Proceedings of the Second NASA Aviation Safety Program Weather Accident Prevention Review

January 2003
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Proceedings of the Second NASA Aviation Safety Program Weather Accident Prevention Review

Proceedings of a conference held at the Hilton South
sponsored by NASA Glenn Research Center
Independence, Ohio
June 5–7, 2001

National Aeronautics and Space Administration

Glenn Research Center

January 2003
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Aviation Safety Program

Weather Accident Prevention
Annual Project Review

Cleveland, Ohio
June 5-7, 2001
Review Objectives

- Communicate progress to NASA Stakeholders, Partners, and Customers
- Solicit feedback on NASA’s Weather Safety Plans and activities from the aviation community.
  - Q&A session after presentations
  - Discussion sessions following each topical session
  - Panel Discussion during last morning session (June 7)
  - Survey of NASA WxAP plans/products
- Catalyst for future partnerships and collaboration with aviation community
- Enhanced integration of NASA Weather Accident Prevention Project Elements
- Preparation for NASA FY02 detailed planning activities
Review Objectives

Aviation Safety Program

Weather Accident Prevention

Aviation Safety Investment Strategy Team Recommendations

FAA and National Weather Service MOA on Aviation Weather Safety

National Aviation Weather Initiatives and Plans

NASA-FAA-Industry-Other Agencies Planning Workshops and Reviews

NASA-FAA-Industry Joint Safety Assessment and Implementation Teams

Integration with Other Non-AvSP NASA Projects
Attendees of Review

NASA AvSP Management/Researchers
NASA Base Management/Researchers
  FAA
  NWS
  NTSB

Avionics Industry
  Airlines

Aircraft Manufacturers
  Pilot Associations

Aircraft Associations
  Academia
  DoD
Survey

• Evaluate NASA’s weaknesses/strengths

• Evaluate NASA products being developed
  • Technical Issues
  • Coordination Issues
  • Implementation Issues
  • Others

• Identity disclosure is voluntary

• Use postage-paid envelope

• Summary of surveys will be forwarded to all attendees
Meeting Logistics

- Message Board available at registration table
  - Telephone Messages: 216-447-1300
  - FAX: 216-642-9334

- Coffee and snacks available during breaks

- Lunch available in the pool area Tuesday and Wednesday ($10 each) – Sign-up sheet at registration table

- List of local restaurants is available at registration table

- Presentations are on CD-ROM

- Break-out room available for side meetings – Sign-up sheet at registration table
### Day 1 Morning Agenda

<table>
<thead>
<tr>
<th>Time</th>
<th>Agenda Item</th>
<th>Speaker(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00 a.m.</td>
<td>Welcome</td>
<td>Sehra, GRC, Rohn, GRC</td>
</tr>
<tr>
<td>8:15 a.m.</td>
<td>Meeting Objectives and Logistics</td>
<td>Nadell, GRC</td>
</tr>
<tr>
<td>8:30 a.m.</td>
<td>Weather Accident Prevention (WxAP) Project Overview and Status</td>
<td>Nadell, GRC</td>
</tr>
<tr>
<td>9:00 a.m.</td>
<td>Development of WxAP System Architecture and Concept of Operation</td>
<td>Grantier, GRC</td>
</tr>
<tr>
<td>9:30 a.m.</td>
<td>Aviation Weather Information Overview and Status</td>
<td>Stough, LaRC</td>
</tr>
<tr>
<td>10:15 a.m.</td>
<td>Break</td>
<td></td>
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<tr>
<td>10:30 a.m.</td>
<td>Weather Information Communications Overview and Status</td>
<td>Martzakis, GRC</td>
</tr>
<tr>
<td>11:15 a.m.</td>
<td>Turbulence Detection and Mitigation Overview and Status</td>
<td>Bogue, DFRC, Watson, LaRC</td>
</tr>
<tr>
<td>12-1 p.m.</td>
<td>Lunch</td>
<td></td>
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<tr>
<td>Time</td>
<td>Session</td>
<td>Speaker/Institution</td>
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<tr>
<td>1:00 p.m.</td>
<td>Weather Information Network</td>
<td>Leger, Honeywell</td>
</tr>
<tr>
<td>1:15 p.m.</td>
<td>NASA Langley WINN System Operational Assessment</td>
<td>Jonsson, LaRC</td>
</tr>
<tr>
<td>1:30 p.m.</td>
<td>United’s SKY-PAD™ Project</td>
<td>Burns, UAL</td>
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<tr>
<td>1:45 p.m.</td>
<td>Enhanced Weather Radar and Aviation Weather</td>
<td>Kronfeld, Rockwell</td>
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<tr>
<td></td>
<td>Awareness &amp; Reporting Programs</td>
<td></td>
</tr>
<tr>
<td>2:15 p.m.</td>
<td>Satellite Weather Information Service</td>
<td>Kerczewski, GRC</td>
</tr>
<tr>
<td>2:35 p.m.</td>
<td>Pilot Weather Advisor™</td>
<td>Hoffler, Vigyan, Inc.</td>
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<tr>
<td>2:55 p.m.</td>
<td>The Results of the Evaluation of Using Lighting</td>
<td>Nierow, FAA</td>
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<td></td>
<td>Data to Improve Oceanic Convective Forecasting</td>
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<tr>
<td></td>
<td>for Aviation</td>
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<tr>
<td>3:00 p.m.</td>
<td>Oceanic Weather Information: Oceanic Convective</td>
<td>Lindholm, NCAR</td>
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<tr>
<td></td>
<td>Convective Nowcasting Demonstration (OCND)</td>
<td></td>
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</tbody>
</table>
**Day 1 Afternoon Agenda (cont.)**

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
<th>Speaker(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3:15 p.m.</td>
<td>Break</td>
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<tr>
<td>3:30 p.m.</td>
<td>VHF Datalink (Mode 2) for Cockpit Weather for Air Transports</td>
<td>Tanger, LMGT</td>
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<tr>
<td>3:40 p.m.</td>
<td>Preliminary VLD Mode 2 Bench and Flight Test Results</td>
<td>Skidmore, OU</td>
</tr>
<tr>
<td>4:00 p.m.</td>
<td>Decision-making In Flight With Different Convective Weather Information Sources: Preliminary Results</td>
<td>Latorella, LaRC, Chamberlain, LaRC</td>
</tr>
<tr>
<td>4:30 p.m.</td>
<td>GA Cockpit Weather Information System Simulation Studies</td>
<td>McAdaragh, FAA, Novacek, RTI</td>
</tr>
<tr>
<td>5:00 p.m.</td>
<td>Discussion: Cockpit Weather Systems</td>
<td></td>
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<tr>
<td>5:30 p.m.</td>
<td>Conclude for the Day</td>
<td></td>
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</table>
Day 2 Morning Agenda

**Cockpit Weather Information Systems (cont.)**

8:00 a.m. General Aviation FIS Broadcast System
Joyce, Honeywell

8:20 a.m. FIS Architecture Study Plan
Tanger, LMGT
Nichols, Johns
Hopkins APL

**Airborne Weather Reporting System**

8:45 a.m. TAMDAR Development Strategy
Schmidt, FAA

8:55 a.m. TAMDAR Capabilities Development
Daniels, LaRC

9:25 a.m. TAMDAR Datalink Development
Andro, GRC

9:45 a.m. Overview of the Business Feasibility of the TAMDAR System
Kauffmann, ODU

10:15 a.m. Break

10:30 a.m. Impact of MDCRS/TAMDAR data on National Weather Service (NWS) Operations
Weiss, NWS
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<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Speaker/Institution</th>
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<tbody>
<tr>
<td>10:50 a.m.</td>
<td>Discussion: Airborne Weather Reporting System</td>
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<tr>
<td></td>
<td><em>Airborne Turbulence Warning System</em></td>
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</tr>
<tr>
<td>11:25 a.m.</td>
<td>Airborne Turbulence Warning System Development</td>
<td>Bogue, DFRC</td>
</tr>
<tr>
<td>11:40 a.m.</td>
<td>Meteorological Case Studies of Turbulence Encounters</td>
<td>Ferris, MIT Lincoln Labs.</td>
</tr>
<tr>
<td>12-1 p.m.</td>
<td>Lunch</td>
<td></td>
</tr>
<tr>
<td>1:00 p.m.</td>
<td>Weather Associated With the Fall 2000 Turbulence Flight Tests</td>
<td>Hamilton, LaRC</td>
</tr>
<tr>
<td>1:20 p.m.</td>
<td>Numerical Simulation of Event 191-6 of NASA’s Flight Tests</td>
<td>Proctor, LaRC</td>
</tr>
<tr>
<td>1:40 p.m.</td>
<td>Unbalanced Supergradient Flow – It’s Role In Organizing Severe Turbulence In Both Convective and Clear Air Case Studies</td>
<td>Kaplan, NCSU</td>
</tr>
<tr>
<td>2:00 p.m.</td>
<td>Simulations of Continuous and Discrete Turbulence Events</td>
<td>Sharman, NCAR</td>
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Day 2 Afternoon Agenda (cont.)

Airborne Turbulence Warning System (cont.)

2:20 p.m. Development and Flight Test of In Situ Turbulence Algorithms Robinson, AeroTech
2:45 p.m. Turbulence LIDAR Development Status Clark, LaRC
3:00 p.m. Break
3:15 p.m. Flight Test Results for a Turbulence Detection Radar Schaffner, LaRC
4:00 p.m. Market Assessment of Forward-Looking Turbulence Sensing Systems Kauffmann, ODU
4:30 p.m. Turbulence Secure Cabin Exercise Bogue, DFRC
5:00 p.m. Discussion: Airborne Turbulence Warning System
5:30 p.m. Conclude for the Day
Day 3 Morning Agenda

**Airborne Turbulence Warning System (cont.)**

8:00 a.m.  Feasibility Study of Transport-Aircraft Control Systems for Turbulence Effects Mitigation  
           Borland, Boeing CAG

8:20 a.m.  Turbulence JSAT/JSIT Status  
           Bogue, DFRC

**Implementation, Operation, and Technology Development**

8:40 a.m.  NASA-FAA-NOAA Partnering Strategy  
           Colantonio, GRC

9:00 a.m.  Flight Information Services Data Link (FISDL)  
           Moosakhanian, FAA

9:20 a.m.  Airline Implementation of Cockpit Weather Systems  
           Sambrano, UAL

9:40 a.m.  Break

10:00 a.m.  Panel Session: Cockpit Weather Information Systems: Current and Future Challenges for Implementation, Operation, and Technology Development

11:45 a.m.  Annual Review Wrap-up

12:00 noon  Annual Review Concluded
Aviation Safety Program

Weather Accident Prevention (WxAP)
Project Overview and Status

Shari-Beth Nadell, Acting Project Manager
NASA Glenn Research Center (GRC)
Cleveland, OH
Outline

• Weather Accident Prevention Project Background/History

• Project Modifications

• Project Accomplishments

• Project’s Next Steps
Weather Safety Benefits Needed

41% during cruise
27% due to visual flight operation in instrument flight conditions

GA Aviation Accidents 1982-1993
(22,053 total accidents)
Source: AOPA Air Safety Foundation

Turbulence Injuries (33%)
Non-Turbulence-related Injuries (67%)

Commercial Transport Serious Injuries 1990-1996
Fatal/Non-fatal Accidents
Source: NTSB Data

Weather-related (33%)
Non-weather-related (67%)

Commercial Carrier Accidents 1983-1995
Source: NTSB
White House Commission on Safety and Security Sets Goal of 80% reduction in fatal accidents within 10 years

National Aviation Weather Program Strategic Plan-Office of the Federal Coordinator for Meteorology

Aviation Safety Investment Strategy Team

Project Evolution

Aviation Safety Program

Weather Accident Prevention

NASA Base Program (AOS)

Focused Program: AvSP WxAP

Base Program: AOS Aircraft Icing

FY97  FY98  FY99  FY00  FY01

Aviation Safety Investment Strategy Team

National Aviation Weather Initiatives

FAA-NASA Weather Safety Memorandum Of Agreement *Signed June, 2000*

FAA-NASA Memorandum Of Understanding Signed On Aviation Safety

Commercial Aviation Safety Team and GA Joint Steering Committee activities initiated

NASA-Other Agency Weather Safety Memorandum Of Agreements (in progress)
NASA AvSP Organizational Structure

Aviation Safety Program Office
Michael Lewis, Director
George Finelli, Deputy Director
Connie Smith, Secretary
Brian Smith, Dep Prog Mgr (ARC)
Jaiwon Shin, Dep Prog Mgr (GRC)
Frank Jones, Asst Tech Mgmt
Glenn Bond, Senior Prog Analyst

AvSPEC

1.1 Technical Integration
Vincent Schultz (LaRC)

1.2 Program Integration
Michael Beesehore (FAA)
Carrie Walker (HQ)

Programs

Projects

2.1 Aviation System Monitoring & Modeling
Irvin Statler (ARC)

2.2 System-Wide Accident Prevention
Tina Beard (ARC)

2.3 Single Aircraft Accident Prevention
John White (LaRC)

2.4 Weather Accident Prevention (WxAP)
Shari-Beth Nadell (acting) (GRC)

2.5 Accident Mitigation
Douglas Rohn (GRC)

2.6 Synthetic Vision
Daniel Balze (LaRC)

Elements

Aviation Weather Information (AWIN)
2.4.1 Paul Stough (LaRC)

Weather Information Communication (WINCOMM)
2.4.2 Gus Martzakis (GRC)

Turbulence Detection and Mitigation (TDAM)
2.4.3 Rod Bogue (DFRC)
WxAP Project Goals/Objectives/Products

Aviation Safety Program
Weather Accident Prevention

Goal
Develop enabling technologies to reduce weather-related accident causal factors by 50% and turbulence-related injuries by 50% by year 2007.

Objectives
- Provide the Flight Deck with Higher Fidelity, More Timely Intuitive Graphical Information
- Detect & Mitigate Weather Hazards

Products
1. Cockpit weather display technologies and design guidelines and pilot decision support tools
2. Weather Information data link technologies, architecture, and design guidelines
3. Improved low-altitude Automet technologies and design guidelines
4. Turbulence hazard characterization
5. Forward-looking turbulence sensor technologies and system design guidelines
6. Turbulence mitigation procedure guidelines
### Project Schedule and Milestones

**Aviation Safety Program**  
**Weather Accident Prevention**

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone Description</th>
</tr>
</thead>
</table>
| FY00 | Initial AWIN Concept and Forward-Looking Turbulence Detection Flight Evaluation  
*COMPLETE* |
| FY01 |  |
| FY02 | Flight Demonstration Of Forward-Looking Turbulence Warning System |
| FY03 | Turbulence Flight Management System Demo |
| FY04 | National AWIN Capability  
National Datalink Capability  
Turbulence Product Integrated With AWIN  
International AWIN Capability  
International Datalink Capability |
Product Development Strategy

- Strong Industry cost sharing through Cooperative Research Agreements (CRA)
- Airline/operator participation in CRAs
- Cost/Market assessment studies funded
- FAA/NASA/NWS Working Groups being established
- Participation in Industry/Government working groups dealing with technology and standards development: RTCA, ICAO Joint Safety Assessment/Implementation Teams, etc.
- Strong National Turbulence Research Coalition assisting in defining NASA direction
Project Modifications

• Reasons for modifications
  » Resource limitations (funding, staff)
  » Customer feedback and recommendations

• Content of changes
  » Research area focus modifications
  » WBS modifications

• Research area focus modifications

  » Nowcasting/Forecasting technology development eliminated
    • Feedback from joint Turbulence PDT and FAA meeting
    • FAA responsible for developing nowcasting/forecasting products
    • NASA responsible for investigating turbulence characteristics and defining hazard metrics

  » Turbulence Mitigation technology development refocused
    • Flight System Controls development descoped to investigation of autopilot usage in turbulence encounters
    • Integration of turbulence warning information on the flight deck added
Project Modifications (concl.)

- Research area focus modifications (concl.)
  
  » Specific technology development focus on commuter aircraft and rotorcraft eliminated
    • Addresses the spectrum of users and key accident areas
  
  » Graphical weather presentation and usage research and technology development limited to cockpit systems
    • FAA responsible for developing ATC and AOS products and technologies
  
  » Research focus on AutoMET sensor and datalink technology development increased
    • GA Wx JSIT Recommendation
    • National Aviation Wx Program Council feedback
    • FAA Wx requirements office input
    • WxAP Project Review feedback
  
  » Research focus on Satellite Datalink Communications technology development increased
Modified WxAP Products

**Weather Accident Prevention (WxAP)**
*Shari-Beth Nadell, GRC*

- **Aviation Weather Information**
  *Paul Stough, LaRC*

- **Weather Information Communications**
  *Gus Martzakis, GRC*

- **Turbulence Detection & Mitigation**
  *Rod Bogue, DFRC*

**Products**

- **AWIN System**
  *Cockpit Weather Display Technologies, Pilot Decision Support Tools, Ground-to-Air Datalink Technologies*

- **AutoMET System**
  *Airborne Weather Reporting Sensor Technologies, Air-to-Ground, Air-to-Air Datalink Technologies*

**Turbulence**

- Sensor Technologies
- Mitigation Procedures
- Characterization
Project Accomplishments

- Completed Project Milestone #1: Initial AWIN and Forward-Looking Turbulence Detection Flight Evaluation
- Total of six flights between September and December 2000 (including two ferry flights to DFW)
- Four WxAP experiments were conducted:
  - In-Situ Turbulence Algorithm
  - Turbulence Radar
  - AWIN-Weather Information Network (WINN) System
  - Enhanced Weather Radar

WINN Display Mounted in the B757 Cockpit

EWxR multifunction display with ship's weather radar data to 50 nmi and NEXRAD data beyond.

Turbulence Radar Installation on B757
Project Accomplishments (cont.)

- Successful completion of the first test subject data collection flight of the AWIN Convective Weather Sources (COWS) experiment on August 9, 2000
  - Experiment investigates how situation awareness and flight deck decision making is affected by access to different sources of weather information
  - Conditions investigated included: conventional audio information only, out-the-window visual cues plus conventional audio information, and a composite radar image (a tethered AWIN display) plus the conventional audio information

Honeywell AWIN Display in King Air Cockpit

NASA BE-200 King Air
Project Accomplishments (cont.)

- TAMDAR Sensor tested in NASA GRC Icing Research Tunnel, March 21-23
  - Preliminary results indicate the overall infrared sensing principle is sound and detected both glaze and rime ice
  - Probe de-icing method needs to be reworked with respect to heater size and placement and the software algorithm that tried to melt the ice or declare the sensor "contaminated"
  - Next-generation unit will have the temperature sensor better isolated thermally from the heater
  - TAMDAR sensor development task initiated with GTRI and ODS; kickoff meeting April 25
• Continued to develop Broadband SATCOM Datalink
  › Enabling technologies: phased array antennas, broadband mobile terminal
  › Joint NASA/Boeing development
  › Up to 1000x capacity increase
  › Ground-mobile experiments
  › Proof flight test Dec, 2000 (DC-8)
  › Upcoming B-757 experiments
  › Enabling to new Connexion by Boeing datalink service
Project Accomplishments (concl.)

- Test development planning for Turbulence Secure Cabin Exercise
  - First implementation will use FAA CAMI B747 Cabin Evacuation simulator training facility
  - Secure Cabin Exercise team includes NASA, FAA, airlines, cabin attendants associations, etc.
  - Three cabin scenarios will be used to develop requirements for “securing” a cabin prior to a turbulence encounter
  - Will provide important input to the development of Airborne Turbulence Warning System requirements and procedural guidelines

FAA CAMI B747 Cabin Evacuation Simulator
Project’s Next Steps

- Develop systems architecture and concept of operations for WxAP technology products.
- Revisit and redefine project milestones based on accomplishments over first two years of the program.
- Update NASA plans per stakeholder comments (i.e. THIS REVIEW), requirement studies, joint team recommendation etc.
- Continue to integrate and leverage activities with FAA, NWS and DoD.
- Continue to seek greater participation with aviation user community.
Aviation Safety Program

Weather Accident Prevention (WxAP)
Development of WxAP System Architecture
And Concepts of Operation

David Grantier, WxAP LII Systems Engineer
7800 Systems Engineering Division
NASA Glenn Research Center
Cleveland, OH
Outline

Aviation Safety Program - Weather Accident Prevention

• Background Information on System Architecture/CONOPS Activity

• Activity Work In Progress

• Anticipated By-Products
WxAP Project Evolution FY’01

• Prior Systems Engineering Activities
  • AvSP LI Product Notebooks
  • Bob Sutton, Pat Corcoran ARI, AvSP LI Systems Engineers

• Project philosophy/structure towards Product Based Development
  • Acceptance to modify Level II, III Milestones
  • Define, identify NASA WxAP Products

• Focus on WxAP technologies, not an optimized NASA WxAP System
  • AWIN, WINCOMM, TDAM
  • 2/7-8/01 GRC LII/LIII TIM
Task Origin

Aviation Safety Program - Weather Accident Prevention

• 3/27/01 WxAP LIII Integration Meeting at LaRC

• Scope:
  • To create a NASA WxAP System Architecture and associated Concept of Operations Document.
  
  • Demonstrate a system implementation that includes AWIN, WINCOMM, and TDAM technologies for Commercial Transport and GA (where applicable).
  
  • Systems may not fully utilize the full scope of capabilities that are available from any one of the WxAP LIII elements.
  
  • System will be the WxAP Level II and Level III’s vision of potential applications of these technologies.
Task Origin (cont.)

Aviation Safety Program - Weather Accident Prevention

• Justification:
  • To date, WxAP Level III development has been largely a bottoms-up effort with limited systems guidance from WxAP Level II due in large part to the maturity level of the LIII technologies.
  
  • The Level III Elements are moving into a more critical period of technology development and demonstration and the need for a WxAP System Architecture is evident.
  
  • The products of this activity will allow the WxAP Level III elements to refine their development activities and to accommodate WxAP system level requirements in their technologies.
  
  • Anticipated by-products of this activity include WxAP ’02 (and ’04) Flight Requirements.
Modified WxAP Products

Aviation Safety Program - Weather Accident Prevention

Weather Accident Prevention (WxAP)
Shari-Beth Nadell, GRC

Aviation Weather Information
Paul Stough, LaRC

Weather Information Communications
Gus Martzakis, GRC

Turbulence Detection & Mitigation
Rod Bogue, DFRC

Products

AWIN System
Cockpit Weather Display Technologies,
Pilot Decision Support Tools,
Ground-to-Air Datalink Technologies

AutoMET System
Airborne Weather Reporting Sensor Technologies,
Air-to-Ground, Air-to-Air Datalink Technologies

Turbulence Sensor Technologies
Turbulence Mitigation Procedures
Turbulence Characterization

Wx Products (external source)
Architecture Task Goal:
Map WxAP Products on System Architecture

WxAP Proposed Products:

• Cockpit Weather Display Technologies and Pilot Decision Support Tools

• Airborne Weather Reporting Sensor Technologies

• Weather Information Datalink Systems Technologies for Ground-to-Air Dissemination

• Weather Information Datalink Technologies for Air-to-Ground and Air-to-Air Dissemination

• Turbulence Characterization Technologies

• Forward-looking Turbulence Sensor Technologies

• Turbulence Mitigation Procedures
5/10-11/01 WxAP LII/LIII SE Meeting at LaRC

Attendees:

- Dave Grantier/GRC  WxAP LII SE
- Dwayne Kiefer/GRC/QSS WxAP LII SE
- John Bowen/GRC/ZIN WxAP LII SE
- Ed Johnson/LaRC AWIN LIII SE
- Tom Tanger/GRC/CMST WINCOMM SE
- Dale Force/GRC WINCOMM SE
- Jim Watson/LaRC TDAM SE (acting)
- Pat Corcoran/ARI AvSP LI SE

Meeting Summary:
The objective of this meeting was to familiarize each of the WxAP, AWIN, WINCOMM and TDAM personnel with each other, and to uncover the basic composition of each element. The meeting consisted of the WxAP LII System Engineers presenting their understanding gleaned from the available Level III documentation. The presentations were then supplemented and where necessary, corrected by the Level III System Engineers. The overall result of the meeting laid the informational and personal groundwork for future collaborations within the groups, and a starting point for the genesis of a NASA WxAP System Architecture.
NASA WxAP CONOPS Issues Currently Identified
(5/11-12/01 WxAP SE TIM at LaRC)

• NASA WxAP Implementation Time Phasing

• NASA WxAP Flight Phase
  ✓ Preflight, Take-off, Enroute, Landing, Postflight

• Aircraft Classifications
  ✓ GA, Transport, Other?

• Communications Protocols
  ✓ VDL-2,3, UAT, Mode S, SatCom

• Aircraft Hardware
  ✓ Radio, Processors, Sensors, Cockpit Displays

• Aircraft Services
  ✓ Other AvSP technologies, other Wx information on plane

• Ground Communications Network
  ✓ IP-6, ATN
Examples of WxAP System Architecture sketches from WxAP SE working group meeting (5/11-12/01 LaRC)
Example WxAP Architecture Sketch

Aviation Safety Program - Weather Accident Prevention

Revised Architecture
Example of WxAP initial System Architecture from FY’01 B-757 ARIES Flight Test Requirements Document (S. Rickard/LaRC)

Integrated WxAP Experiments High-Level System Architecture

Aviation Safety Program - Weather Accident Prevention

Example of WxAP initial System Architecture from FY’01 B-757 ARIES Flight Test Requirements Document (S. Rickard/LaRC)
NASA WxAP Elementary CONOPS

The “Building Blocks” of a WxAP CONOPS:

✓ Data is Transferred to Aircraft
✓ Data is Received by the Aircraft
✓ Data is Displayed to the Pilot
✓ Data is Collected on the Aircraft
✓ Data is Transmitted from the Aircraft
✓ Data is Received on the Ground
Anticipated By-Products of Architecture/CONOPS Activity

- WxAP LII Requirements Document
- Formulation of WxAP FY’02 and ’04 Flight Requirements
- More efficient evaluation of potential WxAP integration with other AvSP LII projects
- More efficient participation in AvSP LI Systems Engineering activities
- WxAP LII and LIII Project Management tool
Aviation Weather Information Overview and Status

Weather Accident Prevention Project Review

Cleveland, Ohio
June 5 to 7, 2001

Paul Stough
Crew/Vehicle Integration Branch
NASA Langley Research Center
Hampton, VA 23681-2199
(757) 864-3860
E-mail: h.p.stough@larc.nasa.gov
Outline

• Background

• Research Areas

• Progress since last year
• Weather is a major contributing factor in accidents:
  – 33% Commercial carrier
  – 27% General aviation

• Many accidents are due to lack of weather situation awareness and poor decisions.

• Provision of strategic weather information during the en route phase enables avoidance of adverse conditions.
Guidance

• NASA Aviation Safety Program
  – Aviation Safety Investment Strategy Team
  – Executive Council

• National Aviation Weather Program Council
  – National Aviation Weather Program Strategic Plan
  – National Aviation Weather Initiatives

• FAA Safer Skies: Focused Safety Agenda
  – Weather Joint Safety Analysis Teams
  – Weather Joint Safety Implementation Teams

• FAA Aviation Weather Research Program

• Friends of Aviation Weather

• WxAP Project Review
Plan

Aviation Weather Information

Goal
Develop technologies and methods for providing pilots with accurate, timely and intuitive information during the en route phases of flight which, if implemented, will enable a 25 to 50% reduction in aircraft accidents attributable to weather situation awareness.

Objectives

| Develop Needed Weather Products and Sensing Capabilities |
| Develop Enhanced Weather Presentations and Decision Aids |

Challenges

| Improved Forecasts Need Better Input Data |
| Existing Aircraft Need Retrofit Capability |
| Pilot Workload Should Not Be Increased |

Approach

| Use Aircraft as Airborne Weather Data Collectors |
| Develop Multi-Purpose Sensor Systems |
| Develop Installed and Portable Systems |
| Provide Decision Aids |
AWIN System

Aircraft Capabilities
User Capabilities
Decision Aids

User Interface
Processor
Presentation

Data Link

Weather Reports
Onboard Weather Sensors
Flight Information
Navigation Information

Ground Wx System
Weather Products
Flight Information

Special Use Airspace
Obstacles

Data Link

Position
Flight Plan
Traffic
Terrain
Market Segments

Transport Business

Commuter

General Aviation Rotorcraft
Technology Development Level

Technology Readiness Level
- System Implementation
- System/Subsystem Evaluation
- Technology Development & Demonstration
- Research to Prove Feasibility
- Basic Technology Research

Implementation Readiness Level
- Operation of Certified System
- Certification Approved
- Certification Standard Established
- Draft Cert. Standard Developed
- RTCA/SAE or Equivalent Convened
- Application for Certification
- Commercial Product Dev. Initiated
- Industry R&D Funding Committed
- Technology Transfer Initiated
NASA Research Team

Aviation Weather Information

- Dr. Jennifer Burt (757) 864-8304
  Human Factors/Presentation
- Mr. Jim Chamberlain (757) 864-2147
  Flight Experiments
- Mr. Taumi Daniels (757) 864-4659
  Airborne Weather Sensing
- Mr. Walt Green (757) 864-3355
  Systems Engineering
- Dr. Ed Johnson (757) 864-7602
  Systems Engineering
- Mr. Ken Jones (757) 864-5013
  Flight Experiments
- Dr. Jon Jonsson (757) 864-2001
  Human Factors/Presentation
- Dr. Kara Latorella (757) 864-2030
  Human Factors/Decision Aiding
- Dr. Ray McAdaragh (757) 864-1941
  Human Factors/Presentation
- Mr. John Murray (757) 864-5883
  Meteorology
- Dr. Robert Neece (757) 864-1827
  Enhanced Weather Radar
- Mr. Phil Schaffner (757) 864-1809
  Airborne Hazard Processor

Mr. Paul Stough (757) 864-3860
Project Management
NASA Facilities

General Aviation Work Station

NASA C-206

NASA BE-200

Transport Research Flight Deck

NASA B-757
Partnerships

Aviation Weather Information

Flight Standards Certification
Weather Policy Weather Products
Flight Information Services

Aviation Weather Center
Forecast Systems Lab

Cooperative Research Agreements

Research Triangle Institute
Academia
Timeline

National AWIN Capability

FY00 | FY01 | FY02 | FY03 | FY04

Flight Evaluation of Initial AWIN Concept

International AWIN Capability Integrated with Turbulence Detection

Current AWIN Technologies ➔ Next Generation AWIN Technologies
AWIN Research Areas

- Enhanced Weather Radar
- Airborne Weather Reporting
- Airborne Hazard Awareness System
- Display Guidelines
- Decision Aids
- Automatic Speech Recognition
- Cooperative Research Agreements
Cooperative Research with FAA

- Human factors researcher assigned to the AWIN Team
- Joint funding of research
- Data-link Weather Information Systems Enhancements
  - Investigate effects of data-linked in-flight weather displays on pilot decision making and flight operations
  - Investigate the benefits and limitations of using cockpit presentations of time-delayed data-linked weather information with real-time airborne weather radar for Part 121 operations
  - Investigate feasibility of using cockpit access to data-linked weather information in place of in-situ destination weather reporting for Part 135 operations
  - Define the cost considerations and incentives for aircraft owners to equip their aircraft and provide airborne weather reporting as part of a national implementation
Cooperative Research

- Worldwide Transport Weather Information Systems
  - Honeywell Weather Information Network (WINN)

- Nationwide General Aviation Weather Information Systems
  - ARNAV
  - Honeywell

- Elements of Weather Information Systems
  - Honeywell Weather Avoidance Using Route Optimization as a Decision Aid
  - Rockwell Aviation Weather Awareness and Reporting Enhancements (AWARE)
  - Rockwell Enhanced On-Board Weather Radar (EWxR)
  - Rockwell Airborne Hazard Awareness System (AHAS)
  - NCAR Oceanic Convective Nowcasting Demonstration (OCND)
  - NRL Ceiling and Visibility Forecasting Improvements
Honeywell Weather Information Network

Technology Development

Honeywell Citation Jet
Honeywell simulator
UAL B-777 simulator
NASA B-757

Avionitek display in NASA B-757

In-Service Evaluation

United Airlines Spring 2001

Electronic Flight Bag in UAL Airbus
Weather Information Communications (WINCOMM)
Overview and Status

Weather Accident Prevention
2nd Annual Project Review
June 5-7, 2001
Cleveland, OH

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System Elements

Weather Products → Distribution → Presentation

Enhanced Weather Products (AWIN) → Communications Networks and Data Links (WINCOMM) → Operator Support (AWIN)
Technology Investment Areas

- Datalink Requirements & Architecture Analyses:
  - Mid-Term (2010)
  - Far-Term (>2020)

- Air/Ground Datalinks
  - Ground-based (terrestrial)
  - Satellite-based
  - Airborne-based

- Network Technologies
  - Aeronautical Telecommunications Network (ATN)
  - Internet Protocol (IP)

(Focus: Commercial Air Transport and General Aviation)
NAS Information Exchange

Options:

- Analog Voice
- ACARS
- VDL Modes 2-4
- Mode S
- UAT
- SATCOM
- HFDL
- Commercial
- Proprietary Links
FIS Datalink Architecture Analyses*

Key results to date:

- SAIC, ARINC, TRW, Crown Communications Weather Datalink Architecture Study (May, 2000) and in-house analyses:
  - Broadcast is preferable to addressed 2-way for FIS (Weather)
  - VHF-Broadcast can support regional FIS data, however challenge to meet national implementation goals (coverage/interference)
  - Need broadband solution which could support regional/national goals (SATCOM and/or line-of-sight)
- Hybrid broadcast solution, optimal:
  - Ground-based narrowband for local/regional FIS
  - SATCOM for national/strategic
FIS Datalink Architecture Analyses*

On-going tasks:

- Comprehensive AutoMET/TAMDAR datalink architecture options

JH/APL tasks:
- Independent investigation of ground, satellite and hybrid datalink architectures for FIS
- 2007-2015 implementation timeframe
- Investigation of ‘ADS-B’ datalinks for FIS/Wx and low-altitude AutoMET (TAMDAR) dissemination
  - Mode S (1090), UAT, VDLM4
  - Supported by high fidelity modeling and simulation
Air Transport: Ground-based Datalinks*

- Phase I (FY98-00) efforts (Boeing & Honeywell) utilized off-the-shelf comm for rapid implementation (air phone, VHF/ACARS, ...)

- Optimal long-term operational end-solution may differ (VDL Mode 2, SATCOM)

- Recent In-Service-Eval's (ISE) of HI system by UAL (Electronic Flight Bag concept)
Results to date:
• Grants with Ohio University to assess addressed VDL-Mode 2 datalink for weather dissemination.
• Laboratory bench testing completed
• Initial flight experiments completed (Ohio U King Air)

Future activity:
• Partnering with ARINC to jointly evaluate VDL-2 datalink performance for FIS (Weather) applications. (VDL-2 is future upgrade to ACARS)
• Experiments will include both signals-in-space as well as network characterization (ATN).
• Hardware will be integrated on NASA B-757 research aircraft for upcoming flight experiments with ARINC ground-system.
Air Transport: Ground-based Datalinks*

Equipment

Ohio University King Air

Transmitter Location

NASA Langley B757 Aircraft
Air Transport: Satellite-based Datalinks*

Worldwide Transport

Technology development and operational evaluation of graphical weather to the cockpit via broadcast SATCOM for commercial transport oceanic operations

AsiaStar Antenna Beam Coverage

System Configuration

WorldSpace
AsiaStar Satellite

Wireless Onboard LAN Radio

Satellite Receiving Antenna

Pilot's Laptops
With LAN cards

LAN Antenna

SIU
FSU-2000 File Server

Satellite Receiver
Air Transport: Satellite-based Datalinks*

Worldwide SATCOM Transport Datalink:

• NASA / Rockwell Collins / Jeppesen / American Airlines / Worldspace team
• Government/industry cost-sharing
• In-Service Evaluation via two American Airlines B-777s flying transpacific routes
• 1st 777 install completed, including all certs
• 2nd 777 install completion May, 2001
• Trial ‘runs’ completed to Japan
• First ‘official’ flight May 21, 2001; commence data collection thereafter
Air Transport: Satellite-based Datalinks

- Enabling technologies:
  - Phased array antennas
  - Broadband mobile terminal
- Joint NASA/Boeing development
- Up to 1000x capacity increase
  - 256 Kbps off aircraft
  - 2.18 Mbps to aircraft
- Ground-mobile experiments
- Proof flight test Dec, 2000 (DC-8)
- Upcoming B-757 experiments
- Enabling to Connexion by Boeing
General Aviation: Ground-based Datalinks

- Cooperative NASA research with ARNAV and Honeywell (NavRadio)
- VHF-based broadcast & 2-way datalinks
  - VDL-Mode 2
  - GMSK
- Addresses near-term need for broadcast of graphical weather to the G/A cockpit
- Resulting FAA/industry implementation:
  - G/A focused service volume
  - Dual vendors (ARNAV & Honeywell)
  - 5 year FAA contract (FY00-04)
  - 2 national frequencies per vendor
  - Free text weather products
  - Fee-based value/graphical products
General Aviation: Satellite-based Datalinks

Flight test and evaluation of worldwide weather datalink capability using broadcast Satellite Digital Audio Radio Services (S-DARS).

Johannesburg, South Africa
September, 1999
General Aviation: Satellite-based Datalinks

AVSP
Aviation Safety Program

Weather Information Communications

PWA™ airborne weather display
PWA™ antenna
PWA receiver

Satellite providing CONUS coverage

PWA™ weather data

Based on US Patent
#5265024
Nov. 23, 1993

SBIR Phase III with ViGYAN
• Enable Pilot Weather Advisor™
• Low-cost SATCOM broadcast datalink
• Initial flight evals Fall, 2001
Low-Altitude AutoMET Reporting

- Use aircraft operating below 20,000 ft altitude to sense and report
  - Moisture
  - Temperature
  - Winds

- To be used by:
  - Forecast models
  - Weather briefers
  - Controllers
  - Other aircraft

- Investigating numerous airborne-based datalinks and architectures for technical feasibility

MDCRS & AMDAR Coverage from Transports

20,000 ft. MSL

AutoMET Coverage

Ground Level
AutoMET: Airborne-based Datalinks*

Airborne-based Datalinks:

• Extension of MDCRS service (ACARS/ARINC)
• VHF/GMSK (ARNAV Systems)
• VDL-Mode 2 (ARINC & HI)
• UAT (FAA Capstone & UPSAT)
• Satellite (OrbComm, others)
• ADS-B Datalinks (JH/APL)
Network Protocols Development

- Past tasks with MIT/LL for FIS:
  - ATN and Internet Protocol (Mobile IP) network feasibility
  - IP-over-VDL Mode 2 datalink interface definition

- Joint NASA/ARINC research:
  - FIS over IP/VDL-Mode 2
  - FIS over ATN/VDL Mode 2

- ATN over broadband SATCOM feasibility

- Next-generation Mobile IP research for aeronautical app’s
FAA/NASA Collaboration

- FIS Datalink & Weather Requirements Offices (AUA & ARW)
  - Co-funded tasks under NASA/FAA Memo of Agreement:
  - Low-altitude AutoMET datalink technical architecture alternatives
  - FIS/Weather datalink technical architecture analyses:
    - Mid-Term (2004-2007)
    - Far-Term (2010 and beyond)
  - Terminal area weather datalink communications alternatives

- Office of Architecture and System Engineering (ASD)
  - Joint Research Project Definitions (JRPDs):
  - FIS datalink architecture analyses & NAS Architecture integration
  - Terminal area broadband communications

- CAPSTONE Program (Alaska)
  - UAT datalink investigation for AutoMET; SATCOM augmentation
Summary

- NASA datalink technology investments in
  - FIS datalink architecture development guidelines
  - Ground, satellite and airborne weather datalink systems and supporting network standards

- Strong partnerships with industry, FAA and academia evidenced by
  - Cost-shared NASA/industry technology development
  - Jointly co-funded NASA/FAA tasks

- As a result, beginning to see introduction of 1st generation systems into the marketplace

- Continued future NASA research and technology development into breakthrough, next-generation systems and component technologies.
Turbulence Detection & Mitigation Element

Weather Accident Prevention
Second Annual Review
June 5-7, 2001

Rod Bogue
NASA Dryden Flight Research Center
Briefing Outline

Organization
Scope of Turbulence Effort
Background
Turbulence Detection & Mitigation Program Metrics
Approach
Turbulence Team Relationships
WBS Structure
Deliverables
TDAM Changes
FY-01 Results/Accomplishments
Out-year Plans
Element Status
Aviation Safety Program Organization
Scope of Turbulence Effort

- Turbulence from Natural Atmospheric Processes
- Parts 121, and 91 (Scheduled Carriers, Commuters & GA)
- Tactical (Enroute)
- Both Avoidance & Encounter Mitigation
- Flight Deck Integration

Note:*↓ = Reduced effort, *↑ = Starting effort.
Background

- Turbulence Costs
  - Primary Cause of In-Flight Injuries (9 encounters/24 injuries per month)
  - Cost estimated at >$100M/yr. for airlines

- Turbulence Initiators
  - Convective Storms (within and as far as 40 miles away from visible clouds in clear air)
  - Jet Stream (at confluence of multiple streams and near boundaries)
  - Mountain Wave (upward propagating from disturbances near the surface)
Turbulence Detection & Mitigation Program Metrics

- **WxAP Objective #3:** Provide commercial aircraft sensor with 90% probability of detection of severe Convective and Clear Air Turbulence thirty seconds to two minutes before encounter.

- **WxAP Milestone #2:** Flight demonstrate certifiable forward-looking on-board turbulence warning system with Type-I and Type-II error probability commensurate with airborne wind shear technology (TRL/IRL of 7/4)
Approach

- Build a Turbulence Team from Industry, Academia, and Government to address requirements, approaches, and solutions
- Utilize the Commercial Aircraft Safety Team (CAST) to determine requirements for Air Carriers (http://www.cygnacom.com/turbulence/)
- Address Air Carrier Issues with Technology Approaches with assistance from FAA Rule-Making, and Improved Procedures
- Address GA Issues with improved Weather Products Disseminated through Aviation Weather Information
Turbulence Team Relationships

NASA

AeroTech Research

Coherent Technologies, Inc.

Air Force MANTECH

LIDAR Technology

Turbulence PDT Team

Turbulence Encounters

NCAR

Atmospheric Science

WindShear Experience

Radar Signal Algorithms

LaRC/DFRC Research/Flight Assets

Honeywell Collins/Rockwell

Boeing

RTI

NCSU

FAA Aviation Weather Program

Radar Signal Processing

Aircraft Controls

Aircraft Mods

Private Industry

Academia

Government
WBS Structure

- Requirements Definition (CAST)
- Severe Events Database
- Hazard Metric Development
- Turbulence Characterization
- Detection
- Mitigation/Flight Deck Integration
- Sensor Performance Assessment
- Sensor Development
- Algorithm Development
- Demonstration & Verification
- Turbulent Flight Control Algorithm
- Flight Deck Display Integration
- Assess Mitigation Options
Major Deliverables/Products

- Turbulence Characterization
  - Validation of In-situ Algorithm
  - Turbulence Hazard Metric

- Detector Technology
  - Radar (software)
  - Lidar (hardware/software)

- Encounter Mitigation Technology
  - Assessment of Conventional Aircraft Control Authority

- Flight Deck Integration
  - Display Integration
Element Changes

- Program Changes
  - Elimination of Forecasting/Nowcasting WBS
  - De-scope of Mitigation
  - Initiation of Flight Deck Integration

- Staffing Changes
  - Level III Deputy
    - Bruce Kendall - interim
    - Jim Watson
  - Level IV
    - Neil O’connor - Turbulence Characterization Lead
    - Robert Neece - Detection & Mitigation Lead
    - Phil Schaffner - Radar Principal Investigator
    - Ivan Clark & Phil Gatt - Lidar Co-principal Investigators
Element Accomplishments

• Turbulence Characterization & Sensor Development
  – Research Radar Flight Experiments
    • 3 Flights (15 hours)
    • Predicted atmosphere along flight path
    • Verified turbulence in-situ algorithms
    • Established relationship between rms aircraft g-load and radar observables
  – CDR for B-757 Lidar Installation

• Radar Flight Sensor Certification/Flight Deck Integration
  – Participated in NASA-FAA-Industry Workshops (3) for Forward Looking Turbulence Sensor Certification*
  – Selected and modeled 4 turbulence encounters for candidate sensor verification & certification

Note: * indicates item will not be covered later in detail
Element Accomplishments (cont.)

- **Turbulence Mitigation**
  - Flight Control Report (Boeing)
  - Phase 2 SBIR for Feedforward Active Encounter Mitigation (CTI)*

- **Guidance Activities**
  - Commercial Aviation Safety Team
    - Completed Turbulence Joint Safety *Assessment* Process
      - (30 Interventions- Technology Development, Procedures, Training)
    - Chartered Turbulence Joint Safety *Implementation* Process
      - Prioritized Interventions - Selected for Implementation
      - Developed Projects - Identified Outputs
  - Secure Cabin Exercise
    - Established Team - FAA (CAMI), Airlines (5), Flight Attendant Organizations(2), ARI Consultant
    - Exercise Planning in Progress
Element Plans

- Turbulence Characterization & Sensor Development
  - Research Radar Flight Experiments with real-time Radar Algorithm in operation (Early FY-02 and Late FY-02)
  - Research Lidar Flight Experiments (Summer FY-01 on DC-8, Later FY-02 on B757)

- Radar Flight Sensor Certification
  - Support NASA-FAA Certification Team effort with flight tests and algorithm validation activities
  - Continue analysis of turbulence encounters for sensor verification & certification
Element Plans (cont.)

- Turbulence Mitigation
  - Flight Control Assessment (Boeing)
  - Support Phase 2 SBIR for Feed-forward Active Encounter Mitigation

- Commercial Aviation Safety Team
  - Complete Turbulence Joint Safety Implementation Process
    - Refine Projects and Outputs
    - Transition Projects to CAST Management

- Secure Cabin Exercise
  - Conduct wide-body exercise at CAMI in September 01
  - Develop Plans and conduct narrow-body exercise in FY-02
Summary - Status of Elements

- Turbulence Characterization
  - Accident analysis developing robust cases for certification
  - Developing turbulence weather analysis models

- Detection
  - Radar flight tests in December provided promising results for detecting turbulence in the vicinity of convective activity
  - Lidar flight tests in FY-01 expected to confirm/validate performance at cruise altitude

- Encounter Mitigation
  - Promising assessment of mitigation control options

- Flight Deck Integration
  - Planning for display integration with NASA-FAA Certification Team
Out-of-Scope "Turbulence"

"Sorry to interrupt, folks, but we've just had a report of some turbulence ahead. So please stay in your seats a little while."

"Ready? One, two, three!"
Out-of-Scope “Turbulence” (cont.)
Weather Information Network

NASA

Aviation Safety Program

June 5, 2001
Data

- Turbulence Detection and Forecast
- Weather Radar (US only)
- Satellite
- Convective Detection and Forecast
- Icing Detection and Forecast
- METARs (icon and text)
- TAFs (text)
- SIGMETs
- High level Sig Wx Prog
- Surface Analysis
- Winds Aloft
System Overview
Multiple weather providers push information to the Honeywell Data Center (HDC).

The HDC receives, decompresses, reformats and recompresses the information.

Once reprocessed the HDC stores the information in a ready directory until called on for delivery.
Communications

- Using standard airborne telephony (UHF or Satcom) the user establishes a link with the HDC.
- Once established, the user requests an update of information, based on position.
- The HDC replies by sending all information requested, through matching the user’s request with the current master directory of all information.
- This process is repeated on a periodic basis.
Airborne 2

Optional

- GPS Sensor

Required

- EFB PC/Display

Optional for short trips

- 115V/400 Hz Power Supply

Navigation
- Position
- Altitude
- Heading
- GMT
- Groundspeed

Phone Line to Telephone

Required

- Once information is received it resides on the PC until requested
- The unit will require power for durations greater than the battery life
- The unit may use navigational (GPS) information to facilitate moving map display
Airborne Displays

- **LRU**
  - Avionitek ICIS
  - Northstar CT-1000
  - Honeywell flat panel

- **Portable Electronic Device**
  - Fujitsu 3400
  - HP OMNI 4150
  - Toshiba Tecra
  - Qube
  - Fujitsu 2300
  - Northcoast
Current status

- Completed evaluation flights on UAL A-320 and Delta B-777
  - "CHANGED ALT. TO TEST THE CAT FUNCTION. APPEARED TO WORK WELL."
  - "IMPLEMENT A S A P !!!!!!!!"
  - "NEED TO BE ABLE TO INSERT WPT'S INTO MIDDLE OF FLT PLAN ROUTINE."

- Additional, multiple evaluations now under contract and planned for the summer of 2001

- Officially a commercial offering

- Technical thrust
  - Further cost and function improvements
  - Overall robustness improvements
Our Airspace System

• Current and projected growth in the air carrier and air cargo industry is 5.6% for the next 20 years
  – Currently 11,000 jet aircraft worldwide
  – Projected 33,000 jet aircraft by 2019 (IATA, 1999/Boeing 2000)

• ATA projects a 250% increase in delays by 2007, caused by a 43% passenger increase and 2500 addl. A/C. (ATA, 1999)

• FAA projects that, in 2007, more than 800 million passengers will fly in the United States—three times the number who flew in 1980. (Gore, 1997)

• The ATS data link focus group suggests that “airline operations will be critically constrained by the year 2005 if nothing is done to curb delay growth.” (ATS Data Link Focus group, 1999)
NASA Langley WINN System Operational Assessment

Jon Jonsson, Ph.D.
NASA Langley Research Center
Aviation Safety Program
AWN B-757 Flight Test

OBJECTIVES

- Determine if near real-time weather information presented on the flight deck improves pilot situational awareness of weather.

- Identify pilot interface issues related to the use of WINN system during test flights.
Aviation Safety Program
AWIN B-757 Flight Test

APPROACH

- NASA pilots used for test subjects (4).
- Flights conducted on typical airline routes.
- Test flights scheduled on days of expected convection along the flight path.
- Video and audio recording of pilot use of WINN.
- Situational awareness data (verbal & scaled).
- Post test questionnaire.
Aviation Safety Program
AWIN B-757 Flight Test

Flight Deck Research Station (FDRS)  Conventional B-757
Near-Time Cockpit Weather Display on NASA B-757
Selected Post-Test Questionnaire Results

- Overall WINN interface intuitive to pilots.
- Bezel buttons preferable to touch screen to access weather products.
- Weather forecast products useful in decision making.
- WINN anticipated to save time and fuel.
- History feature useful for strategic planning.
- History feature not useful for tactical planning.
Selected Post-Test Questionnaire Results

✓ Colors on the display appeared clearly and accurately.
✓ Entering different altitudes to examine CAT wx product.
✓ METAR and TAF entry for reporting.

Δ Squawks corrected on WINN-Lite Display.
“Six to One; Half Dozen to the Other”

Areas Requiring Further Research

- ✔ Position of display.
- ✔ Ease of determining displayed weather product age.
- ✔ Identification of a precision controller.
- ✔ Ideal time for automated weather updates.
Generally I think, this [system] can obviously provide some very good strategic weather planning information. I still think that for tactical [flying]--deviating around individual cells--or looking out to about 100 miles, I would probably still prefer [using] my aircraft weather radar. But looking down the road, an hour or two down the road, this system could be very helpful.

How best to implement new products (NEXRAD, CAT) with existing systems?
Research Issues Emerging from 757 Flight Test

Color schemes with multiple weather products being shown on the display.

Cloud top information crucial for decision making.

NEXRAD: Is the db Reflectivity occurring at my cruise level or 10,000 feet below me?

Age of data.
  - Update Rate?
  - How to Display?
Questions and Comments
United's SKY-PAD™ Project

FLIGHT OPERATIONS TECHNOLOGY
innovations in flight

Capt. Joe Burns
Director – Flight Operations Technology
Overview

- Previous AWIN project
- Current AWIN/EFB Activity - Phase I
- UAL Future “Sky-Pad” activity - Phase 2-4
AWIN Team Members

- Honeywell Inc. (Team Lead)
- National Center for Atmospheric Research
- National Weather Service
- The SITA Group
- ARINC
- WSI
- Kavouras
- Allied Signal
- United Airlines
- NASA
Products WINN Tested:

- CONUS Radar*
- Worldwide Satellite*
- Convection*
- Nowcasting
- Airports (METARS/TAFS)
- Turbulence Forecast
United WINN Enablers:

- ClassTrax/CrewTrax
- TrainTrax
- PubTrax
- Netlink
- PalmLink
B-777 PAT Locations

- The First Officer's PAT location is on the right sidewall. The Captain's PAT is located on the opposite sidewall.
Aircraft Information System

- Dispatch
- Crew Desks
- Air Traffic Controllers
- Reservations
- Marketing
- Security
- Pilot Access Terminal (PAT)
- SAMC
- AMOSS
- WINN
- Ground Services
- Maintenance Access Terminal
  Located in cockpit
- Maintenance
- Passenger Services and Communications
- Onboard Services
- Flight Training Center
- Safety
- Located in cabin
- Medical Emergencies
Weather Information Network (WINN)

SIGMET, METARS, TAF, and airport ATIS information may be displayed in a graphic format and in text.

The FMC’s flight plan route is automatically displayed.

Data is displayed in a “North up” format or in a “Track up” format.

Winning data are available worldwide via automatic data link.

Proprietary information for making better decisions.

Enhances pilots’ situational awareness.

The WINN program automatically centers and tracks the aircraft’s location or by manually panning to any location.

UAL Sky-Pad
**Electronic Documents**

**Jepp View**

Origin airport tabs are displayed on the left side of document.

The FMC's current flight plan route is displayed on to High, Low, Area, Departure, and Arrival charts.

Waypoint functionality on charts is the same as on the Navigation Display.

Emergency escape route documents for high terrain areas are available (E RTE).

JappView interfaces with the FMC to select origin and destination airports' SID, STAR, runway data, emergency engine out procedures ("T Pro"), airport, and approach charts.

Aircraft's printer provides copies of selected chart.

Find and Help functions provide access to legend and glossary information.

**UAL Sky-Pad**
Current EFB/AWIN Project

- Just finished 40+ segments on A320 in-service evaluation
- 90% mission success rate
- Average of 1-2% per leg gain due to increased wx enhancement!
- Trial Turbulence plot very successful (+5 min. notification in radar style graphics)
- Potential reduction in 40-50% of ACARS traffic
Current EFB/AWIN Project

- Cooperative agreement helped pay for product development of our system
- Fujitsu Pen Tablet, GPS, GTE Airphone
- Tested products included:
  - WINN-Lite graphical Weather software with NEXRAD, Turbulence, SAT, SIGMETS, TAFs. METARs, etc in GPS Geo-referenced moving map.
  - Full World Jepp plates with moving map ship’s position overlay (including airport diagrams)
  - Digital FOM and AFM (from PUBTRAX)
Current EFB/AWIN Project

- 3.3 lbs vs 48
- At home/hotel Unimatic/Apollo access
- 50/50 Line/TK crews in Test
- First ever Approved use of Internet Protocol to 121 Line service flight deck
Joe and Dave with AWIN/EFB Unit

UAL Sky-Pad
Graphical Sigmets on WINN Display
Correlation with Display

UAL Sky-Pad
Correlation with Radar ND

UAL Sky-Pad
Future “Sky-Pad” activity – Phase II

- Potential funding from FAA
- Human Factors design in Simulators
- Permanently mounted monitor (same size as Jepp Chart) or Tablet on moveable arm with FMS style keyboard attached to moveable docking station
- L-Band, VDL/2, or Airphone weather receiver, power interface
- All EFB functions, weather, and Moving Map situation display (runway inc...
- STCs to be included
Future “Sky-Pad” activity – Phase II

- 2 Airbus aircraft to be part of FAAs OpEval/3 next May
- Teaming partners include:
  - L-band sat -or- VDL/2 Network -or- GTE
  - Commodity weather, messaging, receiver
  - NASA - funding?, WINN weather software
  - FAA - funding and certification
  - FMS style display vendor
  - UAL - Project management, General Contractor, digitized manuals, charts, hf
UAL “Sky-Pad” Fleet Deployment – Ph III

- A320/777 in 2002/2003
- All others in 2004-2005
- Includes - all paper docs, aircraft CBT, Weather Graphics, Wireless messaging, Animated Jepps, FMS position overlay, Moving Map, home access to all UAL network systems, home study and training, Bluetooth or RF airport link
Phase IV – Broadband integration

- 2003-05
- Integrates with broadband server
- Total high speed internet appliance
- 80% of AOC communications
- Customer Resource Management
- Crew Resource Management
Sky-Pad Payback and savings

- Shipping of charts and printing
- reduced weight
- medical out of service
- reduction in ACARS
- 1-2% reduction in annual fuel burn
- 2% reduction in total block time
- 80% reduction in all turbulence injuries
Questions?
Enhanced Weather Radar and Aviation Weather Awareness & Reporting Programs

Kevin Kronfeld
EWxR Program Manager
Rockwell Collins
Advanced Technology Center
Motivation

• Weather is the cause or contributing factor to nearly 25% of aviation accidents and 35% of fatalities.
  – *Improved weather information for pilots may break the chain of events that lead to an accident.*

• Weather is the number one source of flight delays in the United States.
  – *Improved weather information may provide pilots with a more efficient means of navigating around hazardous weather.*
Background

- In 1998, NASA initiated the Aviation Weather Information (AWIN) program.
  - Enhance the safety and efficiency of aircraft operations by improving the availability and quality of weather information to the flight crews.
- September 1998, NASA, Rockwell Collins, and Rockwell Science Center started two cooperative research agreements, termed Enhanced Weather Radar (EWxR), Aviation Weather Awareness and Reporting (AWARE).
EWxR

- 1999 Accomplishments:
  - Track storms.
  - Determination of storm dynamics, such as speed and heading.

- 2000 Accomplishments:
  - Integrate NEXRAD image data into ARINC 453 video data format and display it on a standard radar indicator, multi-function display (MFD), or xVGA monitor.
  - 9/24/00 - Successful flight test on NASA’s 757.

- 2001 Accomplishment
  - Flight plan analysis
EWxR Display
AWARE

- 1999 Text -> Graphics interpretation and decision analysis.
  - METARs and SIGMETs.
- 2000 Experimental NCAR products integration.
  - Icing, turbulence, convective weather products.
- 2001 IFR Summary Display Implementation.
  - Implement IFR Summary Display.
  - Incorporate Area Forecast data into Hazard Analysis model.
- 2001 PIREP Integration.
  - PIREP integration.
  - Hazard Analysis for IFR pilots.
- 2001 Demonstration on NASA 757.
AWARE Processing

_Parsing from text data_

**Weather Event Database**

- **Icing Event**
  - Unique_ID:
  - Spatial_Extent: ...
  - Temporal_Extent: ...
  - Type: Rime
  - Severity:
  - Direction:
  - Velocity:
  - Supercedes:

- **Turbulence Event**
  - Unique_ID:
  - Spatial_Extent: ...
  - Temporal_Extent: ...
  - Type: Clear air
  - Severity: Moderate
  - Direction:
  - Velocity:
  - Supercedes:

**Data models**

- Sufficient statistics analysis & Information filtering for planning
- Image/signal processing
- Flight planning assistance & Decision-support analysis
AHAS

- Develop flexible COTS-based platform with aircraft interfaces necessary for operational evaluation of:
  - AWIN systems
    - EWxR display formats, storm analysis, flight plan analysis logic
    - AWARE weather analysis and decision aids
  - Integrate new datalinked weather products from the AWC.
  - Integrate new atmospheric hazard sensors, such as the TDAM experiment.
Further Studies

- What ranges are useful for display of NEXRAD on a weather radar indicator?
- What will be the effect of simultaneously displaying radar data taken from different angles and altitudes?
- How well does the data from from various weather data sources correlate?
- What NEXRAD update rate is necessary and how much latency is acceptable?
- Which weather product(s) will be most useful?
Further Evaluations

- Continue experiments of EWxR, AWARE, and AHAS systems on NASA’s 757 through Fall 2001.
- Fall 2001 - Participate in FAA’s study of utility of ground-based weather information in the cockpit.
Satellite Weather Information Service
June 5, 2001 Update

R. S. Haendel
Agenda

- Overview
- Program Phases
- Phase 1 Description
- Phase 2 Aircraft Configuration
- Satellite World Wide Coverage
- Team Members
- Phase 2 Status
- Weather Graphics
- Air Coverage
- Data Routing and timing
- Weather Benefits
Overview

- In-service evaluation of real time graphical weather information on flight deck
- Provide updated graphical weather to pilots while enroute for strategic flight decisions
- Trials to verify commercial benefits and technology feasibility
- End solution is to provide wide area coverage for all classes of aircraft
Program Phases

- Phase 1, Installed on single engine aircraft
- Phase 2, Installed on two revenue service Air Transport Aircraft
  - Transoceanic routes
- Phase 3 Plan, Install on 6-15 aircraft, all types
  - Transcontinental routes
  - CONUS operations
Program Phases

Phase 1. Verified that geostationary satellite can provide a sufficient signal level to aircraft using a fixed pattern antenna.

- Trials in South Africa in September, 1999
- Cessna 182 aircraft, Afristar satellite

Phase 2. Validate the usefulness and pilots preferences of real time weather data

- Routes to the Pacific rim with American Airlines B777-200.
- Trials beginning June 2001, using Asiastar satellite

Phase 3. Planned extended trials to include Air Transport, Business, and General Aviation in USA and South America

- XM radio or other satellite (USA) , Early 2002.
- Ameristar satellite (S. America) , July 2002
Phase 1 System

WorldSpace Afristar Satellite (21° East)

TDM X-Band

TDM L-Band

Patch Antenna

WorldSpace Johannesburg (ROC) Regional Operations Center

Uplink Equipment

Transmission PC

Transmission Feeder Link Station (TFLS)

Flight Test Aircraft Cessna C172

Rockwell Collins
Phase 2 System Configuration

- Laptops
- File Server
- Satellite Receiver
- Low Cost Antenna
- Wireless LAN
Geographical Coverage

WorldSpace satellites located at:

- Africa serves entire Africa and some Europe
- Asia, serves all of Pacific rim from Korea through Malaysia China and Eastern Russia, India, etc.
- Central America (2002), serves S. American and Caribbean
WorldSpace Coverage Areas

(NOTE: AmeriStar footprint shown pending frequency coordination outcome)
Phase 2 Team Members

- **Rockwell Collins**
  - Data Storage, Displays, Receivers, Antennas, Integration, STC, Data Reduction and Analysis

- **WorldSpace Corporation**
  - Satellite channel, Receiver card, Ground Station Feed

- **Jeppesen**
  - Weather Products & Laptop Software

- **American Airlines**
  - STC Installation Support, Flight Test and Evaluation
Phase 2 Status

Systems installed on two American Airlines B777-200. STC approved by FAA. Aircraft now in revenue service.

System includes:

- Patch antenna,
- Satellite receiver,
- File Server Unit (FSU),
- Avionics Secure Interface Unit,
- Wireless LAN network and
- Pilot laptop computer(s)

Approved Software

Test Coverage uses Asiastar NE Beam.
Weather Graphics

- Winds and Temperatures aloft
  - Flight Levels 050 through 450
- Surface Weather (Ceiling, Winds and Visibility)
- Hi-level Significant Weather
- Visible and Infra Red satellite imagery
- Surface analysis
- Update rate varies from once per hour to once per 6 hours
  - Specific to type of graphic
- All weather graphics have track file and aircraft position overlays, zoom capability.
- Detailed geographic features and airport diagrams can be inserted by pilots as needed.
- File server provides “time lapse” weather movement graphics as called for by pilots
Satellite Infrared Imagery
N. Pacific High level Significant WX
Winds & Temps Aloft at 39,000 ft
Surface Analysis
Air Coverage and Pilot Updates

- Two B777-200 aircraft operate as needed for all long haul routes for American Airlines.
  - These aircraft are not restricted only to Trans-Pacific routes.
- City pairs presently covered include:
  - Chicago, Dallas, San Jose CA to/from:
  - Narita, Osaka and Taipei.
- System provides coverage using NE Asiastar Beam (see map)
  - Coverage enroute up to 5 hours.
- Pilots get same material on the ground via AA’s company Intranet at both ends of the routes.
- Analysis data obtained from Questionnaires and FDRs.
Data Routing

• Jeppesen generates weather graphics at scheduled intervals at Los Gatos, CA.
• Graphics are encoded and sent to WorldSpace GES in Melbourne, Australia and American Airlines in Dallas via Internet FTP.
• Melbourne GES uplinks each file to satellite 3 times at short intervals.
• Satellite transmits data at 64 Kbits/second.
• Satellite receiver recovers files, checks data validity and transfers valid data to File Server Unit (FSU) for storage.
• FSU manages data files and makes files available to pilot via WLAN on aircraft. FSU maintains aircraft position and time. Provides information to laptop to allow aircraft to be plotted on graphics.
• Time delay from Jeppesen to Aircraft is less than 60 seconds.
  • Satellite typical transmission time - 2.5 to 8 seconds
Weather Benefits

- American Airlines has keen interest in adverse weather.
  - Early flight change decisions based on weather data leading to:
    - Higher on-time arrival rates
    - Improved fuel savings
    - More comfortable ride to passengers (avoid turbulence)
  - Better weather data for remote routes such as South America and Pacific rim.
  - Enhanced flight safety
    - Reduce number of injuries due to unexpected turbulence.
PILOT WEATHER ADVISOR™

Rockwell Collins

Keith D. Hoffler
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Hampton, Virginia

NASA Weather Accident Prevention Workshop June 4-7, 2001
Outline

• Brief history of Pilot Weather Advisor™

• Pilot Weather Advisor™ - SBIR Phase III
  – System overview
  – Work planned

• Commercialization of Pilot Weather Advisor™

• Concluding remarks
NASA Storms Hazard Program

- 1978: Program initiated
- 1982: Uplink RADAR data to NASA F-106
- 1989: System studies of uplinking Wx data to cockpit

Norm Crabill: “Why can’t I have this in my airplane?”
SBIR Phase I and II

- Phase 1 awarded Dec. 1990 by NASA Langley Research Center
  - Developed display icons and system architecture
  - Demonstrated system using Qualcomm’s Omnitrac Satellite system aboard a Piper Malibu (fixed map)
  - Briefed NASA LaRC in ‘91 (NASA CWIN followed)
- Phase 2 awarded Dec. 1991 by NASA Langley Research Center
  - Developed and demonstrated GPS based moving map in C-182
  - Demonstrated cell phone based datalink before takeoff in a C-182
  - Developed business plan and sought satellite provider
  - Awarded US Patent #5265024 on Nov. 23, 1993
Since SBIR Phase II

- Matured system and business components for commercialization
  - Weather data
  - Airborne antenna and receiver
  - Datalink
  - Multi-function display and electronic flight bag
- Serve on RTCA SC-195 committee developing FIS-B MASP
- Revised client software and ported to CT-1000 and Flight Guide 3000
- Demonstrated in Cessna 182 using satellite phone
- Updated broadcast schedule – from every 15 minutes to 5 minutes
- Developing concepts for additional weather products
  - Lightning
  - Turbulence and icing
  - Winds aloft
  - Others
- Developed revised business plan
- Seek investment
- SBIR Phase III awarded by NASA Glenn – March 2001
Multi-Function Displays

- GA instrument panels are currently experiencing dramatic changes
  - Satellite navigation, GPS
  - Affordable daylight readable displays
  - FAA’s interest in benefits of new technology (FIS-B)
- Multi-Function Displays are becoming widely accepted
  - Panel mounted, portable
  - Wide cost range, applicable to all market segments
  - Ingest, process, and display various types of information
    - Present uses
      - Moving map
      - Engine monitoring
      - Attitude instruments
      - Onboard weather
    - Future capabilities
      - Datalinked weather
      - Traffic
      - Terrain
      - ATC directives

Avidyne display installed in Cessna 182
Electronic Flight Bags

Northstar CT-1000

ADR Flight Guide 3000
Work Planned

- Conform to FIS-B MASPS and MFD platform requirements

- Develop Hardware
  - Satellite link design: hub and receiver
  - Antenna design and qualify
  - Electronic flight bag
    - CT-1000
    - FlightGuide 3000
  - MFDs

- System Integration and Testing
  - Ground Integration Testing
  - Aircraft In-Flight Evaluations (begin October 2001)
PWA™ Coverage

- Full Continental US coverage at all altitudes
- All US data
  - Composite radar
  - METARs
  - TAFs
  - Other
- Colors now compliant with RTCA SC-195 FIS-B MASPS
- Higher resolution radar image (2km grid)
- CT-1000 initial user interface developed
- 5 minute update rate
PWA™ Animation Loop
PWA™ Commercialization

- ViGYAN has formed Indra Systems to commercialize PWA™
- Expect to make first announcement at Oshkosh, 2001
- Flight evaluations begin October 2001
- Limited sales late in 2001
- Expect certification in first quarter of 2002
- Expand to marine and other markets
- Additional weather products in the future
Concluding Remarks

- Pilot Weather Advisor™ system will be a NASA R&D and SBIR success story
- System provides continental US coverage at all altitudes
  - All continental US data
  - Automatic continuous updates
- Initial flight evaluations expected in October 2001
- **Indra Systems** has been formed to commercialize the system
The Results of the Evaluation of Using Lightning Data to Improve Oceanic Convective Forecasting for Aviation

Wx Accident Prevention Review (NASA)
Cleveland, Ohio
June 5, 2001
Dr. Alan Nierow - FAA (alan.nierow@faa.gov)
TOTAL LIGHTNING FROM NASA's OTD (1998)

Orbits: 3042  Areas: 137464
Flashes: 795063  Groups: 3758261
Events: 7685027
(Created: 06/07/99)

Flash scale

Oceanic Lightning Experiment

• WHY:
  • International Convective SIGMET Coverage (by AWC)
  • Explore possible requirement from other agencies

• WHO:
  • Sponsors: AWC, Global Atmospherics Inc (GAI) & FAA.
  • Networks: U.S., Canada, France, Germany & Japan.

• PARTICIPATION:
  • FAA→Oceanic ARTCCs (OAK, NYC) + MIA/JAX
    • CWSUs & Traffic Managers
  • Other→NWS/DoD/Airlines for Evaluation

• WHERE: Gulf of Mexico, Atlantic & Pacific regions

• DURATION: April 1999 - January 2000

NOTE: NASA’s AWIN Safety program investigating feasibility of displaying lightning data in cockpit
AWC product (Atlantic sector)
Need for Extended Coverage for
International Convective SIGMETs
Participants’ Responses

ENHANCED SAFETY

- AIRLINES - Yes, the only real-time tool available to meteorologists/dispatchers is satellite imagery which users often have trouble interpreting.

- NWS/FAA - This product can identify concentrated areas of convection outside of previous limitations, it most certainly has the potential of enhancing safety.

- DOD - Helps us avoid areas of turbulence caused by convection which cannot be predicted by current weather models.

- FAA - The ability to better predict and avoid areas of severe weather will increase the safety of flights.
Participants’ Responses (cont’d)

INCREASED EFFICIENCY

- AIRLINES - Knowing where the convective areas are enhances pre-flight planning which will save fuel...the product should be available to ATC, pilots and dispatchers.

- NWS/FAA - An oceanic weather short-term planning product (similar to convective SIGMETS) could be developed as a result of this product.

- DOD - Fuel savings and better routing would also result from the product.

- FAA - This product can allow controllers to slightly alter the routings if needed and keep the traffic flowing smoothly. There will be much less “reaction” to weather events based on PIREPS and deviation requests.
Results of the Experiment

- Lightning data found useful for producing International Convective SIGMETS
  - Provides AWC forecasters means of detecting oceanic convection in satellite imagery
- FAA personnel (TMU)/Airlines found it useful for flight planning over Gulf of Mexico, Western Atlantic, and Caribbean regions
- CWSUs issued Center Wx Advisory based upon this product
- DoD personnel used data to
  - Delineate potential areas of turbulence or windshear
  - Assist in pre-flight briefings over Caribbean & Central America
- Concerns
  - Tropical/Mid Pacific & Eastern Atlantic: Accuracy & detection efficiency needs improvement
**SUMMARY**

- **Collaborative Decision Making/Situational Awareness**
  - Capability to differentiate between clouds (cirrus) and convection
  - Improved common situational awareness of hazardous weather by ATC, dispatch & cockpit
  - Earlier track adjustment - minimal route deviation & enhanced thunderstorm detection in data-sparse regions

- **Future work**
  - Possible use of operational/experimental product via Internet, FAA WX system (WARP) for use by Traffic Managers and also into cockpit
  - Oceanic Convective products could utilize satellite/model data and lightning data for Strategic and Tactical planning purposes
  - OCND

*Note: MIT/LL study cited a $16M potential savings due more efficient flight routing & reduced incidence of turbulence-related injuries for Atlantic, Caribbean & South America*
Oceanic Weather Information: Oceanic Convective Nowcasting Demonstration (OCND)

Weather Accident Prevention Annual Review
Cleveland OH
5 June 2001

Tenny Lindholm
The National Center for Atmospheric Research
Boulder Colorado
Overview

- Oceanic/remote area aviation weather requirements
- On-going research addressing requirements
- Oceanic Convective Nowcasting Demonstration (OCND)
What the industry needs

- Timely generation and distribution of weather information for en route oceanic operations
  - Weather information (vs. data) addressing hazards
    » Convection
    » Turbulence—convective induced and clear air (CIT/CAT)
    » Icing
    » Volcanic ash dispersion
  - High-resolution (time and space) flight-level winds
  - Distribution infrastructure and displays—ground and airborne
What we are doing

- FAA sponsored Product Development Teams (PDTs) within AUA-430 and led by NCAR
  - Oceanic Weather PDT. Products for data sparse regions include
    » Convective diagnoses, nowcasts, forecasts
    » Turbulence, all types
    » In-flight icing
    » Volcanic ash
    » High resolution winds
  - National C&V PDT
    » High-resolution (time and space) national C&V diagnoses and forecasts
- Development and implementation of “intelligent weather systems”
Oceanic Weather

- "Intelligent weather systems"
  - Use of expert system framework to mimic what a meteorologist does to generate a forecast
  - Allows fast and precise assimilation of all data that can add skill to generate informational products
  - Result: rapidly and frequently updated, high resolution, 4-dimensional graphic of the weather hazard that is easily transmitted to ground and airborne users
Oceanic Convection

- For example, diagnosing and nowcasting convection
  - Visual satellite imagery to locate clouds
  - Infrared satellite imagery to determine cloud tops
  - Water vapor channel to determine spot winds
  - Global numerical model data for assimilating spot winds and creating a uniform wind field
  - Lightning data and cloud classification algorithms to distinguish convection
  - Plus use of any available ground station data and radar data

Integration yields a precise diagnosis and nowcast of convection in 3 dimensions


**OCND—Prelude to OWPDT**

- **Purpose**
  - Primary focus: Demonstrate and implement an end-to-end weather hazard and product dissemination system for remote/oceanic areas. Users include airline dispatch, air traffic control, and the airborne flight crew (data link).
  - Develop operationally useful weather products, including the automated process to create them, for remote/oceanic areas. Products include convection, turbulence, in-flight icing, and satellite-based winds (diagnoses, forecasts).

- **Participants**—NCAR (lead), United Airlines, Aviation Weather Center (NWS), Naval Research Laboratory, Oakland Oceanic ARTCC, ARINC

- **Sponsors**—FAA Aviation Weather Research Program (AWRP) and NASA Aviation Weather Information (AWIN) Program

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National Center for Atmospheric Research
OCND Program

- OCND regional focus—flights to/from CONUS and New Zealand/Australia
  - Automated product creation (convective hazards initially) at NCAR
  - Transmission to and display at United dispatch and Oakland Center
  - Data link to the aircraft via ARINC
  - Evaluation, feedback, and further development
Summary

- Convective diagnosis—ready now. Check it out at http://www.rap.ucar.edu/projects/ocnd/realtime_sys/
- Convective nowcasts, CIT, CAT, in-flight icing—in the development pipeline and will be ready for evaluation in FY03
- Product development includes dissemination infrastructure
- Initial feedback from flight crews and dispatch indicates the information is of high value
- Status of data link to the flight deck…
VHF Datalink (Mode 2) for Cockpit Weather for Air Transports

Weather Accident Prevention
2nd Annual Project Review
June 5-7, 2001
Cleveland, OH

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VHF Datalink (Mode 2) for Cockpit Weather for Air Transports

WxAP - Weather Information Communications

Experiments

• Overall Goal/Objective:
  – Assessment of the datalink capabilities of VDLM2 for potential use in dissemination of Weather to the cockpit in 2007 based on the WINCOMM requirements. This assessment will provide characterization including identification of any gaps for potential improvements/enhancements.

• Implementation Mechanism:
  – Ongoing in-house/external effort
  – Ohio University Grant

• Technical Results to Date:
  – Ohio University Grant:
    • The emphasis of this grant was to provide characterization of the Physical and Link Layer of VDLM2. A combination of both Lab and Flight Tests were conducted. The radios generally performed as expected with minor discrepancies being noted.
VHF Datalink (Mode 2) for Cockpit Weather for Air Transports

WxAP - Weather Information Communications

- **In-House**
  - An analysis of existing studies and simulations were performed looking at the full 7 Layer Stack, Application Layer to Physical Layer. Results were inconclusive due to unresolved conflicts existing between the studies and simulations.

  - **Future Plans:**
    - Additional testing and analysis to resolve discrepancies noted in the Ohio University testing.
    - Modeling and simulation of VDLM2 to resolve conflicts identified in the existing studies and simulations analysis.
    - Performance characterization of VDLM2 in a relative environment with a representative traffic load depicting a fully loaded VDLM2 operational network.
Preliminary VDL Mode 2
Bench and Flight Test Results

Trent A. Skidmore and Aaron A. Wilson
Ohio University Avionics Engineering Center
Presentation Overview

- VDL Integrated Performance Evaluation Rack
  - VIPER Ground & Airborne Equipment Description
- Pre-flight Bench Testing
  - Spectral characteristics and Receiver (Rx) sensitivity
  - Block Diagram & Sample Test Message
- Flight Testing
  - Goals
  - King Air Antenna Performance
  - Flight Test Results
VIPER Equipment Description

• VDL Mode 2 (VDLM2) Equipment
  – Park Air Radio (PAR) 5525D8 Multimode Transceivers
    • Currently operate in transmit (Tx) or receive (Rx) mode only
    • Advanced Relay Corporation HDLC Cards

• Host Computers
  – CyberResearch MPC-6020 with 10.4” LCD Display
    • Software configures Tx or Rx option
    • Spectrum analyzer & Ohio U. program measures power

• GPS Receivers
  – Novatel 3151 (12 Channels)
VIPER Ground and Airborne Components

- Top
  - Novatel GPS Receiver
- Middle
  - Park Air VDL Mode 2 Transceiver
- Bottom
  - CyberResearch Computer
VDL Mode 2
Bench Test Configuration

- Bench test simulates flight test environment
- VIPER Tx Computer Generates Test Messages
  - Simulated “weather-related” data (Actual weather info to be used later)
  - Message length and duty cycle limits require further investigation
Measured Spectral Characteristics

Park Air Radio Spectral Output (118, 127, 136 MHz) with Max Hold & RBW = 1 kHz

Indicated Power (dBm) vs. Frequency Offset from fo (kHz)
**Tx Characteristics**

- Tx computer generates test messages
  - 223 bytes in length
  - Message counter for determining message count
  - GPS location of Tx station
  - Random fill bits
  - 32-bit checksum
  - Weather-related messages will be used eventually
- Messages rate = approx. 3/2 seconds = 1.5 Hz
- Power measured with HP8591E Spec Analyzer
  - Resolution Bandwidth (RBW) = 1 kHz for trace
  - RBW = 30 kHz for sensitivity measurements
Rx Mode Characteristics

- PAR VDLM2 equipment does not output “bad” messages
  - Raw Bit Error Rate (BER) not readily available
  - Use Message Failure Rate (MFR)
  - Determine sensitivity by post-processing data
- Reported MFR based on 10,000 messages
  - Test time per data point was approximately 2 hours
- Screen displays GPS time, range, message count, and count difference
Measured Sensitivity (view 1)
**Measured Sensitivity (view 2)**

- Set MFR=1e-6 for plotting purposes
- Interpolated Sensitivity Points

<table>
<thead>
<tr>
<th>Power (dBm)</th>
<th>Approx. MFR</th>
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<tr>
<td>-101</td>
<td>1e-5</td>
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<td>-103</td>
<td>1e-3</td>
</tr>
<tr>
<td>-104</td>
<td>1e-2</td>
</tr>
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</table>

Measured sensitivity compares well with -103 dBm claimed by manufacturer.
Flight Test Preparation

King Air C-90 (N200U) Aircraft

- Vertically Polarized (VPOL) Rx antenna on top of aircraft fuselage
Flight Test Configuration

VDLM2 Ground Station

GPS and VHF Antennas on Hangar Roof

Novatel GPS Receiver

VIPER Transmit Computer

VDL Mode 2 Transmitter

VDLM2 Airborne System

GPS and VHF Antennas on top of aircraft fuselage

Novatel GPS Receiver

Signal Splitter

VDL Mode 2 Receiver

21 dB Amplifier

VIPER Receive Computer

HP 8591E Spectrum Analyzer
Flight Test Profile

- Tested the 210° compass radial to the extent of coverage at two altitudes above ground level:
  - 2,000 ft. AGL (typical minimum vectoring altitude)
    - Timely weather should not be needed below this altitude
  - 18,000 ft. AGL (bottom of current ARINC coverage)

210° radial chosen from Ohio University Airport (UNI) to minimize traffic-based course deviations.
Current Method for Measuring In-Flight Received Power

- Use HP8591E Spectrum Analyzer (SA)
  - Power Measurement Settings
    - Resolution Bandwidth = Video BW = 30 kHz
    - Center measurement on known Tx frequency
      - Max Hold for 3 seconds
        - Allows for non-synchronized operation (SA & VDLM2)
    - Peak Search and record value at center frequency
- Customized Ohio U. data logging software
  - Multitasks with VIPER software under Windows 2000
  - Time tags power measurement with GPS time for post processing
A Collection of Interesting Pictures
Data File 1
Shakedown Flight
Data File 1
Shakedown Flight (2)
Predicting Performance at 2,000 ft and 18,000 ft (AGL)

- Model written by Ohio University
- Models terrain as uniform spherical earth
- Can vary surface conditions
  - Salt water - Swamp
  - Fresh water - Desert
  - Average earth (used in this analysis)
- Assume isotropic VPOL Tx antenna
- Coverage performance varies from free space due to multipath and path length difference
Predicting Performance (2)

- Rx at 2,000 ft
  - Signal expected to be lost at ~45 NM
- Rx at 18,000 ft
  - Signal expected to be lost at ~140 NM
- Signal increase beyond loss region is artificial (need model update)
- Radio horizon using 4/3 earth radius propagation estimate
Data File 2
Radial at 2000 ft AGL
Data File 2
Radial at 2000 ft AGL (2)
Data File 3
Radial at 18,000 ft AGL

Ground Track with Message Errors Indicated (o) (File: UNI4)

Outages caused by air-to-ground communications
Data File 3
Radial at 18,000 ft AGL (2)
Comparing Received Signal Strength to Predicted (2,000 ft)
Comparing Received Signal Strength to Predicted (18,000 ft)
Comments on Received Data versus Model Prediction

- Flight test data and model are not in very good agreement (yet) - still under investigation
  - Flight data is biased from model (6 - 16 dB)
  - Model predicts location of fades at 18,000 ft AGL
- Potential sources of model mismatch
  - Rx and Tx antenna calibration error
  - Tx antenna on hangar edge
  - Non-uniformity of local terrain

Flight test data & model agreement with Horizontal Polarization and the LAAS VDB has been very good.
Decision-making in flight with different convective weather information sources: Preliminary Results from the Langley CoWS Experiment (COnvective Weather Sources)

Jim Chamberlain
Crew Systems & Operations Branch
NASA Langley Research Center

Kara Latorella
Crew/Vehicle Integration Branch
NASA Langley Research Center

Presented at the NASA Weather Accident Prevention Workshop—2001 – Chamberlain & Latorella
Outline

- CoWS Experimental Apparatus Development
  - Ground Station
  - B200 Aircraft
  - Airborne System

- CoWS Experiment
  - Experimental Conditions & Objectives
  - Procedures
  - Preliminary Results
  - Conclusions
  - The Future of CoWS
Experimental Apparatus

Approach
Use CRA-developed, removable tethered-display AWIN system in B200

Apparatus
• Honeywell CRA AWIN ground stations
• Langley B200 Super King Air
• Honeywell CRA tethered AWIN system
Ground Infrastructure

Typical Honeywell CRA

AWIN Ground Station

- Satcom antenna & receiver
- Processor & power supply
- VDL transmitter & antenna

Ruggedized, Compact, Self-Contained

AWIN Receiver/Processor at RTI/Hampton can record Wx
Test Range

- Five ground stations, 40nm radius
- Four destinations & flight paths
AWIN Architecture

VHF Antenna

VDL Receiver

Processor, Scan Converter

GPS Antenna

GPS Receiver

Processor, Scan Converter

28 VDC Power

Power Supply

Subject's AWIN Display

Experimenters AWIN Display

Antenna/Power Connections

Seat-Mounted Pallet

Tethered Displays

Presented at the NASA Weather Accident Prevention Workshop- 2001 – Chamberlain & Latorella
Equipment Pallet in the B200
AWIN Display in B200
AWIN Input Devices

Presented at the NASA Weather Accident Prevention Workshop - 2001 - Chamberlain & Latorella
AWIN Display Elements

Presented at the NASA Weather Accident Prevention Workshop - 2001 – Chamberlain & Latorella
CoWS Experiment

- Motivation
- Objectives
- Participants
- Experimental Design
- Experimental Protocol
- Preliminary Results
- Conclusions

Presented at the NASA Weather Accident Prevention Workshop - 2001 - Chamberlain & Latorella
Experimental Motivation

- General aviation accident statistics
- The hazards of convective weather
- Aviation Weather INformation (AWIN) systems
Experimental Objectives

How do GA pilots use different weather information sources when approaching convective weather situations?

• Sources
  – Conventional aural (ATC, HIWAS, Flight watch),
  – Out-the-window visual scene + aural
  – AWIN display + aural

• Effects
  – Confidence, Workload, Information Sufficiency
  – Situation awareness, decision quality, individual differences
Participants

• 8 Check-out, 12 Experimental, 6 reported here

• Subject Requirements
  – local GA pilots
  – instrument rating
  – 50-1000 cross-country or 250 - 1000 total flight-hours
  – Has not worked for a scheduled air-carrier in prior year
  – Has not participated in the RTI FISDL simulation study

• Subjects clustered by cross-country hours
  – low (135), medium (379), high (738) (p<.0001)
  – 4 teams of 3 subjects (one of each level)

Presented at the NASA Weather Accident Prevention Workshop- 2001 – Chamberlain & Latorella
Inflight Experimental Conditions

- For each flight

<table>
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<th>“IMC”</th>
<th>VMC</th>
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<tr>
<td>Without AWIN</td>
<td>Aural Cues</td>
<td>Aural + Window</td>
</tr>
<tr>
<td>With AWIN</td>
<td>Aural + Display</td>
<td>X Aural + Display + Window</td>
</tr>
</tbody>
</table>

- For each subject (cue set condition)
  - 6 “proximity” observations of confidence
  - 1 observation of workload & information sufficiency

- Three flights per team
Experimental Conditions in B200

- Aural+Window Subject
- Experimenters
- Pilot in Command
- Aural+Display Subject
- Aural only Subject

Opaque covers for side windows & onboard radar

Presented at the NASA Weather Accident Prevention Workshop – 2001 – Chamberlain & Latorella
Scenarios

• Mission Motivations
  – wedding, graduation, job interview

• Flight Scenario
  – Flying IFR, but in VMC
  – NASA to destination, 1.5-2 hours
  – Convective fronts, moderate+ intensity
  – Approach front ~45°

• Aircraft Performance ~ small single-engine
  – Cruising Altitude = 14000’, above haze layer
  – Cruising Speed ~ 170kts true airspeed
  – not radar-equipped, no deicing equipment
  – not pressurized, but does have Oxygen

Presented at the NASA Weather Accident Prevention Workshop~ 2001 – Chamberlain & Latorella
Scenario Flight Paths

- Test range: 5 ground stations, 40nm radius
- Four destinations & flight paths

- Charleston, WV
- Clarksburg, WV
- Abingdon, VA
- Hickory, NC

Presented at the NASA Weather Accident Prevention Workshop: 2001 - Chamberlain & Latorella
Experimental Protocol

• Preflight
  – Introduction to CoWS, assignment to conditions
  – Mission, route, and regional information briefing
  – Weather briefing
    » DUATS text & graphics,
    » Audiotaped FSS briefing, twice
    » Review
    » Preflight SA questionnaire
  – Intervening tasks
    » AWIN training, personality, risk, weather knowledge test

• Flight
  – Outbound phase
  – Inbound phase

• Debriefing

Presented at the NASA Weather Accident Prevention Workshop - 2001 – Chamberlain & Latorella
In-flight Protocol

Outbound Protocol
- ATC
- Pilot Report
- FW
- Pilot Report
- HIWAS
- Pilot Report
- Weather SA Questionnaire

Inbound Protocol
- Draw position & weather
- Inbound questionnaire
- Usability questionnaire

Presented at the NASA Weather Accident Prevention Workshop - 2001 - Chamberlain & Latorella
Preliminary Results - Confidence

• Summary of ANOVA
  – Cue set ~ Highly significant \((p<.0001)\)
  – Proximity to weather ~ Not significant \((p=.691)\)
  – Cue set X Proximity ~ Not significant \((p=.275)\)

• Pair-wise comparisons (LSD)
  – Aural v. Window \((p<.0001)\)
  – Aural v. Display \((p<.0001)\)
  – Window v. Display \((p=.491)\)
Preliminary Results - Information Sufficiency

- Summary of ANOVA
  - Cue set ~ Significant ($p<.061$)

- Pair-wise comparisons (LSD)
  - Aural v. Display ($p=.009$)
  - Window v. Display ($p=.094$)
  - Aural v. Window ($p=.242$)

Number of Additional Sources Requested

- Aural: 12
- Window: 9
- Display: 6
Preliminary Results - Workload

- **Summary of ANOVA**
  - **Performance Rating**
    » *Cue set ~ Significant* ($p<.091$)
    » *Subjects ~ Significant* ($p<.03$)
  - **Physical Rating**
    » *Subjects ~ Significant* ($p<.02$)

- **Pair-wise cue set comparisons (LSD)**
  - **Performance ~ not significant**
    » *Trend: Aural < Display, Window*

- **Subjects did report that workload was similar to that when actually flying.**
Conclusions

- Reliance on AWIN in IMC and close to hazards
  - As confident as visuals - possibly over-confident
  - Less likely to seek information from ground sources
  - Perceived performance similar to window condition
  - Data is at least 6 minutes old, was as old as 30 minutes

- Implications: design, training, & use guidelines
  » RTCA FIS-B Minimum Aviation System Performance Standards.
  » Document: DO-267
  » note added to indicate need for age v. timestamp
  » Need more salient indication or alerting
The Future of CoWS

- Other Experimental Results
  - Full data set - Effects of cues on inflight SA & decisions
    » proximity to convective frontal weather
  - Effects of individual characteristics
    » personality, risk tolerance, weather knowledge
  - Effects of weather graphics on preflight SA

- Usability Assessment of an available AWIN system

- Canned cues for subsequent comparative analysis
  - Onboard weather radar, AWIN radar mosaic,
  - Pilot observations, ground sources (ATC, FW, FSS),
  - HIWAS, video of external view.
CoWS
Convective Weather Sources

Questions?
General Aviation
Cockpit Weather Information System
Simulation Studies

Ray McAdaragh, Ph.D.
FAA Human Factors Division / NASA AWIN Program

Paul Novacek
Research Triangle Institute (RTI)

FAA / NASA Cooperative Research

June 5, 2001
Project Goals

- Develop a Better Understanding of the Use of Data-Linked Weather Information
- Provide Guidance to FAA/Manufacturers on the Use of Data-Linked Weather Information
- Recommend Guidelines for Inclusion in the AIM and ACs
Description

- A Series of Rigorous Investigations Using Piloted Simulation of the Effects of Various Data-Linked Cockpit Weather Information Treatments
Research Triangle Institute (RTI) Completed Experiments

- Use of a Data-Linked Weather Information Display and the Effects on Navigation Decision Making in a Piloted Simulation Study

- The Effects of Ownship Information and NEXRAD Resolution in use of a Weather Information Display
Research Triangle Institute (RTI) Current Experiment

- An Investigation into the Use of NEXRAD Image Looping and the Use of the National Convective Weather Forecast Product on a Moving Map Display for General Aviation
First RTI Experiment

June 1999 to August 2000

Investigate the use of a Data-Linked Weather Information Display and the Effects on Navigation Decision Making in a Piloted Simulation Study
Objective & Hypothesis

- **Objective:** To investigate the potential for misuse of weather information, and thus provide guidance to the FAA

- **Hypothesis:** Delayed weather information datalinked to a cockpit display may lead to navigation decision errors
Experiment Design

- Two groups of pilots, 12 with a datalinked weather display and 12 without a weather display
- The simulator mission consisted of a two-leg mercy flight with convective weather along the route
- All subjects were current Instrument Flight Rules (IFR) qualified pilots
- Primary data collected consisted of weather related navigation decisions.
RTI Simulation Hardware Configuration
RTI Cockpit Research Facility
Datalinked Weather Display Configuration
Datalinked Weather Display Screen Layout
Mission Scenario

Take-off from Newport News
   Pick-up medicine at Richmond
      Encounters thunderstorm that prevents landing at Richmond (decision 1)
      Divert or waved off from Richmond
   Continue flight to Wallops Island with medicine.
      Encounters thunderstorms enroute to Wallops (decision 2)
   Lands successfully at Wallops Island Airport
Experiment Procedure

1. Pilot given Risk Aversion and Weather Knowledge tests
2. Pilot briefed on mission, simulator and weather display
3. Pilot provided instruction and practice in the simulator
4. Pilot planned flight (charts, weather reports provided)
5. Pilot performed the mission, data was collected
6. Pilot completed Immediate Reaction Questionnaire
7. Pilot participated in structured interview, data was collected
8. Pilot completed open-ended questionnaire

(each experiment session took approximately 5 hours)
Conclusions

- The weather display system used in this study did not improve pilot decision making
  - Situational awareness increased but at a cost of higher workload
  - Pilots were unable to easily perceive their proximity to potentially hazardous weather conditions
  - Pilots had difficulty determining storm movement
  - Display caused less reliance on other weather sources
Recommendations

• Provide the following features
  – Ownship information symbology
  – Direction and rate of hazardous weather
  – Intuitive NEXRAD image age information
  – Provide METAR code translation
  – Develop training curriculum
  – Emphasize that a weather display not to be used for navigation
Second RTI Experiment

September 2000 to April 2001

Investigate the Effects of Ownship Information and NEXRAD Resolution in the use of a Weather Information Display
Objective & Hypothesis

- **Objectives:** Explore the relationship between delayed uplinked weather information and aircraft ownship. Explore the effect of differing sizes of NEXRAD cell size on pilot judgement.

- **Hypothesis:** There is a potential for misuse of delayed weather information superimposed onto a moving map display with aircraft ownship. Additionally, weather display resolution is an integral element of weather situational awareness, and has a significant effect on pilot judgement.
Comparisons of follow-on experiment to previous baseline experiment

Experiment similarities:
- Identical facilities
- Similar subject pilot selection process
- Similar data collection (expanded)
- Identical materials and procedures
- Similar data analysis (expanded)

Experiment differences:
- Addition of ownship symbology to weather display
- One group of 12 pilots used 4 km NEXRAD cells
- The other group of 12 pilots used 8 km NEXRAD cells
Datalinked Weather Display with Addition of Ownship Symbology
Comparison of Small and large NEXRAD cells

(both maps cover identical geographical areas)
Relationship to Previous Baseline Experiment

Follow-On Experiment

Group A
12 Pilots
No Weather Display

Group B
12 Pilots
With Small Weather Cell Display

Group C
12 Pilots
With Ownship and Small Weather Cells

Group D
12 Pilots
With Ownship and Large Weather Cells

Previous Baseline Experiment—Neither group has Ownship Symbology

(red arrows denote statistical comparisons)
Mission Scenario
(identical to baseline experiment)

Take-off from Newport News
Pick-up medicine at Richmond
Encounters thunderstorm that prevents landing at Richmond (decision 1)
Divert or waved off from Richmond

Continue flight to Wallops Island with medicine.
Encounters thunderstorms enroute to Wallops (decision 2)
Lands successfully at Wallops Island Airport
Experiment Procedure

1. Pilot given Risk Aversion and Weather Knowledge tests
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6. Pilot completed Immediate Reaction Questionnaire
7. Pilot participated in structured interview, data was collected
8. Pilot completed open-ended questionnaire

(each experiment session took approximately 5 hours)
Data Collection

The primary data collected consisted of weather related navigation decisions...

— good or poor, based on objective criteria

... and the weather information gathering methods used to arrive at those decisions.

— weather services used, and how the pilot integrated the information
Conclusions

• Datalinked weather display increased situational awareness of hazardous weather

• Introduction of ownship symbology did not increase number of good decisions, but did decrease workload

• Introduction of larger NEXRAD cells did have a positive effect on decision making

• Use of datalinked weather display compelled some pilots to forgo use of corroborating weather sources

• Textual METAR teletype codes were difficult to decipher in high workload situations

• Pilots questioned validity of METAR data due to age

• Larger NEXRAD cells contributed to stimulus area effect
Recommendations

• Provide ownship information symbology
• Provide more effective means of distance determination
• Provide intuitive NEXRAD image age information
• Train pilots in the use and limitations of datalinked weather displays
• Provide METAR teletype code English translations
• Investigate depiction of direction and rate of hazardous weather movement
Overview of Continuing Research
(started May 2001)

An Investigation into the Use of NEXRAD Image Looping and the Use of the National Convective Weather Forecast Product on a Moving Map Display for General Aviation

- Determine the effects of NEXRAD looping on pilot decisions and workload
- Determine the effects of using a nowcast product on pilot decisions and workload

The experiment will be similar in design, procedures, equipment, mission and analysis to the previous two experiments
Datalinked Weather Display with the National Convective Weather Forecast Product

(blue outlined areas indicate one-hour forecast of cell movement)
Some Possible Future Experiments

- Investigation into the use of Data-Linked Weather Information Display with Enhanced Weather Products and Decision Aids during Collaboration with Weather Service Providers (Collaborative Decision-Making Training Issues)


- Investigation into Workload and Decision-Making Effects of an Integrated Weather and Navigation Display System
QUESTIONS?
General Aviation FIS Broadcast System

Honeywell International
AWIN System Project Overview
AWIN Phase I Overview
AWIN Phase II Plans
FIS Overview
AWIN Phase I Overview

- Developed Airborne Receivers and Displays
- Developed and built Ground Stations
- Deployed VDL Mode II Ground Stations
  - MN, WI, CO, KS, VA
  - VA stations used for CoWS Experiments
- Provided technical support for the Ground Station network.
Petersburg VA
AWIN Phase II Overview

- Support Mid-Atlantic Test Range
- VDL Mode 2 RF Propagation Study
- Bi-directional FIS Study
- FIS Lightning Data Product Study
- Miniaturized VDL Mode 2 Radios
Test Range Support

- Continuation / Enhancement of AWIN VDL Mode 2 Network
  - Technical support for VA Ground Stations
  - Exploring transition to FIS network by implementing a Private Experimental Channel
    - Leverage FIS Subscription Control Encryption
    - Only NASA will be able to read the data
    - Allows the continuation of experiments and new data product evaluations

- License Display Software
Flight Testing Program

RF system performance tests
- Single transmitter located in Olathe
- Transmitted packets with known data
- Aircraft flew at 5000 ft AGL
- 19" rack Rx in Aircraft
- Multi-flight test (>40 hours total)

Data Collection
- Time
- GPS Position
- Bit Error Rate (BER)

Data Usage
- "Calibrate" RF simulation tool
- Refine Ground Station placement
VDL Mode 2 RF Propagation Analysis

White lines show the aircraft position where BER was less than $10^{-3}$
Bi-Directional FIS Study

- Bearer System Evaluation
  - Focus on GA market parameters
- Return Path Usage Analysis
  - User requests tailored service
  - Response uplinked via FIS-B system
- VDL 2 Augmentation
  - Geographical footprint
  - Altitude
Lightning Data Product Analysis

- Examine the differences between lightning data collected by on-board systems and terrestrial network data
  - Cloud-to-cloud vs ground strike
  - Data latency
  - Position accuracy

- Leverage the study to determine education parameters for FIS users
Miniaturized VDL Mode 2 Radio

• Increment 1
  – Mini VDL2 Receiver
  – Increase integration of safety products
  – Generate platform for portable FIS receiver

• Increment 2
  – D8PSK “Radio on a Chip”
  – Transceiver
  – Enable further integration, create a next-generation portable platform core
FIS Overview
BASIC Products
- METARs
- PIREFs (pilot reports), urgent and routine
- SPECI surface observations
- TAF terminal forecasts
- AIRMETS
- SIGMET
- Convective SIGMETs
- Alert weather watches

Value-Added Products
- NEXRAD
- Graphical METARs
- NOTAMs
- Graphical SIGMET and AIRMET display
- NLDN lightning data
- Special use airspace status
- Winds aloft information
- Convective nowcast
- Icing nowcast
- Turbulence nowcast
KMD 550 Multi function Display

KDR 510 FIS Receiver

KGS 511 Ground Station
Independence KS

June 5, 2001
Lyons KS

June 5, 2001
FIS Installations
FIS Architecture Study Plan

JHU/APL

Robert Nichols and William Kasch
Information Transfer Group
JHU Applied Physics Laboratory
Laurel, MD

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Outline

• Study Background
  - NASA/Glenn Tasking
  - APL Overview

• Architecture Process
  - Schedule
  - Requirements
  - Technology
  - Candidate Architectures
  - Scoring

• Summary
NASA/Glenn Tasking

- NASA/Glenn has tasked APL to “support the investigation of systems and architectures, currently under development, that have the potential to support the dissemination of timely weather information to aircraft”
  - VDL Mode-4, Mode-S (1090), UAT modeling/simulation for TAMDAR (EPIREP) and FIS-B
  - FIS architecture: independent assessment to determine a single optimum WINCOMM architecture
- Focused on 2007 - 2015 implementations
- Period of performance - 9 months
Applied Physics Laboratory

- Not-for-profit university research and development laboratory
- Division of The Johns Hopkins University founded in 1942
- Staffing: 3,300 employees
  105 subcontractors
  (64% scientists & engineers)
- Annual commitment level:
  ~$500M (75% DoD)
# APL Communications System Development Spectrum

## Concept Development, System and Operational Architectures, Proof-of-Concept Demonstrations, Technology Assessment and Development
- Army FCS
- Turbo Code
- Software Radio
- Turbo CPM
- SATCOM Planning Integration
- SATCOM for Missile Defense
- Multifunction Buoyant Cable Array

## Concepts of Operation, System Specifications, Statements of Work, RFPs
- AEHF Terminal
- Control CONOPS
- SATCOM for JCTN
- WAMS

## Source Selection Teams, Independent Technical Evaluation Teams
- ADS-B Link Eval.
- MUOS AoA
- Teleports AoA
- Advanced EHF Crypto. System

## System Production and Testing
- DIMS
- ODOCS
- Polar EHF
- Wavelet Compressed Video

## Integrated Product Teams, System Integration Testing
- CNPS
- IMPCS
- NASA TDRS
- Tactical Tomahawk

## System Operations Research, Field Testing and Follow-On Engineering Support
- CEC Range Extension
- NESP
- MDR
- Terminal Testing
- FBM & SCAP

(Selected Programs)
Architecture Assessment Process

- Previous WINCOMM Studies
- NASA/Glenn
- Comm. Technology Surveys

FIS Requirements → Technology Descriptions → Candidate Architectures → Scoring → Scoring & FIS Architectures
### High-Level Schedule

*Draft*

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<tr>
<th>Tasks</th>
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<th>CY02</th>
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<tr>
<td>- Sensitivity</td>
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Requirements

- The assessment of WINCOMM architectures will require a precise description of requirements
- Requirements will be generated from:
  - Existing studies when possible
  - NASA/Glenn and APL in cases of new requirement areas
- The requirement areas to be considered will include (in no specific order):
  - **Capacity**
    - What are the information exchange requirements?
    - What are the per aircraft and aggregate data rates to be supported?
  - **Connectivity/Topology**
    - What topology will be suitable/achievable for WINCOMM (e.g., hub/spoke, flat)?
Requirements (cont’d)

- Requirements areas (cont’d)
  - **Number of elements**
    - How many aircraft must be supported in the architecture?
    - How many other elements (ground nodes) are required?
  - **Platform constraints**
    - What aircraft constraints exist in terms of size/power/weight?
    - What ground node constraints exist?
  - **Coverage**
    - Is global or regional coverage required?
    - Will requirements change with aircraft flight phase?
  - **Link availability**
    - What is the expected percentage of time that the link will need to be available?
    - Is this characterized by successful message receipt?
Requirements (cont’d)

- Requirements areas (cont’d)
  - **Latency**
    - What are the required timing constraints on information receipt?
    - How does this vary by information type, aircraft type and flight phase?
  - **Cost**
    - What is the targeted aircraft cost?
    - What are the constraints on infrastructure cost?
  - **Traffic type**
    - Is the traffic expected to be continuous or bursty?
    - If bursty, what are appropriate statistics?
  - **Protection**
    - Should the link information be encrypted and/or protected in particular ways?
Technology

- Technologies will be identified from previous studies and APL surveys.
- Possibilities include both LOS and SATCOM systems projected to be mature in the time frame of interest.
- All possess advantages and disadvantages. Examples:
  - Existing aviation links may have lower cost due to current equipage and infrastructure.
  - SATCOM provides large coverage and broadcast capabilities.
  - Cellular infrastructure in place but coverage limitations exist.
  - Etc.
## Technology (cont’d)

### Example Technologies for Consideration

<table>
<thead>
<tr>
<th>Aviation Links</th>
<th>Satellite Communications</th>
<th>Related Technologies</th>
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<tr>
<td>- ADS-B candidates</td>
<td>- GEO/MEO/LEO constellations</td>
<td>- Compression</td>
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<td>- GSM</td>
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<td>- UMTS</td>
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</table>
Candidate Architectures

- Architectures will be developed using the technologies with input from the requirements
- Architectures may consist of a single communications technology or hybrid concepts

An example hybrid:
Scoring

- Scoring necessary for two reasons:
  - To quantitatively determine the ability of an architecture to support each requirement (quantify the advantages and disadvantages)
  - To combine the varied requirements into a single score for ranking purposes
- Quantitative approach will be developed by APL and NASA/Glenn
- Sensitivity analysis will be conducted to examine the dependencies of different scorings and weightings
- Similar approaches used by APL in recent DoD Analysis of Alternatives
Summary

- Goal of task is to determine the best communications architecture to support FIS
- A process has been developed to enable an independent assessment while leveraging the substantial investments already made
TAMDAR Development Strategy
Tri-Agency Team

Prepared for the
NASA Weather Accident Prevention
Annual Project Review
June 5-7, 2001
Sandra Schmidt
FAA Aviation Weather Policy Division, ARW-100
202-366-4437
Background

- Formed TAMDAR Interagency Team
  - FAA/NASA/NWS
- Developing Operational Concept for collection and distribution of Aircraft Derived Meteorological Information below FL200
- Conducting TAMDAR studies to provide input to the FAA alternatives analysis.
  - NASA Langley - Sensors & Incentives
  - NASA Glen - Communication Alternatives
  - FSL - Data Quality
Government Initiatives

- FAA/NWS partners in current Meteorological Data Collection and Reporting Service (MDCRS)
  - MDCRS data is basis for quality of current RUC model forecasts
  - TAMDAR data could fill current data void regions leading to even better RUC model forecasts
- FIS Data Link Policy addresses the need to conduct investment analysis
- FAA Safer Skies recommended study of government/industry role in the development/implementation of TAMDAR system
Benefits

- Improve quality of Models/Forecasts to include warnings/advisories
- Alert NAS users of weather hazards
- Confirm existing weather conditions
Issues/Concerns

• Quality and Coverage of Aircraft Derived Meteorological Data
• Accuracy of Sensors
• Development of Business Case to support system architecture
TAMDAR Capabilities Development

June 6, 2001

Taumi Daniels
NASA Langley Research Center
Hampton, Virginia
(757) 864-4659
t.s.daniels@larc.nasa.gov
Outline

- Goal & Background
- TAMDAR Sensor Development & Testing
- Coverage Analysis
- Related FAA & NOAA Activities
- Fleet Operational Evaluation
- Alternate Method
- Summary
"Demonstrate a TAMDAR system capability through a fleet evaluation in the NAS under a FAA, NOAA, NASA, and Industry joint effort."
TAMDAR Background

National Aviation Weather Program Council (Federal Coordinator for Meteorology, NASA, FAA, NTSB, NWS, DOD, Department of Agriculture)

- National Aviation Weather Program Strategic Plan, April 1997
- National Aviation Weather Initiatives, January 1999

- Implement data link capabilities for Flight Information Services (FIS)
- Develop and implement multifunctional color cockpit displays incorporating FIS products
- Expand and institutionalize the generation, dissemination, and use of automated PIREPS to the full spectrum of the aviation community, including general aviation
- Improve underlying weather forecasting services
- Require, develop, and implement aviation weather-related training packages for users
- Improve aviation weather information telecommunications capabilities for ground-ground dissemination of aviation weather products
- Establish objective standards for characterizing various weather phenomena for national and international use
TAMDAR Background

- NavRadio Team Phase I CRA propose low cost electronic pilot report capability
- Transmitter design stymied by lack of frequency allocation; effort focused on sensor
- After many acquisitions, NavRadio ➔ Honeywell, Int.
- Phase II CRA not pursued by Honeywell, Int.
- Effort becomes project under AWIN
- Tri-Agency Team formed to develop concept of operations
- GTRI / ODS task contract in place to complete sensor development
- ARNAV Phase II CRA to deploy sensors and test data link
TAMDAR is envisioned to downlink weather data from non-jet aircraft. The weather data will be sent to FSL, FSS, ATC, AWC, and others via a ground-based infrastructure and to other aircraft. New weather products will be generated and uplinked to the cockpit.
AWIN System

Aircraft Capabilities → Decision Aids
User Capabilities → Presentation

User Interface → Processor

TAMDAR Infrastructure
Ground Wx System
Onboard Sensors
Weather Products

Flight Information
Navigation Information

Traffic
Special Use Airspace
Obstacles

Position
Flight Plan
Terrain

Data Link

Data Link
Sensor Development

- Task Contract with GTRI and subcontractor ODS
- Subtask 1: Requirements Definition and Design Review
- Subtask 2: Sensor Fabrication
- Subtask 3: Flight test on research aircraft
- Future Tasks: Evaluate flight test results; make design modifications as needed, fabricate additional units; conduct fleet evaluation; evaluate results
Sensor Development

- Current version of sensor ground tested and flight tested
- Next version of sensor currently under development
- Flight test of next version planned for 10-11/01 on-board University of Wyoming B200 atmospheric research aircraft
- Possible flight testing during International Water Project (IHOP) 5-6/02
NASA Ground Tests

- **Langley 7 x 10 Inch Low Speed Tunnel (5/2001 – 6/2001)**
  - Air speed, temperature, pressure comparison
- **Langley Test & Dynamics Branch Facilities**
  - “Shake and Bake” testing includes temperature, pressure, and vibration
  - Testing to be conducted May – June 2001
  - Piggyback on another test
  - ODS also tested Model 1000 Icing Sensor
NASA Ground Tests
NASA Ground Tests

3/21 First Run Icing Response
NASA Ground Tests
NASA Ground Tests

3/21 IRT TAMDAR

- airspeed
temp
- relhum
dewpt

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<tr>
<td>15:32:35</td>
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NASA Ground Tests

3/21 IRT TAMDAR

- pressure
• Three flight test series scheduled, August – November 2001
• AWIN, WINCOMM coordination for data link testing
• Goal: To provide support to WINCOMM for TAMDAR system architecture tests (Cessna 206H)
• TAMDAR in support role, not central research effort
ETMS Analysis of IFR Flights

Average weekly operations over 12 months

Many thanks to Nancy Kalinowski, ATA-2

Source: FAA ATA-200 AT Airspace Lab Brent Brunk
ETMS Analysis of IFR Flights

FL: 0 - 50
ETMS Analysis of IFR Flights

FL: 50 - 100

TIME COVERAGE (ALT. %)
- Less than 0.0017
- 0.0017 - 0.1833
- 0.1833 - 0.375
- 0.375 - 0.4687
- 0.4687 - 0.5327
- 0.5327 - 0.6417
- 0.6417 - 0.7333
- 0.7333 - 0.825
- 0.825 - 0.9167
ETMS Analysis of IFR Flights

FL: 100 - 150
ETMS Analysis of IFR Flights

FL: 150 - 200
ETMS Analysis of IFR Flights

Estimated % CONUS Coverage of TAMDAR flights

Altitude range (ft)

Source: FAA ATA-200 AT Airspace Lab Brent Brunk
Capstone and TAMDAR

- FAA Capstone agreed to AWIN proposal to include TAMDAR into Bethel Area operational evaluation
- NASA to deliver 10 certifiable sensors
- FAA Capstone to support equipage, certifications, installations, and modifications to communications infrastructure
- ODS to support installations and calibrations
Representatives from NASA Langley, NASA Glenn, FAA ARW-100, FAA AUA-400, NOAA FSL, NOAA NWS meet to coordinate activities related to TAMDAR

- First action: No longer use term “E-PIREP”

- Currently drafting “Concept of Operations”
NOAA FSL Activities

- Goal of Fleet Operational Evaluation is to get the data to NOAA Forecast Systems Lab
- Challenges for FSL:
  - Provide consultation on sensor development
  - Identify and establish sources of corroborative weather information
  - Perform data validation, collection, storage and archival
  - Investigate meteorological phenomena revealed by this new high resolution data
  - Develop new weather products
Disseminate data to NOAA FSL via one of the following:

- ARNAV
- Honeywell
- UPS AT
- EchoFlight
- ARINC
- Cellular Modem
- FlyTimer
- Orbcomm
- SITA
Fleet Operator Selection Criteria

- Two or more fleet operators
- At least 50 aircraft of same type
- 24 x 7 operations
- Extensive routes in geographically diverse regions
- Can be FIS & TAMDAR equipped
- Can participate in 6 month duration research project
- Candidates: UND, ERAU, OU, United Express, UPS, Federal Express
Calibration Issues

- Sensors are factory calibrated
- Capability to perform field calibration with external connection to instrumentation
- Possibly perform self-checking via ASOS or other sources via data link
- Ground truth checking at FSL
- Need to establish calibration schedule and standards
- Some pilot training may be involved
Certification for Fleet O. E.

- Fleet Operational Evaluation would require:
  - FAA Certification of sensor
  - Selection of fleet operator and aircraft type
  - Certification Plan
  - RTCA DO-160E testing
National Demonstration

- AvSP goal for a 2002 National Demonstration
- Some Potential Activities Include:
  - Cessna 206H cross-country flight with data link
  - B200 King Air (NASA 8) flights with data link
  - International Water Vapor Experiment (IHOP) using University of Wyoming King Air with data link
  - Planned Fleet operational evaluation most likely to occur in 2003
Alternate Method

- NPOESS – National Polar Orbiting Operational Environmental Satellite System – DoD, NASA, NOAA team with partners EUMETSAT and NASDA
- 5 NPOESS satellites, deployed from 2008 to 2011, operational through 2018, each equipped with a subset of ten different sensors.
- ATMS – Advanced Technology Microwave Sounder
- VIIRS – Visible Infrared Imaging Radiometer Suite
- CrIS – Cross-track Infrared Sounder
Alternate Method

- ATMS – Advanced Technology Microwave Sounder
  - Ten altitude bands, from 4 to 37 Km
  - Measures water vapor and temperature
  - 32 Km spot size

- CrIS – Cross-track Infrared Sounder
  - Measures water vapor, temperature and pressure

- VIIRS – Visible Infrared Imaging Radiometer Suite
  - Measures temperature and pressure
• NASA FAA NOAA Industry Collaborative Effort
• TAMDAR Sensor Development
• Ground/Flight Testing
• FAA Capstone
• NOAA FSL
• WINCOMM Datalink Evaluation
• Fleet Operational Evaluation
• AWIN National Demonstration
TAMDAR Datalink Development
For
Weather Accident Prevention Annual Project Review
Cleveland, Ohio, Hilton South
June 5-7, 2001

Monty Andro/Stephen C. Wiersma

NASA Glenn Research Center
Cleveland, OH 44135
(216) 433-3492
mandro@grc.nasa.gov
TAMDAR Objectives

Use aircraft operating below 20,000 ft altitude to sense and report
  • Moisture
  • Temperature
  • Winds

to be used by
  • Forecast models
  • Weather briefers
  • Controllers
  • Other aircraft

NASA Inter-Agency Effort
  • NASA Glenn Research
  • NASA Langley Research

MDCRS & AMDAR Coverage from Transports

20,000 ft. MSL

TAMDAR Coverage

Ground Level
**TAMDAR Conops**

Conops Development by team of FAA, NASA, NOAA, and NWS.
- Based on the RTCA DO-252, Minimum Interoperability Standards (MIS) for Automated Meteorological Transmission (AUTOMET)

**General Communication Considerations**
- Support plane to plane communications
- Ascent, descent and en-route sensitive sampling rates.
- Immediate updates of HAZMET type reports (icing)
- 5 min latency from sample time to weather processing center
- Data rate based on precision, sample rate, and update rate.
TAMDAR Com Activities

Studies

**ADS-B Candidates:** UAT, MODE S, VDL 4  
*Issue: Surveillance band (UAT and MODE S), VDL4 questionable near term solution.*

**FIS G-IPPA’s Honeywell, ARNAV**  
*Issue: Broadcast only license.*

**2 Way VDL-2 ARINC, SITA**  
*Issue: targeted towards carriers.*

**Satellite Based** Globalstar, Orbcom/Echoflight, Generic Satellite Systems  
*Issue: Financial stability.*
TAMDAR Com Activities

FAA TAMDAR Architecture Study

Flight Experiments
  • UAT Cessna Demonstration
  • Orbcom/Echoflight Cessna Demonstration

Capstone Collaboration
CAPSTONE

Roles and Responsibilities
(Task A: TAMDAR Datalink Architecture)

NASA WINCOMM will:
- Perform UAT laboratory assessment
- TAMDAR flight sensor
- UAT flight assessment
- UAT for TAMDAR datalink assessment/evaluation
- Jointly develop plans for TAMDAR insertion into Capstone
- Overall TAMDAR datalink architecture validation in Capstone environment

FAA Capstone will:
- Provide a UAT flight transceiver and associated support avionics
- Provide a UAT ground station
- Jointly develop plans for TAMDAR insertion into Capstone for a multi-aircraft demonstration
- Provide field assistance for TAMDAR field testing in Capstone
- Provide demonstration aircraft and integration of TAMDAR and Capstone equipment.
- Provide field performance data for analysis
NASA WINCOMM will:
- Perform analyses of potential candidate SATCOM systems for AK. Analyses will investigate footprint coverage, link budgets, and system information capacity, latency and integrity.
- As necessary, provide access to NASA-owned facilities, communications system hardware such as SWIS, Globalstar, and Echoflight and test instrumentation for the investigation.
- Jointly develop necessary test plans
- Perform end-end system assessment of SATCOM augmentation scenarios.

FAA Capstone will:
- Provide AK region operational datalink requirements
- As necessary, provide access to Capstone infrastructure and integration of SATCOM hardware for end-to-end field evaluation
- Jointly develop necessary test plans
- Provide field performance data for analysis and final documentation
UPS AT assisting in software modifications to avionics and ground station (GBT)

- Combined avionics, ground station, and sensor demonstration
- Modify avionics to accept 15.5 byte TAMDAR data
- Encapsulate TAMDAR data in a extended type message
- Modify GBT to output TAMDAR data
- Maintain current UAT framing and signaling
Orbcom/Echoflight Flight Experiment

WxAP - Weather Information Communications

- TAMDAR messages encapsulated into email messages and transmitted through Echoflight system.

- Ground based systems receive and store email messages with TAMDAR data.

- Evaluate message reliability and delay
UAT, MOD-S, VDL 4 assessment will be accomplished by JHU-APL

- Leverage existing JHU-APL work for ADS-B simulations
- Will evaluate air communication only
- Ground communication assessment will accomplished at NASA Glenn
- Transfer models to NASA Glenn
WINCOM Studies

ARINC Study
- Assess current MDCRS architecture in supporting new participants (part 121, part 91)
- Investigate data link coverage and availability
- Investigate ground distribution and loading
- Assess and propose plans for improvement

Honeywell and ARNAV
- Leverage existing Cooperative Research Agreements
- Work with vendors to complete assessment

Satellite Based
- Leverage existing and on-going in-house architecture studies
- Include assessment of in-house laboratory experimentation
Task 3 FISDL Communications Assessments:

Subtask 1 of 2

"... provide assessments of communications alternatives for implementing a national system for collecting, processing and disseminating electronic pilot report data ...

FAA Needs:

- Assessment and recommendations of data link communications technology and ground communications infrastructure that supports national downlinking of electronic pilot reporting.

Schedule

- Final Report 9/01
Overview: Business Feasibility of the TAMDAR System

Paul Kauffmann
Erol Ozan

Department of Engineering Management
Agenda - Current Status

- Introduction: Study Objectives and System Description
- General Aviation Market Analysis
- Carrier Market Analysis
  - Commuter, business, package
- Competitive Weather Source Analysis
- Weather Information Providers
- Policy Issues and Implications
- Conclusions
What is TAMDAR?

- Tropospheric Airborne Meteorological Data Reporting
  - Past reincarnations: EPIREPS, AUTOMET
- Components: sensor package, signal processors, and communications equipment
  - Operational Concept: Carried aloft by participating aircraft to report weather conditions to ground-based receiving stations for distribution into a national system.
Forecast Lead Time and Benefits

Improving Benefits With a Seamless Suite of Forecast Products
Sensor Package: General Concept

- GPS location
- Indicated Airspeed
- Pressure Altitude
- Temperature
- Relative Humidity

Target price of one manufacturer: $5,000
Market target: 2003

- Magnetic Heading
- Winds aloft (direction & speed)
- Accelerometer (Turbulence)
- Ice detection and warning
TAMDAR Study Questions

- Most likely installation scenarios:
  - Cost of installation and operation of sensor
  - Adoption motivation / policy issues
  - Cost of alternate weather information sources
  - Potential for new weather products
  - Societal / aviation benefits

- Key: Develop an integrated business case.
Integrated Team Approach

Forgive me if I left anyone out!

Communication Link
Package Carriers
Commercial Carriers
GA
ATA

AOPA
Commuter airlines
Weather Service
Weather Information Providers
GA Survey Overview

- Focus: Explore issues related to GA involvement and motivation to participate
- New aircraft equipment
  - Study of 40 models and weather equipment
- In service equipment
  - Oshkosh survey (141 participants)
  - AOPA web survey (138 participants)
New Aircraft Weather Equipment

- Examined standard weather information equipment on 40 models of new aircraft.

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<tr>
<td>With weather instruments</td>
<td>47.5%</td>
</tr>
<tr>
<td>Models with weather radar</td>
<td>17.5%</td>
</tr>
<tr>
<td>Models with stormscope</td>
<td>27.5%</td>
</tr>
<tr>
<td>Without weather instruments</td>
<td>52.5%</td>
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- Conclusion: opportunity to offer weather information even to new aircraft owners as incentive to participate.
Oshkosh / AOPA Surveys

- To determine motivations of current GA owners, two surveys were conducted. Goals included:
  - Identify weather related equipment
  - Assess importance of cockpit weather information
  - Determine incentive priority

- Oshkosh shown - Very similar results for AOPA.
Weather Related Equipment

- 75% below 18,000 ft.
- 89% single or multi engine piston
- 79% less than 20 hours per month

Oshkosh Survey - Weather Equipment

- Other: 2%
- Wind speed: 13%
- Outside air temperature: 94%
- Ice sensor: 5%
- Weather radar: 14%
- Stormscope: 15%
- Weather information: 4%
- Fixed GPS: 41%
- Portable GPS: 43%
- Multi function display: 12%
Cockpit Weather Data

Rate importance if you could select TAMDAR data for display in the cockpit (1-5 very important):

- Lat-long
- Humidity
- Dew point
- Turbulence
- Winds aloft
- Ice sensor

Importance of cockpit display

Increasing importance
TAMDAR Incentive

Rate importance of these incentives for those who install TAMDAR.

Incentive Importance Rating

- Payment for transmitting data: 2
- Tax incentives: 3
- Contribute to aviation safety: 4
- GPS location in emergency: 4
- Free weather information: 4
- Air to air weather data: 4

Increasing importance
How much would you pay for EPIREPS?

- $0-1000
- $1,001-2,000
- $2,001-3,000
- $3,001-4,000
- $4,001-5,000
- $5,001-7,000
- $7,001-10,000
- $10,001-40,000

Participants are willing to pay for weather data rated 4 or 5.

For weather data items rated 4 or 5:

- Oshkosh-Willingness to Pay

- Non recurring cost that participants are willing to pay for weather data rated 4 or 5.
Summary - GA Analysis

- Owners motivated for weather information
  - Opportunity for new aircraft and current fleet
- Low cost threshold for instrument purchase plus data link costs
- Operational issues
  - Data quality, instrument repair
  - Consistency of data input and transmission format
  - System management and control
Data Link Issue

- In GA study, it was clear that the main cost factor was the recurring and non-recurring cost of the data link.

Conclusion: Examine market segments that may already (or soon will) have data link systems

- Focus: Regional airlines, business, package carriers
Current ACARS Status

- Estimates of current fleet
  - 6500 aircraft currently ACARS equipped
  - 1500 are high end GA
- Current message cost (hesitation!):
  - Automet message with identifier data: 103 characters
  - Typical transmission costs $0.07-$0.08 per kilo character (1000 characters)
  - For one data point $\approx$ $0.01$
  - Commonly quoted ranges $0.04$ to $0.10$ appear high.
Current Market Analysis

- Current surveys under way to analyze:
  - Regional airlines, package carriers, business operators

- Areas of interest:
  - Current Fleet characteristics and changes in next five years (issue of regional jets)
  - Typical flight characteristics
  - Current fleet management / communications equipment
  - Motivations to participate
Regional Carrier Responses

• Typical fleet transition:
  - Large regional carrier currently has 68 turboprop and 46 jets - none with GPS or ACARS/AFIS
  - In five years, estimates 160 jets and 19 turboprop - all with GPS and ACARS/AFIS

• Flight characteristics:
  - 8 flights per day
  - Average distance is 160 for props, 360 for jets
Fleet Management / Communication

- As noted, many aircraft are not equipped with GPS and/or ACARS/AFIS (airborne flight information system).
- Transition discussed with change to jets.
- High priorities for change include:
  - Cost reduction (automate OOOI data-in, off, on, in)
  - ATC communications (e.g. pre departure clearance)
  - Future services (free flight requirement, ADSB, etc.)
Typical Recent Business Case

- Large commuter airline decided to install flight management system in regional jet fleet:
  - Total installed cost was $35,000 for communications and interface equipment
  - Net monthly deficit per tail in “hard cost saving” was $350.
  - Justified as worthwhile by better access to ATC
Weather Information Providers

- Survey of viewpoint of weather information providers (for profit):
  - Goal: Is there commercial potential in TAMDAR?
- Packaged data set: Aviation, DOTS, military
- Improved forecast products: Above + broadcast
- Several comments focus on cost effective selection of data points.
Competitive Weather Sources

- TAMDAR complements other weather data
  - Provides opportunity for data correlation (e.g. satellites).
- However there is an issue of cost saving in other data gathering areas and cost effectiveness.
- Example: Weather balloons gather data for many purposes. Could the number be reduced?
Canadian AMDAR Case

- Weather balloon replacement considerations in Canada:
  - Cost of AMDAR flight: 30 observations @$0.04 each = $1.20 (VHF transmission- satellite higher)
  - Annual cost = 365*$1.20
  - Annual cost of a weather balloon launching is over $300

- Is a daily AMDAR flight worth more than a balloon launch? Is this a trade off that is appropriate in some cases or many cases?
Cost Summary - Estimates

- Sensor Suite: Target- $3500-$6500 including installation
- Communication system: $10,000-$35,000
  - Prefer to build on existing or planned flight information systems (e.g. ACARS)
- Data link costs: $0.01 per data point
How to Structure the Business Case?

- Program is aviation focused but societal benefits.
- Current issues in NAS, crowding, delays, etc.
  - TAMDAR can improve this
- Conclusion: build base business case on aviation impact
- Issue: How far can this move us forward?
TAMDAR Forecast Impact

- TAMDAR should improve short term forecasts in the following areas:
  - Significant convection / severe weather
  - Cloud cover / ceiling / fog / visibility
  - Low level winds direction / shift
  - Low level temperature structure
  - High level winds, jets
  - Precipitation type (icing, snow, rain)
  - Maximum / minimum temperature
  - Turbulence and wind shear
  - Other: ____________________________

Current survey areas under discussion.
TAMDAR Terminal Operation Impact

Quantify delays from:

- Convection or severe terminal area weather.
- Terminal cloud cover, ceiling, visibility or fog
- Anticipation of wind direction or wind shift in the terminal area.
- Icing and snow in the terminal area
- Terminal area turbulence and wind shear
- Weather activity in arrival paths or departure gates into or out of the terminal area
- General precipitation conditions in the terminal area
- At smaller airports due to “ripple” effect of delays at hubs.
TAMDAR Airline Operations Impact

- Costs from reduced flight time or fuel use from improved flight planning prior to take off.
- Costs from reduced fuel consumption due to improved flight rerouting en route.
- Costs related to carrying excessive fuel as a precaution for forecast inaccuracy.
- Costs related to diversion or hold decisions for aircraft in flight.
- Costs related to hold decisions for aircraft on the ground.
- Costs due to improved ground operations.
- Costs related to improved traffic flow management.
Policy Issues and Implications

Also studying possible policy implications - objective measures needed:

- **Input measures** (Incentive and operating cost of the TAMDAR system).
- **Output measures** (the number of data points).
- **Outcome measures** (the amount of improvement in weather aviation delay and operating costs).
- **Impact measures** (the decrease of weather related aircraft accidents in which TAMDAR weather data played a significant role, the improvement of aviation efficiency which resulted from TAMDAR data, increase of quality and efficiency of product and services which are weather related).
The Policy Investment Role in TAMDAR Technology: Principles

- There will always be areas where public benefits ... substantially exceed the returns that can be realized by private investment alone. Federal investment is essential in these areas. The President's Committee of Advisors on Science and Technology provides the following criteria for government investment in technology

- "Areas of national importance where the marketplace alone cannot justify a sufficient level of technology investment by private industry"

- "...Where the benefits are too widely spread for any one company to recover its investment at a profit..."
Business Case Example

- Per FAA, direct operating cost of 89M delay minutes was $3B in 1999.
  - Weather is a causal factor in about 70% or $2.1B.

- Cost range-equippping 2000 TAMDAR aircraft (WORST CASE):
  - Non recurring cost: $33M (as incentive, TAMDAR pays half of $20k / unit plus sensor).
  - Recurring cost: Two flights per day at $1 each*2000*365 =$1.5M (Optimization model: Erol Ozan dissertation focus)
Is TAMDAR Worthwhile?

○ For a five year life at 7%, previous cost is:
  - PV = ($39M)
  - Uniform annual cost = ($9.5M) per year

○ Based only on direct operating cost figure, we need a 0.45% reduction in direct delay related weather costs to pay for TAMDAR.
  - Does not include many other possible cost savings and societal benefits (passenger costs, indirect costs, etc.)
Conclusions - Next Steps

- TAMDAR appears to have great potential to impact forecasting and aviation operations
- Significant challenge to document the savings impact of TAMDAR
  - Working group: NWS and ATA
- Things we don’t know are diminishing
- Many thanks to all who have helped us get this far!
National Weather Service
Aviation Services Branch

Impact of Meteorological Data Collection and
Reporting System (MDCRS) / Tropospheric
Airborne Meteorological Data Reporting (TAMDAR)
Data on National Weather Service (NWS) Operations

Carl Weiss
MDCRS / TAMDAR Topics

- MDCRS Overview
- Value of MDCRS Observations to Numerical Weather Prediction (NWP)
- Value of MDCRS Observations in Operational Settings
- Added Value of TAMDAR Observations
- Recommendations
MDCRS Overview

- Participating airlines: United, UPS, American, FedEx, Northwest, Delta

- More than 80K observations daily over continental United States (CONUS)
  - ~1450 Aircraft

- 30 UPS aircraft making moisture measurements

- Aeronautical Radio, Inc. (ARINC) contracted by the Federal Aviation Administration (FAA) and NWS to:
  - Separate meteorological data from Aircraft Communications Addressing and Reporting System (ACARS) messages
  - Process data into Binary Universal Form for data Representation (BUFR) format
  - Send data to NWS and Federal Aviation Administration (FAA) via Global Telecommunications System (GTS)
MDCRS Overview (Continued)

- NWS / National Centers for Environmental Prediction (NCEP) uses MDCRS data for NWP

- NWS / Weather Forecast Offices (WFOs), Center Weather Service Units (CWSUs) and National Centers use MDCRS data in daily operations
MDCRS Use in NWP

- Accurate forecasts depend upon accurate analyses which, in turn, depend on accurate observations
- NCEP has been using automated aircraft observations for NWP since mid-1980s
- MDCRS wind / temp data included in both NCEP global & regional models since early 1998
- NCEP receives ~65K MDCRS reports daily
  - Average hourly totals of MDCRS reports range from ~1000 reports (non-peak) to ~3200 reports (peak)
  - 45% of these reports arrive within 10 minutes of observation time
  - 65% within 15 minutes
  - 70% within 20 minutes
MDCRS Use in NWP
(Continued)

- **MDCRS usage in Rapid Update Cycle (RUC) model**
  - Continuous availability of high-quality aircraft data led to development of RUC
  - Currently, RUC runs hourly
  - MDCRS data comprises up to 62% of the total observations used in an hourly RUC model run

- **MDCRS usage in Global and Meso-eta models**
  - Both model runs increased from twice (every 12 hrs) to 4 times (every 6 hrs) daily because of MDCRS data availability
MDCRS Use in Operations

- NWS / WFOs, CWSUs, National Centers use MDCRS data in their daily operations
- Real-time MDCRS data available to offices via Forecast Systems Laboratory (FSL) Web Site
- WFO usage includes:
  - Refining Terminal Aerodrome Forecasts (TAFs) & Transcribed Weather Broadcasts (TWEBs)
  - Monitoring initiation / intensification / suppression of convection
  - Forecasting precipitation type in winter storms
  - Issuing high wind warnings
  - Validating model performance
MDCRS Use in Operations (Continued)

- CWSU use includes:
  - Supporting air traffic flow to busy airports
  - Refining areas of icing and turbulence
- Aviation Weather Center use includes:
  - Utilizing data via RUC analysis
- Tropical Prediction Center use includes:
  - Supplementing hurricane recon flight data over land areas
  - Supporting marine & aviation forecasting for Gulf of Mexico, tropical Atlantic
MDCRS Use in Operations (Continued)

- Storm Prediction Center use includes:
  - Determining stability for convective events
  - Determining precipitation type in winter storms
May 3, 2001 TAF Example (Continued)
May 3, 2001 TAF Example (Continued)

TAFONT
TAF
KONT 030556Z 030606 VRB03KT P6SM SCT030
   FM0900 03007KT P6SM SKC TEMPO 1418 05015G25KT
   FM2100 30011KT P6SM SKC
   FM0300 VRB03KT P6SM SKC=

TAFONT
KONT 031125Z 031212 VRB03KT P6SM SKC WS010/06025KT
   TEMPO 1215 04015G25KT
   FM1500 05020G35KT P6SM SKC
   FM2200 30011KT P6SM SKC WS020/06025KT
   FM0400 VRB03KT P6SM SKC=
May 3, 2001 TAF Example
(Continued)

SPECI KONT 031108Z COR VRB03KT 6SM.....

METAR KONT 031153Z 06018G32KTS 7SM CLR....
METAR KONT 031253Z 06023G31KTS 10SM CLR....
METAR KONT 031353Z 06021G29KTS 10SM CLR....
METAR KONT 031453Z 06018G27KTS 10SM CLR....
METAR KONT 031553Z 06021G34KTS 10SM CLR....
METAR KONT 031653Z 06022G37KTS 10SM CLR....
METAR KONT 031753Z 06027G40KTS 10SM CLR....
Value Added by TAMDAR Observations

- TAMDAR observations will be a valuable complement to MDCRS
  - “Gap filler” (especially during ascent / descent)
  - Soundings will be available at airports other than major hubs
  - Enroute data will be in mid-troposphere, where the weather “is”
Recommendations

- Data must be of comparable quality to MDCRS
- Data must be timely
- Data must be reliable
- Moisture component is crucial
- High resolution reporting format (ascent / descent) is critical
- Initial focus to be on regional carriers & high-end general aviation
Airborne Turbulence Warning System Development

Weather Accident Prevention
Second Annual Review
June 5-7, 2001

Rod Bogue
NASA Dryden Flight Research Center
An End-to-End Tactical Turbulence Warning System

- Detection Hardware
- Signal processing algorithm
- Turbulence hazard tables
- Turbulence Alert criteria
- Display/Alert

Aviation Safety Program
Weather Accident Prevention
Turbulence Detection & Mitigation Role in Overall Warning Plan
Model for Reducing Air Carrier Turbulence Accident Rate

FAA/NASA TDAM Roles & Contribution

- Mature Detection Technology
- Design Develop Weather Products
- Implement in Target Fleet
- Realize Air Carrier Accident Rate Reduction

Industry

Government (FAA/NASA)
Meteorological Case Studies of Turbulence Encounters

Richard Ferris
Outline

• Basis for Investigations
• Data Collection
• Case Studies
  – West Palm Beach, FL (Convective)
  – Wilmington, DE (Convective)
  – Cross City, FL (Convective)
  – Cape Girardeau, MO (CAT)
  – Houston, TX (Inconclusive)
• Conclusions
• Future Work
Basis for Investigation

- **Assistance to:**
  - National Transportation Safety Board (NTSB)
  - Dryden Flight Research Center (DFRC)

- **NTSB**
  - Analyses to help determine cause of upsets

- **DFRC**
  - Flight Operations Quality Assurance (FOQA) data
  - Weather analysis of selected turbulence cases
  - Safeguards taken to prevent unauthorized disclosure
Basis for Investigation

- Flight data recorder data alone will not suffice to determine causality

- Need to understand meteorological phenomena to develop an overall avoidance system

- Results will provide insights into issues that arise in both encounter analysis and development of automated systems

- Unclear if one would have identified operationally significant turbulence without apriori knowledge of upset location
Data Collection

- Mishap locations and flight profiles provided by NTSB and FOQA data

- Weather data obtained from National Climatic Data Center
  - NEXRAD Archive Level II
  - Satellite imagery
  - Upper air charts/soundings
  - Surface charts

- Data processed, generated, and analyzed locally
Case Study 1 (NTSB)

- Severe turbulence near West Palm Beach, FL
- One pax seriously injured
- Initially at 16,000 ft
- Loss of over 3000 ft in 30 sec
- Recovered and landed at MIA
Case Study 1

- Frontal boundary
- Multi-layered clouds
- Widespread convection
- Winds at altitude: 240/35
- Only available radar-KAMX
Case Study 1

- Plan view at incident time
- Nearest convection: 42 dBZ cell approximately 20 km to SSW
- Nothing indicative of severe turbulence
Case Study 1

- Incident along 24 degree radial at 128 nm
- Time: Approximately 10 minutes before upset
- Shear zones visible
Case Study 1

- Time: Approximately 5 minutes before upset
- Shear zones remain visible
Case Study 1

- At time of upset
- 16.5 m/s couplet present approximately 3 km from aircraft
Case Study 1 Conclusions

- Aircraft was flying outside and downwind of convection
- Aircraft experienced upset indicative of severe turbulence
- Initial data revealed nothing exceptional
- Cross-sectional analysis and supporting evidence suggest a convectively induced mid-level windshear may have impacted the aircraft’s flight path
- Aircrew flight control inputs were also a major factor
Case Study 2 (FOQA)

- Near Wilmington, DE
- Heading: 49.6 degrees
- Comp. airspeed: 266.0 kts
- Altitude: 7712 ft
- Auto Pilot: On
- Max G: +1.98
Case Study 2

- Sfc chart at Incident - 91 min.
- Complex low off NJ coast
- Cold front/trough moving through area
- Snow and rainsshowers from NE to Virginia
Case Study 2

- Satellite images approximately 1 minute after Incident (I)
Case Study 2

- 850 mb (5000 ft) winds at t+4.5 hrs. (310/45)
- Trough in area
- Strong cold air advection
Case Study 2

- NEXRAD reflectivity (left) and velocity (right) during Incident
Case Study 2

- Enlarged version of previous images during Incident

Max 27 dBz or Level 1 intensity

Significant windshear with 30 m/s (~58 kt) couple at height of 1.6 km (~5249 ft)

MIT Lincoln Laboratory
Case Study 2

- Vertical cross section at 1 - 2 min.
- Significant velocity shear
Case Study 2

- Spectrum width value of 15.5 m/s
Case Study 2 Conclusions

- Aircraft entered line of convection induced by front/trough
- Reflectivity values in area of 27 - 39 dBZ
- Small but significant velocity shear of 30 m/s present
- Spectrum width indications of severe turbulence
- Upset likely caused by penetration of boundary between line of convection (rising air) and dry slot (sinking air)
Case Study 3 (NTSB)

- Near Cross City, FL
- IMC at cruise altitude of FL330
- One second of moderate turbulence
- Max G: +1.75, -0.28
- One FA seriously injured, two FA and one pax - minor injuries
Case Study 3

- Sfc chart at 1 - 44 minutes
- Stationary front through area
- High temps/dew points
Case Study 3

- IR satellite image at I + 1min
Case Study 3

- Level 5 thunderstorm just west of aircraft 1 min before upset
- Rapid motion to southeast
Case Study 3

- New thunderstorms at 1.5 minutes after upset to N and NE
- Confirmed by pilot
Case Study 3

- Upper level shear noted in both major storms at 1 + 4 min.
- Max shear of 16.5 knots
Case Study 3 Conclusions

- Original level 5 thunderstorm produced outflow
- Explosive secondary growth, especially at mid-levels
- Level 6 thunderstorm in area likely produced upset
Case Study 4 (NTSB)

- Near Cape Girardeau, MO
- Initial descent from FL230
- "Intense" turbulence for 30 sec
- Max G: +2.5, -0.79
- Two FA hurt, one seriously
Case Study 4

- Sfc chart at t + 10 minutes
- Strong surface high over KS/MO
- Fair weather in area
Case Study 4

- Satellite images at 1 - 5 minutes
Case Study 4

- 500 mb (18,000 ft) winds at 1 - 4 hours (250/55 kts)
Case Study 4

- NEXRAD data 1 minute after upset
- No significant returns
Case Study 4 Conclusions

- Aircraft likely experienced severe CAT associated with jet stream and converging winds at altitude.
Case Study 5 (FOQA)

- Near Houston, TX
- Heading 179.8 degrees
- Comp. airspeed: 232.0 kts
- Altitude: 7648 ft
- Auto Pilot: On/Off
- Max G: +1.74
Case Study 5

- Sfc chart at 1 - 1 minute
- Large high off mid-Atlantic
- Cold front exiting Rockies
- Dry line in west Texas
- No sig wx in airspace
Case Study 5

- IR satellite images taken at 1 - 16 minutes
Case Study 5

- Upper air charts at 850 and 700 mb at 1 - 3 hours
- Vertical profile at 1 - 3 hours (LCH)
Case Study 5

- NEXRAD data at $I + 1$ minute
- Normal clear air returns

At 7700 ft (2.4 km) reflectivity is negligible.

At 7700 ft (2.4 km) velocity is undeterminable because of too few returns.
Case Study 5 Conclusions

- Deep convection / thunderstorms ruled out
- Aircraft heading directly into warm / moist southerly flow
- At or just above cloud deck
- Possible wind surge not detectable in radar data
Overall Conclusions

- Wide range of causes for in-flight turbulence from convection to the jet stream

- Upsets can be captured by DFDR data but explanations may remain elusive

- High resolution data can assist in determining cause in many instances

- Pilots should continue to adhere to well known thunderstorm and CAT avoidance rules-of-thumb.
Future Work

- Automated turbulence detection needs to integrate:
  - ground and airborne radar
  - thermodynamic and wind profiles
  - satellite data

- Systems to warn of turbulence using airborne radars need to use winds aloft information to determine region of hazard "down wind" of convective cells (Case 1)
Future Work

• Fast update information sensors/systems needed to avoid rapidly developing convective cells (Case 3)
  – ASR9 and ARSR4 (Corridor Integrated Weather System)
  – High update rate convective initiation forecasts

• Convective forecast algorithms can facilitate convective turbulence avoidance
  – Terminal Convective Weather Forecast (TCWF)
  – Regional Convective Weather Forecast (RCWF)
  – National Convective Weather Forecast (NCWF)
Weather Associated with the Fall-2000 Turbulence Flight Tests

David W. Hamilton and Fred H. Proctor

NASA Langley Research Center

Hampton Virginia

Session: Airborne Turbulence Warning System
Weather Accident Prevention Annual Project Review
5-7 June 2001, Cleveland, Ohio
Outline

• Introduction
• Flight Experiments
  – Equipment for turbulence detection
  – Flight requirements
  – Flight preparations
• Turbulence Metrics
• Research Flights
• Summary
Turbulence Threat

- Sudden, unexpected encounters with turbulence, usually lasting 10-30 seconds, have led to frequent injuries aboard commercial aircraft
- A recent study of 44 turbulence encounters resulting in injuries:
  - 82% were found to be near or within convective activity
  - Mountain wave (2%), CAT (16%)
Flight Experiments

- NASA-Langley’s ARIES B-757 flew into regions favorable for convectively-induced turbulence

- ARIES equipment
  - *In situ* sensors measure wind, temperature and acceleration
  - Onboard Doppler radar for forward turbulence detection

- Data collected for events ranging from smooth air to severe turbulence
Flight Requirements

- Flight days were chosen based on likelihood of convectively-induced turbulence within flight range of NASA Langley
  - Test days limited by availability of B-757

- Altitudes of interest: between 18,000 and 40,000 ft

- Direct penetration into regions with Level 3 radar reflectivity were avoided
Flight Preparations

- Meteorology team at NASA-Langley prepared: 2-day, 1-day, and day-of forecasts in support of flight tests
  - Brief researchers
  - Brief pilots for flight planning

- Products Used:
  - NCEP models, i.e. RUC, ETA, etc.
  - NC State’s operational mesoscale model
  - Airmets, Pireps, NCAR’s ITFA
  - Satellite and Radar

- Meteorologist on board provided guidance into turbulent regions
Turbulence Metrics

- Quantification of *in situ* turbulence:
  - Root mean square of normal load acceleration: $\sigma_{An}$
  - Eddy dissipation rate: $\varepsilon^{1/3}$

- Defined a significant turbulence event as:
  $$\sigma_{An} > 0.15$$

  - $\sigma_{An} > 0.20$ moderate
  - $\sigma_{An} > 0.30$ severe
The Flight Experiments

- R-181, November 16, 2000
  - most events having levels below threshold for moderate turbulence

- R-190, December 13, 2000
  - severe turbulence; similar to NTSB accident accounts

- R-191, December 14, 2000
  - strongest encounter of the season; encounters with storm tops.
R 181 – Nov 16, 2000

- Mississippi-Louisiana Gulf Coast region favorable for convective turbulence

- Broad overrunning of rain with embedded convective cells
  - Peak storm top: 30,000 ft
  - Cell movement: from west-southwest at 45 kts

- 3 significant turbulence events with peak in situ measurement:
  - $\sigma_{\text{m}} = 0.21$
  - $\varepsilon^{1/3} = 0.25$
21 UTC Surface Analysis
Nov 16, 2000
Flight Path for 181
Reported PIREPS on Nov. 16, 2000

1749 – 2020 UTC

Pilot Reports (PIREPs) of Turbulence
1749z – 2000z 11/16/**
Flight 181 – Path with Nowrad

2100 UTC Radar Composite

# 181-4  # 181-7  # 181-8
R – 190 December 13, 2000

• Along Gulf Coast; convective turbulence experienced in Central Mississippi and NE Louisiana

• Broad overrunning area of rain and convective cells with embedded thunderstorms
  – Peak storm tops: 43,000 ft
  – Cell movement: from southwest at 65 kts

• 2 significant turbulence events with peak in situ measurement:
  – $\sigma_{\Delta n} = 0.35$
  – $\varepsilon^{1/3} = 0.47$
Flight 190 – Path with Satellite

1901 UTC Visible Satellite

# 190-4

# 190-6
On Edge of Convection
R – 191  December 14, 2000

- S Georgia and N Florida Panhandle; severe turbulence experienced near Tallahassee, FL and Valdosta, GA

- Narrow line of convective cells
  - Peak storm tops: 39,000 ft (11.8 km)
  - Cell movement: from southwest at 40 kts

- 2 significant turbulence events with peak in situ measurement:
  - $\sigma_A = 0.44$
  - $\varepsilon^{1/3} = 0.74$
18 UTC Surface Analysis
Dec 14, 2000
Flight 191 – Path with Nowrad

1900 UTC Radar Composite
On Approach to Convective Line
( viewed from northwest)
<table>
<thead>
<tr>
<th>Event</th>
<th>Altitude (MSL) (k ft)</th>
<th>Peak In Situ Turbulence $\sigma_\lambda n$ $\varepsilon^{1/3}$ (m$^{2/3}$/s)</th>
<th>Peak Vertical Wind (m/s) *from 20 Hz data</th>
<th>Horizontal Scale/Duration of Event</th>
<th>Peak Radar Reflectivity (along flight path)</th>
</tr>
</thead>
<tbody>
<tr>
<td>181-4</td>
<td>22</td>
<td>0.21 0.25</td>
<td>4 m/s -4 m/s</td>
<td>7 km / 33 sec</td>
<td>NA</td>
</tr>
<tr>
<td>181-7</td>
<td>19</td>
<td>0.15 0.16</td>
<td>5 m/s -1 m/s</td>
<td>10 km / 50 sec</td>
<td>25 dBz</td>
</tr>
<tr>
<td>181-8</td>
<td>19</td>
<td>0.16 0.18</td>
<td>6 m/s -1 m/s</td>
<td>6 km / 30 sec</td>
<td>27 dBz</td>
</tr>
<tr>
<td>190-4</td>
<td>24</td>
<td>0.28 0.47</td>
<td>12 m/s -6.5 m/s</td>
<td>15 km / 70 sec</td>
<td>20 dBz</td>
</tr>
<tr>
<td>190-6</td>
<td>24</td>
<td>0.35 0.45</td>
<td>11 m/s -6 m/s</td>
<td>7 km / 32 sec</td>
<td>23 dBz</td>
</tr>
<tr>
<td>191-3</td>
<td>33</td>
<td>0.34 0.60</td>
<td>9 m/s -15 m/s</td>
<td>7 km / 30 sec</td>
<td>35 dBz</td>
</tr>
<tr>
<td>191-6</td>
<td>33</td>
<td>0.44 0.74</td>
<td>18 m/s -15 m/s</td>
<td>6 km / 25 sec</td>
<td>33 dBz</td>
</tr>
</tbody>
</table>
TASS 100 m Simulation
Correlation of Peak Load With Peak RMS Load (5 sec. window)

Based on Measurements for 34 Turbulence Encounter Cases

\[ y = 7.6084 \times 10^{-2} + 2.6193x \quad R^2 = 0.958 \]

DATA SOURCES
- 18 NASA Events
- 10 NTSB Accidents
- 6 FOQA Incidents

Moderate, Severe, Extreme

Peak RMS g's

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

Peak RMS g's

0.0 0.5 1.0 1.5 2.0 2.5 3.0
SUMMARY

- 3 flight experiments into regions favorable for convectively-induced turbulence
  - most events lasting ~30 seconds
  - 3 severe turbulence encounters (based on $\sigma_{\Delta n}$)
  - all severe events appeared discrete-like, although bathed in a continuous spectrum of turbulence.
  - all turbulence events associated with radar reflectivities < 35 dBz
SUMMARY (cont.)

- R-190 similar to NTSB accident accounts;
  - severe encounter occurred on periphery of large storm
  - encounter associated with weak radar reflectivity (< 22 dBz)

- R-191 being modeled with LES
FUTURE FLIGHT PLANS

- Colorado – late Aug to early Sept
- Langley – late Sept to early Oct
Numerical Simulation of Event 191-6 of NASA's Flight Tests

Fred H. Proctor and David W. Hamilton

NASA Langley Research Center

Hampton Virginia

Session: Airborne Turbulence Warning System
Weather Accident Prevention Annual Project Review
5-7 June 2001, Cleveland, Ohio
Outline

• Introduction
• Description of Turbulence Event
• TASS Model
• Initial Conditions
• Results from Model Simulation
• Summary
Introduction

- Numerical Simulation of Event 191-6
- Severe Turbulence Encountered by NASA Langley B-757 during Event 191-6
- Occurred as B-757 Penetrated Updraft Plumes Near Storm Top
- Data Available for Model Validation
  - Ground Based Radar (i.e. Nexrad)
  - Satellite
  - NASA B-757
    - In Situ Winds and Accelerations
    - Onboard Doppler Radar
    - Eyewitness Accounts
R – 191-6  December 14, 2000

- Severe turbulence encountered ~40 km NE of Tallahassee FL (TLH)

- Narrow line of convective cells
  - Peak storm tops: 39,000 ft (11.8 km)
  - Cell movement: from southwest at 40 kts

- 2 significant turbulence events with peak \textit{in situ} measurement:
  - $\sigma_{ng} = 0.44$
  - $\varepsilon^{1/3} = 0.74$
MODELING ROADMAP

- Step 1: Derive initial sounding based on mesoscale model prediction; configure domain; retrieve and prepare observed data for case verification.

- Step 2: Coarse-grid simulation: should capture large scale characteristics of storm: 125x125x70 grid points with horizontal grid size of 200 m

- Step 3: Fine-grid simulation: 250x250x150 grid points, with grid size of 100 m

- Step 4: Nested grid simulation
  - 5 km region near cloud top
  - Minimum grid size less than 25 m.
  - Validate results
TERMINAL AREA SIMULATION SYSTEM (TASS)

- 3-D Large Eddy Simulation (LES) Model
- Meteorological Framework
- Prognostic Equations for:
  - 3-Components of Velocity
  - Potential Temperature
  - Water Vapor
  - Liquid Cloud Droplets
  - Cloud Ice Crystals
  - Pressure
  - Rain
  - Snow
  - Hail/graupel
  - Dust/insects/tracers

- 1st-order subgrid turbulence closure with Richardson-number dependency
- Surface friction layer based on Monin-Obukhov similarity theory
- Cloud microphysics
TASS -- History

- Development began in 1983 for NASA/FAA Windshear Program
- Recently applied in NASA’s Wake Vortex Program for improving airport capacity (i.e. AVOSS)
- Generation of data sets for Windshear Sensor Certification
- Supported NTSB Investigation of 1994 Charlotte and 1999 Little Rock Aircraft Accidents
- Simulations Applied to:
  - Cumulonimbus Convection
  - Tornadic Storms & Supercell Hailstorms
  - Microbursts & Microburst Producing Storms
  - Reconstruction of Microburst Windshear Encounters
  - Aircraft Wake Vortices
  - Atmospheric Boundary Layer
  - Flight Turbulence
TASS Domain Configuration

Physical Domain size
- Horizontal \((X,Y)\): 25 x 25 km
- Vertical \((Z)\): 14 km

Domain orientation and lateral boundary conditions
- Domain rotated 66° clockwise:
  - \(X\) – coordinate orthogonal to convective line
  - \(Y\) – coordinate along line
- Lateral BC:
  - Periodic boundary at \(Y=\{0, X^*\}\);
  - Open at \(X=\{0, Y^*\}\)
- Computational resolution
  - Horizontal – 100 m (251 x 251 grid points); can resolve horizontal scales down to 400-200 m
  - Vertical – 100 m, stretched grid at \(Z<2100\) m with grid size decreasing to 50 m at \(Z=0\) (148 levels)
TASS Domain Configuration

1900 UTC Radar Composite

#191-6

#191-3
TASS Simulation of Event 191-6, 14 Dec 2000

**TASS Input Data**

Input Sounding

- Environmental winds, temperature, dewpoint, & pressure
- From MASS 6-km forecast at time & location near event
- Boundary layer temperature & moisture from TLH observation

Convection initiated at model time zero

- Spheroidal thermal impulse
  - Peak amplitude 2.0° C
  - Dimensions – 4 km horizontal x 2.1 km vertical
MASS TLH sounding
TASS Simulation of Event 191-6, 14 Dec 2000

*Simulated Storm Characteristics*

- Near solid line of convection
- Overshooting tops to 11.5 km (38,000 ft)
- Cell motion: 19 m/s (37 kts)
- Moderate rainfall at surface (no hail)
- Persistent multi-cell type convection
- Turbulence associated with storm tops
- Cloud top rise rates about 10 – 12 m/s (30-40 ft/s)
Table 3. Model Comparison

<table>
<thead>
<tr>
<th>Variable</th>
<th>TASS</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Storm Tops</td>
<td>11.5 km</td>
<td>11.8 km</td>
</tr>
<tr>
<td>Peak Radar Reflectivity at Ground</td>
<td>53.5 dBz</td>
<td>55 dBz</td>
</tr>
<tr>
<td>Peak Radar Reflectivity at z=9 km</td>
<td>38.9 dBz</td>
<td>40 dBz</td>
</tr>
<tr>
<td>Cell Motion (toward)</td>
<td>ENE at 19 m/s</td>
<td>ENE at 17 m/s</td>
</tr>
<tr>
<td>Width of Convective Line near Ground Level (based on 20 dBz)</td>
<td>6 km</td>
<td>8 km</td>
</tr>
<tr>
<td>Peak Vertical Velocity at Flight Level (z~10.3 km)</td>
<td>Max 17 m/s</td>
<td>Min -11 m/s</td>
</tr>
<tr>
<td>Peak Eddy Dissipation Rate (m²/s)</td>
<td>0.86</td>
<td>0.74</td>
</tr>
<tr>
<td>Horizontal Scale of Turbulence Patch at Flight Level</td>
<td>5 km</td>
<td>6 km</td>
</tr>
</tbody>
</table>

*from 1 Hz in situ data
Radar reflectivity near ground ($dBz$)

PPI Display From TLH Nexrad
(1.4° tilt)

TASS Radar Reflectivity at
$T = 49$ min and $z = 156$ m

TASS
(Horizontal Cross Section)
(major tick every 5 km)
Upper-Altitude Structure of Convective Line

PPI Display From TLH Nexrad (9.8° tilt)

TASS Radar Reflectivity at
T = 49 min and z = 9 km

TASS (Horizontal Cross Section at 9 km AGL)
TASS Simulation of Convective Line viewed from southeast
(cloud/precipitation surfaces)
Radar reflectivity from onboard turbulence radar (dBz) at $-4^\circ$ tilt. (Range rings every 4 km)
TASS radar reflectivity (dBz) at 9.3 \textit{km} altitude corresponding to time and location of echo in previous slide (major ticks every 4 \textit{km})
TASS radar reflectivity (dBz) at 10.3 km altitude (major ticks every 4 km)
TASS Eddy Dissipation Rate to the $1/3$ power ($m^{2/3}/s$) at time and location corresponding to previous slide.

EDR$^{1/3}$ at $T=49$ min and $Z=10.3$ km
Spectra: TASS Simulation of R-191-6, $\Delta=100$ m averaged over x-y plane at $z=10.3$ km

-5/3 slope
TASS Vertical Velocity every 1 m/s
T=48 min, Z=10.3 km
Profile 2: Comparison of TASS with In Situ

- TASS W 48 min, z=10.3 km
- TASS RRF 48 min, z=10.3 km
- 100 m mov. avg (W (191-6 in Situ))
Profile 3: Comparison of TASS with In Situ

- TASS W 48 min, z=10.3 km
- TASS RRF 48 min, z=10.3 km
Summary

- Observed Large-Scale Features Captured by 100 m Simulation, Although Details of Storm Structure Differ from Measurements
- Turbulence Associated with Buoyant Plumes in Upper-Levels of Storm
- Turbulence and Strong Vertical Velocity may Occur within Weak Radar Reflectivity
- Downdraft Regions may Contain Weaker Radar Reflectivity than Updraft Regions (at flight level)
Future/Ongoing Work

- Finer Grid Resolution Needed to Capture Important Scales of Motion that Affect Aircraft Normal Load Accelerations
- Data Set from this Case Delivered to NCAR for Addition of Small-Scale Karman Turbulence
- A Nested-Grid with Grid Size of 25 m to be Applied in Future Simulation
Unbalanced Supergradient Flow: Its Role in Organizing Severe Turbulence in Both Convective and Clear Air Case Studies

Michael L. Kaplan

North Carolina State University
What is Supergradient Flow?
(Flow Which Exceeds Gradient Wind Balance)

\[(V^{**2}/R) > (PGF + FV)\]

\[V=\text{Horizontal Wind Velocity}\]
\[R=\text{Radius of Flow Curvature}\]
\[PGF=\text{Horizontal Pressure Gradient Force}\]
\[FV=\text{Horizontal Coriolis Force}\]
Presentation Overview

- 44 Case Synoptic Observational Signal
- Clear/Convective Accident Synoptic Signal
- Simulated Mesoscale Supergradient Flow
- Mass Perturbation/Supergradient Imbalance
- Flanking/Trailing Microvortex Genesis
- Single Characterization/Forecasting Index
Primary Observed Synoptic Signals in the 44 Case Studies

- 1. Immediate Upstream Curvature (98%)
- 2. Convection < 100 km Away (86%)
- 3. Upward Vertical Motion (82%)
- 4. Absolute Vorticity < 10-4 S-1 (80%)
- 5. Jet Entrance Region (77%)
- Indicates: Horizontally Changing Curvature in Proximity to a MASS Perturbation in the Entrance Region of 1 or More Jet Streams
MASS Model Numerical Simulations

CGI Clear Air       CTY Convective
12 km Hydrostatic   18 km Hydrostatic
6 km Hydrostatic    6 km Hydrostatic
2 km Nonhydrostatic 2 km Nonhydrostatic
Enhanced Vertical   Bogus Raob RH
500m                500m
Nonhydrostatic      Nonhydrostatic
125m                125m
Nonhydrostatic      Nonhydrostatic
60m Nonhydrostatic  60m Nonhydrostatic
Single Characterization/Forecast Index

- Cross Product of $\text{DEL}(M)$ and $\text{DEL}(\text{ZETA})$
- $\text{DEL}(M) = \text{Gradient}\ (\text{CpT}+\text{GZ})$
- $\text{DEL}(\text{ZETA}) = \text{Gradient}\ (\text{DV}/\text{DX}-\text{DU}/\text{DY})$
- $\text{PGF} \times \text{DEL}(\text{ZETA})$ on Isentrope
- $\text{PGF Vector}$ and $\text{Vortex Tube Intersect}$
Summary of the Organization of the Turbulence Environment

- Jet Streak Entrance Regions Merge In the Presence of Curved Flow
- Deformation Zone Forms As Momentum Converges and Centrifugal Force Increases
- Cross-Stream (Z) Vortices are Produced in Supergradient Flow Confluence Zone
- MASS Perturbation (Moist Convection /Frontogenesis) Modifies Along-Flow PGF
- (Y) Vortex Converges (Z) Vorticity=Hazard
Simulations of continuous and discrete event turbulence

R. Sharman
National Center for Atmospheric Research
Research Applications Program
Boulder, CO

Second AvSP WxAP Annual Project Review
Cleveland, Ohio
6 June 2001
Continuous vs. discrete turbulence

Measured vertical acceleration from NASA flight test

Wind derived vs in-situ algorithm
Continuous turbulence: Use of a von Karman representation

Advantages:
• Case studies show von Karman is a good representation
• Simple analytic formulation
• Only two parameters:
  – (correlation) length scale
  – intensity

Disadvantages:
• Larger scales may be misrepresented
• Computation that produces accurate spatial statistics is not so straightforward

von Karman Turbulence Simulations

- Uses technique of Frehlich, Cornman, Sharman which minimizes errors in structure (correlation) functions
von Karman Turbulence Simulations: Applications to radar detection

- Using von Karman turbulence data with known statistics + radar simulation allows evaluation of radar turbulence estimation algorithms

Von Karman gridded 3d fields of velocity and reflectivity
von Karman Turbulence Simulations: Applications to radar detection (cont.)

Q: What simulation grid resolutions are required?
A: It depends!

200 winds X 25 phases
von Karman Turbulence Simulations: Applications to mesoscale cloud models

- Numerical simulations of clouds are good at resolving larger scales but smaller scales are misrepresented.
- But von Karman is a good representation of smaller scales.
- So add the two, modulating the von Karman intensities by the large scale resolved motion.
Numerical simulations + von Karman subgrid. Merged spectrum
Numerical simulations + von Karman subgrid. Structure function fit and merger
American Airlines 757 encountered severe clear-air turbulence at 37,000 ft enroute SEA-JFK 10 July 1997 2141 Z near Dickinson ND
- 12 sec, -.75 - + 2.01 g’s
- 22 injuries, flight diverted to DEN
- No sigmet in area
Discrete event simulation (cont) - radar mosaic
Dickinson, ND discrete event simulation

- **3 step procedure**
  - MM5 simulation
    - triply nested grid (27,9,3 km)
    - 35 vertical levels
  - Clark-Hall cloud model
    - nested grids, highest resolution 50 m
  - Add subgrid von Karman
Dickinson, ND discrete event simulation - MM5 results
Dickinson, ND discrete event simulation - 2d high resolution simulations

- 2d simulations aligned with flow
- High resolution (16m) Clark-Hall cloud model
- Clouds forced by heated surface
- Initialized with Bismarck, ND 0Z sounding
Dickinson, ND discrete event simulation - 2d high resolution simulations: results
Dickinson, ND discrete event simulation - 2d high resolution simulations: results
Development and Flight Test of In Situ Turbulence Algorithms

Paul A. Robinson

AeroTech Research (USA), Inc.
Hampton, VA 23666

2nd Weather Accident Prevention Annual Project Review
Cleveland, OH, June 5-7, 2001
In Situ Turbulence Product Integration in Communications Infrastructure

Turbulence severity transmissions "auto PIREP's" (thresholded onboard receiving aircraft)

On-board aircraft systems:
- turbulence hazard metric
- eddy dissipation rate measurement

Tactical Products reported/forecast turbulence updates

Communications Network

Strategic Products
AOC, Dispatch, ATC, FBO:
- forecast/reported turbulence
- location and severity

NWS, FSS "Free Wx" (e.g., RUC-2)

Turbulence forecast models

eddy dissipation rate
AeroTech’s Task Areas

- Develop, implement, and test in situ algorithms on NASA B-757 Research Aircraft:
  - 3-D wind & turbulence recovery
  - atmospheric/meteorological diagnostics
  - distributed load analysis
  - hazard metric for radar

- Data analysis of flight test data

- Support radar algorithm development
Algorithm Development Process

1. Define algorithm specifications and requirements
2. Develop code and implement in NASA 757 simulator. Verify operation & incorporate results in flight code.
3. Implement and “shakedown” test on B-757 aircraft
4. Fly in turbulence
NASA B-757 Turbulence Flight Experiment Setup

Flight Deck Research Station

Transport Research System (TRS)
RMS Normal Load - Flight 191
flight conditions: R191-06
Vertical Gust and R.M.S. Vertical Gust ($G_{Wg}$)

[+ up]

Vertical Winds (m/s)

Time (s)

[5 sec window]

$G_{Wg}$ (m/s)

Time (s)
**Normal Load and R.M.S. Normal Load ($\sigma_{\text{up}}$)**

**[+ up]**

-50 0 50 100 150 200 250

Normal Load (g)

**[5 sec window]**

$\sigma_{\text{up}}$ (g)

0 0.1 0.2 0.3 0.4 0.5

0 50 100 150 200 250

Time (s)
Correlation of Peak Load With Peak RMS Load (5 sec. window)

Based on Measurements for 34 Turbulence Encounter Cases

\[ y = 7.6084e^{-2} + 2.6193x \quad R^2 = 0.958 \]

DATA SOURCES
- 18 NASA Events
- 10 NTSB Accidents
- 6 FOQA Incidents

Graph showing the correlation between Peak Load and Peak RMS Load with data points categorized as moderate, severe, and extreme.
Comparison of RMS Lateral Accelerations Between Forward and Aft of Aircraft

(5-sec Running Window)
Comparison of RMS Normal Loads Between Forward and Aft of Aircraft

(5-sec Running Window)
Effect of Aircraft Type on Turbulence Response

B-757

B-747

Bizjet

light

moderate

severe
**Future Work**

- Continue flight test of algorithms
- Support fleet implementation of NCAR algorithm
- Continue radar algorithm development support including certification process
Turbulence Lidar Development Status

Weather Accident Prevention (WxAP)
Annual Project Review

Ivan Clark
NASA Langley Research Center

Philip Gatt and Stephen Hannon
Coherent Technologies, Inc.

Cleveland, OH, Hilton South
June 5-7, 2001
Overview

- Background information
- Technical accomplishments to date
  - ground and flight test activities
- Plans
  - flight test activities
  - algorithm development and performance simulation
Overview

Background information

Technical accomplishments to date
- ground and flight test activities

Plans
- flight test activities
- algorithm development and performance simulation
General Principle of Infrared Doppler Radar (Lidar) Turbulence Measurement

Aviation Safety Program

50-100 m pulse transmitted 100-200 times per second

Infrared Doppler Turbulence Sensor

50-100 m pulse

Light scattered off of naturally-occurring dust particles

Beam (potentially scanned)

Pulse Envelope (50-100 m)

Relative wind induces a Doppler frequency shift in the backscattered light; this frequency shift is detected by the sensor

Turbulent Event

Relative Airspeed

Distance or Time Ahead of Aircraft
Turbulence Product Development Team
Objective

- Develop a robust detection capability that spans the full range of turbulence environments

  - Provide Timely Reliable Tactical Warning to:
    - Deviate,
    - Institute Cabin Safety Measures, and/or
    - Institute Mitigation Measures

  - Provide Real-Time Alerts to AWIN Network
Complete Detection Capability Provided through Dual Wavelength Radar

**TDAM Objective:** Develop a robust detection capability that spans the full range of turbulence environments

- Convective Storms (within and as far as 40 miles away from visible clouds in clear air)
- Jet Stream (at confluence of multiple streams and near boundaries)
- Mountain Wave (upward propagating from disturbances near the surface)

**X-Band Radar**

<table>
<thead>
<tr>
<th>Reflectivity</th>
<th>Upper Troposphere</th>
<th>Lower to Mid Troposphere</th>
<th>Cirrus/Ice Clouds</th>
<th>Light Precip</th>
<th>In-Cloud Convection</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Band Radar</td>
<td>0 dBZ</td>
<td>10 dBZ</td>
<td>30 dBZ</td>
<td>50 dBZ</td>
<td></td>
</tr>
<tr>
<td>Lidar units</td>
<td>-100 dBβ</td>
<td>-80 dBβ</td>
<td>-60 dBβ</td>
<td>-40 dBβ</td>
<td></td>
</tr>
</tbody>
</table>

Aviation Safety Program
Technology Readiness Development Needs

- Lidar needs are similar to those for microwave radar and include:
  - definition and characterization of hazard
  - hazard algorithm for quantifying the threat
  - validated algorithm(s) for using the IR radar to detect, discriminate, and quantify the threat
  - simulation test case development
  - validated system performance with properly designed field tests
Detection Issues

Detection/False Alert must consider the random nature of turbulence
- multiple turbulence warning levels
- multiple turbulence classes/types
- viewing longitudinal velocity behavior and inferring the vertical

Definition of errors required (not just Type I and Type II)
- common issue for radar/lidar
- must minimize scatter

Lidar Observable
(Velocity Structure Function or Spectral Width)

Hazard Level
(e.g., RMS g-loading)
Flight Testing: Objectives and Needs

- More flight hours at cruise altitudes
  - identified as a major gap
  - measuring turbulence levels requires a large number of flight hours

- More flight hours in moderate or stronger turbulence
  - mid-level altitudes with focus on convective (storm) and breaking wave turbulence
  - performance envelope for onboard radar and lidar

- Extended data sets for aerosol/turbulence correlation modeling

- Scanning versus single line of sight configuration
  - scanning will enable better characterization of turbulent events
    - more direct comparison with radar for joint tests
  - include a mixture of both modes
Program Assets and Resources:
Government Agency and Industry

Aviation Safety Program

AFRL System for Precision Air Drop
Installed in C-130 Fuel Pod

NASA/ACCLAIM System
Transceiver Head
(on Low Rack)

CTI/ARO MAG-1 Transceiver (future)
CTI Ground Station
Control Electronics
Signal Processor

NASA Scanner
Overview

- **Background information**
- **Technical accomplishments to date**
  - ground and flight test activities
- **Plans**
  - flight test activities
  - algorithm development and performance simulation
TDAM 1998 Accomplishments: Lidar

**Juneau lidar deployment**
- characterization of low altitude wind shear and turbulence
- generated validated data sets to support development of lidar turbulence and wind shear detection algorithms

**ACCLAIM/Electra flights**
- Detected light to moderate turbulence at ranges between 3 and 6 miles ahead
- Penetrated turbulence to verify
- Operated 15 hours in a variety of conditions from ground to 25kft
Sample Doppler Spectrum from ACLAIM/Electra

Aviation Safety Program

Isolated moderate to severe turbulence ahead and later penetrated it for confirmation.
B-720 Compact Lidar Flight Tests

- Collected lidar data to demonstrate CAT IR product capability at cruise altitudes
  - data consistent with performance model predictions
  - justified parametric system scaling for compact next-generation system

- Flights aboard Honeywell-owned B-720
- Conducted October, 2000
  - focus on cruise altitude operation
  - no significant turbulence encountered
Overview

• Background information
• Technical accomplishments to date
  – ground and flight test activities
• Plans
  – flight test activities
  – algorithm development and performance simulation
FY01/02 Lidar Flight Tests

**Aviation Safety Program**

- **DC-8 flight tests**
  - lidar operates in a piggy-back fashion
  - joint data for post-flight correlation with
    - in-situ
    - aerosol particle measurements
  - support lidar performance scaling and algorithm development efforts

- **B-757 flight tests**
  - joint with other WxAP tests
  - primarily focus on convective turbulence
  - joint data for post-flight correlation with
    - in-situ
    - radar measurements
  - support lidar performance scaling and algorithm development efforts
  - investigate scan strategy tradeoffs
Transceiver Status

**Aviation Safety Program**

- AFRL hardware delivered in March 2000
  - Specs after tune-up at CTI
    - 2.0125 μm wavelength
    - 9.3 mJ (out of telescope), 440 nsec pulse duration, 100 Hz PRF
    - 8 cm beam diameter, 10 cm aperture, internal telescope focused at 1.5-2.5 km
    - 20% small beam efficiency measured in June
    - horizontal path data show range performance to 10-12 km (Colorado data)
DC-8 Flight Test Status

- **DC-8 volcanic ash encounter**
  - engine replacement required

- **Initial flight window (FY00) dropped**
  - Air-Sci program cancelled

- **CAMEX DC-8 flights scheduled for August-September**
  - piggyback status
  - ~100 flight hours total
DC-8 Lidar Flight Test Status/Plans

- Forward-looking periscope installed at FS1015
- Integrated AFRL / NASA Lidar system undergoing ground testing at LaRC
- Instrument upload scheduled for July
- Flights anticipated in August-September
  - piggyback on CAMEX includes in-situ turbulence and aerosol
- Research focused on:
  - cruise-condition flight data
  - correlation with atmospheric aerosols
  - correlation of wind shear measurements with other CAMEX measurements
B-757 LiDAR Instrument Layout

Aviation Safety Program

Rack Configuration

[Diagram of B-757 LiDAR Instrument Layout]
B-757 LIDAR Instrument Layout

Aviation Safety Program

Station 2 Pallet

Medium Profile Equipment Rack

Low Profile Equipment Rack
B-757 Lidar Flight Test Status/Plans

- NASA Critical Design Review held in May 2001
- Design for forward-looking scanner installation approved for FS450
- Integrated AFRL / NASA scanning Lidar system undergoing ground testing at LaRC
- Flights anticipated in early CY02
  - joint with Turbulence Radar and Turbulence In-Situ
- Research focused on:
  - scanning effects and strategies
  - synergism with radar
  - convectively-induced turbulence
Lidar Algorithm Development Objective

- Develop reliable detection and discrimination algorithms for Doppler lidar prediction of turbulence hazard
  - exploit understanding of unique aspects of lidar phenomenology
  - incorporate common aspects of radar developments
Lidar Algorithm and Simulation: FY00-02 Approach and Plans

- Maintain synergy with radar algorithm development
- Establish SNR requirements and averaging/resolution/performance trades for spectral width and structure function algorithms
- Establish link to hazard metric algorithm(s)
- Incorporate test cases in more sophisticated simulation
- Test on additional data sets (joint lidar/radar test data)
- Produce more robust performance predictions and feed back into algorithm development
  - false alarm mitigation
Lidar Algorithm Development and Simulation: FY01/02 Activities

- Focus on single line of sight algorithms/analyses and leverage existing tools
- Pursue structure function and spectral-width-based algorithms
  - small SNR regime: long range (longer warning times)
  - large SNR regime: correlation of vertical loading with longitudinal observations
  - investigate scan strategy impacts
- Develop preliminary performance predictions based on combination of simulated and flight test data
- Truth metrics initially limited (simulation using 2DOF a/c)
Lidar Algorithm Development and Simulation: Leveraging

- **CIRES/NCAR:**
  - Space Lidar for NASA (SPARCLE)
  - extending detailed simulations

- **CTI**
  - simulation for wake vortex detection
  - existing real-time algorithms

- **Synergy with radar**
  - NCAR and RTI developments

- **Results in cost-effective development with near-term results**
Lidar Summary

* Emphasis areas
  - flight testing
  - algorithm development and associated performance analyses

* Flight tests accomplished CY99-00
  - NASA ACLAIM Electra flights
  - industry-funded B-720 flights

* Flight tests planned for late CY01, early CY02
  - DC-8 flights planned for August-September, piggy-back on CAMEX
  - B-757 flights in early CY02, joint with Turbulence Radar and In-Situ

* Algorithm work highly leveraged
  - NCAR and CTI developments
  - synergy with radar work (NCAR & RTI)

* Parallel industry program to develop a clear air turbulence product
  - focus is on cost reduction and reliability improvement
Turbulence Lidar Development Status
Reference Foils
SUPPORTED MILESTONES
(Through FY 02 only; Excludes WINCOMM)

Aviation Safety Program

**WxAP Level II**
- Initial AWIN Concept and Forward-Looking Turbulence Detection Flight Evaluation
- Flight Demonstration of Forward-Looking Turbulence Warning System
- National AWIN Capability

**AWIN Level III**
- Software Demonstration
- Initial AWIN Concept Flight Evaluation
- Weather Products and Sensor Selection
- Prototype Concept Flight Tests of National AWIN Capability
- Detection System Flight Test with AWIN
- Turbulence In-Situ Algorithm Demonstration

**Turbulence Level III**
- Flight Demo of Turbulence Detection Concept
- Demonstrate Turbulence Detection System
- Enhanced In-Situ Algorithm Flight Demo (uncoupled from AWIN) (L-IV milestone)
- In-Situ Algorithm Concepts Flight Evaluation (L-IV milestone)
• Turbulence Initiators

- Convective Storms (within and as far as 40 miles away from visible clouds in clear air)

- Jet Stream (at confluence of multiple streams and near boundaries)

- Mountain Wave (upward propagating from disturbances near the surface)

Localized “events” like these are extremely difficult to reliably forecast
Demonstration of Lidar Turbulence Detection
Good Correlation with Onboard Data out to 40 sec Lag (Flight 2)

Aviation Safety Program

Eddy Diss Rate: Sep=293m @ 1963m
- Lidar
- W-vel
- Accel

Eddy Diss Rate: Sep=270m @ 5068m
- Lidar
- W-vel
- Accel

Time Evolution, Beam Pointing
Jitter (A/C Pitch) Can Reduce
Accuracy for Long Lags
Background: Demonstration of Lidar Turbulence Detection

Good Correlation with Onboard Data (Flight 2)

Aviation Safety Program

Correlation of 1.3 km lagged structure function about as good as that between rms acceleration and rms vertical velocity.
Flight Test Results for a Turbulence Detection Radar

Weather Accident Prevention
Second Annual Review
June 5-7, 2001

Phil Schaffner
Turbulence Radar Principal Investigator
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Presentation Outline

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

- Introduction
- Flight Configuration
- Flight Operations Summary
- Event Summary
- Data Report and Analyses by Flight
- Flight Test Summary
- CY01 Flight Plans
Aviation Safety Program Organization

Aviation System Monitoring & Modeling
Level 2- Projects
- Aircraft Icing (Base Program)
- System-Wide Accident Prevention
  - 2.2 Dave Foyle (ARC)
- Single Aircraft Accident Prevention
  - 2.3 John White (LaRC)
- Weather Accident Prevention
  - 2.4 Shari Nadell (GRC)
- Accident Mitigation
  - 2.5 Doug Rohn (GRC)
- Synthetic Vision
  - 2.6 Dan Baize (LaRC)

Level 3- Elements
- Government/Industry Program Leadership Team
- Aviation Safety Program Office
  - 1.0 Mike Lewis
- Technical Integration
  - 1.1 Vince Schultz (LaRC)
Turbulence Detection Level 4 Sub-element

Sensor Performance Assessment
Sensor Development
Algorithm Development
Demonstration & Verification
Objectives

**WxAP Objective #3**

Provide commercial aircraft sensor with 90% probability of detection of severe Convective and Clear Air Turbulence thirty seconds to two minutes before encounter.

**WxAP Milestone #2**

Flight demonstrate certifiable forward-looking on-board turbulence warning system with Type-I and Type-II error probability commensurate with airborne wind shear technology. [TRL/IRL of 7/4]

**Goal for NASA/FAA/Industry**

Advance warning of $\geq 30$ sec. with POD $\geq 80\%$ for phenomena with reflectivity $\geq 15$ dBz.
Flight Operations Summary

• Weather Support
  – Forecasting and pre-flight recommendations
    • 2-, 1-, and day of operation forecasts
  – Pilot briefings
  – Onboard tactical recommendations
  – Real-time observations

• In Situ
  – Data Collection
  – Real-time engineering displays
  – Post-flight processing

• Turbulence Radar
  – Data collection
  – Real-time engineering displays
  – Aircraft response algorithms
  – Post-flight processing
**CY’00 Radar Flight Test Objectives**
- Collect airborne radar signatures of turbulence (along with aircraft response) to enable characterization and algorithm development/refinement.
- Assess the performance of the latest-generation turbulence detection and hazard estimation algorithms.

**Design Layout**

**As Built**

- **Antenna**
- **R/T Unit**
- **Recorded Information**
  - Radar Configuration/Control (RS-232)
  - A/C State Parameters (4xARINC 429)
  - Radar Health Parameters (ARINC 429)
  - Radar EQ (Fiber Channel)

- **Alt-Trans Antenna Sweeps**
  - Std. WX/WS
  - Research Mode

- **Recorded Information**
  - Radar Configuration/Control (RS-232)
  - A/C State Parameters (4xARINC 429)
  - Radar Health Parameters (ARINC 429)
  - Radar EQ (Fiber Channel)
Baseline Algorithm Methodology

- Includes time-domain interference-rejection filter
- Frequency/Doppler-velocity domain spectral width estimation
- Optional averaging over range and/or azimuth
- Estimates turbulence correlation length
- Thresholding using CFAR (constant false alarm rate) threshold calculated from the spectra
- Estimates point variance from spectral width and bin-to-bin variance of average velocity
- Uses Hazard Tables to predict RMS accelerations from point variance
• The NCAR Efficient Spectral Processing Algorithm (NESPA) is a multi-stage approach to finding high-quality Doppler moments in real-time.
• Data quality is improved by averaging the spectra over multiple azimuths and ranges.
• Hazard metrics are produced by scaling the second moment estimates using tables and combining the results from three elevation angles.
• Confidence measures based on many different indicators (e.g. SNR, continuity, etc.) of data quality are used in the multi-stage processing and are also used in the calculation of the hazard metrics.
• Relate radar estimates of spectral width or point variance to predicted variance of aircraft accelerations

• Key part of system to go from radar data processing algorithm output to aircraft effects
<table>
<thead>
<tr>
<th>Hazard Levels: RMS Vertical Acceleration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation</strong></td>
</tr>
<tr>
<td>------------------------------------------</td>
</tr>
<tr>
<td><strong>Light</strong></td>
</tr>
<tr>
<td><strong>Moderate</strong></td>
</tr>
<tr>
<td><strong>Severe</strong></td>
</tr>
<tr>
<td><strong>Extreme</strong></td>
</tr>
</tbody>
</table>
**Goal:** Advance warning of $\geq 30$ sec. with POD $\geq 80\%$ for phenomena with reflectivity $\geq 15$ dBz.

<table>
<thead>
<tr>
<th>Alerts Based on Radar Observables</th>
<th>Predicted Hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Alert</td>
<td>$\sigma_{\Delta n} &lt; 0.2g$</td>
</tr>
<tr>
<td>May Alert</td>
<td>$0.2g \leq \sigma_{\Delta n} &lt; 0.3g$</td>
</tr>
<tr>
<td>Must Alert</td>
<td>$\sigma_{\Delta n} \geq 0.3g$</td>
</tr>
</tbody>
</table>
Correlation of Peak Load With Peak RMS Load (5 sec. window)

\[ y = 7.6084 \times 10^{-2} + 2.6193x \]

\[ R^2 = 0.958 \]

**DATA SOURCES**
- 18 NASA Events
- 10 NTSB Accidents
- 6 FOQA Incidents

Based on Measurements for 34 Turbulence Encounter Cases
Flight Test Summary

• Checkout/ferry flights (154, 155, 169)
• 3 Data flights
  – 181: 3 to 4 very low reflectivity encounters with light turbulence
  – 190 & 191: low reflectivity encounters with light to severe turbulence
• 18 \textit{in situ} events identified from data flights
• 7 events selected for detailed radar analysis
## 18 Event Summary Table

**AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation**

<table>
<thead>
<tr>
<th>Flight-event</th>
<th>No Alert &lt; 0.2 g</th>
<th>0.2 &lt;= Alert &lt; 0.3 g</th>
<th>Alert &gt;= 0.3 g</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>181-01</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>181-02</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>181-03</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>181-04</td>
<td></td>
<td>X</td>
<td></td>
<td>+/- 30 deg roll</td>
</tr>
<tr>
<td>181-05</td>
<td>X</td>
<td></td>
<td></td>
<td>30 deg roll</td>
</tr>
<tr>
<td>181-06</td>
<td>X</td>
<td></td>
<td></td>
<td>-30 deg roll</td>
</tr>
<tr>
<td>181-07</td>
<td>X</td>
<td></td>
<td></td>
<td>+/- 30 deg roll</td>
</tr>
<tr>
<td>181-08</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190-02</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190-03</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>190-04</td>
<td></td>
<td>X</td>
<td></td>
<td>30 deg roll</td>
</tr>
<tr>
<td>190-05</td>
<td>X</td>
<td></td>
<td></td>
<td>50 deg roll</td>
</tr>
<tr>
<td>190-06</td>
<td></td>
<td>X</td>
<td></td>
<td>40 deg roll</td>
</tr>
<tr>
<td>190-07</td>
<td>X</td>
<td></td>
<td></td>
<td>55 deg roll</td>
</tr>
<tr>
<td>191-03</td>
<td></td>
<td>X</td>
<td></td>
<td>30 deg roll</td>
</tr>
<tr>
<td>191-04</td>
<td>X</td>
<td></td>
<td></td>
<td>---</td>
</tr>
<tr>
<td>191-05</td>
<td>X</td>
<td></td>
<td></td>
<td>30 to 50 deg roll</td>
</tr>
<tr>
<td>191-06</td>
<td></td>
<td>X</td>
<td></td>
<td>30 deg roll</td>
</tr>
<tr>
<td>Flight-event</td>
<td>In Situ $\sigma A_n$</td>
<td>NESPA</td>
<td>Baseline</td>
<td>Hazard</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------</td>
<td>-------</td>
<td>----------</td>
<td>----------------</td>
</tr>
<tr>
<td>181-07</td>
<td>0.15</td>
<td>&lt; 0.2</td>
<td>&gt; 0.2</td>
<td>light</td>
</tr>
<tr>
<td>181-08</td>
<td>0.16</td>
<td>&lt; 0.2</td>
<td>0.32</td>
<td>light</td>
</tr>
<tr>
<td>190-04</td>
<td>0.28</td>
<td>&lt; 0.2</td>
<td>&lt; 0.27</td>
<td>moderate</td>
</tr>
<tr>
<td>190-06</td>
<td>0.2 &amp; 0.35</td>
<td>&lt; 0.2</td>
<td>0.3</td>
<td>severe</td>
</tr>
<tr>
<td>191-03</td>
<td>0.34</td>
<td>0.2</td>
<td>0.32</td>
<td>severe</td>
</tr>
<tr>
<td>191-04</td>
<td>0.14</td>
<td>&lt; 0.2</td>
<td>low reflectivity</td>
<td>light</td>
</tr>
<tr>
<td>191-06</td>
<td>0.44</td>
<td>0.32</td>
<td>near 0.4</td>
<td>severe</td>
</tr>
</tbody>
</table>
# Weather Summary

<table>
<thead>
<tr>
<th>Flight/Day</th>
<th>Weather</th>
<th>Primary Region of Interest</th>
<th>Peak Storm Tops</th>
<th>Cell Movement (from)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FI-181 16 Nov 2000</td>
<td>Broad Area of Rain with Embedded Convective Cells</td>
<td>Southern Mississippi &amp; Louisiana</td>
<td>30,000 feet</td>
<td>WSW at 45 kts</td>
</tr>
<tr>
<td>FI-190 13 Dec 2000</td>
<td>Broad Area of Rain and Convective Cells with Embedded Thunderstorms</td>
<td>Northeast Louisiana</td>
<td>43,000 feet</td>
<td>SW at 65 kts</td>
</tr>
<tr>
<td>FI-191 14 Dec 2000</td>
<td>Narrow Line of Convective Cells/Thunderstorms</td>
<td>Florida Panhandle &amp; South Georgia</td>
<td>40,000 feet</td>
<td>SW at 40 kts</td>
</tr>
</tbody>
</table>
Flight 190 Satellite Weather

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

1901 UTC Visible Satellite

# 190-4

# 190-6
Flight 190 Event 06 Normal Loads

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation
Reflectivity (dBZ) Event 190-06
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:45:21 or 67521 seconds
g-Loading (rms g) Event 190-06

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:55:30 or 68130 seconds
18:56:05 or 68165 seconds
• Little reflectivity within scan range

• *In situ* peak rms g \( \approx 0.33 \) at 68170 seconds

• Missed prediction of *in situ* peak

• Detection of \( \approx 0.35 \) g 5 km (20 seconds) ahead at 68177 seconds where *in situ* shows \( \approx 0.25 \)

• Many areas >0.3 off track
Flight 191 Weather
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation
Flight 191 Weather

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

1900 UTC Radar Composite

#191-6

#191-3
Flight 191 Event 03 Normal Loads

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

[Graph showing normal load and sigma plots over time]
g-Loading (rms g) Event 191-03

18:26:54 or 66414 seconds
Reflectivity (dBZ) Event 191-03
AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:27:11 or 66431 seconds
g-Loading (rms g) Event 191-03

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

18:27:09 or 66429 seconds
Summary - Event 191-03

- Good reflectivity on port side near path, low reflectivity along path at beginning of run
- *In situ* peak rms g ~ 0.33 at 66470 seconds
- Predictions of > 0.32 g along path at 66429 9.5 km (44 seconds) ahead
- Multiple hits on successive scans down to ~ 5 km
Flight 191 Event 06 Normal Loads

AvSP / Weather Accident Prevention / Turbulence Detection and Mitigation

67458 sec.
g-Loading (rms g) Event 191-06

18:43:22 or 67402 seconds

Kilometers (North-South)

Kilometers (East-West) - Radar Source at Origin

Radar Derived Hazard Metric

10 m/s
g-Loading (rms g) Event 191-06

18:43:46 or 67426 seconds
• Two major “blobs” of reflectivity 25-40 dBZ
• *In situ* peak rms g ~ 0.43 at 67458 seconds
• Prediction of ~ 0.4 g at 16km (63 seconds) ahead at 67402 seconds
• Multiple detections until 67450 seconds
Type I and Type II Errors

- I: Missed Detections/Alerts
- II: False Detections/Nuisance Alerts
- Insufficient Data to Predict Performance
- Performance Predictions Will Require Modeling and Analysis
- Unlikely to Acquire Sufficient Experimental Data to Allow Statistical Analysis
# Turbulence Radar Results Summary

## Combined Event Based *A’Posteriori* Scoring for 7 Radar Events

<table>
<thead>
<tr>
<th></th>
<th>In Situ</th>
<th>Radar</th>
<th>Low dBZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bumps</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Nulls</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>
Conclusions

- Use and method of averaging/filtering will be a key factor in detection and reduction of false alarms
  - Lack of averaging may cause over-alerting
  - Averaging can reduce peak load estimates
- \textit{In Situ} truth not available for large part of data
  - Validated models would enable more thorough algorithm evaluation
  - Modeling/simulation will support error analysis
  - Lidar can provide comparison data
• S/W and H/W upgrades

• Flight objectives
  – 40 events 0.2 g or better
  – Vary radar pulse configuration
  – Weather variety
  – Sufficient reflectivity for radar detection
  – Record I & Q and aircraft data
  – Test detection algorithms in real time
  – Research turbulence display for NASA pilots
Market Assessment of Forward-Looking Turbulence Sensing Systems

Research Sponsor:
NASA Weather Accident Prevention Project (WxAP)
Paul Kauffmann, Old Dominion University
Overview

• Technologies and Study Objectives
• Study Approach
• Results:
  - Business Model: Injury rates, cost of injuries, indirect costs
  - Market penetration rate estimates
  - Product success characteristics
Objectives

- Identify cost and benefit data related to next generation of forward sensing turbulence technologies:
  - Enhanced X band, LIDAR, combined product
- Integrate into a business case that will evaluate feasibility of market success for the commercial transport fleet.
Technology Focus

- Examine three possible forward sensing turbulence system(s) that may achieve market success over the next 5-10 years:
  - 1) Next generation enhanced X band turbulence radar systems for convective turbulence.
  - 2) LIDAR based turbulence systems to sense clear air turbulence.
  - 3) A combined, hybrid system including both enhanced radar (X band) and LIDAR to sense both convective and clear air turbulence.
Study Approach

- Telephone interviews and data gathering
  - Structure issues and questions
  - Literature search
  - Information from a variety of sources
- Survey developed and analyzed
  - Corroboration of verbal data and other sources
  - Issue: small sample size
Business Case Equation

- Base Business Case defined by:
  - Net $ benefit of Turbulence System =
    - Investment – operating costs + savings from reduced turbulence accidents and incidents + savings from flight operations improvements (damage, diversions and flight time) + intangible benefits
  - Intangible benefits may be valued indirectly: the value to make case positive.
Accident / Incident Rates

- A variety of benchmarks:
  - AWS&T article: Part 121 carriers experienced an average of 130 events per year in a three - year period from 1994-96.
  - Study participant: 750 turbulence related events per year for Part 121 carriers.
  - FAA report: from 1981-1997, 342 reports of turbulence affecting major air carriers for an annual average of 27 events
NTSB Accident Reports

Turbulence Accidents - NTSB Data (1983-99)

![Turbulence Accidents Chart]

Turbulence Accidents per Million Flight Hours - Part 121 Carriers

![Turbulence Accidents per Million Flight Hours Chart]
Injury Rates

Per NTSB data, injury rates per accident:
Data from Crew Reports

- Crew report data analyzed to develop an estimated annual average, for Part 121 fleet:

<table>
<thead>
<tr>
<th></th>
<th>Clear Air</th>
<th>Wake</th>
<th>Convective</th>
<th>Total</th>
<th>1999 NTSB Accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence events</td>
<td>136.6</td>
<td>123.8</td>
<td>529.4</td>
<td>789.8</td>
<td>NA</td>
</tr>
<tr>
<td>Injury events</td>
<td>106.7</td>
<td>89.7</td>
<td>371.4</td>
<td>567.8</td>
<td>15</td>
</tr>
<tr>
<td>Minor FA injuries</td>
<td>123.8</td>
<td>132.3</td>
<td>431.2</td>
<td>687.4</td>
<td>20</td>
</tr>
<tr>
<td>Serious FA injuries</td>
<td>17.1</td>
<td>0.0</td>
<td>21.3</td>
<td>38.4</td>
<td>10</td>
</tr>
<tr>
<td>Minor PA injuries</td>
<td>17.1</td>
<td>12.8</td>
<td>89.7</td>
<td>119.5</td>
<td>87</td>
</tr>
<tr>
<td>Serious PA injuries</td>
<td>0.0</td>
<td>8.5</td>
<td>8.5</td>
<td>17.1</td>
<td>5</td>
</tr>
</tbody>
</table>

Survey Participant Estimates

- Survey participants estimate higher annual incidents:

<table>
<thead>
<tr>
<th>Annual turbulence incidents for Part 121 Carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower 90% interval</td>
</tr>
<tr>
<td>151</td>
</tr>
</tbody>
</table>
FAA Injury Costs

- “Willingness to Pay” approach:

<table>
<thead>
<tr>
<th>Classification</th>
<th>Willingness to Pay</th>
<th>Emergency / Medical</th>
<th>Legal / court</th>
<th>Total Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Death</td>
<td>$2.7M</td>
<td>Not a significant addition to WTP value</td>
<td></td>
<td>$2.7M</td>
</tr>
<tr>
<td>Minor injury</td>
<td>$34,000</td>
<td>$2,000</td>
<td>$2,500</td>
<td>$38,500</td>
</tr>
<tr>
<td>Serious Injury</td>
<td>$482,000</td>
<td>$27,600</td>
<td>$12,200</td>
<td>$521,800</td>
</tr>
</tbody>
</table>

Issue: Unclear how these costs relate to business case in industrial setting.
Other Benchmarks for Injury Costs

- Lindsey (2000): average FA injury cost is $10k-15k and average passenger injury between $50,000 - $60,000 (combined serious and minor).

- Search (2000): direct payment cost of $600k for serious passenger injuries and $100k for minor injuries. Total annual Part 121 cost of FA injuries is $11M.
### Survey Results

- Survey response estimates:

<table>
<thead>
<tr>
<th>Injury Category</th>
<th>Lower</th>
<th>Expected</th>
<th>Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serious Flight Attendant</td>
<td>64748</td>
<td>164286</td>
<td>263823</td>
</tr>
<tr>
<td>Minor Flight Attendant</td>
<td>9292</td>
<td>25000</td>
<td>40708</td>
</tr>
<tr>
<td>Serious Passenger</td>
<td>76587</td>
<td>170000</td>
<td>263413</td>
</tr>
<tr>
<td>Minor Passenger</td>
<td>3256</td>
<td>33333</td>
<td>63411</td>
</tr>
</tbody>
</table>

*Survey: 90% Confidence Interval for mean cost of injury*
Total Injury Cost Estimate

- Using data from this study:

<table>
<thead>
<tr>
<th>Injury Category</th>
<th>Annual Injuries (Table 4)</th>
<th>Expected Cost $</th>
<th>Total Cost $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Flight Attendant</td>
<td>687.4</td>
<td>25,000</td>
<td>17,184,125</td>
</tr>
<tr>
<td>Serious Flight Attendant</td>
<td>38.4</td>
<td>164,286</td>
<td>6,312,536</td>
</tr>
<tr>
<td>Minor Passenger</td>
<td>119.5</td>
<td>33,333</td>
<td>3,984,725</td>
</tr>
<tr>
<td>Serious Passenger</td>
<td>17.1</td>
<td>170,000</td>
<td>2,903,157</td>
</tr>
<tr>
<td><strong>Total Annual Part 121 Industry Injury Cost</strong></td>
<td></td>
<td></td>
<td><strong>30,384,542</strong></td>
</tr>
</tbody>
</table>
## Industry Cost Benchmarks

- Turbulence costs are $30M- $60M:

<table>
<thead>
<tr>
<th></th>
<th>Survey</th>
<th>Lindsey</th>
<th>Search</th>
<th>FAA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Table 9</td>
<td>Average flight attendant injury: $12,500</td>
<td>Flight attendant injury cost not estimated</td>
<td>Serious injury: $521,800</td>
</tr>
<tr>
<td></td>
<td>Table 9</td>
<td>Average passenger injury: $55,000</td>
<td>Serious passenger injury: $600,000</td>
<td>Minor injury: $38,500</td>
</tr>
<tr>
<td>Minor Flight Attendant</td>
<td>17,184,125</td>
<td>9,072,364</td>
<td>$11,000,000 estimated as total flight attendant cost</td>
<td>Total serious injury cost: $28,960,694</td>
</tr>
<tr>
<td>Serious Flight Attendant</td>
<td>6,312,536</td>
<td>7,514,052</td>
<td>11,954,174</td>
<td>Total minor injury cost: $31,065,910</td>
</tr>
<tr>
<td>Minor Passenger</td>
<td>3,984,725</td>
<td>2,903,157</td>
<td>10,246,435</td>
<td></td>
</tr>
<tr>
<td>Serious Passenger</td>
<td>3,984,725</td>
<td>2,903,157</td>
<td>10,246,435</td>
<td></td>
</tr>
<tr>
<td><strong>Total Part 121 Cost Estimate</strong></td>
<td><strong>30,384,542</strong></td>
<td><strong>16,586,416</strong></td>
<td><strong>33,200,609</strong></td>
<td><strong>60,026,604</strong></td>
</tr>
</tbody>
</table>
Convective or Clear Air?

- What proportion of the costs are related to CAT? (LIDAR vs X Band)
  - For analysis: 2/3 incidents are convective

<table>
<thead>
<tr>
<th></th>
<th>Convective</th>
<th>Clear Air</th>
<th>Wake / Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 4- Crew Reports</td>
<td>67%</td>
<td>17%</td>
<td>16%</td>
</tr>
<tr>
<td>Clark (1997)</td>
<td>50%</td>
<td>33%</td>
<td>17%</td>
</tr>
<tr>
<td>Lindsey (2000)</td>
<td>50%</td>
<td>34%</td>
<td>16%</td>
</tr>
</tbody>
</table>

Issue: Is CAT over reported?
Non – Recurring Investment

From the survey data:

<table>
<thead>
<tr>
<th></th>
<th>OEM Purchase Cost</th>
<th>Retrofit Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-90%</td>
<td>Expected</td>
</tr>
<tr>
<td>X Band</td>
<td>25728</td>
<td>44643</td>
</tr>
<tr>
<td>LIDAR</td>
<td>48193</td>
<td>72500</td>
</tr>
<tr>
<td>Combined</td>
<td>59147</td>
<td>82500</td>
</tr>
</tbody>
</table>

Confidence intervals for mean cost shown
Differentiated based on original purchase on new aircraft and cost to retrofit existing fleet.
Operational Savings

- Operational Savings:
  - Fuel Savings: Search estimated $595 per aircraft per year
  - Diversions: Three found in the crew reports. Lindsey indicates that most continue.
  - Aircraft damage: Primarily cart and cabin related.

- Conclusion: Operational savings appear to be marginal decision factors
Business Case Injury Cost

- Consider investment for Part 121 carrier with 600 aircraft (per aircraft basis):
  - 80% success

<table>
<thead>
<tr>
<th></th>
<th>Total</th>
<th>Clear Air</th>
<th>Wake</th>
<th>Convective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatality events @ 0.2 /yr for industry</td>
<td>$108,000</td>
<td>$20,301</td>
<td>$17,053</td>
<td>$70,647</td>
</tr>
<tr>
<td>Minor Flight Attendant</td>
<td>$3,719,304</td>
<td>$669,937</td>
<td>$716,139</td>
<td>$2,333,228</td>
</tr>
<tr>
<td>Serious Flight Attendant</td>
<td>$1,366,277</td>
<td>$607,234</td>
<td>$0</td>
<td>$759,043</td>
</tr>
<tr>
<td>Minor Passenger</td>
<td>$862,439</td>
<td>$123,206</td>
<td>$92,404</td>
<td>$646,829</td>
</tr>
<tr>
<td>Serious Passenger</td>
<td>$628,354</td>
<td>$0</td>
<td>$314,177</td>
<td>$314,177</td>
</tr>
<tr>
<td>Total</td>
<td>$6,684,374</td>
<td>$1,420,677</td>
<td>$1,139,773</td>
<td>$4,123,924</td>
</tr>
<tr>
<td>Annual cost per aircraft</td>
<td>$11,141</td>
<td>$2,368</td>
<td>$1,900</td>
<td>$6,873</td>
</tr>
</tbody>
</table>
## X Band Case - Possibly Favorable

- Using 12% rate, five years, retrofit option and 80% reduction:
  - Intangibles: diversion, damage, others

<table>
<thead>
<tr>
<th>Percent injury cost reduction</th>
<th>80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business decision based on single aircraft model</td>
<td>X Band Base Case</td>
</tr>
<tr>
<td>Non Recurring Investment</td>
<td>$43,750</td>
</tr>
<tr>
<td>Annual injury savings</td>
<td>$5,499</td>
</tr>
<tr>
<td>Annual operating savings</td>
<td>$595</td>
</tr>
<tr>
<td>Annual intangible benefits</td>
<td>NA</td>
</tr>
<tr>
<td>Increased annual maintenance</td>
<td>0</td>
</tr>
<tr>
<td>Project life</td>
<td>5</td>
</tr>
<tr>
<td>Rate of return</td>
<td>12%</td>
</tr>
<tr>
<td>Net present value</td>
<td>-$21,784</td>
</tr>
</tbody>
</table>
LIDAR Business Case - Unfavorable

Possible market potential appears small:

<table>
<thead>
<tr>
<th>Percent injury cost reduction</th>
<th>80%</th>
<th>Value to Reverse Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business decision based on single aircraft model</td>
<td>LIDAR Base Case</td>
<td></td>
</tr>
<tr>
<td>Non Recurring Investment</td>
<td>$87,500</td>
<td>$7,600</td>
</tr>
<tr>
<td>Annual injury savings</td>
<td>$1,894</td>
<td>$28,053</td>
</tr>
<tr>
<td>Annual operating savings</td>
<td>$595</td>
<td>$26,754</td>
</tr>
<tr>
<td>Annual intangible benefits</td>
<td>NA</td>
<td>$26,159</td>
</tr>
<tr>
<td>Increased annual maintenance</td>
<td>$4,375</td>
<td>NA</td>
</tr>
<tr>
<td>Project life</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>Rate of return</td>
<td>12%</td>
<td>NA</td>
</tr>
<tr>
<td>Net present value</td>
<td>-$94,298</td>
<td></td>
</tr>
</tbody>
</table>
### Combined Product Case - Unfavorable

- Incremental expenditure over X band appears unjustified:

<table>
<thead>
<tr>
<th>Percent injury cost reduction</th>
<th>80%</th>
<th>Value to Reverse Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business decision based on single aircraft model</td>
<td>Combined Base Case</td>
<td></td>
</tr>
<tr>
<td>Non Recurring Investment</td>
<td>$97,500</td>
<td>$11,221</td>
</tr>
<tr>
<td>Annual injury savings</td>
<td>$7,393</td>
<td>$31,327</td>
</tr>
<tr>
<td>Annual operating savings</td>
<td>$595</td>
<td>$24,529</td>
</tr>
<tr>
<td>Annual intangible benefits</td>
<td>NA</td>
<td>$23,934</td>
</tr>
<tr>
<td>Increased annual maintenance</td>
<td>$4,875</td>
<td>NA</td>
</tr>
<tr>
<td>Project life</td>
<td>5</td>
<td>NA</td>
</tr>
<tr>
<td>Rate of return</td>
<td>12%</td>
<td>NA</td>
</tr>
<tr>
<td>Net present value</td>
<td>-$86,279</td>
<td></td>
</tr>
</tbody>
</table>
Business Case Issues

- Influence of other factors:
  - Competition to own cockpits
  - Market leadership: Integrated suite of weather products
  - Demonstrated commitment to Safety
  - Competitive pressures if lead adopter purchases
  - Long flights and out of seat entertainment
  - Issue of free flight
Importance of Decision Factors

- Aircraft damage - retrofit
- Aircraft damage - new aircraft
- Free flight requirement - retrofit
- Free flight requirement - new aircraft
- Reduced fuel costs - retrofit
- Reduced fuel costs - new aircraft
- Competitive advantage - retrofit
- Competitive advantage - new aircraft
- Late arrival / diversion - retrofit
- Late arrival / diversion - new aircraft
- Passenger injury - retrofit
- Passenger injury - new aircraft
- Flight attendant injury - retrofit
- Flight attendant injury - new aircraft

Survey importance of decision factors in business case decision
Penetration rates consistent with weak business case
Detect some forms of clear air turbulence
Obtain FAA certification as a non-essential system
Automatically gather algorithm performance data to enhance algorithm performance
Require minimal pilot training
Integrate ground-based turbulence data into the cockpit turbulence display
Transmit turbulence information to ground weather stations
Transmit turbulence data directly to other aircraft
Provide useful information during takeoff and descent flight operations and decision-making
Provide useful information during en route flight operations and decision-making
Part of an integrated weather awareness system
Consists primarily of software changes to the current generation of X band systems
<table>
<thead>
<tr>
<th>Feature</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detect some forms of convective turbulence</td>
<td>3.7</td>
</tr>
<tr>
<td>Obtain FAA certification as a non-essential system</td>
<td>3.5</td>
</tr>
<tr>
<td>Automatically gather algorithm performance data to enhance algorithm performance</td>
<td>3.2</td>
</tr>
<tr>
<td>Require minimum pilot training</td>
<td>4.0</td>
</tr>
<tr>
<td>Integrate ground-based turbulence data into the cockpit turbulence display</td>
<td>3.5</td>
</tr>
<tr>
<td>Transmit turbulence information to ground weather stations</td>
<td>3.4</td>
</tr>
<tr>
<td>Transmit turbulence data directly to other aircraft</td>
<td>3.0</td>
</tr>
<tr>
<td>Provide useful information during takeoff and descent flight operations and decision-making</td>
<td>3.8</td>
</tr>
<tr>
<td>Provide useful information during en route flight operations and decision-making</td>
<td>4.2</td>
</tr>
<tr>
<td>Part of an integrated weather awareness system with shared display and alarm system</td>
<td>4.0</td>
</tr>
<tr>
<td>A stand-alone weather information system</td>
<td>1.4</td>
</tr>
<tr>
<td>Combined Product Characteristics</td>
<td>Rating</td>
</tr>
<tr>
<td>---------------------------------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Obtain FAA certification as a non-essential system</td>
<td>2.7</td>
</tr>
<tr>
<td>Automatically gather algorithm performance data to enhance algorithm performance</td>
<td>3.4</td>
</tr>
<tr>
<td>Require minimum pilot training</td>
<td>3.9</td>
</tr>
<tr>
<td>Integrate ground based turbulence data into the cockpit turbulence display</td>
<td>3.9</td>
</tr>
<tr>
<td>Transmit turbulence information to ground weather stations.</td>
<td>3.5</td>
</tr>
<tr>
<td>Transmit turbulence data directly to other aircraft</td>
<td>3.2</td>
</tr>
<tr>
<td>Provide useful information during takeoff and descent flight operations and decision making</td>
<td>3.7</td>
</tr>
<tr>
<td>Provide useful information during en route flight operations and decision making</td>
<td>4.4</td>
</tr>
<tr>
<td>Part of an integrated weather awareness system with shared display and alarm system</td>
<td>3.7</td>
</tr>
<tr>
<td>Be a stand-alone turbulence system</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Summary of Success Characteristics

- Part of an integrated weather awareness system
- Minimum pilot training (human factors)
- Focus on en route data but descent and take off also important
- Integrate ground based turbulence data.
Turbulence Warning

- Estimated minimum warning for market success:

<table>
<thead>
<tr>
<th>Expected Warning in Minutes</th>
<th>Severe Turbulence</th>
<th>Moderate Turbulence</th>
<th>Light Turbulence</th>
</tr>
</thead>
<tbody>
<tr>
<td>X band</td>
<td>3.06</td>
<td>2.16</td>
<td>1.13</td>
</tr>
<tr>
<td>LIDAR</td>
<td>2.68</td>
<td>1.93</td>
<td>1.06</td>
</tr>
<tr>
<td>Combined</td>
<td>3.53</td>
<td>2.30</td>
<td>1.28</td>
</tr>
</tbody>
</table>
Detection Accuracy

- Accuracy threshold for market success:

<table>
<thead>
<tr>
<th></th>
<th>Severe Turbulence</th>
<th>Moderate Turbulence</th>
<th>Light Turbulence</th>
</tr>
</thead>
<tbody>
<tr>
<td>X band</td>
<td>90%</td>
<td>88%</td>
<td>83%</td>
</tr>
<tr>
<td>LIDAR</td>
<td>91%</td>
<td>88%</td>
<td>84%</td>
</tr>
<tr>
<td>Combined</td>
<td>93%</td>
<td>90%</td>
<td>85%</td>
</tr>
</tbody>
</table>
Example of Distribution

- The averages represent a range of accuracy estimates. For example:

![Severe Turbulence Detection Accuracy](chart)

- Percent Responses
- Detection Accuracy Interval
- 100% - 95%
- 95% - 90%
- 90% - 85%
- 85% - 80%
- Less than 80%

- X band
- LIDAR
- Combined
Summary

- Market potential primarily based on injury cost reduction
- X band has the greatest market potential
  - Initial costs must be kept low
  - System integration, accuracy, and ability to detect some clear air turbulence are critical.
- LIDAR and a Combined product have a very weak business case
  - Market penetration potential: new aircraft for long flights.
Secure Cabin Exercise

Briefing

Rod Bogue
NASA Dryden Flight Research Center
Secure Cabin Objective

• To determine the estimated time required to configure a commercial aircraft cabin for safe transit of atmospheric turbulence.
Cabin Secure Time

• The time from first announcement of hazard until the cabin is declared secure.

• **Approach**
  
  • Conduct series of timed aircraft cabin preparation simulations on wide-body and narrow-body aircraft
    - Professional cabin crew staff from United and American
    - Paid passenger subjects
    - Guidance from Cabin Evacuation Drill experience

• Use team of experienced operational staff to develop plans and procedures
Secure Cabin Participating Organizations

- Flight Attendants
  - AFA, APFA
- Air Carriers
  - United, Jet Blue, American, Delta, Continental
- Airframe Manufacturers
  - Boeing
- Government Agencies
  - FAA/CAMI, NASA
Simulation Variables

- Passenger load and Flight Attendant compliment
- Cabin Class (first class, business class, main cabin)
- Cabin Activities (food service, beverage service, lavatory utilization, night conditions)

**Scenarios**
- Full Meal Service
- After movie restroom call
- Long Haul night situation
Responsibilities

- Scenario Development - Secure Cabin Team
- Cabin Crew Staffing - UAL/American
- Pax Staffing - NASA funded
- Experiment Coordination - NASA
- Data Collection/Analysis - NASA/CAMI
- Report/Conclusions - Secure Cabin Team
Draft Plan

- Perform Wide-body exercise in the FAA/CAMI Cabin Evacuation facility at Oklahoma City in mid-September 2001
- Obtain passenger subjects from CAMI contractor
- Utilize CAMI Cabin Evac. facilities and expertise for exercise support (video, cabin set-up, test experience)
- Plan & conduct Narrow-body exercise at future date
CAMI 747 Cabin Evacuation Facility
Exercise Status

- Team Established and Functioning (3 meetings, conference calls)
- Approach defined, developing detailed scenarios
- Facilities Identified
- Experiment Protocol Approved
- Defining Space Act agreement
- Defining PAX participant staffing
Schedule

- Revise Draft Plan  10 June 01
- Complete 747 Configuration  1 July 01
- Finalize Plan  15 July 01
- Conduct Wide-body Exercise  10-14 Sept. 01
- Draft Report  15 Nov. 01
- Final Report  15 Jan. 02
- Conduct Narrow-body Ex.  4Q FY-02
Risks/Mitigations

- Process Logistics
  - CAMI / NASA Ames IRB Approval
    - Closely coordinate with CAMI Staff
    - Expand/Augment CAMI Role in Exercise
  - Recent MOA funds transfer uncertainty
    - Located a second MOA for backup

- Exercise Injury Liability
  - IRB review of Exercise plan
  - CAMI partnership with Cabin Evac Experience
  - Injury insurance from Pax supply contractor
Risks/Mitigations

- Passenger Seatbelt Unfamiliarity
  - Passenger training
  - Pre-exercise demonstrations
"Feasibility Study of Transport-Aircraft Control Systems for Turbulence Effects Mitigation"

Christopher J. Borland
Vincent M. Walton

The Boeing Company
Commercial Airplane Group
Seattle, WA

NASA Weather Accident Prevention Review
June 5-7, 2001
Study Objectives

- Use turbulence inputs from injury-accident FDR data
- Assess capability of current aircraft control systems to reduce turbulence-induced acceleration response in the cabin
- Assess new control law strategies with current (on-board) and advanced (forward-looking) turbulence sensors
- Identify key issues to practical implementation
Analysis of Turbulence Accidents and Wind Field Determination

- NASA Ames provided FDR data from NTSB for five accidents (1975-85).
- Boeing Accident/Incident Investigation Group provided FDR data for five accidents (1997-99).

Most of these data show some interesting similarities:

- Severe turbulence onset often gives little or no warning.
- Positive and negative spikes in acceleration, with negative excursions to below 0 g, lasting about 1-2 seconds.
- Duration of severe turbulence is often brief, 5-10 seconds.
Analysis of Turbulence Accidents and Wind Field Determination (cont’d)

- FDR data can be used (sort of) to extract the wind field (Ref: Bach and Wingrove AIAA papers)
  - Alpha vane, Nz, θ, air data using kinematics only
  - Nz, θ, δe using aero characteristics from A/C model
- Peak velocities of over 140 ft/sec have been seen.
- Some time histories strongly suggest vortex encounters due to Kelvin-Helmholtz instabilities (shear layers from jet streams, thunderstorms, mountain waves).
Case B-1 - Wz

Graph showing data for Case B-1 with two lines labeled wz-aoa and wz2-Nz.
Case B-2 - Nz (c.g.)

A/P - 747-100
Loc: Pacific Ocean (NRT-HNL)
Inj/Fat - 70+/1
Seat Belts - ON
Case B-3 - Nz (c.g.)

A/P - 747-200
Location: Atlantic (FCO-CCS)
Inj/Fat - 26/0
Seat Belts: unk
Current aircraft systems and requirements

- Turbulence Mitigation requires modification of the aircraft lift and pitching moment through:
  - Direct lift control; and/or
  - Pitch Control

- Current non fly-by wire aircraft in the commercial fleet (737, 747, 757, 767) have no direct lift control surfaces.

- For this study, pitch control alone has been used. Current elevator rate and deflection limits (with nonlinear limiting) have been used to set requirements.

- Current autopilot modes do not effectively counteract severe turbulence.

- Autopilot actuator capabilities may be inadequate to provide mitigation.
Control System Development and Performance

Study Assumptions:

- Nonlinear aircraft model (757-200) with existing nonlinear actuators
- Knowledge of the vertical gust profile ahead of the aircraft
- Quasi-static elastic aircraft (no flexible mode dynamics)
- Feed-forward controller design to avoid stability issues
- Control law parameters varied for optimal performance
- Direct input to control actuator (not currently available)
Aviation Safety Program

Noise Bias, Scale Factor, 
Time Advance

Linear Turbulence
Sensor Model

Threshold

High Pass 
Filter

TFR Filter

Low Pass
Filter

Saturation

Elevator Angle

Elevator
Nonlinear
Actuator

Nonlinear
Aerodynamic
Model

System
Outputs

Final Design Stage

Elevator
Linear
Actuator

Nonlinear
Aerodynamic
Model

Intermediate Design Stage

Elevator
Linear
Actuator

Nonlinear
Aerodynamic
Model

Initial Design Stage

Elevator
Linear
Actuator

Linear
Aerodynamic
Model

CONTROL SYSTEM DESIGN MODEL
Sensitivity Studies

Turbulence input sensitivity

- 13 Time histories used as input to 757-200 nonlinear simulation model, control performance assessed
  - 5 NTSB Cases
  - 3 Boeing Cases
  - 5 Vortex Cases

Sensor sensitivity

- Forward looking sensor compared with nose air data sensor for one case
Case B-1 Nz-aft System Off vs On
Case B-2 Nz-aft System Off vs On
Case B-3 Nz-aft System Off vs On
Forward Looking vs. Nose Air Data - System Off vs. On

- $N_z(\text{aft})$
- $N_z(\text{cg})$
- $N_z(\text{pil})$

Legend:
- System Off
- Forward Looking
- Onboard

Aviation Safety Program
Issues for Further Study

Aerodynamic Modeling Issues

- Nonlinear simulation data has limited negative angle of attack range
- Unsteady aerodynamics – angle of attack, control, gust lag functions
- Gradual gust penetration – wing sweep, wing to tail lag
- Stall Hysteresis – simulation is quasi-steady

Structural Modeling

- Dynamic Aeroservoelastic Model required for loads and flutter evaluation

Actuator Modeling

- “Physical model” required in place of “functional model”

Air Data System Modeling

- Need accurate measure of the “lead” for onboard air data
Lidar Modeling and Accuracy

- Current simulation assumes “perfect” measurement of vertical gust velocity
- Lidar requires multiple off-axis measurements with spatial and temporal interpolation which will affect accuracy
- Additional errors such as bias and noise will affect accuracy
- Signal processing lags should be included
- Base motion “jitter” can be determined from structural dynamic model, isolation and/or motion compensation should be included

Multiple Flight Condition Modeling

- All simulation to date on single aircraft model at single flight condition. Effects of variations in altitude, Mach, gross weight, c.g. should be determined
Issues (Cont’d)

Autopilot / Manual Control Input Effects

• Current simulation models have no autopilot

• Need autopilot model to separate autopilot and manual inputs

• Need to assess whether autopilot and manual inputs make situation better or worse

• What is the effect of warning time on the pilot’s reaction?

• What is the effect of various gust profiles on the pilot’s reaction?

• How does the pilot react in the presence of a turbulence mitigation system?

• What do we show the pilot?

• These should be answered by a real-time simulation study.
Issues (Cont’d)

Control System Development Issues

- Redundancy Management
- Control Augmentation (SAS)
- Multiple Sensor Control
- Line of Sight Command for Maneuvering Aircraft
- Ride Quality vs Safety Requirements
- Gust Spectral Content Filtering
- Alternate Control Law Development Schemes
- New PCU Input vs Existing Autopilot Actuators (Autoland Mode)
- Direct Lift Control
Recommendations for Further Work

Continue Modeling Improvements (aerodynamic, structural, sensor, control)

Evaluate Structural Load and Autopilot Effects

Continue Control Development Studies

Select Candidate Aircraft for Demonstration

Determine Forward Looking Sensor Accuracy by Flight Test

Perform Real-Time Simulation

Design and Installation of Required Aircraft System Modifications

- Sensors
- Computer
- Actuators

Flight Demonstration
Turbulence JSIT Status

Rod Bogue - NASA Dryden Flight Research Center
Outline

- CAST Process
- Intervention & Project Statistics
- JSAT Turbulence Model
- Initial Project Subject Candidates
- Status
CAST Process for Defining and Implementing a Data-Driven Safety Enhancement Plan

**Data Analysis**
- Select highest leverage areas of interest
- Initiate/ approve JSAT
- Conduct JSAT analysis

**Set Safety Priorities**
- Review/approve JSAT report
- Initiate/approve JSIT
- Conduct JSIT Analysis
  - Prepare initial project proposals
  - ID Immediate Action(s)
- Initial project selection
- Immediate Action approval

**Implement Safety Enhancements**
- Preliminary Project planning
- IA preliminary planning
- Initial project approval
- Immediate Action initial approval
- Detailed project plans
- Immediate Action specific plans
- Final project approval
- Final Immediate Action approval
- Execute & Monitor progress
  - Adjustments as necessary
  - Integrate into existing work and distribute
Intervention & Project Statistics

- 30 Interventions From JSAT
- 16 Above the Line (53%)
- 5 Projects
- 2 Research Recommendations
Initial Project Subject Candidates

- Flight Attendant, Passenger and Cabin Secure Procedures
- Flight Attendant and Passenger Turbulence Injury Exposure
- Practices for Turbulence Avoidance
Initial Project Subject Candidates (cont.)

- Quality of Turbulence Information
- Turbulence Detection Technology
- Turbulence Displays and Data Dissemination
- Turbulence Effects Mitigation through Aircraft Control System Action
Status

- JSIT Chartered 12 January 2001
- 3 Sub-Teams Organized
- 4 Full Meetings
- Obtained CAST E-Level Approval
- Finalizing Project Executive Summaries
- CAST added Cost/Benefit Assessment and Nationwide Facility Resource Needs Assessment
- Expect G-Level approval in early FY-02
NASA-FAA-NOAA
Partnering Strategy

Weather Accident Prevention
Project Review
June 7, 2001

Dr. Ron Colantonio, Inter-Agency Coordination Manager

Glenn Research Center
Aeronautics at Lewis Field
Content

Pros for Inter-Agency Collaborations

Pitfalls in Inter-Agency Collaborations

Progress to Date

Summary

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Partnership 101
Resource Flows in Partnerships

- Pooling Arrangements: Two or more organizations combining similar resources
  - Cost and/or risk sharing
  - Gaining influence of stakeholders
  - Information sharing/benchmarking
  - Standard Setting

- Trading Arrangements: Two or more organizations exchanging dissimilar (but mutually valued) resources
  - Developing synergy through complementary competencies

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Higher Level Inter-Agency Collaboration Needed

Collaborations leading to Reliance on Critical Path Dependencies

Past

Future

Very Limited Resources

Limited Resources

Collaborations leading to Risk Reduction and Intellectual Augmentation

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What Defines a Good Partner

1. Resources- Do they possess the resources/capabilities we seek?

2. Incentives- Do they have adequate motivation and commitment to the success of the venture/partnership?

3. Cultural/Trust- Does it feel like their business approach fits well with ours?
Why Partnerships Fail

40-60% of all partnership/alliances fail

1. Environmental Reasons
   • Failure to anticipate changing R&D demands
   • Inability to reconcile macro-cultural issues

2. Strategic Reasons
   • Purpose not clearly articulated

3. Structural Reasons
   • Weak Incentive structure; ill suited for strategic purpose

4. Behavioral Reasons
   • Egos and personal dislike (person versus organization)

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Current Inter-Agency Collaborative Activities

- **NASA-DOD-DOE Alliance in Propulsion & Power**
  - Completed five “Collaboration Workshops” during the past year
  - Generated detailed roadmaps for collaborative activities in 9 technology areas

- **NASA-Air Force Propulsion Collaboration**
  - Goldin/Peters agreement to increase collaboration

- **NASA GRC-Sandia Labs Collaboration**
  - MOU signed for broad suite of Aero/Space technologies

- **NASA-FAA Alliance under NASA-FAA Umbrella MOUs**
  - Aviation Weather Safety MOA signed
  - Aviation Air Emissions MOA being prepared
  - Accident Mitigation MOA being prepared

- **NASA-Canadian Agencies (CNRC, TC, MSC) Icing Alliance**
  - Aircraft Icing Research Alliance (AIRA) signed to do joint icing research per single strategic plan

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**Glenn Research Center**

Aeronautics at Lewis Field
Partnering Status

- FAA Flight Safety and Weather R&D Initiatives
- NOAA NWS Initiatives

Collaboration Planning

NASA Aviation Safety Program

Five Technology Areas Jointly Examined by NASA, FAA and NOAA for Collaboration

- Aviation Weather Information in the Cockpit Technologies
- Weather Products
- Automet Technologies
- Forward Looking Weather Sensors
- Turbulence Controls and Mitigation Systems

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Aeronautics at Lewis Field
NASA-FAA Partnership

Memorandum of Agreement between NASA and FAA concerning Weather Accident Prevention R&D Activities was signed in June 2000. The MOA states NASA and FAA will jointly develop the following products:

1. Aviation Weather Information Technologies for NAS and users
2. Aviation Weather Products
3. Electronic Pilot Reporting/Automet Technologies
4. Forward-Looking Weather Hazard Sensors
5. Turbulence Controls and Mitigation Systems

This MOA was signed by FAA Associate Administrator of Research and Acquisitions, Air Traffic Services and Regulation and Certification as well as NASA Associate Administrator for Aero-Space Technology

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Aeronautics at Lewis Field
NASA-NOAA/NWS Partnership

Memorandum of Agreement between NASA and NOAA/NWS concerning Weather Accident Prevention R&D Activities has been drafted and is under review. The MOA states NASA and FAA will jointly develop the following products:

1. Aviation Weather Information Technologies for NAS and users
2. Aviation Weather Products
3. Electronic Pilot Reporting/Automet Technologies
4. Forward-Looking Weather Hazard Sensors

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Proposed FAA-NASA-NOAA Teams

- Automet Team
- AWIN Systems Team
- Wx Comm Working Group
- Forward-Looking Turbulence Detection Team
- Turbulence Product Development Team
- Turbulence Controls Alliance

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Summary

• NASA, FAA, NOAA fully endorse the partnership vision and direction.

• Current NASA, FAA and NOAA collaboration activities going well.

• Interagency implementation agreements in progress toward integrating collaboration activities into agency program plans.
Flight Information Services Data Link (FISDL)

Alfred Moosakhanian

NASA Weather Accident Prevention Project Review

June 7, 2001
FIS Policy Implementation

- FAA published Airborne FIS Policy Statement based on industry petition through the GA Coalition:

  The FAA’s goal “... is to use digital data link to deliver information to the pilot ... and will use the private sector’s FIS capabilities ... to bring FIS services and products to the market place quickly and efficiently.”

- FAA signed Government-Industry Project Performance Agreements (G-IPPAs) with two FISDL Service Providers
  - ARNAV Systems, Inc; Puyallup, WA
  - Honeywell International, Inc; Olathe, KS
FISDL System Overview
FISDL Cockpit Display
Unique G-IPPA Provisions

chengive competitive strategy with two FISDL Service Providers designed to use “market pressure” to stimulate and control quality and cost of FISDL services

- No system specifications; rather based on:
  - FAA Statement of Objectives, and
  - SOW submitted by ARNAV and Honeywell

- FAA provides access to 4 VHF channels (136 MHz “protected” spectrum)

- ARNAV and Honeywell each provide independent system infrastructure and service at no cost to FAA
Key Provisions: FAA Commitments

- Five year agreement with opportunity for renewal
  - Access to 4 VHF channels (136 MHz “protected” spectrum) with spectrum engineering support
  - Access to FIS/Wx data within FAA systems; these data are also available to all other vendors as well
- Publish ACs, other publications, and necessary standards
- Sponsor studies to develop applications/benefits & NAS changes
- Evaluate implementation of GA Automet (TAMDAR / E-PIREPs)
  - Includes evaluation/validation of operations concepts and procedures for national deployment of downlink and possible crosslink of aircraft derived weather data from commuter, and low-altitude general aviation operations
Key Provisions: Provider Commitments

- System infrastructure and service at no cost to FAA
  - Full national coverage (CONUS + Hawaii; Alaska Optional)
    - Access from at least 5000’ to 17,500’; sfc to 45,000’ desired

- Products designed for aviation use and based on approved data sources
  - Conform to guidelines (ICAO, RTCA, SAE G10) for cockpit display
  - Basic products at no fee (METAR/SPECI, TAF/AMEND TAF, SIGMET, Conv SIGMET, AIRMET, PIREPs, Alert Wx Watches)
  - Valued-added products for fee

- Education/training materials for pilot users and FAA

- Archive all broadcast transmissions for at least 15 days

- Quality assurance that addresses system risks and user concerns
Implementation Status

- Product review/approval procedures for value-added FISDL products established
  - ARW-200 (Weather Standards) Team Lead
  - Initial products (ARNAV and Honeywell) have been reviewed and accepted

- AIM Revision including FISDL overview in Section 7 published

- Advisory Circulars drafted by Flight Standards and Aircraft Certification

- FIS-B MASPS published by RTCA/SC-195
  - DO-267, March 27, 2001
  - Provides communications protocols and presentation guidelines for FIS digital broadcast and cockpit display
Implementation Status (Cont’d)

› ARNAV achieved operational status with GMSK data radio technology (July 2000)
  ➢ TSO and STC have been issued

› Honeywell developing VDL Mode 2 data radio technology.
  ➢ IOC of ground system scheduled for June 2001
  ➢ Radio certification by 4th Quarter 2001
FISDL Examples - ARNAV

Regional NEXRAD
FISDL Examples - ARNAV

200 Nautical Mile NEXRAD
FISDL Examples - ARNAV

- POSITION IS N46°55.42 W120°30.49
- METAR ICAO ZULU WIND VISIBILITY
  - METAR KPWT 222215Z AUTO 20011G19KT 10SM FEW001 SCT017 BKN060 08/06 A2975
  - METAR KTCH 222159Z RTD 19020G25KT 5SM -RA FEW020 BKN030 OVC070 10/07 A2977
  - METAR KBF1 222153Z 17015G24KT 8SM RA FEW022 SCT030 OVC098 09/07 A2974
  - METAR KSEA 222156Z 21013KT 7SM RA SCT019 BKN025 OVC030 08/07 A2975

PRESS ANY KEY

Full Text METAR Report
Airline Implementation of Cockpit Weather Systems

Capt. David Sambrano
Flight Technical Manager
Background UAL ISE

- Just finished 40+ segments on A320 In-Service Evaluation
- Tested products of WINN program included:
  - CONUS Radar*
  - Worldwide Satellite*
  - Convection*
  - Nowcasting
  - Airports (METARS/TAFS)
  - Turbulence Forecast
Weather Information Network (WINN)

SIGMET, METARs, TAF, and airport ATIS information may be displayed in a graphic format and in text.

The FMC’s flight plan route is automatically displayed.

Data is displayed in a “North up” format or in a “Track up” format.

Covective, Volcanic Ash, Turbulence, Winds, Icing, Radar (conus only), Satellite, Lightning, and “Nowcasting” weather data are available worldwide via automatic data link.

Provides quality information for making better decisions.

Enhances pilots’ situational awareness.

The WINN program automatically centers and tracks the aircraft’s location and communicates with any location.

FLIGHT OPERATIONS TECHNOLOGY
Innovations in flight.
ISE Results

- Real time radar images.
- Turbulence predictions were accurate.
- Coded airport very effective in divert decision.
  - METAR Wx table format very good.
- SAT imagery results.
- Graphical Sigmets good.
METAR Table Format
Net Results of Having Real Time Wx

- More accurate flight planning.
  - LAX-JFK 8am departure
- ATC ground stops.
- UAL size carrier can save est.1-2% fuel per year. (NASA Langley study)
- Est. 2% reduction in total block time
- Est. 80% reduction in all turbulence injuries.
- CAT/Wx predictions internationally.
- First phase towards true Free Flight.
Implementation Issues

- Display...where and what kind?
  - Removable PED display on adjustable simple mount. (Sky-Pad)
  - Not in primary field of view.
  - Cost effective for procurement to AT/GA.

- Certification Issues:
  - Supplemental information?
  - Collaborative decision making.
  - Other software driving certification?
Implementation Issues

- Data pipe to the aircraft?
  - L-Band, Satellite, GTE Phone data receiver.
  - AT/GA solutions that are cost effective. $$$
- STC’s of mounting unit.
- 80% of AOC communications
United Focus

- AT/GA solution.
- Solution must be cost effective.
- Safety makes this priority.
Questions?
FIS Implementation

• Implementation
• Operation
• Future Technologies
Preliminary Groundstation Site Map
System Integration Efforts

“Turkey” Integration (Began in November 2000)
- 1st End-to-End Integration Testing using Single Cell
- Hub and Groundstation prototype testing.
- Terrestrial network prototype testing.
- Broadcast network RF performance testing.
- Flight Testing to baseline RF performance
- RF Propagation Analysis

“Frosty” Integration
- Phase 1 (Complete Terrestrial Supercell)
  - Validate RF performance / Assess interaction between cells.
  - Test initial product package.
  - Validate terrestrial Wide Area Network (WAN) design and operation.
  - Achieve reliable 7x24 network operation.
  - Blue label VDR / Display tests.
  - Test ground station deployment process.
  - Perform Flight Testing
- Phase 2 (Business Systems / Network Management)
  - Integrate and test WOC.
  - Subscription / Provisioning process integration and test.
  - Customer interface.
  - Integration of Billing systems.
  - Completion with IOC
  - Perform Flight Testing
FIS Supercell Frequency / Time Slotting

Coverage at 5000 ft AGL
(Smooth Earth propagation model)

2 Frequencies, 4 Time Slots

<table>
<thead>
<tr>
<th>$f_1$: 136.45 MHz</th>
<th>$f_1t_1$</th>
<th>$f_1t_2$</th>
<th>$f_1t_3$</th>
<th>$f_1t_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_2$: 136.475 MHz</td>
<td>$f_2t_1$</td>
<td>$f_2t_2$</td>
<td>$f_2t_3$</td>
<td>$f_2t_4$</td>
</tr>
</tbody>
</table>

Note: $t_1$, reserved for special cases.
FIS Network Frequency / Time Slotting

2 Frequencies, 4 Time Slots

\begin{align*}
\text{f}_1 &: 136.45 \text{ MHz} \\
\text{f}_2 &: 136.475 \text{ MHz}
\end{align*}

Note: \( f_2 \) reserved for special cases
KMD 550 Multi function Display

KDR 510 FIS Receiver

KGS 511 Ground Station
Subscription Control

• Broadcast only system
  – No Handshaking
  – Free products vs Premium products
  – Subscription by year / month
  – Encryption solution
Operation Challenges

• Management of Ground Station Network
  – Network siting stability
  – Maintenance
    • Monitoring
    • Automation of monitoring
    • Logistics

• Manage Comm Link costs
Future Technologies

• Higher level of integration
• Portable Market
• 2 Way FIS
National Business Aviation Association (NBAA)

Tenny Lindholm
The National Center for Atmospheric Research
for
Bob Lamond
NBAA
What NBAA Wants...

- Shared situational awareness between the ground and flight deck
- Graphics (3-D if appropriate)
- Other FIS-B products (including current textual weather information)
- 3-4 year capability (not 2010)
NBAA Operational Environment

- Service to many diverse major and smaller terminals
- Generally high-end equipment; however, there is a wide spectrum from helicopter to large bizjets
  - SATCOM
  - VHF digital radios
  - ACARS
  - FIS-B—yes
  - Display options
- Critical need to complete the mission
- Short-notice operations
Bottom Line for NBAA

- Access to data and information ASAP. That is,
  - NBAA has perhaps the best equipage in the industry; however, inflight operators cannot access weather information because the infrastructure is not in place
  - An incremental buildup of capability is okay, recognizing the infrastructure takes time
- A spectrum of capabilities
- Graphics
  - Mirror what is available on the ground for the flight deck
- Comprehensive national (and international) coverage
- Don't get too consumed with cutting edge development, unless there is a clear benefit
  - Technology has been demonstrated
  - Further focus on R&D vs. implementation will slow the introduction of needed capability
Proceedings of the Second NASA Aviation Safety Program Weather Accident Prevention Review

K. Gus Martzaklis, compiler

National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135–3191

E–12817


The Second NASA Aviation Safety Program (AvSP) Weather Accident Prevention (WxAP) Annual Project Review held June 5–7, 2001, in Cleveland, Ohio, presented the NASA technical plans and accomplishments to the aviation community. NASA-developed technologies presented included an Aviation Weather Information System with associated digital communications links, electronic atmospheric reporting technologies, forward-looking turbulence warning systems, and turbulence mitigation procedures. The meeting provided feedback and insight from the aviation community of diverse backgrounds and assisted NASA in steering its plans in the direction needed to meet the national safety goal of 80-percent reduction of aircraft accidents by 2007. The proceedings of the review are enclosed.