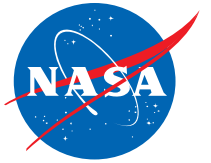


Improving the Safety of Current and Future Aircraft Through Integrated Health Monitoring

April 12, 2007

Richard W. Ross
Associate Principal Investigator, Airframe Health Management
Integrated Vehicle Health Management
Durability, Damage Tolerance, and Reliability Branch
NASA Langley Research Center
richard.w.ross@nasa.gov
(757) 864-6541

Outline

- Need for Improved Aviation Safety
- NASA's Aviation Safety Program
- Future Concept of Operation
- IVHM Project
  - Vehicle Health Technologies
  - Environmental Hazards Technologies
  - Systems Technologies
  - Benchmark Problems
- Partnership Opportunities
- Summary
- Questions?

Need for Improved Aviation Safety

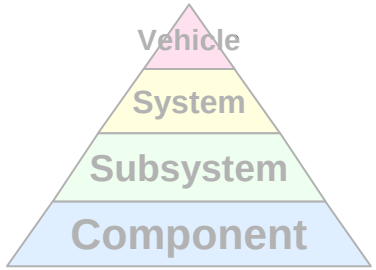
Forward fuselage, Aloha Airlines (1 person killed)

Vertical Tail, American Airlines Flt 587 (265 killed)

Engine, Delta Flight 1288 (2 people killed)

U.S. Forest Service C-130, near Walker, CA (3 killed)

NASA's Aviation Safety Program



NASA

Space Operations Mission Directorate

Aeronautics Research Mission Directorate
Lisa Porter

Exploration Systems Mission Directorate

Science Mission Directorate

Fundamental Aeronautics Program

Aviation Safety Program
Herb Schlickenmaier

Airspace Systems Program

Aeronautics Test Program

Integrated Resilient Aircraft Control

Integrated Vehicle Health Management
Ashok Srivastava

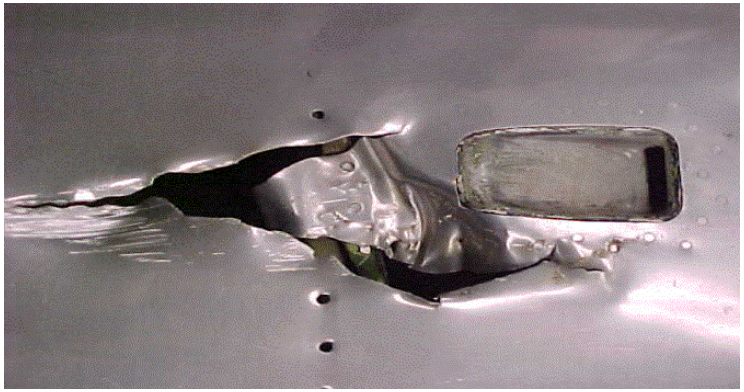
Aircraft Aging and Durability

Integrated Intelligent Flight Deck Technologies

Aviation Safety Program

Integrated Vehicle Health Management (IVHM)
- Continuous assessment
- In-flight
- Life of vehicle

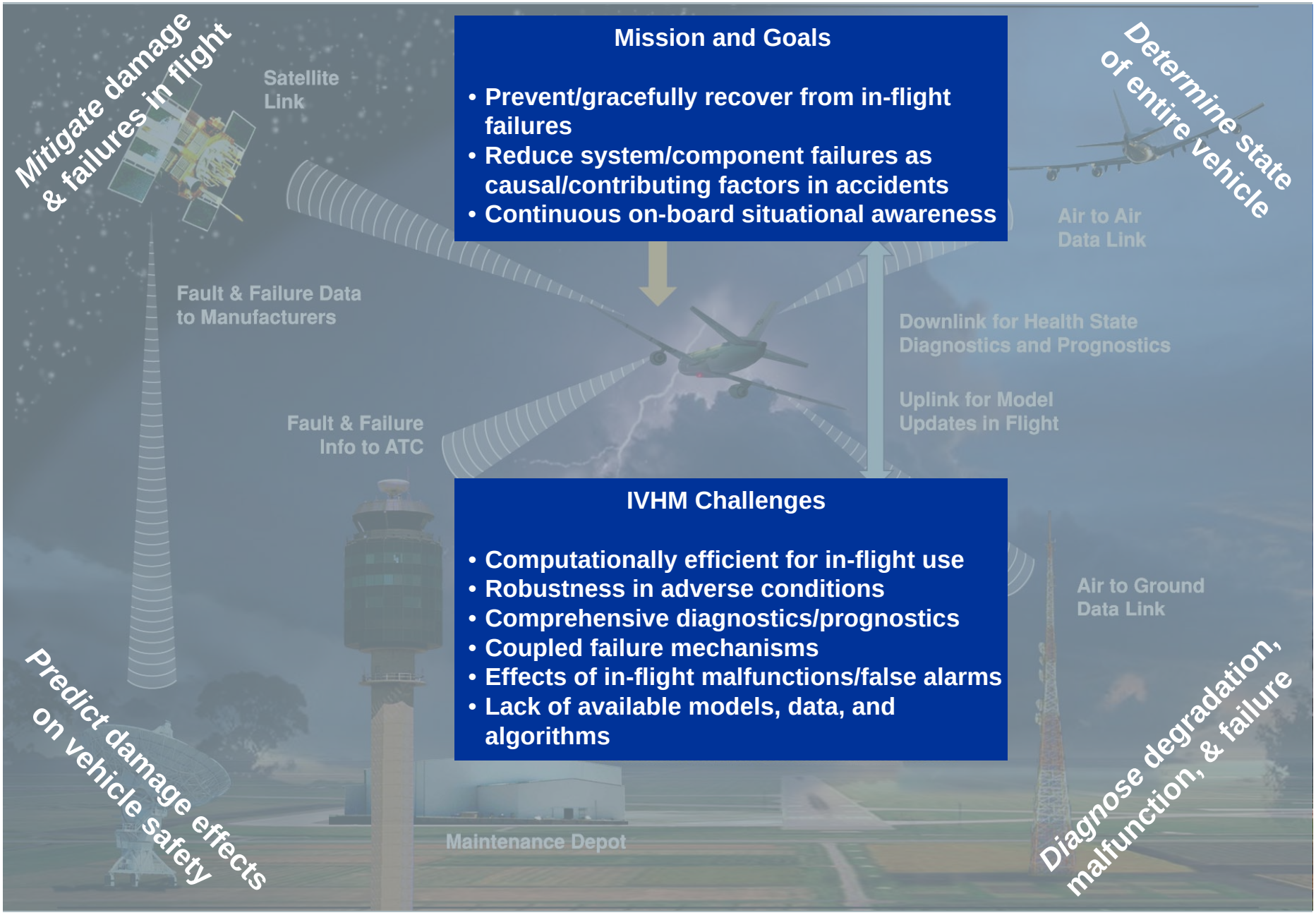
Integrated Resilient Aircraft Control (IRAC)
- Robust control systems
- Overcome upset flight conditions
- Duration of flight



Integrated Intelligent Flight Deck (IIFD)
- Adaptive flight systems
- Synthetic vision
- In-flight

Aircraft Aging and Durability (AAD)
- In-depth analysis
- Periodic inspection
- Ground-based
- Life of vehicle

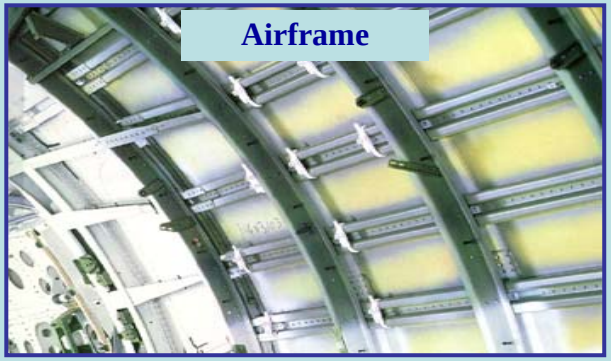
IVHM Future Concept of Operations



IVHM Research Areas

Vehicle Health Technologies

Airframe



Propulsion

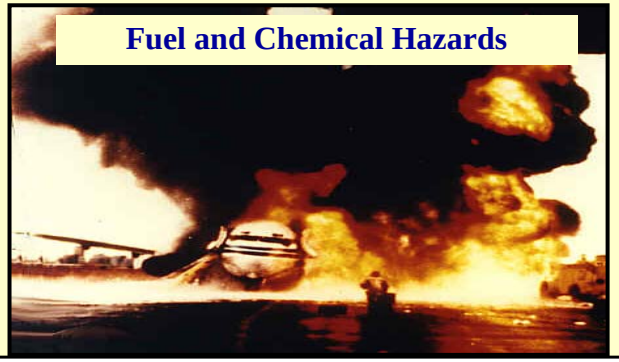
Aircraft Systems

Environmental Hazards Technologies

Engine Icing

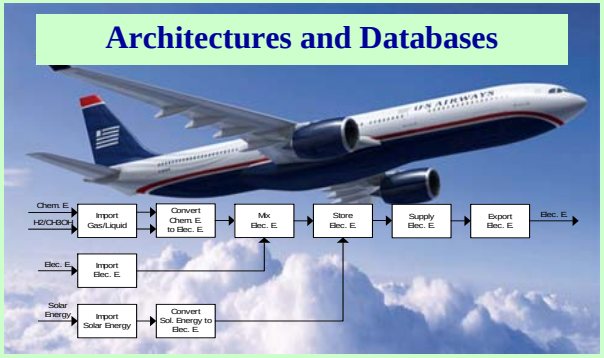
Electrical Hazards

Fuel and Chemical Hazards

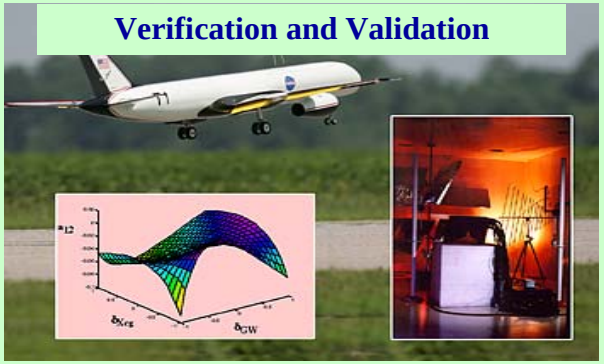


Systems Technologies

Architectures and Databases



Verification and Validation

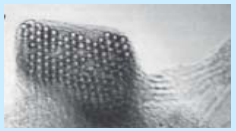


Integration & Assessment

Vehicle Health Technologies

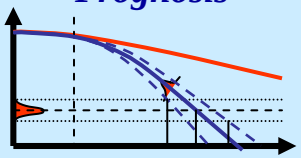
Airframe

Detection



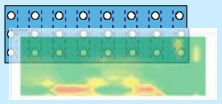
- Carbon nanotube
- Surface acoustical wave
- Fiber Bragg grating

Prognosis



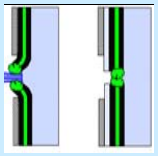
Damage progression algorithms

Diagnosis



- Feature extraction, classification, & reasoning
- Residual methods

Mitigation



- Healing materials
- Metals and composites
- Small scale damage

Integrated Continuous Health State Management

- ***In-flight detection & diagnosis***
- ***Continuous prediction of damage propagation***
- ***Mitigation of structural damage***

- *Early detection of engine failure*
- *Structural damage to propulsion components*
- *High-temperature sensor technology*

- *Flight-critical avionics*
- *Complex interactions*
- *Hybrid reasoning*

Propulsion

Gas Path

Model-Based Diagnostics

Residual Monitoring

Performance Trend Monitoring

Prognosis for Hot Structures

Life management by load alleviation

Structural Health

Thrust Asymmetry

High-Temperature Sensors, Electronics, and Communications

Aircraft Systems

Electromechanical Systems

Data-driven diagnostics & prognostics

Model-based diagnostics and sensor fusion

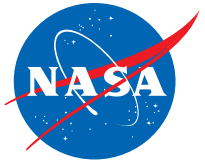
Electrical Power Systems

Diagnostic & prognostic models

Avionics and Electronics

Multi-level detectors for transient & soft failures

Vehicle Health Technologies



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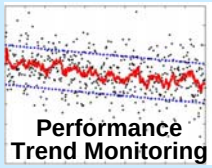
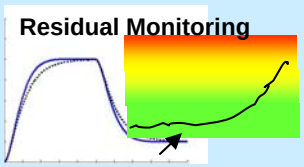
Propulsion

Gas Path

Model-Based Diagnostics





Prognosis for Hot Structures

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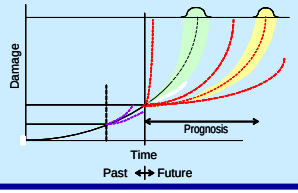
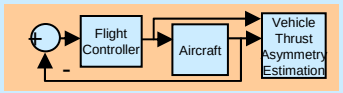
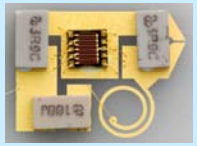


Structural Health

Thrust Asymmetry



High-Temperature Sensors, Electronics, and Communications



Aircraft Systems

Electromechanical Systems

Data-driven diagnostics & prognostics

Model-based diagnostics and sensor fusion

Electrical Power Systems

Diagnostic & prognostic models

Avionics and Electronics

Multi-level detectors for transient & soft failures

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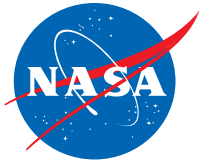

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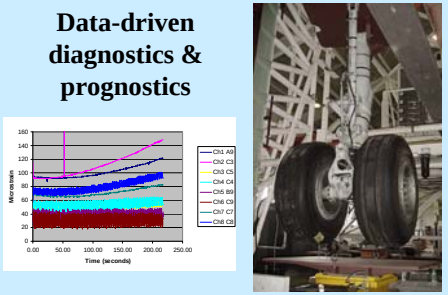
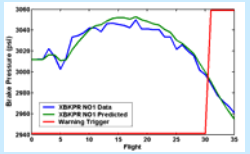


Model-based diagnostics and sensor fusion



Electrical Power Systems

Diagnostic & prognostic models

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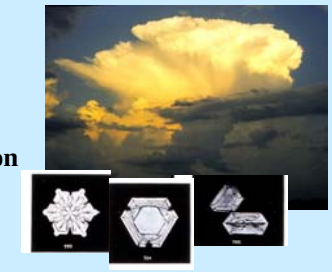
Engine Icing

Physics-Based Models

Ice accretion physics



State Monitoring

- Detect environmental conditions
- Detect engine performance changes
- Predict event potential & mitigation path

Detection: Sensors

Measure ice content and crystal size

Environmental Hazard Detection & Effects Mitigation

- ***Direct (ice) & indirect (engine performance) detection***
- ***Diagnostic & prognostic ice accretion models***

- *Detect & mitigate electromagnetic interference*
- *Detect & mitigate ionizing radiation SEE*

- *Monitor fuel tank safety*
- *Develop efficient and safer fuels*

Electrical Hazards

Lightning and EMI/EMC

EM Modeling and Testing

- EM propagation
- Field penetration

Detection & Mitigation

- Empirical data
- Physics based
- Statistical models

Ionizing Radiation

SEE Modeling and Testing

Hybrid Models

Single Event Effects Mitigation

- Architecture
- Rad-hard components

Fuel & Chemical Hazards

Fuel Tank Fire/Explosion

Safety analysis for future fuels

Onboard Fuel Monitoring

- Vapor Pressure / Phase
- Ignition Energy

Mitigation: Reduce detonation potential

Chemical Hazard Monitoring

Metal-oxide nano sensors

Electrical arcing and hydraulic leak detection

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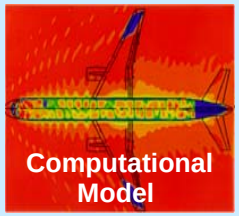
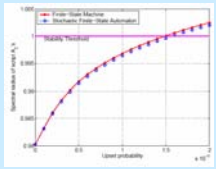


Detection & Mitigation

- **Empirical data**
- **Physics based**
- **Statistical models**

Ionizing Radiation

SEE Modeling and Testing



Hybrid Models

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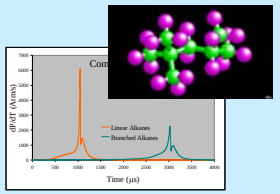
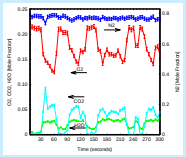


Onboard Fuel Monitoring

- **Vapor Pressure / Phase**
- **Ignition Energy**



Mitigation: Reduce detonation potential

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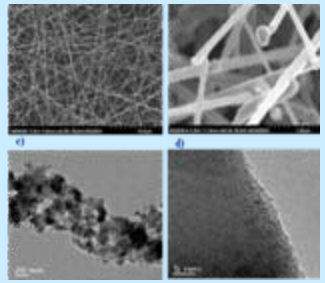
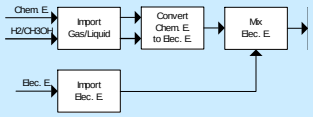


Electrical arcing and hydraulic leak detection

Systems Technologies

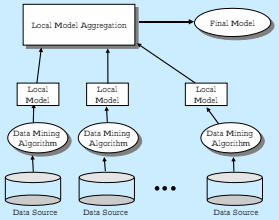
Architectures & Databases
Design & Analysis Tools

- Automated system level trades
- High-level functional models



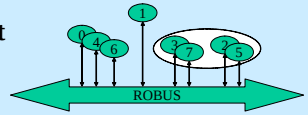
Reasoning, Databases, & Data Mining

- Vehicle-wide health state reasoning
- Failure/hazard management



Processing System Architectures

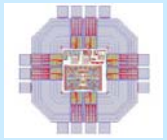
Fault tolerant nodes / links



Self-reconfiguration

Sensing System Architectures

- Reconfigurable antennas
- Adaptive protocols



Integrated Continuous Health State Management

- *Design, analysis, & reasoning tools*
- *Databases and data mining*
- *Processing and system architectures*
- *Verification and Validation*
- *Analytical, simulation, and experimental methods*
- *Cost-benefit analyses for IVHM technologies*

Verification and Validation

Analytical Methods

- Software verification
- Uncertainty modeling
- Nondeterministic adaptive system analysis

Experimental Methods

- Sub-scale flight tests
- Multidisciplinary HIL testing

Simulation Methods

- Guided Monte Carlo
- Robustness analysis
- Bifurcation analysis

Run-Time Performance Monitoring

- Online analysis
- Real-time margin estimation

System Integration and Assessment

Integration Methods and Tools

Assess tradeoffs:
- Cost
- Performance
- Safety

Assessment Methods and Tools

Evaluate safety investments
- Determine exposure
- Determine benefit
- Determine cost effectiveness
- Derive metrics

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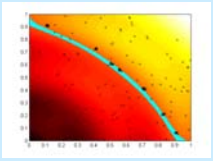

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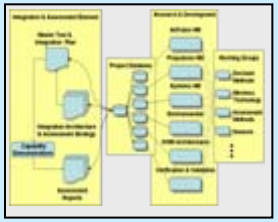

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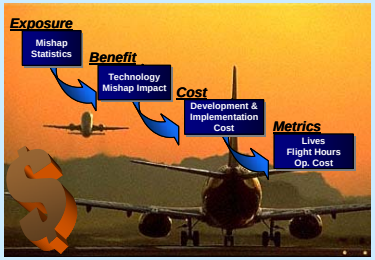

Evaluate safety investments
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- **Determine benefit**
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- **Derive metrics**

Benchmark Problems: Lightning Strikes

EM/Current Sensors & Sensor Architecture

Signal Processing & Data Fusion Module

Chemical Sensors & Sensor Architecture

Signal Processing & Data Fusion Module

Lightning Virtual Sensors, Data Mining, and Data Fusion

IVHM Processing Architecture

Vehicle-Wide HM Module

EPS HM Module

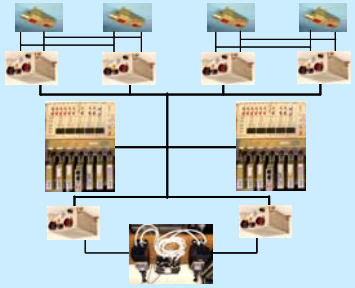
Avionics HM Module

Propulsion HM Module

Fuel Tank Safety Module

Airframe HM Module

Electrical Power System



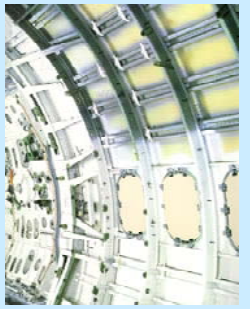
Flight Control System

Guidance and Navigation System

Engine 1

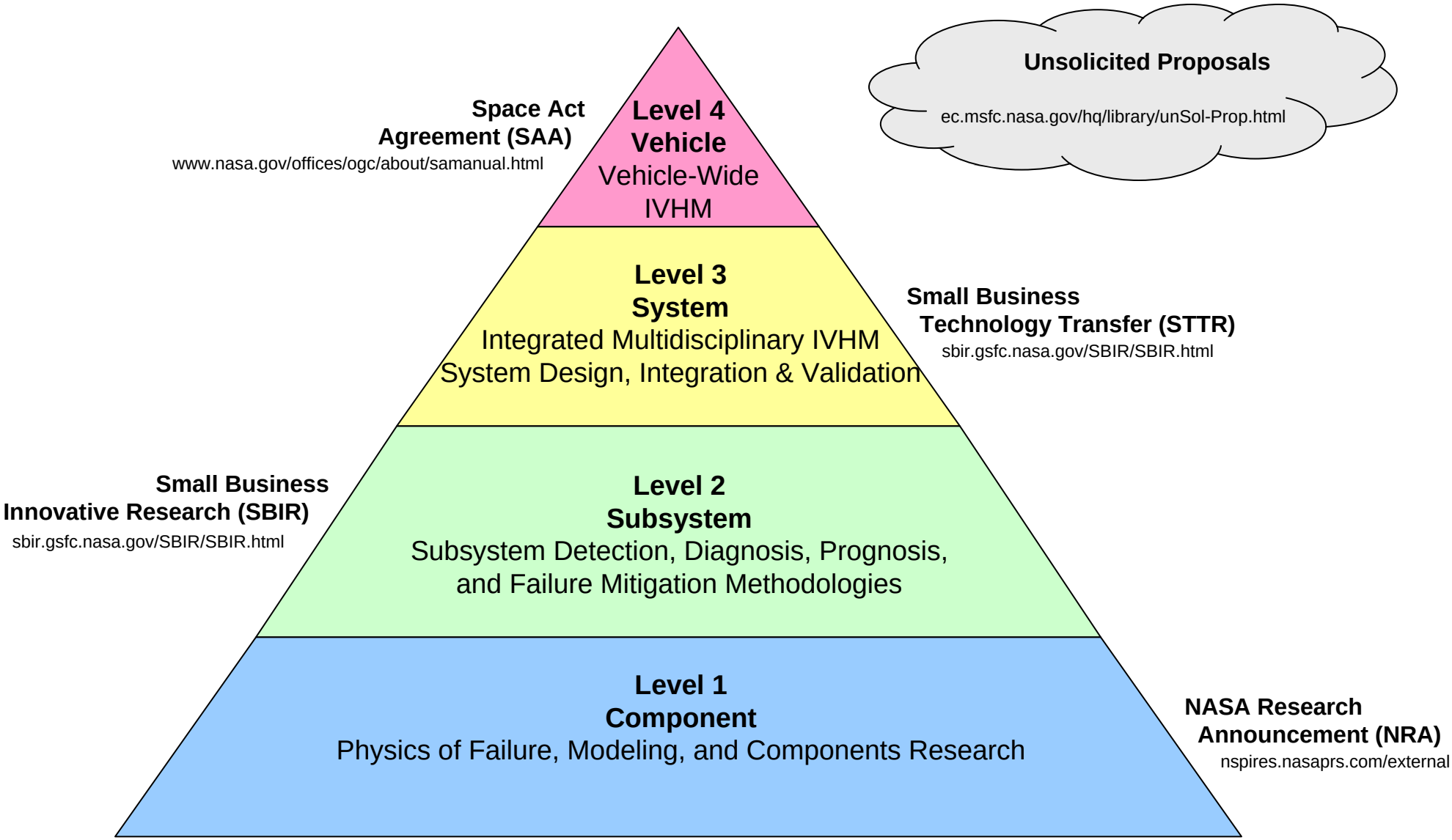
Engine 2

Fuel Tank



Airframe Structure

Partnership Opportunities



Summary

- IVHM is part of a comprehensive four-component Aviation Safety Program
- IVHM provides on-board assessment and management of vehicle health, environmental hazards, and systems technologies
- IVHM addresses the need for in-flight detection, diagnosis, prognosis, and mitigation of in-flight hazards
- IVHM meets the demands of next-generation air transportation systems through innovative technologies including an integrated, on-board approach
- NASA partnership mechanisms include SAA, SBIR, STTR, and NRA opportunities (*see NASA websites for list of current opportunities)*

Questions?

Backup Slides

Partnership Opportunities

- **Space Act Agreement (SAA)**
  - www.nasa.gov/offices/ogc/about/samanual.html
- **Small Business Innovative Research (SBIR) / Small Business Technology Transfer (STTR)**
  - sbir.gsfc.nasa.gov/SBIR/SBIR.html
- **NASA Research Announcement (NRA)**
  - nspires.nasaprs.com/external
- **Unsolicited Proposals**
  - ec.msfc.nasa.gov/hq/library/unSol-Prop.html

Aviation Accidents

- Aloha Airlines (Boeing 737)
  - Forward fuselage
  - 18’ of fuselage separated from the passenger floor line (aft of cabin entrance)
  - <36K flight hours, but high ground-air-ground cycles
  - Linking of fatigue cracks from fastener holes (multi-site fatigue damage)
- AA 587 (Airbus A300, Jamaica Bay, NY)
  - Vertical tail
  - In-flight separation of the vertical tail
  - Loads beyond ultimate
  - Excessive/unnecessary rudder pedal inputs by 1st officer
  - Right rear lug failed at a load of almost 2X design limit load (DLL)

Aviation Accidents

- Delta Airlines Flight 1288 (McDonnell Douglas MD-88)
  - Right engine
  - Front compressor hub on #1 engine shattered, penetrated left aft fuselage
  - Final fracture of fatigue crack, growing from a mfg. defect at tie rod hole in compressor hub
- US Forest Service tanker (C-130A)
  - Both wings detached after dropping payload and leveling out
  - Fast fracture of 12” fatigue crack (not detected during regular inspections)

Aviation Accident Descriptions

- Figure 3(a) shows the forward **fuselage** section of an **Aloha Airlines Boeing 737** shortly after separation of **18 feet of fuselage above the passenger floor line** and immediately aft of the cabin entrance door. Although the airframe had only **35,496 flight hours**, the **number of ground-air-ground cycles was much larger** than might be expected because of the **short duration of many of the aircraft's flights** between the various Hawaiian islands. The cause of the Aloha Airlines accident was attributed to the **linking of fatigue cracks emanating from fastener holes** (multi-site fatigue damage).

- Figure 3(b) shows the **vertical tail** of **American Airlines flight 587**, an **Airbus A300**, as it was recovered from Jamaica Bay in New York. The cause of the American Airlines accident was determined to be the **in-flight separation of the vertical tail** as the result of **loads beyond ultimate** that were created by the first officer's **unnecessary and excessive rudder pedal inputs**. Analyses at NASA Langley Research Center showed that of the six attachment lugs that join the vertical tail and fuselage, the **right rear lug failed first at a load of almost two times the design limit load (DLL).**

- Figure 3(c) shows the **right engine of a Delta Airlines flight 1288**, a **McDonnell Douglas MD-88**, after the **front compressor hub of the #1 engine shattered and penetrated the left aft fuselage**. The cause of the accident was **final fracture of a fatigue crack** growing from a **manufacturing defect at a tie rod hole in the compressor hub**.

- Figure 3(d) shows one of several **tankers operated by the U.S. Forest Service** that recently suffered catastrophic structural failures. In the case shown, **both wings of a C-130A detached** from the fuselage at their respective center wing box-to-fuselage attachment locations after the aircraft dropped its payload and began to arrest its decent and level out. Examination of the center wing box lower skin revealed that failure was caused by **fast fracture of a 12-inch long fatigue crack** that had **not been detected during regular inspections**.

Partnership Opportunities

- Space Act Agreement (SAA)
  - Facilitates industry partnerships
  - Request For Information (RFI) released in January 2006
- NASA Research Announcements (NRA)
  - 8 awards in Round 1
  - Announcement for Round 2 expected in April / May 2007
- Small Business Innovative Research (SBIR)
  - Three topics considered for award
- Small Business Technology Transfer (STTR)
  - Industry development and implementation based on NASA research
- Integration and Assessment Working Group (IAWG)
  - Inter-center coordination of integration architecture and strategy

Partnership Opportunities

- Aviation Safety (AvSafe) Industry Days
  - Held September 2006 at Dulles Marriott
  - 32 participants from 15 companies and organizations
  - 6 working groups formed
- Working Groups
  - Database
  - Generic Systems Modeling and Simulation
  - Sensors
  - Validation, Verification, and Certification Basis
  - Algorithms and Signal Processing
  - Education
- Aerospace Industry Steering Committee (AISC) for Structural Health Monitoring (SHM)
  - NASA is a charter member of the Executive Management Board