ [dollars] and improve safety." "CWIN is an excellent tool that should be available to pilot and dispatch alike. ATC would benefit too." "CWIN is proactive, always preferable to a reactive system." "Great program. Graphical presentation of severe weather is great. Textual history of sequence reports and forecast are great. This gives me much more information to make decisions." "Going back to the normal operation after flying CWIN is like being near sighted and losing your glasses. You can see fine up close and can manage, but everything out in the distance is an indistinct blur."

Most of the flight crews agreed that there is no need for both the Category Map and the Ceiling and Visibility Map. The responses on the questionnaire indicated the pilots were split evenly on which map should be kept. Other suggestions made by at least two flight crews included: have a method of switching directly between the radar and lightning maps; place waypoint identifiers on the routes; mark alternate airports with a different symbol; and, add turbulence and winds aloft maps.

The lightning map was well received with comments like "Lightning is best due to currency. Radar next best." "Lightning is the best for detection of all adverse weather." "The lightning display is the one screen that is essential for good flight planning." "Lightning data are perhaps the most valuable improvement noted." " I especially liked the 'history' feature and the lightning strike feature of the graphical weather display."

On the post-test questionnaire, all the pilots indicated that the CWIN system would fit well into their operational environment.

ENROUTE WEATHER AVOIDANCE: The test subject crews flew shorter enroute segments, used less fuel, and cleared the thunderstorm cells by a greater distance when the CWIN system was available.

Enroute segments were compared beginning at the first waypoint along the cleared route outside the Denver terminal area, and ending at a point 130 n.mi. from the destination airport. In all cases compared, the test crews were at the same cruise altitude and Mach numbers during this entire enroute segment. Climbs to cruise altitude and descents to the destination airport were not included in this comparison.

The data from this comparison, figure 4, show that the flight crews flew 5% shorter enroute segments and burned 5% less fuel when they used the CWIN graphical weather system. The average enroute distance flown was 443.5 n.mi. with the CWIN system and 465.7 n.mi. without. The fuel burned averaged 4825.9 lbs with the CWIN system and 5071.0 lbs without.

The post-test questionnaire included the following question concerning enroute deviations due to weather: "On the average, how often do you have to deviate around adverse weather when **enroute**? Once every ___ flights." The average response by the airline pilots was once in 12.8 flights. This suggests that on the average, an airline could save 5%*1/12.8 = 0.4% of all enroute distance flown and fuel used during domestic enroute flight operations.

Pilot comments concerning enroute weather avoidance included "Graphical weather displays were much more helpful in planning and executing flight than I had anticipated." "CWIN allows more efficient planning of enroute deviations - optimizes safety, fuel burn, time, etc." "Graphics allowed me to forecast or extrapolate my own weather presentation and formulate a plan of action early." "Graphical weather was great to give [a] big picture for planning purposes." "The system definitely gives the pilot confidence that he has in front of him all the necessary information needed to make the best decision." "Builds situation awareness quicker, more complete picture of weather in pilots mind. Decisions can be made sooner with less stress."

SAFETY OF FLIGHT: Figure 4 also illustrates that the test crews cleared the thunderstorm cells by three times the distance when they used CWIN as compared to without CWIN. In computing these distances, the closest cell during the enroute segment was used to determine this dynamic enroute cell clearance. The average cell clearance was 39.8 n.mi. with CWIN and 13.2 n.mi. without. The extra clearance from the thunderstorm cells obtained when using the CWIN system points to a safer and smoother passenger ride.

On the post-test questionnaire the test subject pilots were asked to rate "safety of flight during adverse weather operations" on a scale of 1, representing "current system much better", to 7, representing "CWIN System Much Better". The average response was 6.5 with 18 of the 26 responses being 7.

Pilot comments concerning safety of flight included: "I feel that the graphical WX [weather] instrument is a very good system and that it allows flight crews the ability to give passengers not only a much smoother ride but a much safer one." "It is immediately obvious that with the graphical WX [weather] display, flights would be better planned for both safety and economics." "A great system. Time, effort, money, and life saver."

WEATHER SITUATION AWARENESS: Weather situation awareness that pilots had during these tests was established by stopping the simulation at a predetermined point during one of the scenarios and having the pilot crew answer a questionnaire concerning weather awareness. The predetermined point was located along the enroute segment well before adverse weather could be detected by the airborne radar. The same point in the same scenario was used for all the test subjects. On the questionnaire, the pilots were asked to "Describe in general terms the weather along your intended route of flight." The flight crews using the CWIN system were well aware of a developing line of storms. When the CWIN system was not used, they were not aware of the adverse weather along the route. In response to the question, "Do you have any plans that you are considering at this time concerning possible reroutes?", those using the CWIN system had reroute plans they were considering. When they flew without the CWIN system, they did not. All flight crews were about equal in responses to questions concerning the destination weather and fuel reserves.

Pilot ratings on the post-test questionnaire resulted in the CWIN system being rated as "much better for situation awareness" than the current system of obtaining weather information.

Pilot comments included "Situation Awareness is greatly improved." "CWIN by far better. Builds greater situation awareness." "Builds situation awareness quicker, more complete picture of weather in pilot's mind. Decisions can be made sooner with less stress." "I felt the stress much less and I had more situation awareness with CWIN."

AIRPORT CLOSURE DECISIONS: Data from this part of the test have yet to be evaluated.

Pilot comments included "Choosing an alternate involves consideration for passenger handling, airport facilities, lighting, nav aids, noise curfews, etc. [The] CWIN [system] expedites weather considerations only." "For changing alternates or destination, dispatch (company) will still have to be brought into the loop, the CWIN system should insure we both have the same information to use."

CONCLUSIONS

A simulation test was conducted to evaluate the use of the Cockpit Weather Information (CWIN) system to provide graphical weather presentations to flight crews during flight. The evaluation was to determine the effects that the CWIN system would have on the flight crew's 1) long-range enroute decision process to avoid adverse weather; 2) situational awareness of adverse weather; 3) ability to make quick, logical, and safe rerouting decisions.; and 4) acceptance and utilization of the CWIN system.

Fourteen test flight crews, representing different airlines, airplane manufacturers and vendors were used for these tests. Each crew flew two typical airline flights of approximately 2 hours duration with the CWIN system and two flights without. Recorded data and pilot comments during the test flights and a questionnaire and debriefing after the flights were used for the evaluation.

The results from these tests showed enroute distances and times flown to avoid adverse weather was reduced 5 % when the CWIN system was available for use by the flight crews. The crews were able to make better reroute decisions at an earlier opportunity resulting in a more efficient flight route.

Data from the questionnaire indicated that the airline pilots had to make decisions to change routes while in the air on the average of once in every 12.8 flights. Thus, the CWIN system offers a potential savings of $5\%*1/12.8 = 0.4\%$ of all domestic enroute operating costs for each airline.

Pilot comments indicate that they liked the CWIN system and felt that it would fit well into their operating environment. They expressed a desire to also have their company dispatch equipped with the same CWIN system.

Safety of flight also was considered to have been enhanced by pilot utilization of the CWIN system. When the pilot crews were using the CWIN system, they cleared the thunderstorm activity by three times the distance than when they did not use CWIN. The ability to make early decisions concerning route of flight changes to avoid adverse weather appeared to help keep pilot crews from getting too close to the storms.

REFERENCES

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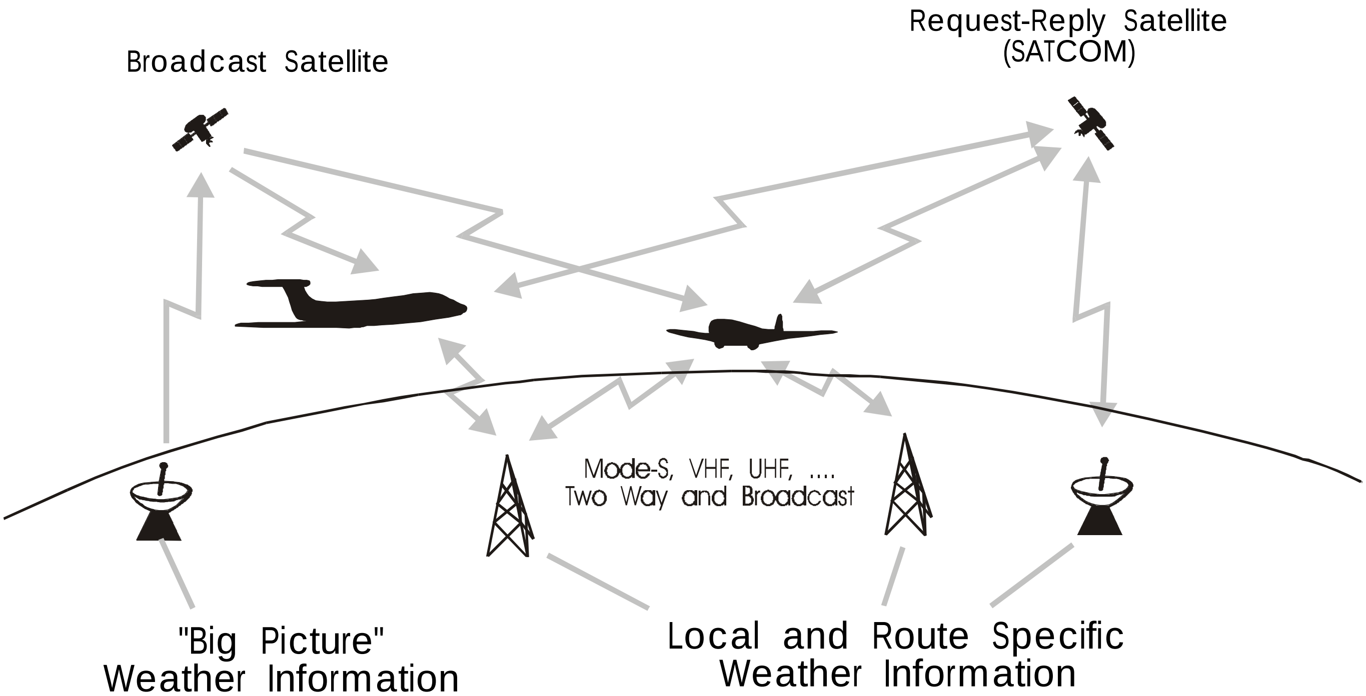

Figure 1: 21st Century Aviation Weather Data Flow

Figure 2: NASA Transport Systems Research Vehicle Simulator

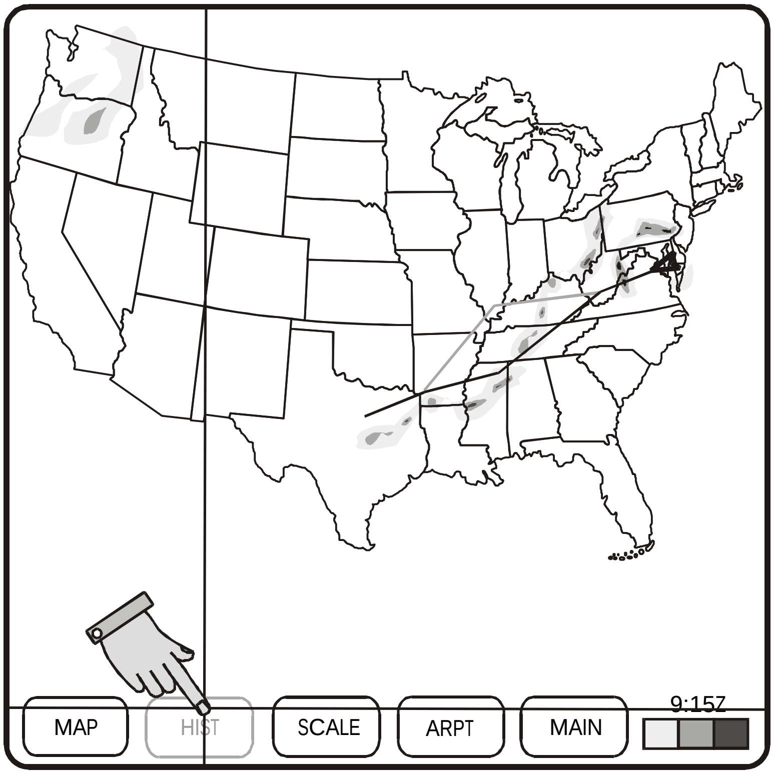

Figure 3: Cockpit Graphical Weather Format

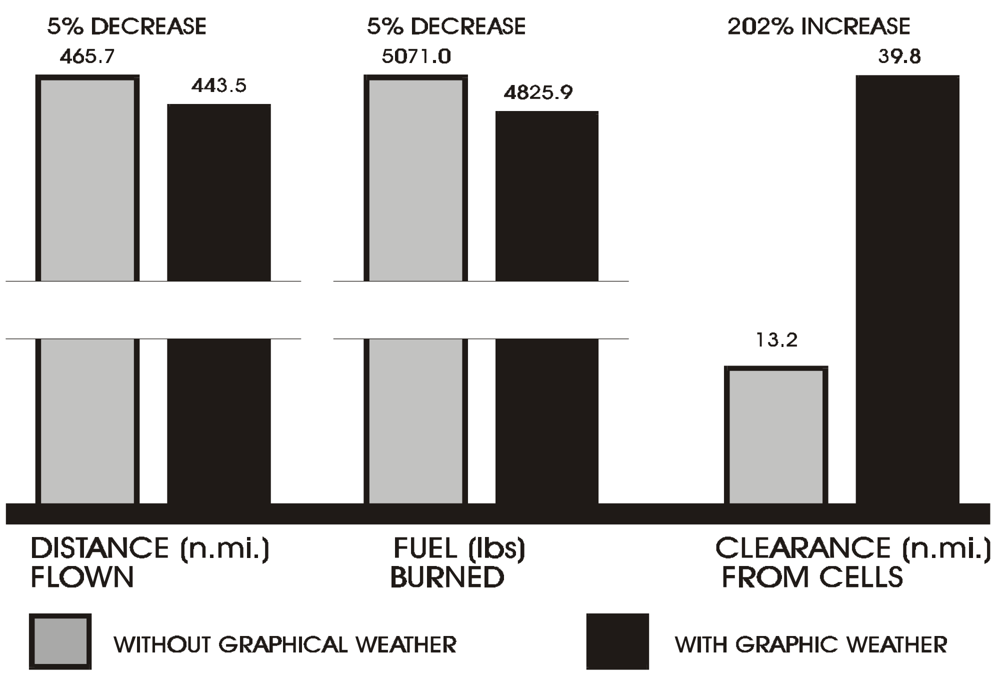

Figure 4: Data Comparison With and Without Graphical Weather