Aviation Safety Program

Integrated Intelligent Flight Deck

Technical Plan Summary

Principal Investigator: Dr. Steven D. Young
Project Manager: Leighton Quon

This document was developed over the past several months by NASA to define the rationale, scope and detailed content of a comprehensive Aviation Safety, Integrated Intelligent Flight Deck research project. It contains reference to past work and an approach to accomplish planned work with applicable milestones, metrics and deliverables. The document also references potential opportunities for cooperation with external organizations in areas that are currently considered to be of common interest or benefit to NASA. This document should be considered a reference document and not a completed research plan.

TABLE OF CONTENTS

FORWARD

A dichotomy exists for new safety technologies developed for civil aviation. Few in the industry will admit to vulnerabilities, especially when the system is already considered safe; generally, new technology must show operational benefit for industry to invest. On the other hand, regulatory officials are hesitant to mandate new technology that can improve safety; not only because the system is already considered safe, but also because of the fragility of the industry with respect to the bottom line. In almost all cases, mandates occur only after tragedy strikes or there is a public outcry. An ever increasing concern is how to maintain, or improve, safety as aircraft and aircraft systems become undeniably more complex. It is clearly a topic for research, and we believe NASA, as both an honest broker and national resource for aviation research and development, is the fitting agency to carry out that research to ensure public safety in the future and to do so in a proactive way.

NASA's 2006 Strategic Plan, Outcome 5 states "…develop technologies for safer aircraft and higher capacity airspace systems." We believe that these two capabilities, safer aircraft and higher capacity airspace systems, fight against each other in many instances. In other words, an aircraft and/or system design that optimizes safety will not be the same design as one resulting from optimizing airspace system capacity. An integrated holistic approach is required to bring about both of these capabilities with sufficient safety margin and maximum capacity potential. For this reason, the Integrated Intelligent Flight Deck Technologies (IIFDT) research plan depends on and leverages research planned within NASA's Airspace Systems Program (ASP) as well as the other elements of NASA's Aviation Safety Program (AvSP). Without an integrated working relationship between safety and capacity research that focuses on predictive capabilities, candidate new designs will be over-conservative resulting in insufficient throughput gains, or over-aggressive resulting in untenable certification risk.

1 TECHNICAL PLAN

Both the aircraft and the airspace system are becoming busier and more complex; flight deck systems and procedures are becoming more complex. Solutions to safety problems, operational problems, and communications problems are traditionally addressed by incrementally adding new systems or extending the functionality of existing systems. The flight deck has a constant, the pilot, whose faculties remain unchanged. Each new system or function attempts to push more information at the pilot, eventually passing the point where the pilot can adapt positively – especially at times of heavy workload. Therefore, systems and functions must be adapted to the pilot's capabilities. Technology is responding by providing pilot aids and automation. However, new solutions tend to arrive singularly resulting in the balance between the pilot and the aircraft system being constantly upset. Each new technology insertion requires a study of the impact and the method of implementation. These studies are often inconclusive because the technology has not been rigorously assessed – only assessed through qualitative small-scale demonstrations of platform- and mission-specific designs and incomplete quantitative evaluation. The result when considered from a broader perspective may not be an improvement in the margin of safety.

NASA believes that future flight deck systems should systematically incorporate integrated displays, decision-aiding functions, information management, and dynamically-allocated human/automation task responsibilities. The future flight deck system is aware of the vehicle and operator state and responds appropriately. The system senses internal and external hazards, evaluates them, and provides key information to facilitate timely and appropriate responses. The system is robust and is adaptable to the addition of new functions and information sources as they become available.

Why should NASA be involved? NASA's mission is to respond to the public interest rather than on a specific product line or profit margin. NASA has the core competencies required to envision the future flight deck and lead the way toward it. NASA is well positioned by charter, experience, and expertise to point the way with ideas, seed the path with collaboration, attack technical hurdles and critical problems, and discover new applications and new technologies. NASA's position as neither industry nor regulator, allows it to facilitate system evolution, or revolution, in concert with other government agencies.

NASA can lead the way to the future for safer flight deck systems.

1.1 RELEVANCE

The IIFDT project comprises a multi-disciplinary research effort to develop flight deck technologies that mitigate operator-, automation-, and environment-induced hazards for future operational concepts. Towards this objective, IIFDT: (a) develops crew/vehicle interface technologies that reduce the risk of pilot error; (b) develops monitoring technologies to enable detection of unsafe behaviors; (c) develops fail-safe methods for changing the operator/automation roles in the presence of detected disability states; and (d) develops a comprehensive surveillance system design that enables robust detection of external hazards with sufficient time-to-alarm for safe maneuvering to avoid the hazards.

IIFDT addresses the integration of the capabilities listed above with future communications, navigation, Air Traffic Management (ATM), and other technologies being investigated either within NASA, other government agencies, or industry. IIFDT tracks improvements in predictive capability through continuous identification and assessment of areas of uncertainty that require investigation. This is accomplished through the development of system design tools; the application of system analysis and data mining techniques that identify phenomena of interest and hazard precursors; and the definition of validation metrics that quantify uncertainties for system and subsystem performance and integrity.

The IIFDT objectives address core vehicle-centric technological barriers to the full realization of the Next Generation Airspace Transportation System (NGATS) as described by the interagency Joint Planning and Development Office (JPDO) (JPDO, 2004). In addition, these objectives respond to safety recommendations published by industry/government organizations resulting from historical data analysis and observed trends (CAST, 2004; NTSB, 2005; NIA, 2005; NRC, 2004; and AOPA, 2004). These organizations have recognized that pilots, automation, and the external environment continue to be causal factors in a large percentage of accidents/incidents. Transitioning toward the NGATS must not only address these findings, but also the implications on flight deck system safety when considering new operational capabilities. Specifically, the envisioned environment includes more automated functions, increased expectations of the flight deck crew, less time to "see-and-avoid", and increased system complexity. Each of these implies a need for flight deck system safety research.

NGATS Vision

The JPDO envisions a safe, efficient and reliable air transportation system for 2025 that removes many of the constraints in our current system, supporting a wider range of operations, and thus, delivering an overall system capacity up to three times that of current operating levels (JPDO, 2004). The concept requires a shift in the historical model of air transportation from a system based on established physical/technology infrastructure and the capabilities of service providers to a system that is flexible and adaptable to the varied needs and capabilities of its users. This concept also requires that safety be approached in a prognostic fashion and promotes a new safety culture that exploits risk from a predictive perspective. The IIFDT project supports this concept by developing adaptive flight deck systems, ensuring flexibility not only on the system-end, but also on the user-end, and with proactive, predictive design and risk assessment tools and techniques necessary for NGATS implementation.

IIFDT uses as a guide an assumed future state of the U. S. National Airspace System (NAS). This future state is based upon the current vision described by the JPDO. As envisioned, the roles and responsibilities of the flight deck elements are clearly expanded; the flight deck system will have access to increasing amounts of information and new and innovative means of communicating its desires to an ATM system; there will be a move from "see-and-avoid" toward "sense-and-avoid" flight operations, and there will be a delegation of varying levels of responsibility to the flight deck for managing separation and generating/negotiating 4D trajectories relative to weather and other ATM constraints. Each of these capabilities is considered from a vehicle-centric safety perspective by the IIFDT project.

In addition, the degree of automation in the aircraft and in the ATM system will increase. Direct pilot/controller communications will be reduced and replaced by agent-based interactions between air and ground systems. The demands of these future systems and the need to keep the flight crew fully aware of current and future safety and ATM situations are challenges for the IIFDT research. An initial assumed future state is made by IIFDT to establish the context of the initial work. Subsequent updates to this assumed future state are made in close coordination with the ASP and based on the research progress. These revisions may require adjustments to our plan as priorities change and as safety issues emerge or are resolved. This approach ensures an integrated and relevant technology toolset in support of NGATS as it comes on-line.

Research Scope

As stated previously, IIFDT develops flight deck technologies that mitigate operator-, automation-, and environment-induced hazards for future operational concepts. The scope includes: (a) development of crew/vehicle interface technologies that reduce the risk of pilot error; (b) development of monitoring technologies to enable detection of unsafe behaviors; (c) development of fail-safe methods for changing the operator/automation roles in the presence of detected disability states; and (d) development of a comprehensive surveillance system design that enables robust detection of external hazards with sufficient time-to-alarm for safe maneuvering to avoid the hazards.

For our purposes, a flight deck and a flight deck system are defined as follows:

- *Flight Deck:* A volume of space designed to accommodate at least one human operator and the interfaces between the operator and the remainder of the flight deck system.
- *Flight Deck System:* A system that includes (1) the entity(s) who have the authority and responsibility for directing the flight of an aircraft, (2) all subsystems that directly interface to these entity(s), and (3) the interfaces between them.

Given these definitions, recognize that pilots often serve more than one role in a flight deck system depending on the aircraft, its equipage, the operational environment, and the mission. For example, in today's NAS, the pilot is a critical component of the communications subsystem (via voice radio), the surveillance subsystem (via "see-and-avoid"), and the navigation subsystem (referencing paper charts). Adaptive Flight Deck Systems (AFDS) change the roles and responsibilities of elements of the system (e.g. pilots) dynamically to meet mission-specific safety and performance needs.

The scope for IIFDT was initially defined by the results of the IIFDT Workshop, an unconstrained brainstorming session, held October 12-13, 2005 at NASA Headquarters (HQ). A visionary ten-year plan was developed. Content and milestones were identified with respect to research needs independent of resource constraints. The workshop results were refined during the Fall of 2005 by gathering and integrating inputs from experts at the NASA field centers who were unable to attend the workshop. Updated workshop results were published by Aeronautics Research Mission Directorate (ARMD).

Figure 1 illustrates the framework of the IIFDT research and identifies research topics or categories (i.e. the block titles). This chart has been modified from the workshop product only at Level 1 in order to align with the project's work breakdown structure. A resource constrained ten-year roadmap of milestones is given in Figure 2. In Figures 1 and 2, four levels are used to represent and distinguish research with varying degrees of complexity and integration across multiple disciplines. Level 4 is at the highest level of flight deck system integration and brings together the results of all other research areas, while Level 1 is where science disciplines are applied to specific problems. The scope includes all four levels; however, most of the in-house research is conducted at Levels 1 and 2. At the higher levels, where the work often involves investigation of complete systems and subsystems, a large part of the research will be accomplished in cooperation with industry partners and other government agencies as collaborative efforts. This approach is commensurate with the ideals of the project, whereby NASA leads industry toward the future for flight deck systems, but NASA does not develop the physical products.

This technical plan summary addresses the initial five years of the project within the guidelines provided by the Internal Call for Proposals (ICP) released by the Aeronautics Research Mission Directorate (ARMD). The content and structure of the project is described within the framework of Figure 1. Section 1.2 provides a list of milestones and metrics for assessing progress over the term of the project. Section 1.3 describes the work to be carried out under each of the block headings in Figure 1 toward achieving these milestones.

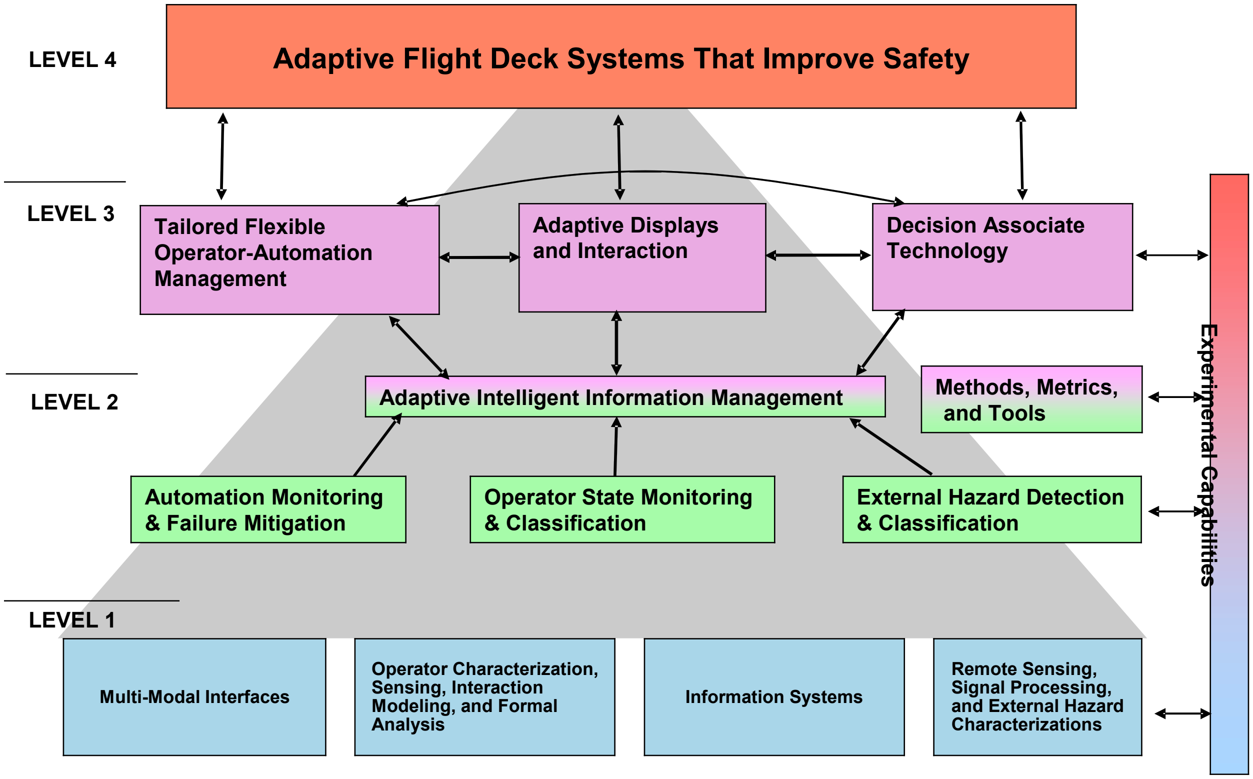


Fig 1. IIFDT research framework

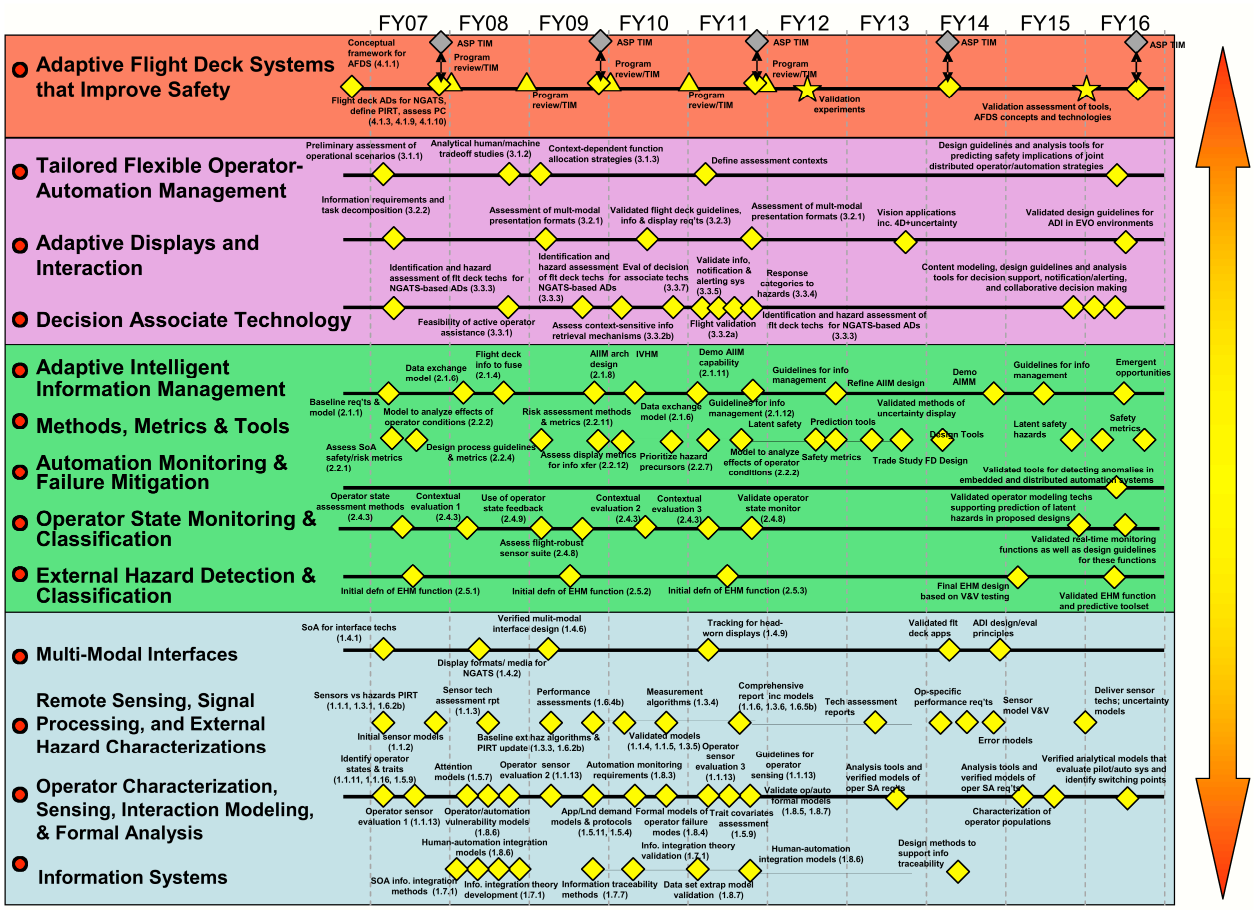


Fig 2. Ten-year milestone roadmap for IIFDT research

1.2 MILESTONES AND METRICS

"Tools, Methods, Concepts, Principles, Guidelines, and Technologies for Revolutionary Adaptive Flight Decks that Improve Safety"

The text above captures the over-arching goal for the project and includes the primary types of products developed by the research team. IIFDT leads by sharing and applying these products to support industry and government in the progression towards more capable and safer flight deck systems. Products are documented and published for wide dissemination throughout the industry. Publication is via NASA-led authorship of conference papers, journal articles, and NASA technical papers; or via national and international regulatory or standards organizations wherein NASA results and expertise are used to develop large-sector consensus on new policies, standards, or recommended practices that should be applied. Examples of these types of organizations include: ICAO, RTCA, SAE, ARINC, and ISO. Other products are developed including benchmarks, metrics, and experimental data. IIFDT products are applied in collaborative research efforts with industry, eliminating barriers to progress and focusing on products that fit within the role and mission envisioned by NGATS for future flight deck systems.

Prioritizing/selecting research activities in which to invest is based on the following factors:
- Safety risk: priority is given to research that addresses more prevalent safety concerns as evidenced by the industry/government recommendations, historical data, or the vision for the NGATS
- Technical risk: higher priority is given to far-term technology concepts
- NASA uniqueness: higher priority is given to those activities where NASA should lead
- Skills: higher priority is given to research that utilizes the current set of core competencies
- Facilities: to manage cost, higher priority is given to research that uses available facilities
- Procurement costs: activities that require large procurements are given lower priority
- Research level: Level 1/2 activities have priority with partnerships sought to enable Level 3/4

Milestones have been defined to chart the course of the project and to identify deliverables (Figure 3). Research topical areas along the left-hand side correspond to the Figure 1 elements. These milestones were distilled from the 10-year roadmap produced by the IIFDT workshop team using the investment strategy described above as well as the guidelines provided by ARMD. For clarity, lower-level dependencies/linkages among milestones are not shown in Figure 3.

Table 1 provides additional detail for the IIFDT research milestones. These milestones can be traced to milestones in the workshop-produced ten-year roadmap by the milestone numbers. This technical plan summary covers a five-year period and is based on the prioritization above, not all of the milestones from the ten-year roadmap are included. Quantitative metrics are given to assess progress, however, in some cases metric entries are more appropriately identified as checkpoints or decision points indicating delivery of baseline information needed to proceed, or an opportunity to change direction. Each milestone entry also includes relationships to other milestones (i.e. depends and supports). The approach to be followed to achieve project milestones is described in Section 1.3.

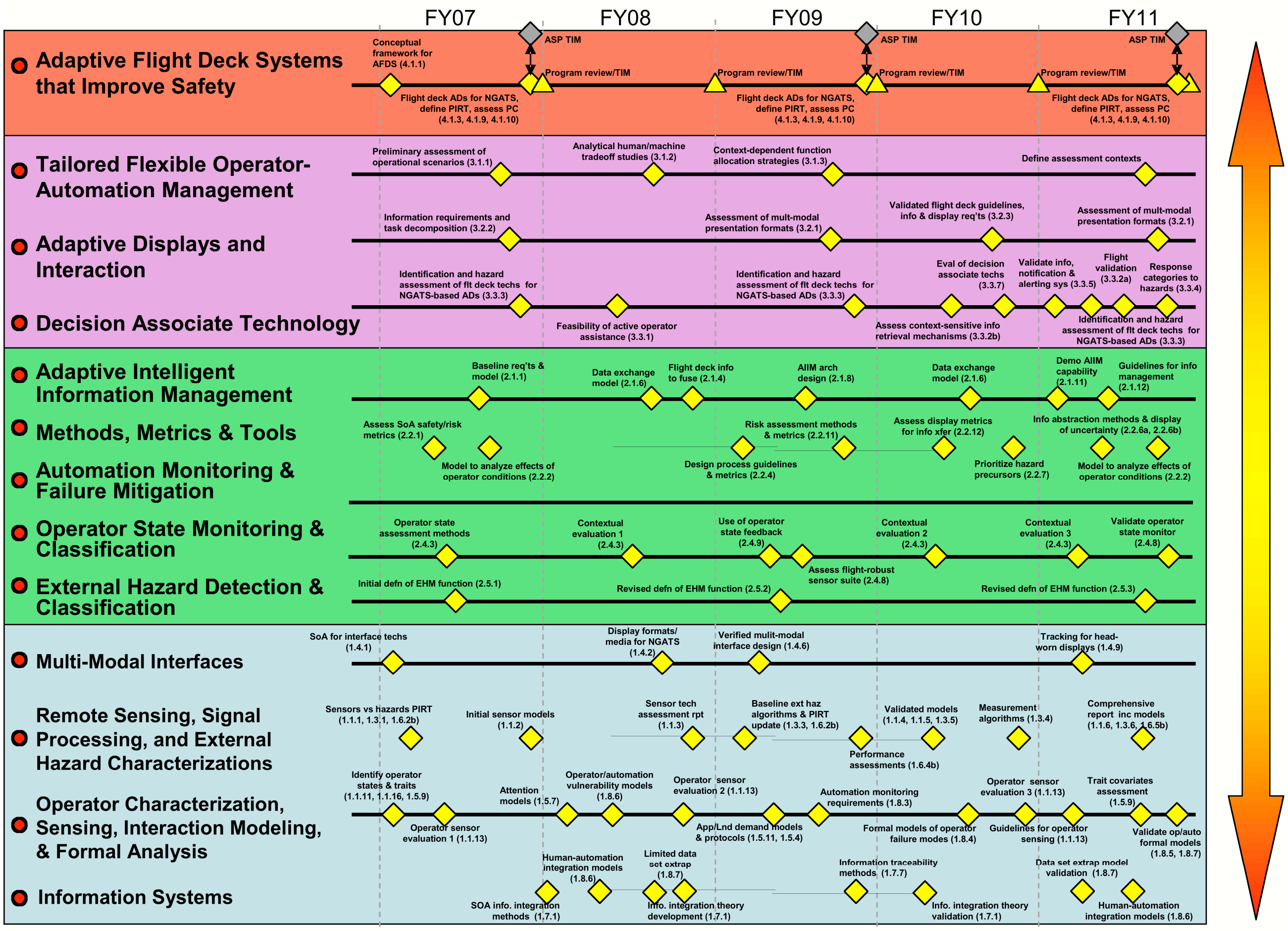


Fig 3. Five-year milestone roadmap for IIFDT research

Table 1. IIFDT Research Milestones

Adaptive Flight Deck Systems that Improve Safety	
4.1.1	(2007) Depends on: Project start-up and previous work; Supports: All L1/2/3 activities
Title:	Specification of conceptual framework for adaptive flight deck systems
Metric:	Framework instantiated for initial NGATS-based Application Domain (AD); note: AD0 to be defined during FY '06 in preparation for project start-up (See Glossary for definition of Application Domain)
4.1.3	(2007, 2009, 2011) Depends on: 3.1, 3.2, 3.3, IVHM, IRAC, ASP; Supports: 3.3.1 (2007), 3.2.3 (2009), 3.3.2b (2009), 3.3.7 (2009)
Title:	Specification of flight deck Application Domains (AD) within the NGATS operational concept; AD0 specified at project start-up; AD1 at end of FY 07, AD2 at end of FY 09, and AD3 at end of FY 11
Metric:	Baseline information for subsequent L1/2/3 activities (Decision Point)
4.1.9	(2007, 2009, 2011) Depends on: PIRTs defined at L1/2/3; Supports: 3.3.1 (2007), 3.2.3 (2009), 3.3.2b (2009), 3.3.7 (2009)
Title:	Phenomena Identification Ranking Table (PIRT) that captures and tracks flight deck research needs
Metric:	Baseline PIRT considering L1/2/3 capabilities against AD requirements (Decision Point)
4.1.10	(2007, 2009, 2011) Depends on: All L1/2/3 activities, ASP; Supports: 3.3.1 (2007), 3.2.3 (2009), 3.3.2b (2009), 3.3.7 (2009)
Title:	Assessment of predictive capability with respect to risk, including results of system analysis and tracking leveraged activities; barriers to predictive capability assessment identified
Metric:	Baseline integrated risk assessment considering L1/2/3 capabilities against AD requirements (Decision Point)
4.1.13	(2011) Depends on: All previous IIFDT activities, ASP; Supports: follow-on activities
Title:	Research plan for future including recommendations for program direction based on lessons-learned, program output to date, and research results
Metric:	Plan subject to review by AvSP, JPDO, and/or CAST for appropriateness (Decision Point)

Tailored Flexible Operator-Automation Management (TFOAM)	
3.1.1	(2007) Supports: 4.1
Title:	Preliminary assessment of functional categories and operational scenarios
Metric:	Baseline database cross-referencing Flight Management tasks with functional categories and operational scenarios (Checkpoint)
3.1.2	(2008) Depends on: 2.4.7, 3.1.1; Supports: 4.1.9
Title:	Perform analytical human/machine tradeoff studies for functional categories
Metric:	Comparative performance scores for both human and machine for each of the cells in the database produced by 3.1.1 (i.e. PIRT for flexible operator automation management) (Checkpoint)
3.1.3	(2009) Depends on: 3.1.2; Supports 4.1
Title:	Define role- and context-dependent function allocation strategies
Metric:	Defined roles for the human and automation based on factor analyses of performance database and factor analysis of pilot/operator pairwise comparisons (Checkpoint)
3.1.4	(2011) Depends on: 3.1.3, 2.2.2, 2.2.7. 2.4.8, 2.4.7, 1.8.3, 1.8.4; Supports 4.1
Title:	Develop and implement prototype function allocation schemes based on context detection ability (decision point for future research)
Metric:	Prototype concepts of function allocation schemes for representative set of strategies defined in 3.1.3. (Checkpoint)
Adaptive Displays and Interaction (ADI)	
3.2.1	(2009, 2011) Depends on: (2009) 1.4.6, 1.6.3a, 3.2.1, (2011) 2.2.6a, 2.2.12a, 3.2.2, 3.2.3; Supports: (2009) 3.2.3, 4.1.3, 4.1.9, 4.1.10; (2011) 4.1.3, 4.1.9, 4.1.10, milestones beyond 2011
Title:	Assessment of initial multi-modal presentation formats and interaction methods for 4D + uncertainty display concepts and virtual visual environments
Metric:	Statistical (confidence coefficients with $p<.05$) and practical significant (effect size > .6) reductions in communication errors, mental workload, and flight technical error, increases in usability and situation awareness compared with baseline capability for AD0 (2009) and AD1 (2011)
3.2.2	(2007) Depends on: 4.1.3; Supports: 2.1.1, 3.2.3, 4.1.3, 4.1.9, 4.1.10
Title:	Flight deck information requirements and task decomposition defined for NGATS-based ADs
Metric:	Flight deck information requirements, task decomposition, and initial concept of operations against AD0 requirements; feedback provided to industry/OGAs with significant ($p<.05$) inter-rater concordance of agreement ratings > 0.8
3.2.3	(2010) Depends on: 1.4.6, 3.2.1 (2007), 3.2.2, 4.1.3 (2009); Supports: 3.2.1 (2011), 4.1.3 (2011), 4.1.9 (2011), 4.1.10 (2011)
Title:	Validated flight deck guidelines; information and display requirements defined for NGATS-based AD0 and AD1 through assessment of usability, acceptability, suitability, and safety of 1st generation adaptive display and interface technologies for present NAS with prediction of effects on future NAS (i.e. NGATS)
Metric:	Meta-analytic experimental statistical outcomes and conclusions compiled for 1st generation adaptive display and interface technologies; significant coefficients of determination and confidence intervals for statistical proportional reduction of error (PRE) and safety uncertainty for AD0 and AD1
Decision Associate Technology (DAT)	
3.3.1	(2008) Supports: 3.2, 4.1
Title:	Completed feasibility study for active operator assistance in approach and landing tasks, including active attention management
Metric:	Set of candidate technologies with predicted potential to support AD0 and AD1 with 90% reduction in automation interface time, elimination of mode confusion, and improved operator awareness of critical decision points and information compared with baseline condition
3.3.2a	(2011) Depends on: 3.3.7; Supports 2.1, 4.1
Title:	Complete validation of selected part-task simulation results in flight environment.
Metric:	Flight test and associated analytical results supporting improved crew awareness and decision making with 90% reduction in programming time and 50% reduction in response time to pop-up hazards compared with baseline condition
3.3.2b	(2010) Depends on: 1.7, 2.1, 3.2
Title:	Assessment of context-sensitive information retrieval mechanisms to support rapid access and display of situation awareness information pertinent to current safety conditions
Metric:	Experimental validation of identified information retrieval mechanisms compared with baseline condition
3.3.3	(2007, 2009, 2011) Depends on: 1.2, 2.1, 2.2, 2.3, 2.4, 2.5
Title:	Identification and hazard assessment for Flight Deck Technologies required for NGATS ADs
Metric:	Hazard assessment for identified flight deck technologies corresponding to AD0 (2007), AD1 (2009), and AD2 (2011) (Checkpoint)
3.3.4	(2011) Depends on: 2.1, 2.3, 2.4, 2.5, 3.3.3 IVHM, IRAC, ASP
Title:	Define response categories to specific hazards identified in 3.3.3
Metric:	Defined response categories for hazards identified for AD0, AD1, and AD2 (Decision Point)

3.3.5	(2011) Depends on: 2.1, 2.3, 2.4, 2.5, IVHM, IRAC, ASP
Title:	Validate information, notification, and alerting system for integrated situation awareness
Metric:	Evaluation standards and analytical assessment of situation awareness of integrated flight deck technologies for AD0, AD1, and AD2 compared with baseline condition
3.3.7	(2010) Depends on: 3.3.1, 2.2.2, 1.8.3, 1.8.4; Supports: 3.1, 3.2, 4.1
Title:	Complete evaluation of selected decision associate concepts (from 3.3.1) in workstation and part task simulation
Metric:	Experimental and analytical results supporting improved crew awareness and decision making with 90% reduction in automation management time and 50% reduction in response time to pop-up hazards compared with baseline condition
Adaptive Intelligent Information Management (AIIM)	
2.1.1	(2007) Depends on 1.4.1, 3.2.2; Supports: 1.4.2, 1.4.6, 1.4.9, 2.2.6, 2.2.12
Title:	Establish baseline model for flight deck information management systems
Metric:	Preliminary model constructed of flight deck information management system using Boeing 787 as baseline system capability; verification against flight simulation functionality or design specification
2.1.4	(2008) Depends on 2.2, 2.3, 2.4, 2.5, IVHM, IRAC, ASP; Supports 3.1.2, 3.2.2, 3.3.2b
Title:	Specify/catalog flight deck information to be fused including metadata requirements, information usage, and information traceability requirements
Metric:	Baseline flight deck information requirements for NGATS-based ADs (Checkpoint)
2.1.6	(2008, 2010) Depends on 1.7, 2.1.1; Supports 2.2, 2.3, 2.4, 2.5, 3.1, 3.2, 3.3
Title:	Define/refine integrated data exchange and metadata model to support high data integrity requirements for AIIM
Metric:	Verification against ISO, RTCA, ICAO, or equivalent standards for data exchange modeling (2008); refined (2010)
2.1.8	(2009) Depends on 1.7; Supports 3.1, 3.2, 3.3
Title:	Preliminary design of AIIM architecture to support TFOAM, ADI, and DAT requirements while accommodating hazard detection inputs; derive requirements for information archival capabilities
Metric:	Preliminary AIIM architecture verified through simulation for AD0
2.1.11	(2011) Depends on 1.1, 1.7; Supports 3.2, 3.3
Title:	Demonstrate AIIM capability; including real-time characterization of data quality (integrity and performance); assess sufficiency of information quality metrics; validate data model
Metric:	AIIM model verified through simulation against AD0 and AD1 requirements
2.1.12	(2011) Depends on 1.1, 1.7; Supports 3.1.5, 3.2.1, 3.3.2b
Title:	Guidelines for adaptive intelligent information management; technology gaps and challenges identified
Metric:	AIIM guidelines, gaps, and challenges published or presented at TIM (Checkpoint)
Methods, Metrics, and Tools	
2.2.1	(2007, 2011) Depends on 1.8, 2.1, 2.4, 2.5; Supports 3.2, 3.3, 3.3.3 4.1
Title:	Assessment of safety and risk metrics for design, test certification, maintainability of flight deck technologies
Metric:	Baseline assessment of risk metrics (2007, 2011) (Checkpoints)
2.2.2	(2007, 2011) Depends on 1.5; Supports 3.1.2, 3.1.4, 3.3.3
Title:	Develop model to analyze the effects of operational conditions, task demands, and organizational policies and procedures on vulnerability to pilot errors and accidents in NGATS highly automated environment
Metric:	Verify model against baseline database of airline accidents and/or other relevant data; analyze interaction of operational conditions, task demands, and organizational policies/procedures with respect to crew and/or ATC error (2007); extend model to account for crew performance in NGATS highly automated operational environment (2011) (Checkpoints)
2.2.3	(2008) Depends on 1.1, 1.3, 1.5, 1.7, 2.5; Supports 3.1, 3.2, 3.3, 4.1
Title:	Define requirements for the application of predictive hazard models, simulation tools and analysis capabilities to mishap re-creation
Metric:	Mishap re-creation tool verified using baseline database of accident events
2.2.4	(2009, 2011) Depends on 1.5, 1.8, 2.1, 2.3, 2.4, 2.5; Supports 3.1, 3.2, 3.3, 4.1
Title:	Define validation and verification metrics and design process guidelines for flight deck technologies (software, hardware and HSI)
Metric:	Initial definition of metrics and guidelines (2009); refined (2011) (Checkpoints)
2.2.5	(2009) Depends on ASMM/VASIP; Supports 3.1, 3.2, 3.3.3, 4.1
Title:	Leverage and validate ASMM/VASIP data integration, data analysis and data mining methods, metrics and tools for flight deck-specific assessment issues and assessment validation
Metric:	Automatic identification of ten most frequently reported safety issues and vulnerabilities revealed through national archives of FOQA/ASAP/ASRS data; results verified by domain experts from operational pilot community and air carrier safety groups

2.2.6a	(2011) Depends on 2.1.1, 1.4.6; Supports 3.3.3
Title:	Validate design principles and associated metrics, tools and methods for design and evaluation of information abstraction and identifying and displaying uncertainty
Metric:	Statistically significant ($p<.05$) experimental validation of method with a 1σ reduction in flight crew decision-making hazard avoidance errors and 30% enhancement of global situation awareness and 50% increase in reaction time to recognition and strategic avoidance of type hazards compared to baseline condition
2.2.6b	(2008, 2010) Depends on 1.1, 1.2, 1.5, 1.7, 1.8, 2.3; Supports 3.1, 3.2, 3.3.3, 4.1
Title:	Develop theories, principles, and methods for design of information extraction and abstraction, integration of information, and displaying uncertainty and context-awareness.
Metric:	Develop information extraction theory and apply to flight deck system (2008); extend application of information extraction theory to multiple aerospace systems (2010) (Checkpoints)
2.2.7	(2010) Depends on 1.3, 1.5, 1.7, 1.8; Supports 3.1.4. 3.2, 3.3.3
Title:	Identification and prioritization of events and trends which could compromise system-wide safety due to new flight deck concepts
Metric:	Tracking of ten highest priority safety hazard precursors, verified by domain experts from aircraft design offices at major manufacturers and air carrier maintenance groups (Checkpoint)
2.2.9	(2012) Depends on 1.1, 1.3, 1.5, 1.7, 1.8; Supports 3.1, 3.2, 3.3, 4.1
Title:	Deliver principles for the design of integrated computation, logic and simulation-based prediction tools for mishap re-creation
Metric:	Tools reproduce historically-understood accidents with better than 90% accuracy
2.2.10	(2007, 2009, 2011) Depends on 1.4, 1.5, 1.7, 1.8; Supports 3.1.2, 3.1.4
Title:	Model-based design tools for assessing and enabling optimal situation awareness and adaptive interface development in human-automation systems
Metric:	Determine architecture of model of operator situation awareness (2007); build preliminary model (2009); and validate model (2011) that correlates to at least $r = 0.80$ with empirical results
2.2.12	(2010) Depends on 2.1.1; Supports 3.2.1
Title:	Define/assess display quality and complexity metrics for optimized information transfer
Metric:	Design and development of quantitative and qualitative display clutter and information complexity metrics composed of structurally high item factor loads, inter-rater agreement, and internal consistencies with statistical significant discriminant and convergent validity coefficients; statistical analyses ($p<.05$) of criterion-related validity through concurrent and predictive validation against baseline condition
Operator State Monitoring and Classification	
2.4.3	(2007, 2008, 2010, 2011) Depends on 1.1.13, 1.5.9; Supports 2.4.7, 2.4.8, 2.2, 3.1, 3.2, 3.3
Title:	Evaluate methods and approaches for real-time assessment of selected sensors' ability to reflect operator states
Metric:	Establish criteria and methods for assessing operator state indices (2007) (Checkpoint)
Metric:	Evaluation of fNIRS technology (2008), facial image analysis (2010), and voice stress (2011) for operator state identification using methods established in 2007
2.4.7	(2007, 2008, 2009, 2010, 2011) Depends on 1.1.15, 1.1.16, 1.5.9; Supports 2.2.4, 2.4.8, 3.1.4, 3.2.1, 3.3.3, 3.3.4, 3.3.5
Title:	Evaluate operator state integrated classification methods
Metric:	(2007) Low fidelity simulation study to investigate operator engagement indices for different levels of human/automation integration (shared with TFOAM); provides baseline for current operator state EEG-related measures
Metric:	(2008) Initial laboratory studies to develop discriminators for fatigue/workload levels and immersion/engagement
Metric:	(2009) Evaluation of the extent to which the fatigue/workload classification algorithm, interfaced with computerized tasks to form a operator state-controlled adaptive automation, can mitigate fatigue/workload-induced performance decrements
Metric:	(2010) Task-relevant study comparing subjective assessment of operator immersion and task engagement with operator state measure indices (Checkpoint)
Metric:	(2011) Validate the adaptive automation approach and interface management interventions in an advanced-concept simulator flight deck (where the actual displays and automation levels can be manipulated) based on best-developed operator state indices; adaptive flight deck system should respond reliably considering operator states; compare results with baseline condition
2.4.8	(2009, 2011) Depends on 1.1.15, 1.1.16, 1.5.9; Supports 2.2.4, 2.4.8, 3.1.4, 3.2.1, 3.3.3, 3.3.4, 3.3.5
Title:	Assess operator state sensors and methods in realistic flight deck operational environments
Metric:	(2009) Assess state of the art airborne operator assessment sensor suite in aviation context; includes data collection test flights with equipment installed (Decision Point)
Metric:	(2011) Validate the most promising fatigue-monitoring indices in a high-fidelity flight simulation environment context against operator state identification requirements
2.4.9	(2009) Depends on: 2.4.7; Supports: 3.3.4, 3.3.5
Title:	Establish the degree to which operator state feedback can be used to manipulate operator state

Metric:	Operator states can be reliably modulated using feedback and interface features (90% success rate for baseline test cases)
External Hazard Detection and Classification	
2.5.1	(2007) Depends on 1.1.1, 1.1.2, 1.3.1, 1.3.2, 1.6.2b, 2.1.1; Supports: 1.1.1, 1.1.2, 1.3.1, 1.3.5, 1.6.2b, 2.1.4, 2.2.1, 2.2.3, 3.3.3
Title:	Concept defined for an external hazard monitoring function, including data source requirements and output products; the function will include hazard level (threat) determination; high priority hazards identified
Metric:	External Hazard Monitoring Function Concept Definition and External Hazard PIRT chart (Checkpoint)
2.5.2	(2009) Depends on 1.1.3, 1.3.3, 1.6.3a, 2.1.6; Supports 1.1.5, 1.3.3, 1.3.5, 2.2.4, 3.3.3,
Title:	Revised definition of the external hazard monitor function and predictive toolset, derived from initial findings of sensor technology development activities; provide preliminary product definitions to other levels and receive requirements. Initial requirements for an external hazard monitor function model. Review hazard and technology investigation priorities.
Metric:	Revised External Hazard Monitoring Function Concept Definition, and revised External Hazard PIRT chart, initial requirements for an external hazard monitor function model, requirements for Level 1 sensor models for integration with the External Hazard Monitor (Checkpoint)
2.5.3	(2011) Depends on 1.1.6, 1.3.4, 1.3.5, 1.3.6, 1.6.4b, 1.6.5, 2.1.6; Supports 1.1.6, 1.3.5, 1.3.6, 1.6.4b, 1.6.5, 3.3.3, 3.3.4, 3.3.5
Title:	Revised definition of the external hazard monitor function and predictive toolset, derived from latest findings of sensor technology development activities. Provide product definitions to other levels and receive requirements. Revised requirements for an external hazard monitor function model. Review hazard and technology investigation priorities.
Metric:	Revised External Hazard Monitoring Function Definition, and revised External Hazard PIRT chart, updated requirements for an external hazard monitor function model (Checkpoint)
Level 1	
1.1.1	(2007) Depends on 2.5.1; Supports 1.1.2, 1.3.1, 1.6.2b, 2.1.1-b, 2.5.1
Title:	Recommendation of sensors vs. external hazards to support selection of an initial set for investigation. Decision point to determine research portfolio content: select and pursue up to three focused investigations of sensor technology and high priority hazards. Research portfolio selections will be based on results of the developed PIRT chart for sensors and hazards, proposed collaborations, supporting external research (NRA agreements), and experience and resources. Icing conditions will be one of the research focuses and an IR Spectrometer concept study will be included.
Metric:	Deliver PIRT chart inputs for external hazards. Deliver a research portfolio description (document) that includes plans for focused investigations, collaborations, NRA research, and associated scope and objectives.
1.1.2	(2007) Depends on 1.1.1, 1.3.5, 2.5.1; Supports 1.1.3, 2.5.1
Title:	Report on initial investigation of sensor models, the development of sensor and validation requirements, and the approach to characterizing the uncertainty associated with data sources (including off-board sources that support tactical decision making). Report on icing detection progress.
Metric:	Deliver Initial Sensor Modeling Report including a review of progress on Infrared (IR) Spectrometer, X-band radar, and millimeter wave radar models: Success criteria -- initial IR Spectrometer model developed, plans for development of X-band model for millimeter wave use including, plans for expansion of X-band capabilities, and validation plans for the models (i.e. modeling approach chosen and model functional and validation requirements determined); Gen2 ground-based icing remote sensing system operational and derived data available real-time via web; Radiosonde system operational and checked out (Checkpoints)
1.1.3	(2008) Depends on 1.1.2, 1.3.5; Supports 1.1.4, 2.5.2
Title:	Provide progress report based on preliminary simulations and validation tests and progress on focused investigations, including preliminary definition of detection performance requirements. Report to Level 2 and coordinate with other Level 1 activities. Decision point regarding continuation of IR Spectrometer investigation (end of feasibility study), objectives for radar and millimeter wave radar studies (associated with re-evaluation of the research portfolio, milestone 1.1.7). Initiate a new technology thrust (most likely laser/LiDAR).
Metric:	Deliver a Sensor Technology Progress Report: Success criteria -- report includes: an assessment of ground-based icing remote sensing, based on comparison to aircraft and radiosonde data; an IR Spectrometer model capable of making performance predictions for selected atmospheric targets, such as wind gusts or turbulence, and for traffic; a preliminary Pulsed Doppler Radar model with millimeter wave capability for atmospheric hazards. Research portfolio and objectives redefined as required.
1.1.4	(2010) Depends on 1.1.3, 1.3.5; Supports 1.1.5, 2.5.3
Title:	Report on progress including associated sensor verification, validation (field tests, lab tests, simulations), and characterization of sensor uncertainty.
Metric:	Progress Report: success criteria -- X-band and millimeter wave radar models validated; initial model developed for selected technology (e.g. LiDAR); and initial assessment of fast-scanning ground-based microwave radiometer and Airborne, Multi-Frequency Radar for icing conditions detection and measurement.
1.1.5	(2010) Depends on 1.1.4, 1.3.5, 2.5.2; Supports 2.5.3
Title:	Deliver sensor models for integration at Level 2.
Metric:	Success criteria -- deliver as a minimum X-band and millimeter wave radar models (includes IR spectrometer if appropriate), models meet requirements for integration set at Level 2.
1.1.6	(2011) Depends on 1.3.5, 1.3.6, 1.6.5, 2.5.3; Supports 1.3.6, 2.5.3

Title:	Report on sensor investigations (including performance prediction capability), models and technology development, quantification of uncertainties, and validation results, to be included in the combined Level 1 comprehensive report
Metric:	Deliver combined Level 1 external hazards comprehensive report and models. The report includes results from all Level 1 areas concerned with external hazards. It includes, as a minimum: reporting on focused studies completed or underway; discussion of uncertainty for sensor data; model capabilities and validation; and performance predictions for sensor technologies versus hazards (Decision point to determine if predictive capability requirements have been met in specific technology areas (e.g. interferometry, icing sensors, IR spectrometry, or X-band radar))
1.1.11	(2007, 2010) Supports 1.1.13
Title:	Identify operator states to monitor
Metric:	(2007) Define hazardous states of awareness and states required for communication to other flight deck agents (crew, automation, presentation management) (exit criteria: requirements document)
Metric:	(2010) Revised hazardous states of awareness and states specified for communication to other flight deck agents (crew, automation, presentation management) (exit criteria: revised requirements document)
1.1.13	(2007, 2009, 2010) Depends on 1.1.11; Supports.1.1.15, 2.4.3
Title:	Assess operator state sensor/method sensitivity and operability under lab-controlled conditions
Metric:	(2007) Assess fNIRS capability to measure cerebral blood recruitment as reflection of cognitive loading
Metric:	(2009) Assess facial image analysis capability to measure blood flow to face as reflection of stress and/or frustration (i.e., infra-red thermal imaging of blood flow)
Metric:	(2010) Assess voice stress analysis capability to measure content, inflection, and phrasing as a reflection of stress and confusion
1.1.15	(2008, 2010, 2011) Depends on 1.1.13; Supports 2.2.4, 2.4.7, 2.4.8
Title:	Develop guidelines for operator state detection sensors and methods
Metric:	(2008) Guidelines for fNIRS use
Metric:	(2010) Guidelines for facial image analysis
Metric:	(2011) Guidelines for voice stress as indicator of operator state
1.1.16	(2007) Supports 1.1.13
Title:	Identify technologies for operator state assessment
Metric:	State of the art review of sensors, data fusion, classification, and modeling/prediction algorithms for operator state assessment
1.3.1	(2007, 2009) Depends on 1.1.1, 2.5.1; Supports 1.3.3, 2.1.1-b, 2.5.1
Title:	Report baseline state-of-the-art of understanding and characterization of high priority hazards, as identified in PIRT chart (2007); deliver baseline characterization algorithms for targeted meteorological hazards (2009) (Checkpoints)
Metric:	Deliver state-of-the-art report that includes degree of understanding of phenomenology, state of characterization and modeling associated with each hazard, and recommendations for external hazard characterization efforts that will compliment sensor technology studies (2007); deliver baseline algorithms for high-priority hazards (2 or more) identified in PIRT chart - algorithms will describe the current knowledge of hazard intensity based upon currently measurable parameters (2009)
1.3.3	(2009) Depends on 1.3.1, 2.5.2; Supports 1.3.4, 2.5.2
Title:	Preliminary assessment of baseline external hazard detection and intensity algorithms for previously-selected hazards; hazards include icing conditions, runway obstacles, and clear air turbulence (Checkpoint)
Metric:	Deliver report that includes assessments based on algorithm output validated via comparison to flight data, ground measurements, and independent remote measurements; report identifies gaps in knowledge versus the high-priority hazards under investigation; deliver information for revision of the hazards vs. sensors PIRT chart (Checkpoint)
1.3.4	(2010) Depends on 1.1.1, 1.3.1, 1.3.3; Supports 1.3.5, 1.3.6, 2.5.3
Title:	Deliver detection and measurement algorithms for previously-selected, remotely-detected external hazards
Metric:	External hazard algorithms examined include those related to the 1.1 sensor technology tasks. These hazard detection and measurement algorithms describe the intensity based upon the developing sensor and up/cross-linked data sources (i.e. meet requirements to support hazard evaluation by the EHM function at Level 2) (Checkpoint)
1.3.5	(Yearly) Depends on 1.3.4, 2.5.1, 2.5.2, 2.5.3; Supports 1.1.2, 1.1.3, 1.1.4, 1.1.5, 1.1.6, 2.5.3
Title:	Deliver external hazard models & databases to support sensor technology development.
Metric:	Yearly delivery of current hazard models, databases, and supporting documentation for roll-up to higher-level activities.
1.3.6	(2011) Depends on 1.1.6, 1.3.4, 1.6.5, 2.5.3; Supports 1.1.6, 1.6.5, 2.5.3
Title:	Report on hazard characterization investigations, models and assessment results.
Metric:	Compilation of hazard models/algorithms and their assessments for sensors, sensor systems, and up/cross-linked data sources examined to date. Assessments will be based upon model/algorithm output comparison to flight data, ground measurements, and independent remote measurements. Results are incorporated into the Combined Level 1 external hazards comprehensive report.
1.4.1	(2007) Depends on state of the art; Supports 1.4.6, 1.4.9, 2.1.1

Title:	Assess state of the art for interface technologies (visual display)
Metric:	Based on information requirements from CONOPS, identify technologies/technology gaps for first generation NGATS concepts.
1.4.2	(2008) Depends on 2.1.1; Supports 1.4.6
Title:	Define and assess initial display formats and media to achieve projected NGATS visual/flight deck information requirements.
Metric:	Compared to current equipage, significant ($p<0.05$) improvements in SA and performance measures, no differences in workload.
1.4.6	(2009) Depends on 1.4.1, 1.4.2, 2.1.1; Supports 2.2.6a, 3.2.1, 3.2.3
Title:	Multi-modal technology integration interface designs
Metric:	Integrated multi-modal interface concept designed, implemented and verified in part task simulation.
1.4.9	(2011) Depends on 1.4.1, 1.4.6, 2.1.1, and 3.2.3; Supports Milestones beyond 2011
Title:	Integration and evaluation of unobtrusive operator tracking technologies
Metric:	Operator tracking technologies to fully support head-worn displays developed and integrated (if head-worn displays required or a superior solution to other concepts).
1.5.4	(2009) Supports 2.2.2
Title:	Complete validation of operational protocols and crew training guidelines for integrated flight deck
Metric:	Protocols and guidelines will be validated through evaluation by operational community experts (Checkpoint)
1.5.7	(2008) Supports 2.2.2
Title:	Use validated models of attention allocation and prospective memory to develop error mitigation strategies.
Metric:	Observational data on crew performance of monitoring tasks and checklist use collected and analyzed (Checkpoint)
1.5.9	(2007, 2008, 2009, 2010, 2011) Supports 1.8.4, 2.2.4, 2.4.3, 2.4.7, 2.4.8
Title:	Identify operator traits as useful covariates or baselines.
Metric:	(2007) Literature review to determine initial definition of operator traits to be investigated based on requirements for information management, human/automation integration, vehicle/operations platform differentiation, and improved human/system evaluations.
Metric:	(2008) Develop pretest assessment protocol to characterize relevant operator traits.
Metric:	(2009) Evaluation of operator traits for statistical power improvement in flight deck technology evaluations (Collaboration in CVI/TFOAM studies)
Metric:	(2010) Guidelines document for use of operator traits and assessment protocol for flight deck technology design and evaluation
Metric:	(2011) Survey of operator trait definitions characterizing vehicle platforms and operations.
1.5.11	(2009) Supports 2.2.10
Title:	Complete pattern analysis of concurrent task demands, interruptions, and procedural execution disruptions
Metric:	Cockpit observational data analyzed in terms of cognitive model of human operator performance (Checkpoint)
1.6.2b	(2007, 2009) Depends on 1.1.1, 2.5.1; Supports 1.6.3a, 1.6.4b, 2.2.1-b, 2.5.1
Title:	Identify and prioritize at least one potential application area associated with sensor technology development work (1.1) with respect to meeting Level 1, 2 and 3 requirements and plan an investigation.
Metric:	(2007) Deliver PIRT chart inputs for external hazards. Deliver a plan for investigation of at least one application area.
Metric:	(2009) Deliver PIRT chart inputs for external hazards. Deliver a plan for investigation of at least one application area.
1.6.3a	(2009) Depends on; Supports 1.4.8, 1.6.4a, 3.2.1 (2009)
Title:	Establish design concept including performance and validation metrics; develop techniques and algorithms for signal (image fusion) and image processing to support Level 2 and 3 requirements
Metric:	Information processing (image fusion) performance and validation metrics defined for crew interface system
1.6.4b	(2009, 2010) Depends on 1.6.2b, 2.5.3; Supports 1.6.5, 2.5.3
Title:	Report on and deliver applications, previously identified in 1.6.2b, and assess performance.
Metric:	(2009) Provide assessment report defining performance of processing techniques and identify any remaining barriers to hazard detection and/or severity estimation. Results are validated by use of experiment or flight data.
Metric:	(2010) Provide assessment report defining performance of processing techniques and identify any remaining barriers to hazard detection and/or severity estimation. Results are validated by use of experiment or flight data.
1.6.5b	(2011) Depends on 1.16, 1.3.6, 1.6.4b, 2.5.3; Supports 1.1.6, 1.3.6, 2.5.3
Title:	Report on processing investigations, models and validation results, to be included in the external hazards combined Level 1 comprehensive report.
Metric:	Report on research results to date, including algorithms, models or processes and associated validation. Results are included in the Combined Level 1 external hazards comprehensive report and model delivery.
1.7.1	(2007, 2008, 2010) Depends on; Supports 2.1, 2.3, 2.4, 2.5

Title:	Identify, review, and assess the state-of-the-art in theoretical approaches for modeling systems, human-automation interaction, interface generation, data extraction and abstraction, and dealing with data integrity and uncertainty
Metric:	Literature review (2007), conceptual approach (2007), development of general theory for data integration and abstraction (2008) (Checkpoints)
Metric:	Validation of general theory for data integration and abstraction against baseline practices (2010)
1.7.7	(2008) Depends on; Supports 2.1, 3.3.2
Title:	Design methods to support information traceability & maintenance of contextual information
Metric:	Validation of prototype design method against baseline practices
1.7.8	(2010) Depends on; Supports 2.1, 3.3.4
Title:	Build adaptable technologies across systems, operations and ground support functions to enable human and systems interoperability
Metric:	Validation of information extraction theory through application to avionics system
1.7.13	(2008) Depends on IVHM, AA; Supports 2.1, 2.2
Title:	Develop information infrastructure for automated tracking of flight critical systems, components, and interactions with aircraft safety history and aging aircraft data
Metric:	Validated simulation of data mining infrastructure
1.8.1	(2007, 2009, 2011) Depends on 1.8.2, 1.8.3, 1.8.4; Supports 3.1.3, 3.1.4, 3.1.5
Title:	Models of distributed operator/automation systems, including definition of desired/required safety properties
Metric:	Machine-checkable formal models and associated scripts and documentation to enable independent review and assessment of modeled claims
1.8.2	(2008, 2010) Depends on 1.8.1, 1.8.3, 1.8.4; Supports 1.8.1, 3.1.3
Title:	Assessment of algorithmic solution space. Determination of existence of algorithmic solutions with respect to specific combinations of automation faults and operator incapacitation.
Metric:	Machine-checkable formal models and associated scripts and documentation to enable independent review and assessment of modeled claims
1.8.3	(2009) Depends on IVHM; Supports 3.1.4,3.1.5
Title:	Formal models of automation monitor requirements, including abstractions of failure modes
Metric:	Machine-checkable formal models and associated scripts and documentation to enable independent review and assessment of modeled claims
1.8.4	(2010) Depends on IVHM; Supports 3.1.4, 3.1.5
Title:	Formal models of operator monitor requirements, including abstractions of operator "failure" modes.
Metric:	Machine-checkable formal models and associated scripts and documentation to enable independent review and assessment of modeled claims
1.8.5	(2011) Depends on 1.8.3, 1.8.4; Supports 3.1.4, 3.1.5
Title:	Validated modeling framework for formal verification of generic agent (human/automation) system integrity monitor
Metric:	Machine-checkable formal models and associated scripts and documentation to enable independent review and assessment of modeled claims
1.8.6	(2008, 2011) Depends on; Supports 3.1, 3.2, 2.2
Title:	Define/refine computational models for prediction of human-automation integration vulnerabilities of flight deck technologies
Metric:	(2008) Initial assessment of computational models for prediction/assessment of human-automation integration vulnerabilities of flight deck technologies
Metric:	(2011) Model-based prediction of human-automation integration vulnerabilities of flight deck technologies (Checkpoint)
1.8.7	(2008, 2011) Depends on; Supports 3.1, 3.2
Title:	Assessment of capability of predictive integrity models to extrapolate from limited data sets
Metric:	(2008) Executable predictive model defined and verified against available data sets
Metric:	(2011) Executable predictive model validated for selected extrapolation cases against available data sets

1.3 TECHNICAL APPROACH

The IIFDT project encompasses research across the spectrum from foundational to highly integrated, and the participants include NASA researchers, industry collaborators, university researchers, and employees of other government agencies and official organizations. The technical approach to this diverse body of work is described in the context of the four research levels and their component elements (Figures 1 to 3).

Each block shown in Figure 1 can be considered a research topic that warrants investment. As the level increases from 1 to 4, the amount of complexity and integration inherent in the research increases. Specifically, research at higher levels must address the manifestation of uncertainties captured and quantified at lower levels. For IIFDT, the Levels can also be loosely aligned with 1) the physics/characterization of the external environment, operator, and hardware/software elements, 2) functional capabilities that support detection, diagnostics, and/or prognostics, 3) subsystem capabilities that support hazard remediation, avoidance, and/or reporting, and 4) system-level capabilities that integrate all of the lower level functions. It is important to note that the Level 2 and 3 capabilities can, in their own right, improve safety individually.

The following subsections describe the technical approach for each of the research topics that comprise IIFDT, starting at Level 4 and proceeding down through the levels. The subsections relate the approach to achieving the Milestones (MS) described in Section 1.2 for the respective research topics given in Figures 1 to 3. In addition, research efforts are put into context by providing background information and discussion in terms of the importance to flight deck safety and performance.

ADAPTIVE FLIGHT DECK SYSTEMS THAT IMPROVE SAFETY (LEVEL 4)

Achieving the Level 4 capability requires a multi-disciplinary research effort to develop flight deck technologies that mitigate operator-, automation-, and environment-induced hazards for future operational concepts. To progress towards this objective, specific Level 1/2/3 activities will (a) develop crew/vehicle interface technologies that reduce the risk of pilot error through reductions in workload and improved situational awareness; (b) develop monitoring technologies to enable robust detection of off-nominal unsafe behaviors; (c) develop fail-safe methods for dynamically changing the role of the operator and automated functions in the presence of detected disability states; and (d) develop a comprehensive surveillance system design that enables robust detection of external hazards with sufficient time-to-alarm for safe avoidance maneuvering.

A conceptual framework for Adaptive Flight Deck Systems (AFDS) considers the integration of the above safety technologies with future communications, navigation, Air Traffic Management (ATM), and other technologies being investigated either within NASA, other government agencies, or industry (MS 4.1.1). Based on this framework, modeling, simulation, and validation activities can be performed to help understand the complex behaviors resulting from the interactions of all disparate functions and services being advocated. Modeling, analysis, and simulation are required as it is unlikely that such a complex system can be comprehensively validated solely though physical testing especially with regard to quantifying operational safety/risk.

Research in this area also tracks improvements in predictive capability through continuous identification and assessment of areas of uncertainty that require investigation (MS 4.1.9 and 4.1.10). This is accomplished through the development of system design tools, the application of system analysis and data mining techniques that identify phenomena of interest (hazard precursors) and to prioritize validation needs, and the definition of validation metrics that quantify uncertainties for system and subsystem performance and integrity.

Because flight deck systems involve a strong coupling of complex physical processes, human behavior, and computer-controlled systems, predictive accuracy is difficult to assess except for applications within, or very near, the validation cases (Oberkampf, 2002). To support other Application Domains (ADs) (e.g. DoD, General Aviation, CEV, Mars airplane), one long-term goal of this research is to attempt to continually move toward the right in Figure 4; wherein performance can be predicted for applications outside, or farther removed from, the validation cases. For these ADs, validation may be infeasible. Even for civil aviation, tools that support inferencing may help reduce certification costs. A second, related, long-term goal is to gradually grow the size of the validation set such that for any new application, we are more likely to have a validation case nearby.

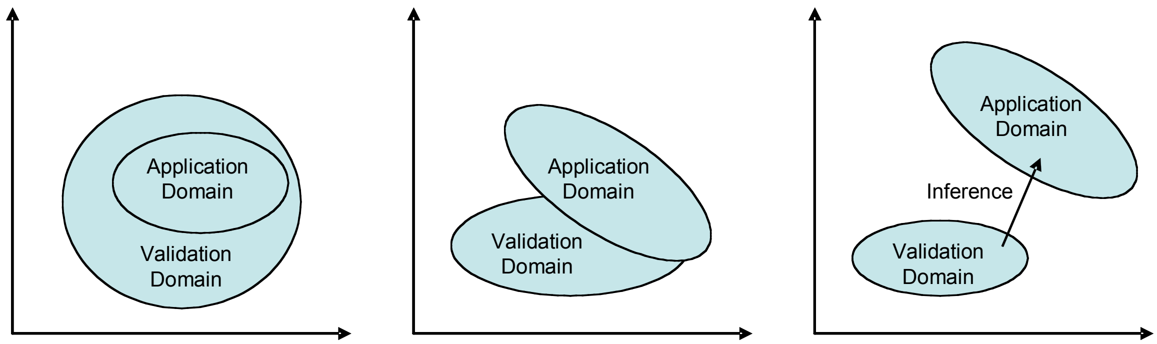


Fig 4. Possible relationships between application domains and validation domains

Because of the multi-disciplinary nature of AFDS concepts, activities in this area will be conducted primarily by a cross-cutting working group consisting of the Principal Investigator (PI) and discipline-specific Co-PIs. It is also expected that multiple workshops will be held with representatives from industry, other government agencies, academia, the other Aero programs, and the other AvSP projects represented.

Tangible realizations of the Level 4 capability, based on the framework defined and the subsequent lower Level activities are not planned within this five-year period. Even the workshop suggested testing/validation of a Level 4 capability should be in year six. There are several factors that prohibit pulling this back to FY ’11 or sooner. However, the project will seek interest from OGA and industry partners who may have a common interest in early testing and can provide resources to that end.

Next, Level 3 research activities are discussed. Consistent with the framework (Figure 1), Level 3 activities are distributed among three categories: (1) Tailored Flexible Operator-Automation Management; (2) Adaptive Displays and Interaction; and (3) Decision Associate Technology. Milestone (MS) numbers used in the workshop product are retained to show traceability back to the original set.

TAILORED FLEXIBLE OPERATOR-AUTOMATION MANAGEMENT (LEVEL 3)

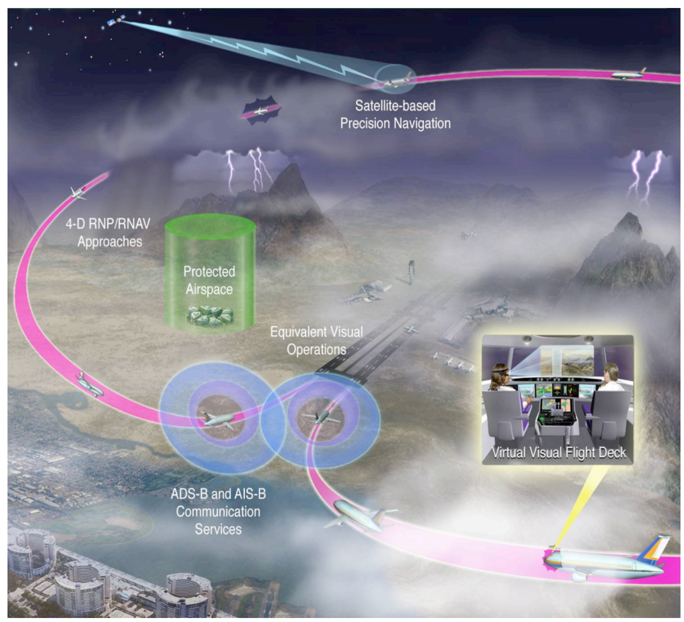
Automation has benefited aviation safety, but has also introduced potential safety issues. Incident and accident data suggesting problems with flight deck automation spurred Billings to suggest that the design of flight deck automation must include explicit design of the roles for the humans and automated agents, as well as ensure that human roles are supported (Billings, 1991). In addition, the FAA Human Factors task force has called for function allocation based on flight crew cognitive tasks and information/coordination requirements (Abbott, 1996). Specifically, the task force called for a holistic approach to function allocation. Appropriate human/automation integration continues to be an important concern. Most recently, JPDO made specific recommendations for more research in the area of “function allocation between humans and automation”.

The objective of this effort is to define operator/automation integration strategies that dynamically optimize the performance of all agents’ (human operators and automation). The allocation strategies consider agent roles, information requirements, authority requirements, and agent abilities and vulnerabilities. Through such a considered approach, the research aims to foster appropriate operator states, and provide a baseline level of safety, even when the human is incapacitated, through intelligent use of complementary automation.

The philosophy for this area of research is to treat the human operator as just another element of the flight deck system rather than a special case (Jordan, 1963; Sarter, 1996). The human is considered a node in the system when analyses of single points of failure are conducted. Unique human needs such as engagement, purpose, and down time are considered in a similar manner as hardware needs and functionalities are considered today. The function allocation between humans and automation is based on roles (Harrison, 2003), authority, and fundamental principles of human and machine behavior (Billings, 1997; Schutte, 1999; Schutte, 2000) (MS 3.1.1). The research addresses safety issues associated with the notion of dynamically reallocating functional responsibilities when there are problems with either the human's or the machine's ability to handle their normal functions (Prinzel, 2000a) (MS 3.1.2). Formal methods analyses allow for a thorough evaluation of allocation concepts beyond traditional simulation studies. The research provides a conceptual framework that can accommodate new technologies as well as new operator roles as they emerge (MS 3.1.3, 3.1.4).

This research effort intends to develop prototype human/automation integration strategies, which include context-dependent, dynamic role and task reallocation, and are supported by formal analyses of human and automation failure modes. Sensitive evaluation scenarios and measurements will be developed to ascertain the system, operator, and automation performance levels. While not technology-dependent, activities benefit from advances in human state assessment and environmental state assessment (e.g. weather, traffic, terrain, aircraft health) developed by other elements of the IIFDT project. The culminating product of this work will be a set of prototype strategies, methods for evaluating human/automation integration performance in flight decks, and models for validating human/automation integration with the ability to extrapolate to new vehicle concepts, operator roles, and automation sophistication.

Fig 5. NGATS implies increased flight deck automation and new function allocations



ADAPTIVE DISPLAYS AND INTERACTION (LEVEL 3)

The primary objective of research in this area is to identify and develop the technology (i.e. solutions, methods, metrics, and guidelines) required to mitigate crew-vehicle interface safety concerns that could potentially constrain implementation of the emerging NGATS operating principles (MS 3.2.1). The effort concentrates on understanding the information transfer needs of the flight crew and applying cutting-edge interface technologies through a successive cycle of development, verification, and validation steps (MS 3.2.2). In particular, research in this area involves revolutionary applications of visual display concepts that have been investigated at Level 1 (see later subsection). Another objective is to provide validated flight deck guidelines and information display requirements to achieve Equivalent Visual Operations (EVO) (MS 3.2.3) in inclement weather conditions. EVO implies a level of

operational flexibility, capacity, and safety margin representative of operations conducted in Visual Meteorological Conditions (VMC).
Strategies for improving timely access to information, reducing the cognitive demands of integrating information across displays, and reducing errors are applied. These approaches increase the effectiveness of the flight deck audio-visual display space by providing "at-a-glance" information, by spatially integrating information across displays, and by making displays more context-sensitive. The approach applies a parametric audio-visual display design space that captures the constraints and affordances of the flight deck. The impacts of this approach to flight deck design are intuitive display concepts that are spatially integrated, effectively de-cluttered, and provide crew access to information as needed. Several methods to improve automation, information, and task management through the use of interface and augmented visualization technology are planned. These works improve flight crew interactions with onboard systems, intra-crew interactions, and coordination and communications with ATM systems.

Visual display and interface technologies reflect what uniquely characterizes the human from the machine. Humans naturally encode information visually, and visual representations optimize the creation of mental models and the integration of disparate complex data sets into meaningful constructs supporting human-machine interaction. In aviation, interface technology has often limited the potential of human information processing. For example, analyses of pilot-air traffic controller (ATC) voice communications reveal a high volume of read-back and hear-back errors and significant cultural issues for users who were not native English speakers (Cardosi, 1996; Morrison, 1989). These voice communication problems are not mitigated completely by controller-pilot data link which can introduce new forms of errors. The consequences have been "clumsy" interfaces; and prototype technology applications to date have increased cognitive demands on pilots and introduced new forms of human error attributable to the mismatch between human unique capabilities and flight deck design.

A corollary to achieving NGATS objectives is the likely increase in automation and new advanced interface needs. Today, issues exist with crew-vehicle interfaces that can be attributed to, in some part, inadequate consideration of how they are integrated as part of a joint distributive cognitive system. For example, the Control Display Unit (CDU) interface to the Flight Management System (FMS) has been extensively studied and shown to introduce new forms of errors (Abbott, 1996; Sarter, 1992). As technology demands increase in the flight deck, these designs cannot adequately support the human user who becomes more of a supervisory controller or monitor. Adaptive displays and interaction are necessary to keep the flight crew "in-the-loop" even when functions become more highly automated.

Research builds upon previous safety-related crew-vehicle interface research (Glaab, 2003; Prinzel, 2000b; Bailey, 2002; Parrish, 2003; Jones, 2005; Young, 2001). These products are referred to as Cycle-0 products that are investigated with respect to our NGATS-based AD0 (MS 4.1.1). Subsequent development of Cycle-1 products adds capability and includes developments designed to increase crew awareness and capabilities supporting NGATS-based AD1. Specific Cycle-1 technologies include, for example, graphical automation interfaces. These

Fig 6. Notional EVO-capable flight deck

capabilities result from Level 1 investigations of multi-modal interface technologies (see later section). Eventually, crew-vehicle interfaces that adequately support the full NGATS operating concept would be included in Cycle-X designs following the term of this technical plan summary.

Figure 6 provides a notional concept of an EVO-capable flight deck. Central to the concept would be large head-down displays driven by advanced graphics computers that have access to comprehensive high-integrity data sets. The resulting head-down presentations are intuitive and adapt to be task-appropriate. In addition, unobtrusive head-worn display devices provide unlimited field of regard for the crew. When combined with advanced interface technologies, it is hypothesized that flight crew situation awareness, workload, and performance can be equivalent, or superior to, current VMC operations.

DECISION ASSOCIATE TECHNOLOGY (LEVEL 3)

The objective of this element is the development of functional capabilities that improve situation awareness, decision making, and resulting action implementation by the pilot-vehicle system. In particular, these functions support tactical decision-making and trajectory management during terminal area operations. Terminal area operations (e.g. take-off, departure, arrival, approach, landing) are chosen as they represent the period of greatest risk exposure, environmental complexity, and workload. In addition, proposed NGATS concepts of operation (e.g. 4D trajectories, EVO, and Super Density Operations) will exacerbate these issues by allocating additional responsibilities to the flight deck and by reducing physical separation between aircraft and other potential hazards.

Functional capabilities include detection and resolution of erroneous information and actions, anticipation of key decision points, evaluation and refinement of potential actions, action selection, and reconfiguration of the other vehicle systems to implement selected actions. Additional considerations for effective support in terminal area operations include compatibility with uncertain, dynamic, time-varying situations and complex multi-tasking operations with competing demands on crew resources and attention.

Previous work such as DARPA’s Pilot’s Associate, the Army’s Rotorcraft Pilot’s Associate, and the European Crew Assistant Military Aircraft (CAMA) system (McNeese, 2002; NATO, 2002) has tended to approach this problem from the perspective of providing an electronic crewmember or assistant. While these systems have enjoyed some success in non-time-pressured situations in which the crew can review and comprehend proposed actions, in time-pressured situations, they have been less successful. In general, these systems have fallen far short of their promise of human-like intelligence and interaction, causing a mismatch between the user’s expectations and the associate’s abilities.

Rather than trying to emulate an electronic crewmember, we apply a strategy of complementary automation (Schutte, 2006; Schutte, 1999), a specific form of human-centered automation (Billings, 1996). The machine and the human work together in symbiosis. The human operator provides common sense knowledge, general intelligence, and creative thinking while the machine provides swift and precise control, extreme vigilance, resistance to fatigue, and encyclopedic memory. In general, tasks are structured so that the human is involved in actions and decisions having significant consequences on the overall mission and safety, and less involved in actions and decisions that are relatively deterministic, time constrained, tedious, repetitious or require great precision. This significantly reduces the complexity of the system, its user interaction, and potential failure modes.

A decision aiding system requires effective integrated consideration of normal and selected non-normal situation elements encompassing Actual Navigation Performance (ANP), terrain/obstructions advisories, weather and traffic advisories, airspace constraints, runway conditions, ATC clearances and requests, dispatch/operation center directives, aircraft performance and status, and status and intentions of the crew. It is unrealistic to expect comprehensive treatment of all these factors within a five-year program; our goal is to develop an extensible framework that can ultimately accommodate all of these factors. This goal will be addressed by identifying hazards for current and future NGATS operations (MS 3.3.3). Analytical and laboratory studies will be used to guide the development of system concepts and define expected system performance criteria (MS 3.3.1). A subset of these concepts will be implemented and evaluated in part-task simulation (MS 3.3.2, 3.3.7) and the actual system performance compared to analytical predictions. Based on the success of these concepts and predications, limited flight trials are used to (MS 3.3.2a) to evaluate system performance in the presence of real-world uncertainties. The end products will be validated decision associate system concepts, design guidelines, evaluation methods, and operational response categories and performance estimates (MS 3.3.4, 3.3.5)

Activities contributing to the development of Decision Associate Technologies are performed within each of the Level 2 research areas. Technologies developed by the Resilient Vehicle Mission Management portion of the AvSP's Integrated Resilient Aircraft Controls (IRAC) project and indications of vehicle health status developed by the AvSP's Integrated Vehicle Health Management (IVHM) project are also necessary to realize the fully integrated IIFDT vision.

Next, Level 2 research activities are discussed. Consistent with the framework defined by the workshop team (Figure 1), Level 2 activities are distributed among five categories: (1) Adaptive Intelligent Information Management; (2) Methods, Metrics, and Tools; (3) Automation Monitoring and Failure Mitigation; (4) Operator State Monitoring and Classification; and (5) External Hazard Detection and Classification. Milestone (MS) numbers used in the workshop product are retained to show traceability back to the original set.

ADAPTIVE INTELLIGENT INFORMATION MANAGEMENT (LEVEL 2)

This research develops integrated information management technologies that ensure real-time performance, accommodate human information needs (including 4D hazard awareness), apply multi-disciplinary solutions to cull, sort, and fuse information for human/automation consumption, and enable comprehensive situational safety analysis.

Flight deck data system concepts and technologies should ensure the availability of quality data as required by users/applications, and be capable of providing timely warnings when a system/subsystem should not be used for its intended function. This applies to existing functions, NGATS-postulated functions, and the functional capabilities described herein at Level 2 and Level 3. Initial work defines a data exchange model that represents content and quality requirements for onboard information management (MS 2.1.6). Data sources to be considered include databases, onboard sensors/systems, data links, and the crew (MS 2.1.4). Baseline models of flight deck information management systems are validated using a prototype AIIM architecture (MS 2.1.1, 2.1.8) and updated based on the requirements of Level 1/2/3 IIFDT-developed functional capabilities for detecting and mitigating hazards. These models are used as a basis for integrated testing/validation experiments at Level 3. Documentation of information management requirements and guidelines resulting from these activities are then produced (MS 2.1.11, 2.1.12).

Another aspect of information management addresses the issue of presenting large volumes of data when display size is limited. The abstraction of data into visual formats in a one-to-one format (e.g. modes and states) has likely been carried close to its practical limit. The same can be said for concentric overlays of data (map, weather, IR etc.). A deeper understanding of the principles of data integration and management is needed to break through this limit. For example, even though there is extraordinary integration present in a person's instant decoding of the emotional meaning of a facial expression, the principles which would allow the organization of vehicle health information to achieve a corresponding degree of processing and comprehension efficiency have yet to be established.

There is a similarity between the idea of populating and enhancing an interface to information and the idea of data compression from Shannon's information theory. The difference is that with respect to interface design, the inter-relationships between the compressed streams are very important. Here the notion of latent centers as places where more information can be progressively packed becomes the criteria for compression. Mathematical descriptions of a display "packing" process, plus formalized structure transformation invariants, and computational methods to support the generation of interfaces are developed (MS 2.1.12). Users are actively involved in the process of guiding an algorithm to construct a display and adapt it to a given situation.

The research considers: (1) the use of structure invariants and transformation invariants in the process of designing (and populating) an interface with information; (2) the visualization of complex data sets (e.g. the thousands of bits of data that are sensed, collected, and computed in a vehicle health monitoring system); and (3) the integration of several sources of information into a single display in a way that reveals coherence and wholeness without cluttering the screen. This work is tightly coupled with other Level 2 activities (Methods, Metrics, and Tools) as well as Level 1 activities (Multi-Modal Interfaces).

Information integration and management research builds on previous crew-vehicle interface research (Bailey, 2002; Jones, 2005) toward meeting the JPDO vision for NGATS. This previous work establishes a baseline and identifies information management technology gaps to address (MS 2.1.1).

METHODS, METRICS, AND TOOLS (LEVEL 2)

Research addresses both flight deck system design and analysis. Seven tasks are identified: Safety Evaluation and Assessment, Automation Interaction Design, Data Extraction Methods, Display of Data Uncertainty, Display Quality/Complexity Metrics, Information Integration, and Mishap Re-creation.

Safety Evaluation and Assessment
Methods and tools are developed to identify and prioritize flight deck safety hazards and to assess overall system safety and risk (MS 2.2.1, 2.2.11). Database monitoring techniques developed in this domain have potential application for monitoring of automated flight deck systems through interrogation of the databases both supported and created by the automated systems. Modeling the logic describing the functional dependencies among the developed flight deck technologies along with their relationships to other relevant flight systems allows safety benefits and the potential for new hazards to be assessed at each level of integration. Risk assessment methods are developed to detect the frequency of emerging system-wide flight-deck safety vulnerabilities and to mitigate the safety risk of implementation of IIFDT products early in the design phase. Pending availability of data from such efforts as the Voluntary Aviation Safety Information-sharing Program (VASIP), capabilities are developed enabling systematic identification and prioritization of flight deck hazards aggregated by occurrence type, phase of flight, aircraft type, and event type (MS 2.2.5).

Integrated Automation Interaction Design Tools
As described in the Level 3 discussion of Adaptive Displays and Interaction and Decision Associate Technology research, automation interaction plays a pervasive role in flight deck systems. NGATS

concepts will continue to increase the dependence on automation, as even more functions/tasks become automated. Designing effective means of interacting with automated functions can enable operators to perform mission tasks while considering the safety implications on flight deck operations. This research activity integrates algorithmic, formal, and computational methods developed at Level 1 into automation design tools (MS 1.7.1, 1.7.7, 1.7.8, 1.8.1, 1.8.2, 1.8.3, 1.8.5, 1.8.6). These tools can be used by domain-expert designers to rapidly define and evaluate requirements specifications in a dynamic environment without having extensive human-computer interaction expertise (Feary, 2004). As compared with existing methods, these tools allow for the specification of more detailed requirements and provide a platform for more rapid automation interaction analyses enabling enhanced evaluations of prototypes earlier in the design process. Validated tools developed as part of this research will be used in the Level 3 research (Adaptive Displays and Interaction and Decision Associate Technology) where functional capabilities are developed and tested. In addition, the validated tools can be applied outside the project wherever human-automation interactions are critical to operational safety (e.g. ASP air traffic management functions or Exploration Systems applications).

Data Extraction Methods

Unifying flight deck information models are developed as a means of extracting and integrating disparate information sources into a common synthesizing framework that supports flexible presentation of information to the pilot (MS 2.2.6). All information sources are processed and transformed into a unified representation that captures and links critical status information pertaining to aircraft systems, environment, and airspace. This approach is based on previous work in building semantic models used by operators in complex scientific and engineering domains (Carvalho, 2005; Keller, 2004). The information models serve as a basis for analyzing the underlying data stream and providing greater situational awareness. In addition, they build a network of relationships that interconnect the underlying data streams. This network provides the building blocks for abstraction of information as well as for information integration and visualization (Keller, 2003; Berrios, 2003). This work is closely aligned with the information management research on high integrity data systems previously discussed.

Displaying Data Uncertainty to the Flight Crew

One research challenge to be addressed is the manner to display information with estimated uncertainty (MS 2.2.6). This problem concerns what should the pilot actions be when confronted with various symbolic elements where uncertainty in the quality of the information can be estimated. For example, uncertainties in location and severity of weather activity could be portrayed to the flight crew to support more informed decision-making with respect to appropriate avoidance responses.

Display Quality and Complexity Metrics

As display concepts incorporate new sources of data onto an already crowded display, appropriate review of the various competing display elements is required to avoid limiting overall effectiveness. This research develops comprehensive display complexity metrics (MS 2.2.12) that have value for a wide range of applications. The resulting product will be an evaluation toolset capable of quantifying the "clutter" or "complexity" of a given display concept and predicting the resulting effectiveness.

Information Abstraction and Integration Methods

An important building block of adaptive displays is the theory and methods for automatic generation of the geometrical form of an interface, with special emphasis on achieving overall coherence, correspondence, and integration of information. A theoretical framework is developed to integrate computational and heuristic methods and tools for generating adaptive displays. Algorithms are used to produce an interface consistent with this framework given the context and the user's monitoring and troubleshooting requirements rather than relying on static, previously designed interfaces. This approach combines methods for display of system cautions and warnings (Spirkovska, 2006) with techniques and tools for automatic generation of correct and efficient procedures for dealing with and recovering from unforeseen situations, disturbances, and failures (MS 2.2.6). The foundation of this work is a formal theory that guides the abstraction of relevant information (and suppression of irrelevant) in a computational way (Degani, 2002). Design guidelines, tools and verification criteria are developed for improving situational awareness and adaptive interfaces in human-automation systems (MS 2.2.10).

Mishap Re-creation

The Mishap Re-creation activity supports the prediction and assessment of accident scenarios that may be postulated when considering NGATS operations. This is done by formulating principles for the creation of integrated predictive analysis tools and flight deck/aircraft aerodynamic interaction models (2.2.9). A component of this work is the creation of a database of aircraft models to feed the interaction models. This research is done under the flight deck project because the overall system model used to predict mishaps has to include both a flight deck and aerodynamic component. A majority of the data sources available to mishap investigators record dynamics information, which is subsequently used to back out flight deck actions and hazards associated with those actions. One of the most common causes of accidents is flight crew error or aircraft/flight deck interaction problems (Boeing, 2005). These tools can provide the ability to predict operational outcomes, and thereby support development of appropriate remediations for potential hazards implied by NGATS.

There is a feedback relationship between this activity and other IIFDT activities: the designs of new flight deck technologies and concepts will determine the parameters of the mishap prediction model, and the tool's predictions will in turn help to refine the design of those technologies. NASA expertise that is not available via the NTSB, the traditional mishap investigation agency, addresses establishing causation in a data-limited environment and predicting hazards of a theoretical concept such as NGATS.

AUTOMATION MONITORING AND FAILURE MITIGATION (LEVEL 2)

This research area is driven by two factors: (1) the history of incidents of automation surprises in the flight deck, including both mode confusion and automation reaching limits and transferring responsibility to pilots who have insufficient state awareness to correctly respond to the situation; and (2) the trend implied by the NGATS vision toward increasing levels of automation. Both can be mitigated by appropriate monitoring techniques.

Given resource constraints, IIFDT does not intend to invest directly in this particular Level 2 area. Activities at Level 1 (Verification Methods), Level 2 (Information Management) and Level 3 (TFOAM, ADI, and DAT) indirectly cover a portion of this gap. In addition, there are similar capabilities being addressed by the Integrated Vehicle Health Management (IVHM) project. The IVHM work provides for the design and verification of distributed architectures capable of diagnosing and reporting internal faults. Decision aid technologies at Level 3 are leveraged to provide this information in a suitable form to the pilot(s).

OPERATOR STATE MONITORING AND CLASSIFICATION (LEVEL 2)

Human flight deck functions are defined by safety, social, and economic motivations (Hancock, 1998), and as such, they are a unique element of the flight deck system. Joint cognitive systems, which preserve the benefits of both human and automation capabilities (see Tailored Flexible Operator/Automation) are most likely to improve safety (Billings, 1991). These rely on improved awareness of operator state and performance. Human performance is often affected by their physical condition, state of awareness, and even emotional state. Future flight deck systems will detect the operator’s state and use the information, when necessary, to compensate for or mitigate hazardous situations. Level 1 research provides instruments and methods for assessing operator traits and operator states. The Level 2 activity investigates these instruments and methods in operational contexts, and integrates metrics to robustly infer operator states that may be hazard precursors (MS 2.4.8, 2.4.7). In order to use state and trait, indices of these characterizations are identified, operationalized, measured, and assessed for reliability, validity, and sensitivity in scenarios designed to modulate these states. Operator states to be investigated include fatigue, immersion/engagement, attention distribution, and human error precursors identified through data mining activities (see Methods, Metrics, and Tools). Subject to resource availability, additional operator state research includes novel indicators of information processing resource loading, situation awareness, and meta-performance awareness (e.g. self-detection of errors).

In 1992, (Pope, 1992) identifies hazardous states of awareness that have been shown to affect aviation safety based on accident reports, and suggests a system that monitors for these states. The states identified, "preoccupation, vigilance, and excessive absorption," were related to data obtainable from EEG measures. Other investigations of accidents and incidents have indicated that fatigue is involved in at least 4-8 % of aviation mishaps, and surveys of pilots and aircrew members reveal that fatigue is an important concern throughout today's 24/7 flight operations (Caldwell, 2005). As sensor technology and methodology advances, other operator states are more accessible, and important to consider; such as immersion (Meehan, 2005) and self error-detection (Fiehler, 2004). While (Pope, 1992) makes the distinction between operator states and the contents of awareness, for the purposes of this program, they are both considered important descriptive characterizations of the operator for in situ communication with other flight deck systems.

DARPA is active in this field and their effort is complimentary to NASA's. The relatively new, DARPA Augmented Cognition Program aims to enhance operator effectiveness by overcoming four primary bottlenecks in cognitive performance (attention, executive functioning, sensory input, and working memory) as detected by psycho-physiological measures (St. John, 2005). The DARPA program can be distinguished from the NASA work by its focus on these information-processing bottlenecks, rather than other operator state phenomena such as task engagement (Pope, 1995) and fatigue. Further, the DARPA study is more focused on development with current state-of-the-art technologies, whereas NASA strategically identifies relevant operator states and technologies toward validly characterizing these states, and employs operator state information for next-generation intelligent interface modulation and human/automation interactions.

Novel approaches to characterizing operator state will be investigated (MS 2.4.3) such as cerebral blood flow using functional Near-Infrared Spectroscopy (fNIRS) (Izzetoglu, 2003), voice stress analysis (e.g. Rothkrantz, 2004), non-traditional postural and muscular responses (e.g. grip pressure, and seating posture) (Balaban, 2004), and indicators of general activity (Pope, 2001). Fundamental laboratory research (see Level 1 Operator Characterization, Sensing, Interaction Modeling, and Formal Analysis) to ascertain baselines, and the diagnosticity, reliability and sensitivity of these approaches will transition in this element to more context-relevant scenarios in partial task simulations and integration of sensors to better infer operator states. This element also aims to identify sensors and measurement approaches that are operational in actual flight environments to validate test scenarios. These more integrated and robust operator state technologies can then be considered as partial definition of "context" and incorporated as a control loop to sensitively modulate interface features (see Adaptive Displays & Interaction – Level 3) such as alerting and operator state feedback (MS 2.4.9), aiding (see Decision Associate Technologies – Level 3), and complementary automation (see Tailored Flexible Automation – Level 3).

EXTERNAL HAZARD DETECTION AND CLASSIFICATION (LEVEL 2)

Vigilant observation of the surrounding airspace for external hazard detection is essential for operational capability and safety. There are five classes of external hazards: (1) meteorological (e.g. icing conditions, convective weather, wind gusts, turbulence), (2) environmental (e.g. volcanic ash), (3) geospatial (e.g. terrain, man-made obstacles, foreign object debris), (4) traffic, and (5) airspace constraints/restrictions. The severity of hazards associated with any of these depends on many factors such as relative proximity and closure rate.

Current “see-and-avoid” operation relies on pilots as the primary surveillance sensor and hazard evaluator, requiring them to maintain cognizance of all observable external threats. Radar, TCAS, and TAWS technologies provide significant safety benefits by supplementing “see-and-avoid”; however, these technologies are limited in many respects and do not provide a complete surveillance picture. As sensor technologies are developed and capabilities to detect and track numerous additional hazards are added, the pilot can no longer be expected to monitor and evaluate individual sensor information. A new layer of integration and evaluation logic is necessary to assimilate and parse sensor and hazard data and provide the key information required for aircraft safety. For the purposes of this research, this system function is referred to as the External Hazard Monitor (EHM). The EHM function provides external hazard detection and classification products to the flight deck technologies that assist the pilot as well as to other onboard or off-board functions (e.g. ATM decision aids) that may require this information.

IIFDT depends on the development of a comprehensive surveillance system approach that uses all available sensor measurements, geospatial databases, and communications inputs (including NGATS net-enabled access to information from *in situ* and forward-looking sensors on other aircraft and hazard information available from ground-based or space-based sensor systems) to derive external environment information elements that support global safety assessments by the information management system, warnings/alerting by decision associate technologies, and direct pilot observations by equivalent visual display technologies. In this system, the EHM function collects information from all available sources and derives hazard information including location, identification, characterization, and classification. A key capability of the hazard monitor is its ability to make determinations of hazard severity. In addition, quality estimates for each derived data element are generated, where quality may encompass metrics such as accuracy, resolution, integrity, timeliness, and confidence. This information is generated for flight deck systems use, but it can be exploited through cooperative efforts with NASA airspace systems programs and with NOAA and the FAA as a source of data to be shared with other NGATS users.

An integrated reliable EHM functional capability is an important part of future flight deck systems that are needed to support the NGATS operations. NASA’s role in the transition to these future flight deck systems is to define and develop the concepts to a level where implementation is feasible and to remove barriers to their implementation. In this five-year project, the EHM function definition and requirements are developed. The original plans for IIFDT included the development of this function that could be integrated with other flight deck system functions. Due to the limited resources available in this program, development and testing of this function

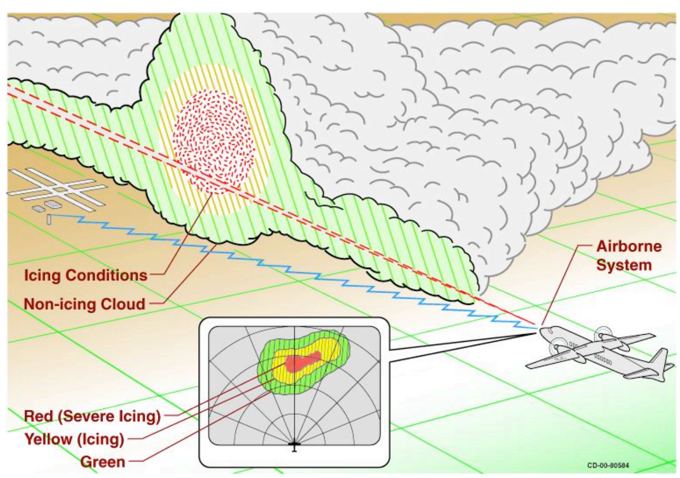


Fig 7. Detecting and avoiding icing conditions

will not be attempted. This is because the EHM requires sensor sub-system modeling for input and supplies output to client flight deck systems. Sensor models would have to be developed in advance of the EHM, or at least concurrently. In this five-year project, energies are directed at sensor model development and hazard investigations at Level 1. Developing and testing the EHM will be pursued in a future program (or via a partner collaboration), during which there will be additional sensor model development, models for client flight deck systems will become available, and the results of hazard investigations will support development of the hazard evaluation capability required in the EHM.

The development of the EHM function in this project includes defining the concept (MS 2.5.1), developing initial input and output requirements as well as functional requirements (MS 2.5.2), and developing the functional and I/O requirements to provide a starting point for actual function development in the subsequent program. As part of the function definition, requirements are derived for all data inputs (e.g. for onboard sensors, databases, and off-board data link sources). Functional requirements are also developed to define the services to be provided by the system to higher-level functions and systems such as decision associate and display technologies at Level 3 (MS 2.5.3).

The development of the EHM concept depends on the Level 1 activities (described later) addressing remote sensing, signal processing, and external hazard characterizations. Research capitalizes on in-house expertise in sensor technologies, data fusion, detection theory, avionics, systems engineering, atmospheric science, geospatial information systems, and communications systems gained from previous NASA programs.

IIFDT LEVEL 1 ACTIVITIES

Next, Level 1 research activities are discussed. To align with the project's discipline-based work breakdown structure, the workshop-defined Level 1 activities have been distributed into four categories: (1) Information Systems; (2) Multi-modal Interfaces; (3) Remote Sensing, Signal Processing, and External Hazard Characterizations; and (4) Operator Characterization, Sensing, Interaction Modeling, and Formal Analysis. Milestone (MS) numbers used in the workshop product are retained to show traceability back to the original set.

INFORMATION SYSTEMS (LEVEL 1)

Level 1 information systems research activities support primarily Level 2 activities in information management and design methods and tools. Activities fall along three themes, (1) data extraction and integration, (2) information integration and abstraction, and (3) automation interaction design.

Data Extraction and Integration

Alternative data processing and integration methods derived from the analysis of human and animal neural cell information processing are developed. In recent years, advances in neurochemistry, non-linear dynamical system theory, and biology have lead to increasingly well-defined models of the operation of living cells. Although the complex genetics, electronics, and architecture of cell behavior are better understood, the translation of these insights into computational tools useful for sensor information processing and flight deck performance has remained focused on only a very limited subset of cell behaviors such as the well-understood Hebbian learning rule that forms the basis of modern neural networks (Jorgensen, 2003).

The new methods for pattern recognition are based on the mathematics of large coupled oscillating networks. This architecture includes dynamical systems models of computation, chaotic logic functions, phase and frequency locked neurons, and the programming of a dynamical system architecture. The utility of these structures is demonstrated by testing the ability of such an architecture to identify human-like meaningful patterns starting in image data such as a pilot-terrain object identification task. Subsequently, the system can be expanded in terms of the number of nodes, complexity of the data flow architecture, and integration into flight deck displays (MS 1.7.13).

To describe and capture data extraction, a formal theory of information integration is developed that explicitly states and exploits the underlying semantics of each data source to be integrated. Correspondences between the different semantic representations form the basis of the integration. These correspondences are dynamically combined to re-express information from the underlying data model to the desired integrated model. In the process, data provenance can be preserved since the derivation of data is explicitly defined. Once the data are re-expressed in terms of the unified information model, it can be used to support other capabilities, such as information browsing and search, display customization, and knowledge discovery (Wolfe, 2004). In particular, derived concepts defined in the models provide more meaningful features and structures, which could be used in data mining techniques to improve their performance over raw data alone (MS 1.7.2).

Information Abstraction and Integration

Corresponding to the Information Abstraction and Integration research described at Level 2 (2.1 and 2.2), fundamental and theoretical work to develop rigorous and systematic methodologies for abstraction of information and integration of data is crucial. As it stands today, human-factors, applied psychology, and Human-Computer Interaction (HCI) communities do not have a strong theoretical approach for integrating and packing information that enhances and maximizes the overall display content to make it effective and useful. When considering the information-rich displays of the future and the need for adaptive displays (Level 3) – the research addresses: methods for integration of several sources of information into a single display in a way that reveals coherence and wholeness without cluttering the screen; methods for visualization of dynamic processes; the use of structure invariants and transformation invariants in the process of designing (and populating) an interface with information; formal methods for describing and modeling some of these structure- and transformation-invariants in condensing information to a given display; developing computational methods to support such generation of interfaces; and methods and tools for presenting caution and warning information to the pilot (MS 1.7.1) . Such methods consider the context of the situation and the problem of multiple failures by synthesizing and interleaving procedures and recovery sequences.

Automation Interaction Design Theory and Method Development

This research is focused on applying state-of-the-art knowledge of human performance to develop theoretic and computational methods to identify error-prone characteristics of automation design (MS 1.8.6). Identifying and understanding those aspects of human-automation interaction that are vulnerable to operational error is required in order to improve the design of error-tolerant automation interfacing strategies. This research complements the research conducted in operator characterization by developing methods derived from the research findings (MS 1.5.4, 1.5.7, 1.5.9, 1.5.11). The initial approach to this effort will be to catalog identified of human-automation interaction operation vulnerabilities. The next step will be to develop algorithms that can reliably predict and rank characteristics of automation design that are likely to expose these vulnerabilities. Validated methods will then be used to support the Level 2 Integrated Automation Interaction Design Tool development activity (see previous section).

MULTI-MODAL INTERFACES (LEVEL 1)

Two research tasks are identified in this area supporting Level 2 (Information Management), Level 3 (Adaptive Displays and Interaction), and Level 4 (AFDS) capabilities.

Visual Display Technologies

The objective of this research is to investigate revolutionary display concepts that optimize operator situation awareness and workload by integrating information across displays to minimize errors and workload associated with the cognitive integration of this information. This task supports Level 2 (Information Management) and Level 3 (Adaptive Displays and Interaction) by helping to overcome the information overload situation that may occur due to the changes in roles and responsibilities of the flight deck for safely managing the aircraft in the NGATS. In the future flight environment more information will be available – and necessary – from external sources (e.g. for Shared Situational Awareness constructs). As visual display and information system technologies continue to increase in capability due to investments by non-aviation industries, advanced display concepts are limited only by the ability of display designers. The challenge is to present the information in such away that information extraction is at-a-glance and utilization is seamlessly integrated into the task that the flight crew is currently working to complete (Theunissen, 1997; Parrish, 1994; Prinzel, 2004; Wickens, 2000). This is in contrast to the past where the display and information system capability limits drove resulting visual interface designs, resulting in specific displays with disparate information presented in a non-integrated manner. Fundamental research determines aviation-specific display requirements (MS 1.4.1, 1.4.2) and opportunities to develop display concepts that maximize crew situational awareness (SA) while reducing workload. This research (1) identifies the capability/limitations of the information and technologies that will be used to create flight deck systems, (2) mitigates common issues witnessed today with human-automation interactions, and (3) remains within the context of the potential future flight deck roles within the overall ATM system (e.g. strategic and tactical weather, traffic, and terrain monitoring/alerting/resolution, with flight path planning and re-planning, and traffic flow management).

Predictive Capabilities and Applications

This task assesses progress towards meeting objectives related to realizing the NGATS concept with margins of safety equal to, or better than, current operations (MS 1.4.6) as applied to crew-vehicle interfaces and the likelihood of crew errors. This effort develops methods for measuring progress and establishing predictive capability for the visual display technologies being developed in the above-mentioned task. This work is both warranted and challenging since the NGATS operational concept may result in major departures from current operations in Instrument Meteorological Conditions (IMC) and there is little or no predictive capability currently available for visual display technologies. If the quantification of the margin of safety can be constrained to addressing crew errors, then an assessment of the relative safety of a specific operation/display concept can be established. The ability to predict the margin of safety, or relative margin of safety for specific flight crew tasks, is essential and can be a valuable tool that facilitates technology development and implementation. Achieving this objective depends on identifying Application Domains (Level 4 products), acquiring adequate experimental data, developing/integrating pilot performance models, and performing appropriate traditional functional hazard analysis techniques to establish the safety margins that can be expected of the prototype crew-vehicle interface concepts.

REMOTE SENSING, SIGNAL PROCESSING, AND EXTERNAL HAZARD CHARACTERIZATIONS (LEVEL 1)

This research is partitioned into four areas: sensor technology development, applications of detection theory, external hazard characterization, and signal processing to be described in the subsections that follow. This research is driven by focusing on high priority hazards and the technologies that can be used to detect and characterize them. The work package is described in the final subsection.

Sensor Technology Development

This activity is comprised of studies of applicable technologies, for the development of a working knowledge base and of focused efforts to deal with specific high-priority hazards and promising technologies. A Phenomena Identification and Ranking Table (PIRT) of hazards versus sensor technologies is used to develop a work package for external hazards detection (MS 1.1.1 and 1.3.1). The package includes three focused investigations: remote sensing for icing conditions, including multi-frequency radar, radiometry, and LiDAR; interferometric infrared (IR) technology, which has potential for multiple hazards (including turbulence, wind gusts, and volcanic ash); and radar development to support the further advancement of radar capabilities to enable improved detection of traffic, runway incursions, and atmospheric hazards (MS 1.1.2, 1.3.3).

Sensor Technology Development expands and maintains a knowledge base in the area of sensors for external hazards; provides high-fidelity validated models for sensors; develops new technologies to cover hazardous vulnerabilities; and produces fundamental sensor predictive capability to enable technology breakthroughs (MS 1.1.4). Sensor technology research defines sensor needs and requirements; identifies technology gaps; quantifies performance of existing sensors, develops models of sensors; validates models through laboratory and flight tests; builds and tests proof-of-concept hardware; and establishes minimum operational performance standards for individual sensors and sensor suites.

The approach in the sensor technology investigation is formulated to build expertise and a predictive capability while attacking high-priority hazards and technologies. Research priorities are set by the evaluation of which hazards are important versus IIFDT goals and which technologies have promise or known capability for those hazards. Other important factors affecting the work include the interests and priorities of our collaborators, technology breakthroughs or challenges, and new priorities for NGATS or safety (MS 1.1.6). Some effort is always reserved to stay abreast of a variety of technologies in order to maintain an awareness of developments and a state of readiness for emerging opportunities and challenges. The limited budget and resources that are available preclude the development of expensive hardware and flight testing in most cases. Most sensor research is conducted by modeling; however, experiments for validation and other purposes may be conducted by enlisting partners through collaboration or by capitalizing on other opportunities. For example, a radar model can be used to simulate performance for a collaborator's radar system, and flight data (new or existing) can be used to validate the model.

Application of Detection Theory

Successful hazard detection relies on a combination of sensor technology, an understanding of the hazard, and the ability to relate observables to the important hazard characteristics. Detection theory provides rational techniques for linking sensor observables to hazard characteristics and determining which of several models of data generation and measurement is most consistent with a given set of data. The foundation of the science relies on statistical hypothesis testing. Given a set of statistical methods and the observed data, a systematic optimal method of determining which model corresponds to the data is developed. The result is the logic that converts sensor outputs to useful hazard information.

Detection theory is applied in all research focused on sensor solutions for specific hazards. Using detection theory, algorithms are developed for relating specific sensor models and associated physical parameters from characterization models to specific hazards (MS 1.3.4). Uncertainty for onboard sensor systems is characterized, calibration testing requirements are developed, and sufficiency of hypotheses and disparity metrics are assessed with respect to detection performance requirements. Error models and metrics are developed for each hazardous situation considered (MS 1.3.5). System performance predictions including probability of detection, missed detection, false alarm rates, and time-to-alarm are developed. Results of detection theory research are used in sensor technology development and in updating the PIRT charts (MS 1.3.6).

External Hazard Characterization
This activity identifies and prioritizes external hazards that can be detected by airborne sensors, identifies measurable information related to hazard level, investigates hazard effects on aircraft, and supports sensor development for hazard detection and measurement. Early activities take a broad approach to baselining the state-of-the-art of characterization of aviation hazards including weather, atmospheric phenomena, runway contamination, and hard targets such as terrain, airborne, and ground obstacles (MS 1.3.1). This research includes phenomenology, physics of existing or new airborne forward-looking sensors, and hazard detection theory (MS 1.3.3). The characterization activities are conducted in close concert with the Level 1 detection element. Results are coordinated with and reported to the Level 2 EHM research. Characterization has also been identified as an area of shared interest with ASP and must be coordinated across programs.

This research investigates approaches to model development and documents requirements for laboratory or experimental validation. This validation effort (MS 1.3.3) will result in phenomenological models that, in combination with sensor or sensor-suite simulations and detection algorithms, predict the performance of sensor systems for detecting and quantifying hazards (MS 1.3.4). Yearly updates provide hazard models and databases supporting sensor development (MS 1.3.5). This activity also provides inputs to update PIRT charts. The final hazard characterization products are physics-based hazard phenomena models, including parameters for use by sensor detection simulations; validation results; and comprehensive documentation of research results (MS 1.3.6). The activity builds on past successes including airborne wind shear detection, high-speed research external visibility systems, wake vortex detection and characterization, and enhanced turbulence detection radar. Some efforts in this area may require cooperative research with industry, universities, or other external partners.

Signal Processing
Sensor performance is based upon extracting and discriminating signatures, or features, that represent potential hazards from the raw measurements. This work provides the fundamental techniques used to enhance and extract salient hazard signatures and to delineate these signatures from nominal (non-hazard) signals and sources. The techniques and principles range from simple stochastic processes to complex principles far abstract from the actual measurements. Products feed Level 1 and 2 elements with pre-detection and post detection information of hazards and their severity (MS 1.6.4b).

Primary Work Package
The Level 1 work package in this area includes three primary investigations: remote sensing for icing conditions; interferometric infrared (IR) technology, which has potential for multiple hazards; and radar development. Priority hazards, at this time, are hard targets including traffic, runway obstacles (e.g. runway incursions), and terrain; icing; and clear air turbulence. All areas of research will contribute to the development of the EHM concept and requirements (MS 2.5.1 – 2.5.3), and all efforts will contribute to a final, comprehensive report for External Hazard Detection (MS 1.1.6, 1.3.6, and 1.6.5b).
Icing Research is an on-going activity with several years of history and is in a different development phase than the other investigations. The work consists of validating sensing methods/models and developing hazard (intensity) algorithms appropriate for a ‘soft’ hazard (one in which contact doesn’t always lead to bad consequences; as opposed to, for example, terrain or traffic). Icing research in IIFDT is decomposed into two areas:

- Icing remote sensing
  - Ground-based: development of vertical staring system to provide a low-cost algorithm testbed
  - Ground-based: initial development of scanning system (prototype terminal area system)
  - Airborne: initial assessment of multi-frequency radar system
  - Airborne: continue to assess radiometry and lidar for airborne application
  - Radiosonde: develop low-cost validation/verification techniques for sensing technologies
- Icing intensity assessment
  - Verification of existing and emerging icing weather products
  - Development of mapping techniques to derive icing intensity from remotely sensed parameters
  - Verification and validation of icing intensity data derived from remote sensors

Initially the investigation of interferometric IR is a feasibility study for a forward-looking interferometer (FLI) for clear air turbulence detection. The feasibility study ends at a decision point in FY08, and interferometer research can be continued as a broader investigation. Objectives of the study are to:

- Identify the means by which an FLI instrument can detect and quantify turbulence hazards to aircraft
- Develop basic instrument requirements for a turbulence sensor
- Conduct a detailed theoretical study to define the optimal spectral channels and the signal-to–noise ratio required for a turbulence detection interferometer

Objectives of the (optional) follow-on work include:

- Create a predictive capability for evaluation of passive IR sensors
- Develop and validate phenomenology characterization for target hazards and sensor models
- Partner with industry to conduct flight tests for validation

Airborne radar serves as the primary remote sensing system on aircraft today. The radar investigation pursues expansion and exploitation of the capabilities of current airborne weather radars as well as new applications of technology. The radar investigation approach is to develop modeling capabilities that facilitate the investigation of radar. Radar technology investigation tasks and objectives include:

- Evaluate available models and modeling environments/tools for efficacy and versatility, and determine the approach and methods to be applied
- Identify requirements imposed to support an interface to an External Hazard Monitor (EHM) model
- Develop an initial X-band pulsed Doppler radar model, leveraging from existing models, and including pulse compression and beam-sharpening
- Develop an initial millimeter wave radar model, based on the X-band model
- Test the initial models by modeling existing systems for which data can be obtained
- Expand radar model capabilities based on needs for high-priority hazards

OPERATOR CHARACTERIZATION, SENSING, INTERACTION MODELING, AND FORMAL ANALYSIS (LEVEL 1)

The technical approach to better characterizing human operators for improved system integration relies on both identifying measurable characteristics of operators that have implications for system design, and modeling the role that operators take in a system with their attendant failure propensities. Fundamental research will be conducted in these areas to improve a priori, and in situ characterization of operators, and to predict performance and human error associated with various human/system role assignments. Current certification practice precludes the dynamic integration of human/system automation planned for IIFDT. Novel formal analysis techniques are required where traditional verification techniques are insufficient for such intricate human/system integrations.

Operator Characterization and Sensing

To improve system performance and evaluation in which humans are a component, we must improve our characterization of human operators. Operator characteristics can be delineated as traits and states (*e.g.* Spielberger, 1966). Operator traits reflect more stable, fundamental characteristics of an individual. Operator traits may indicate categories of users who benefit from specific design characteristics, or characterize important distinctions across vehicle platforms and operational conditions to improve understanding of what innovations may generalize across these. Finally, previous work in this area has underscored the importance of understanding operator trait characteristics as predisposing conditions for susceptibility to the occurrence of hazardous states (Pope, 1992). Constructs related to degree and distribution of attention resources, mechanisms of human error and decision biases, as well as the contents of awareness and emotional affect, are also be considered relevant operator states.

Baseline conditions particular to an individual operator, another type of trait, must also be considered to interpret operator state responses. Operator states may be defined as relatively transitory and environmentally influenced operator “modes.” Operator states must be identified that support *in situ* communication regarding the status of the operator to other agents (human, automation, or information management) and those that reflect the validity of evaluative settings and the performance of operators in these settings.

The technical approaches for characterizing human operators for improved system integration relies on three lines of fundamental research that: 1) characterizes operators in terms of traits that differentiate information presentation or human/automation integration designs or provide a basis by which we can improve the sensitivity of experimental evaluations to assess innovative technologies and operational procedures (MS 1.5.9); 2) identifies operator states, the means for assessing these states, requirements for novel and improved sensors and methods that will reliably and unobtrusively acquiring state-related information (MS 1.1.11); and 3) identifies the state-of-the-art in bioelectric sensors, data fusion, and validation methodologies for operator state assessment (MS 1.1.13, 1.1.15).

Interaction Modeling

When automation, training, and procedures are not well tuned to task demands and human operating characteristics, systems failures occur, usually manifested as operator error. This requires analysis of the cognitive nature of human vulnerability to error as a function of task demands, operating procedures, training, and automation design (Dismukes, in press). Research in human error modeling uses ethnographic methods to characterize perturbations in airline flight operations and conducts cognitive task analysis to characterize the cognitive demands posed by perturbations (Loukopoulos, 2003). Airline accidents and incidents serve as the foundation for a model of crew error as a function of task demands, operating procedures and policies, and equipment design. In addition, this task assesses the common errors to which pilots of advanced technology aircraft are vulnerable and identifies the knowledge and skills necessary to operate advanced technology single-pilot aircraft (Casner, 2002). This research effort produces: validated models of pilot performance characterizing dynamic task demands of current and projected flight operations; operating procedures (MS 1.5.7, 1.5.11, 2.2.2) and automation/adaptive display design guidelines based on minimizing crew error vulnerability; models and tool for coordinating situation awareness among multiple agents in the NGATS (MS 2.2.2); tools to help accident investigators analyze human performance issues; and training curricula and materials to support mastery of knowledge and skill elements for general aviation (GA) pilots to safely operate advanced technology single-pilot aircraft now starting to come on the market (MS 1.5.4).

Formal Analysis for Flexible Operator-Automation Management

The objective is to develop formal mathematical models of mixed human/automation systems that provide strong inferences of safety properties in the presence of predicted combinations of human- and automation-induced hazards or failures. Realizing this vision is not without challenges. The distributed algorithms necessary to realize dynamic function allocation between human and automation are a potential single point of failure (MS 1.8.1, 1.8.2). The safety properties and policies required for the more aggressive concepts have not yet been defined, nor have they been validated (MS 1.8.1). Once defined and validated, there is still the issue of providing compelling evidence that they have been satisfied. Finally, the validity of these analyses depends on the integrity of the predictive models of human and automation failures developed elsewhere in the project (MS 1.8.3, 1.8.4, 1.8.5).

The initial approach for this research effort will be to adapt and generalize existing formal models that were developed for the analysis of fault-tolerant distributed systems (Miner, 2004) (http://shemesh.larc.nasa.gov/fm/spider/spider_pubs.html). These models have been developed using formal analysis tools developed at SRI International (http://fm.csl.sri.com/). The models currently consider only faults of physical origin. The faults are classified according to observable effects. These models will be extended to consider specific classes of human-made faults (Avizienis, 2004) and will be supported by the findings of the Operator Characterization and Sensing basic research.

TECHNICAL PLAN SUMMARY

In response to the implications of the JPDO vision and safety issues identified by industry/government agencies, NASA believes that future flight deck systems should systematically incorporate integrated displays, decision-aiding functions, information management, and dynamically-allocated human/automation task responsibilities. The future flight deck system is aware of the vehicle and operator state and responds appropriately. The system senses internal and external hazards, evaluates them, and provides key information to facilitate timely and appropriate responses. The system is robust and is adaptable to the addition of new functions and information sources as they become available.

To achieve this vision, IIFDT comprises a multi-disciplinary research effort to develop flight deck technologies that mitigate operator-, automation-, and environment-induced hazards for future operational concepts. IIFDT develops crew/vehicle interface technologies that reduce the risk of pilot error, develops monitoring technologies to enable detection of unsafe behaviors, develops fail-safe methods for changing the operator/automation roles in the presence of detected disability states; and develops a comprehensive surveillance system design that enables robust detection of external hazards with sufficient time-to-alarm for safe maneuvering to avoid the hazards.

IIFDT leads by sharing and applying these products to support industry and government in the progression towards more capable and safer flight deck systems. Products are documented and published for wide dissemination throughout the industry. Publication is via NASA-led authorship of conference papers, journal articles, and NASA technical papers; or via national and international regulatory or standards organizations wherein NASA results and expertise are used to develop large-sector consensus on new policies, standards, or recommended practices that should be applied in the industry.

APPENDIX A GLOSSARY OF TERMS

Application Domain

The region representing the design space for a system as constrained by a particular set of end-user requirements. For flight deck systems, this region can be bounded for example by design assumptions, input/output ranges, environmental conditions, vehicle class, envelope limits, crew configuration, and mission class.

Diagnostic

Serving to identify a particular disease or characteristic. (Webster's)

Error

(1) Deviation from correct system state that may lead to a failure (Avizienis, 2004); (2) An occurrence arising as a result of an incorrect action or decision by personnel operating or maintaining a system (JAA AMJ 25.1309); (3) A mistake in specification, design, or implementation. (SAE ARP 4761)

Failure

(1) Delivered service deviates from correct service (Avizienis, 2004); (2) A loss of function or a malfunction of a system or a part thereof. (SAE ARP 4761)

Field of Regard

The area covered via a sensor.

Flight Deck

A volume of space designed to accommodate at least one human operator and the interfaces between the operator and the remainder of the flight deck system.

Flight Deck System

A system that includes (1) the entity(s) who have the authority and responsibility for directing the flight of an aircraft, (2) all sub-systems that directly interface to these entity(s), and (3) the interfaces between them. (see Flight Deck).

Formal Methods

Mathematically based techniques for the specification, development and verification of software and hardware systems (http://en.wikipedia.org/wiki/Formal_methods)

Hazard

A potentially unsafe condition resulting from failures, malfunctions, external events, errors, or a combination thereof. (SAE ARP 4761)

Mitigation

A method, procedure, function, or technology that can reduce the risk of a hazard occurring.

Multi-modal Interface

An interface that employs more than one interface mode between crew and aircraft systems.

Operator

A person, organization, or enterprise engaged in or offering to engage in aircraft operation. (ICAO Annex 13)

Phenomena Identification Ranking Table (PIRT)

For complex systems, the PIRT helps to identify areas where technology development is needed, where major challenges are, and where uncertainties are large. For specified Application Domains, the PIRT considers physical phenomena importance, conceptual model adequacy, verification and validation adequacy, and experimental adequacy. PIRT was originally developed to assess the safety of nuclear reactors and is critical for planning validation experiments because it helps establish both sufficiency and efficiency of the validation activities (Oberkampf, 2002)

Quality

Totality of characteristics of an entity that bear on its ability to satisfy stated and implied needs. Note: entity is an element that can be individually described and considered. (ISO 8402) (ICAO Annex 15)

Remediation

The act or process of correcting a fault or deficiency. (Webster's)

Risk

The frequency (probability) of occurrence and the associated level of hazard. (SAE ARP 4761)

Situational Awareness

The perception of elements in the environment, the comprehension of their meaning, and the projection of their status into the near future. (Endsley, 1990) For example, for pilots, the elements of the environment include, but are not limited to, the crew, passengers, aircraft systems, time, position, weather, traffic, and ATC constraints.

Validation

Confirmation by examination and provision of objective evidence that the particular requirements for a specific intended use are fulfilled. (ISO 8402) (ICAO Annex 15)

"Solving the right equations." (Roache, 1998)

Verification

Confirmation by examination and provision of objective evidence that specified requirements have been fulfilled. Objective evidence is information that can be proved true, based on facts obtained through observation, measurement, test, or other means. (ISO8402) (ICAO Annex 15)

"Solving the equations right." (Roache, 1998)

APPENDIX B ABBREVIATIONS AND ACRONYMS

AD	Application Domain
ADI	Adaptive Displays & Interaction
AFDS	Adaptive Flight Deck Systems
AFRL	Air Force Research Laboratory
AIAA	American Institute of Aeronautics & Astronautics
AIIM	Adaptive Intelligent Information Management
AIS	Aeronautical Information Services
ANP	Actual Navigation Performance
AOPA	Aircraft Owners and Pilots Association
AOL	Airspace Operations Laboratory
ARC	Ames Research Center
ARIES	Airborne Research Integrated and Experiments System
ARINC	ARINC, Inc. (www.arinc.com)
ARMD	Aeronautics Research Mission Directorate
ASAFE	Aviation Safety Analysis and Functional Evaluation
ASMM	Aviation Safety Monitoring and Modeling
ASP	Airspace Systems Program
ATC	Air Traffic Control
ATM	Air Traffic Management
ATOL	Air Traffic Operations Laboratory
AvSP	Aviation Safety Program
CAASD	Center for Advanced Aviation System Development
CAMA	Crew Assistant Military Aircraft
CAST	Commercial Aviation Safety Team
CAVE	Cave Automated Virtual Environment
CDU	Control Display Unit
CMF	Cockpit Motion Facility
CNSL	Communication Navigation Surveillance Laboratory
CONOPS	Concept of Operations
CVI	Crew Vehicle Interface
CVSRF	Crew Vehicle Systems Research Facility
DARPA	Defense Advanced Research Projects Agency
DAT	Decision Associate Technology
DFRC	Dryden Flight Research Center
DFW	Dallas-Ft. Worth International Airport
DoD	Department of Defense
DPM	Deputy Project Manager
EFB	Electronic Flight Bag
EHM	External Hazard Monitor
EVO	Equivalent Visual Operations
EVS	Enhanced Vision System
FAA	Federal Aviation Administration

FAP	Fundamental Aeronautics Program
FDDRL	Flight Deck Display Research Laboratory
FFRDC	Federally Funded Research and Development Center
FLIR	Forward-Looking Infra Red
FMS	Flight Management System
fNIRS	functional Near Infra-Red Spectroscopy
FTE	Full-Time Equivalent
FY	Fiscal Year
GA	General Aviation
GFD	Generic Flight Deck
GN&C	Guidance, Navigation & Control
GRC	Glenn Research Center
HAVS	Highly Autonomous Vehicle Simulator
HCI	Human-Computer Interaction
HCSS	High Confidence Software and Systems
HFACS	Human Factors Classification System
HIDS	High Integrity Data Systems
HSI	Human System Integration
HSR	High Speed Research
ICAO	International Civil Aviation Organization
ICP	Internal Call for Proposals
IFD	Integrated Flight Deck simulator
IHDM	Internal Hazard Detection & Mitigation
IIFDT	Integrated Intelligent Flight Deck Technologies
IMC	Instrument Meteorological Conditions
IPT	Integrated Product Team
IR	Infrared
IRAC	Integrated Resilient Aircraft Control
ISO	International Organization for Standardization
IVHM	Integrated Vehicle Health Management
JPDO	Joint Project Development Office
JSRA	Joint-Sponsored Research Agreement
LaRC	Langley Research Center
LiDAR	Light Detection and Ranging
LVLASO	Low Visibility Landing and Surface Operations
MS	Milestone(s)
NAS	National Airspace System (current instantiation)
NASA	National Aeronautics & Space Administration
NATO	North Atlantic Treaty Organization
NCAT	Non-Cooperative Airborne Traffic
NGATS	Next Generation Air Transport System
NRA	NASA Research Announcement
NRC	National Research Council

NIA	National Institute of Aerospace
NTSB	National Transportation Safety Board
OCAPI	Operator Characteristics And Performance Investigations (Laboratory)
OGA	Other Government Agencies
PI	Principal Investigator
PIRT	Phenomena Identification Ranking Table
PM	Project Manager
POC	Point(s) of Contact
RCI	Rockwell/Collins Incorporated
RF	Radio Frequency
RFD	Research Flight Deck (Simulator)
RFI	Request For Information
RIPS	Runway Incursion Prevention Systems
RTCA	RTCA, Incorporated (aka Requirements and Technical Concepts for Aviation)
SA	Situational Awareness
SAE	Society of Automotive Engineers
SARP	Standards and Recommended Practices
SBIR	Small Business Innovation Research
SDA	System Design & Analysis
SVS	Synthetic Vision Systems
TAWS	Terrain Avoidance Warning System
TBD	To Be Determined
TCAS	Traffic Collision Avoidance System
TFOAM	Tailored Flexible Operator-Automatic Management
TGIR	Turning Goals Into Reality
TIM	Technical Interchange Meeting
URET	User Request Evaluation Tool
VASIP	Voluntary Aviation Safety Information-Sharing Program
VAST-RT	Virtual Airspace Simulation Technologies - Real Time
VISTAS-3	Virtual Imaging Simulator for Transport Aircraft Systems, 3rd Generation
VMC	Visual Meteorological Conditions
VR	Virtual Reality
WBS	Work Breakdown Structure
WXR	Weather Radar
WYE	Work Year Equivalent
XVS	eXternal Vision System

APPENDIX C REFERENCES

(Abbott, 1996) Abbott, K., et. al.: *The Interfaces Between Flightcrews and Modern Flight Deck Systems,* Federal Aviation Administration, 1996.

(AOPA, 2004) *The 2004 Nall Report, General Aviation Accident Trends and Factors for 2003,* Aircraft Owners and Pilots Association (AOPA), 2004.

(Avizienis, 2004) Avizienis, A., J., et. al., Basic Concepts and Taxonomy of Dependable and Secure Computing, *IEEE Trans. Dependable and Secure Computing*, vol. 1, no. 1, pp. 11—33, 2004.

(Bailey, 2002) Bailey, R.E., et. al.: *Flight Test Evaluation of Tactical Synthetic Vision Display Concepts in a Terrain-Challenged Operating Environment*, Proceedings of SPIE, Enhanced and Synthetic Vision 2002*,* Editor: Jacques G. Verly, vol. 4713, pp. 178-189, Apr. 2002.

(Balaban, 2004) Balaban, C.D., et. al.: Postural Control as a Probe for Cognitive State: Exploiting Human Information Processing to Enhance Performance. *International Journal of Human-Computer Interaction, 17*(2), 275-287, 2004.

(Berrios, 2003) Berrios, D. C., and Keller, R. M., Developing a Web-Based User Interface for Semantic Information Retrieval. In Proceedings of the Workshop on Semantic Web Technologies for Searching and Retrieving Scientific Data, International Semantic Web Conference, Sanibel Island, FL, USA, ISWC 2003.

(Billings, 1991) Billings, C.: Human-centered aircraft automation: A concept and guidelines NASA TM 103885, NASA, Washington DC, 1991.

(Billings, 1996) Billings C.: Human-Centered Aviation Automation: Principles and Guidelines. NASA TM 110381, NASA Washington DC, 1996.

(Billings, 1997) Billings, C.: Aviation Automation: The Search for a Human-Centered Approach, Mahwah, NJ: Lawrence Erlbaum Associates, 1997.

(Boeing, 2005) "Statistical Summary of Commercial Jet Airplane Accidents. Worldwide Operations, 1959-2004." Aviation Safety, Boeing Commercial Airplanes. Seattle WA, May 2005.

(Burian, 2005) Burian, B. K. & Boorman, D. J., Boeing non-normal checklists: The Boeing 777 electronic checklist and quick reference handbook (2nd edition). Technical Document. Boeing Commercial Airplane Group, 2005.

(Caldwell, 2005) Caldwell, J., Fatigue in aviation. *Travel Medicine and Infectious Disease*, 3, 85–96, 2005.

(Cardosi, 1996) Cardosi, K.M., An analysis of TRACON (Terminal Radar Approach Control) controller-pilot voice communications. US Department of Transportation, Office of Research and Development report DOT/FAA/AR-96/66). Washington, D.C., 1996.

(Carvalho, 2005) Carvalho, R. E., et. al., *Investigation Organizer: The Development and Testing of a Web-Based Tool to Support Mishap Investigations*. In Proceedings of the IEEE Aerospace Conference 2005, Big Sky, MT, USA, 2005.

(Casner, 2002) Casner, S.M.: Cockpit automation for general aviators and future airline pilots. Iowa State Press: Ames, 2002.

(CAST, 2004) Commercial Aviation Safety Team (CAST) Report, Rev. 10, Oct. 2004.

(Degani, 2002) Degani, A. & Heymann, M., Formal Verification of Human-Automation Interaction. Human Factors, 44(2), 28-43, 2002.

(Dismukes) Dismukes, R. K. & Nowinski, J. L. (in press). Prospective Memory, concurrent task management, and pilot error. To appear in A. Kramer, D. Wiegmann, & A. Kirlik (Eds.) *Attention: From Theory to Practice.* New York: Oxford.

(Erickson, 1999) Erickson, C.W. and Wissel, V.L.H.; *HSR-XVS Surveillance System: Issues Resolution Report*; RTI/7473/009-01F, 1999.

(FAA, 2006) Accident/Incident Data System, Federal Aviation Administration, 2006.

(Feary, 2004) Feary, M. and Sherry, L., *Dynamic Storyboards: Faster, Cheaper Software Prototypes for Usability Evaluation*. In Proceedings of Human Computer Interaction in Aviation, Toulouse, FR., 2004.

(Fiehler, 2004) Fiehler, K., et. al., Neural correlates of error detection and error correction: Is there a common neuroanatomical substrate? *European Journal of Neuroscience 19*(11), 3081-3087, 2004.

(Flemisch, 2003) Flemisch, F. O., et. al., The H-Metaphor as a Guideline for Vehicle Automation and Interaction, (NASA TM-2003-212672), Hampton, VA, 2003.

(Foyle, 2003) Foyle, D. C., & Hooey, B. L., Improving evaluation and system design through the use of off-nominal testing: A methodology for scenario development. Proceedings of the Twelfth International Symposium on Aviation Psychology. 397-402. Dayton, Ohio: Wright State University, 2003.

(Glaab, 2003) Glaab, Louis J, et. al.: *Flight Test Comparison of Synthetic Vision Display Concepts at Dallas/Fort Worth International Airport*, NASA TP-2003-212177, Hampton, VA, 2003.

(Hancock, 1998) Hancock, P. A., & Scallen, S. F., Allocating functions in human-machine systems, *Viewing Psychology as a Whole.* (pp.509-540), American Psychological Association, Washington, DC, 1998.

(Hannon, 1999) Hannon, S.M., et. al.; *Airborne Doppler LiDAR Turbulence Detection: ACLAIM Flight Test Results*; Proc. SPIE, Vol 3707, 1999.

(Harrah, 1993) Harrah, S.D., et. al., NASA's Airborne Doppler Radar for Detection of Hazardous Wind Shear: Development and Flight Testing; AIAA 93-3946, 1993.

(Harrah, 2002a) Harrah, Steven D., et. al.: "The NASA Approach to Realize a Sensor Enhanced-Synthetic Vision System (SE-SVS)," Proceedings of IEEE/AIAA Digital Avionics Conference, Oct. 2002.

(Harrah, 2002b) Steve Harrah, et. al., "Flight Test Results From an Enhanced Turbulence Detection Radar for Commercial Transports," 21st Digital Avionics System Conference, Irvine, California, October 27-31, 2002.

(Harrison, 2003) Harrison, M., et. al., Relating the automation of functions in multi-agent control systems to a system engineering representation. In E. Hollnagel (Ed.), *Handbook of cognitive task design* (pp. 503-524). Mahwah, NJ: Lawrence Erlbaum Associates, 2003.

(Izzetoglu, 2003) Izzetoglu, K., et. al., fNIR Spectroscopy as a Measure of Task Load. *Proceedings of the Engineering in Medicine and Biology Society,* 2003.

(Jones, 2005) Jones, Denise R.: *Runway Incursion Prevention System Testing at the Wallops Flight Facility,* Proceedings of the SPIE Defense & Security Symposium, Enhanced and Synthetic Vision 2005, Vol. 5802-5, March 2005.

(Jordan, 1963) Jordan, N., Allocation of functions between man and machines in automated systems. *Journal of Applied Psychology*, 47(3), 161-165, 1963.

(Jorgensen, 2003) Jorgensen, C. "Oscillating Field Computation," NASA Ames Research Center, Neuro Engineering Laboratory white paper, Dec. 2003.

(JPDO, 2004) *Next Generation Air Transportation System (NGATS) Integrated Plan,* Joint Planning and Development Office (JPDO), Dec. 2004. www.jpdo.aero/site_content/

(Keller, 2004) Keller, R. M., et. al., Semantic Organizer: A Customizable Semantic Repository for Distributed NASA Project Teams. In Proceedings of the International Semantic Web Conference (ISWC), Hiroshima, Japan, 2004.

(Keller, 2003) Keller, R. M., and Hall, D. R. Developing Visualization Techniques for Semantics-Based Information Networks. In Proceedings of the Workshop on Visualization in Knowledge Engineering, 2nd International Conference on Knowledge Capture, Sanibel Island, FL, 2003.

(Loukopoulos, 2003) Loukopoulos, L.D., et. al., Concurrent task demands in the cockpit: Challenges and vulnerabilities in routine flight operations. In *Proceedings of the 12th International Symposium on Aviation Psychology,* 737-742, 2003.

(McNeese, 2002) McNeese, M. Vidulich M., Editors, Cognitive Systems Engineering in Military Aviation Environments: Avoiding Cogminutia Fragmentosa! Human Systems Information Analysis Center, Wright-Patterson Air Force Base, Ohio, 2002.

(Meehan, 2005) Meehan, M., et. al., Review of four studies on the use of physiological reaction as a measure of presence in stressful virtual environments. *Applied Psychophysiology and Biofeedback, 30*(3), 239-258, 2005.

(Mellor, 1994) Mellor, P., CAD: Computer-Aided Disaster, High Integrity Systems, 1(2), p.101-156, 1994.

(Miner, 2004) Miner, P., et. al., A unified fault-tolerance protocol, *Formal Techniques, Modeling and Analysis of Timed and Fault-Tolerant Systems (FORMATS-FTRTFT)*, volume 3253 of Lecture Notes in Computer Science, pages 167--182. Springer, 2004

(Morrison, 1989) Morrison, R., & Wright, R.H., ATC controls and communication problems: An overview of recent ASRS data (pp. 902-07). In R.S. Jensen (Ed.), Proceedings of the Fifth International Symposium of Aviation Psychology. Columbus, OH: Ohio State University, 1989.

(NATO, 2002) Research and Technology Organization (RTO) of NATO, Tactical Decision Aids and Situational Awareness. RTO/NATO BP 25, 7 rue Ancelle, F-92201 Neuilly-sur-Seine Cedex, France, 2002.

(Neece, 2005) Neece, R.T., Britt, et. al., Wake Vortex Tracking Using a 35 GHz Pulsed Doppler Radar. Integrated CNS Conference and Workshop, Fairfax, VA, 2005.

(NIA, 2005) *Aviation Plan for American Leadership*, National Institute of Aerospace (NIA), Apr. 2005.

(NRC, 2004) *Review of NASA's Aerospace Technology Enterprise*, National Research Council, 2004.

(NTSB, 2005) Transportation Safety Board's (NTSB) "Ten Most Wanted Transportation Safety Improvements," 2005. www.ntsb.gov/Recs/mostwanted/aviation_issues.htm

(NTSB, 2006) Aviation Accident/Incident Database, National Transportation Safety Board, 2006.

(Oberkampf, 2002) Oberkampf, W., et. al., "Verification, Validation, and Predictive Capability in Computational Engineering and Physics," Foundations for V&V in the 21st Century Workshop, Johns Hopkins University Applied Physics Laboratory, October, 2002.

(Parrish, 1994) Parrish, R.V., et. al., Spatial awareness comparisons between large-screen, integrated pictorial displays and conventional EFIS displays during simulated landing approaches. NASA Technical Paper TP-1994-3467. Hampton, VA: NASA Langley Research Center, 1994.

(Parrish, 2003) Parrish. R.P., et. al.: "Evaluation of Alternative Concepts for Synthetic Vision Flight Displays with Weather Penetrating Sensor Images Inserts During Simulated Landing Approaches," NASA TP-2003-212643, Oct. 2003.

(Pope, 1992) Pope, A.T., & Bogart, E.H., Identification of hazardous awareness states in monitoring environments. *SAE Transactions: Journal of Aerospace,* 101, 449-457, 1992.

(Pope, 1995) Pope, A.T., Bogart, E.H., & Bartolome, D.S, Biocybernetic system validates index of operator engagement in automated task. *Biological Psychology*, 40, 187-195, 1995.

(Pope, 2001) Pope A.T., *Method And System For Detecting Dangerous Or Ineffective Operator States Through Unobtrusive Sensing And Interpretation Of Activity, LAR-16227,* 2001.

(Prinzel, 2000a) Prinzel, L., et. al., A closed-loop system for examining psychophysiological measures for adaptive task allocation. *International Journal of Aviation Psychology,* 10(4), 393-410, 2000.

(Prinzel, 2000b) Prinzel, Lawrence J; et. al.: *NASA Synthetic Vision EGE Flight Test*, Human Factors and Ergonomics Society Meeting, 2002.

(Prinzel, 2001) Prinzel, L., et. al., Application of physiological self-regulation and adaptive task allocation techniques for controlling operator hazardous states of awareness (No. NASA/TM-2001-211015). Hampton, VA: National Aeronautics and Space Administration, 2001.

(Prinzel, 2004) Prinzel, L.J., et. al., The efficacy of head-down and head-up synthetic vision system displays for retro- and forward-fit of commercial aircraft. International Journal of Aviation Psychology, 14, 53-77, 2004.

(Roache, 1998) Roache, P.J., Verification and Validation in Computational Science and Engineering, Hermosa Publishers, Albuquerque, NM, 1998.

(Rothkranz, 2004) Rothkranz, L.J.M, et. al., In Petr Sojka, Ivan Kopecek, Karel Pala (Eds.): *Proceedings of the 7th International Text, Speech and Dialogue Conference. Lecture Notes in Computer Science 3206 Springer,* pp. 449-456, 2004.

(RTCA/DO-220) Minimum Operational Performance Standards for Airborne Weather Radar with Forward-Looking Windshear Capability; RTCA/DO-220, Appendices A-G.

(Ryerson, 2000) Chuck Ryerson, et. al., Ground-based and airborne remote sensing of inflight aircraft icing conditions, in Proceedings of the 2000 Advances in Aviation Safety Conference, P-355, Daytona Beach, Florida, Society of Automotive Engineers, pp. 165-172, 2000.

(Sarsfield, 2000) Sarsfield, L. P., et. al., Safety in the Skies: Personnel and Parties in NTSB Accident Investigations: Master Volume. Rand Publications, Santa Monica, CA, 2000.

(Sarter, 1992) Sarter, N., & Woods, D.D., "Pilot Interaction with Cockpit Automation: Operational Experiences with the Flight Management System," International Journal of Aviation Psychology, vol. 2, pp. 303-321, 1992.

(Sarter, 1996) Sarter, N. B., Cockpit automation: From quantity to quality, from individual pilot to multiple agents. In R. Parasuraman & M. Mouloua (Eds.), *Automation and human performance: Theory and applications* (pp. 267-280). Mahwah, NJ: Lawrence Erlbaum Associates, 1996.

(Schutte, 1997) Schutte, P. C., *Wings: A new paradigm in human-centered design.* Paper presented at the 9th International Symposium on Aviation Psychology, Columbus, Ohio, 1997.

(Schutte, 1999) Schutte, P. C., Complemation: An alternative to automation. *Journal of Information Technology Impact*, 1(3), 113-118, 1999.

(Schutte, 2000) Schutte, P. C., *Distance: A metric for flight deck design and function allocation.* Paper presented at the 44th Annual Meeting of the Human Factors and Ergonomics Society, San Diego, California, 2000.

(Schutte, 2006) Schutte, P. and Goodrich, K, et al., The Naturalistic Flight Deck System: An Integrated System Concept for Improved Single-Pilot Operations, NASA TM (in review), NASA, Washington DC, 2006.

(Sheridan, 2002) Sheridan, T., Humans and Automation: System Design and Research Issues, John Wiley & Sons, Inc., Santa Monica, CA, 2002.

(Sherry, 2004) Sherry, L. & M. Feary. Task design and verification testing for certification of avionics equipment. In Proceedings of AIAA/Digital Avionics Systems Conference, Salt Lake City, Utah, October, 2004.

(Spielberger, 1966) Spielberger, C.D. Theory and research on anxiety. In C.D. Spielberger ,(Ed.), *Anxiety and Behavior*. New York: Academic Press, 1966.

(Spirkovska, 2006) Spirkovska, L., Integrated System Health Monitoring Decision Analysis Tool: Operations Concept. NASA/TM-2006-213481, 2006.

(St. John, 2005) St. John, M., et. al., Overview of the DARPA Augmented Cognition Technical Integration Experiment. *Proceedings of the First International Conference on Augmented Cognition,* 2005.

(Theunissen, 1997) Theunissen, Eric: Integrated Design of a Man-Machine Interface for 4-D Navigation. Delft University Press, 1997.

(Wickens, 2000) Wickens, C.D., The when and how of using 2-D and 3-D displays for operational tasks. Proceedings of the Human Factors and Ergonomics Society (Volume 3), 44, 403-407, 2000.

(Wiener, 1988) Wiener, Earl, L., Nagel, David C.: Human Factors in Aviation, Academic Press, 1988.

(Wolfe, 2004) Wolfe, S. R., and Keller, R. M. *Exploiting Recurring Structure in a Semantic Network.* In Proceedings of the Workshop on Mining for and from the Semantic Web, KDD, Seattle, WA, USA, 2004.

(Young, 2001) Young, Steven D., and Jones, Denise R.: "Runway Incursion Prevention: A Technology Solution," *Proceedings of the Flight Safety Foundation 54th Annual International Air Safety Seminar,* Athens, Greece, Nov. 2001.