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Sensory Prognostics and Management System II

January 2016

Final Report

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16. Abstract

This document is the final report of the Sensory Prognostics and Management Systems (SPMS) II program. SPMS II set out to assess how existing and future data sources from multiple areas could be used for the benefit of the airlines, Boeing, and the FAA. The program reviewed the applications presented in the SPMS I final report (DOT/FAA/TC-13/1) and a new set of applications presented in the SPMS II Statement of Work, selecting those that could be implemented and transitioned using available data. A set of metrics related to maintenance benefits, cost effectiveness of implementation, and certification was developed and used to survey Boeing subject matter experts and authorized representatives. This evaluation of candidate areas generated a portfolio of potential applications, which were further ranked in three priority levels. Application areas related to structural inspection, such as heavy/hard landing (HHL) assessment, operating with degraded structure, corrosion condition-based maintenance, and remote inspection, were assigned highest priority. The program then studied and documented data sources, the technologies needed to use the data, implementation, and acceptance methods for each of these areas. Case studies for HHL, remote non-destructive testing, and remote tire inspection were developed to provide an evaluation of implementation, concept of operation, and acceptance methods. Finally, the program's conclusions and recommendation were included in this final report.

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LIST OF ACRONYMS

A&P	Airframe and/or Powerplant maintenance technician
A4A	Airlines for America
AC	Advisory Circular
ACI	Analytical conditional inspection
ACMF	Airplane Condition Monitoring Function
ACMS	Airplane Condition Monitoring System
AHM	Airplane Health Monitoring
AIMS	Airplane Information Management System
AMI	Airline modifiable information
AMM	Aircraft maintenance manual
AR	Authorized representative
BPI	Bonded Process Instruction
BR&T	Boeing Research and Technology
BRSL	Bonded repair size limits
CAD	Computer-aided design
CBM	Condition-based maintenance
CBM+SI	Condition-based maintenance plus structural integrity
CFR	Code of Federal Regulations
CG	Center of gravity
DAL	Design Assurance Level
DFDR	Digital flight data recorder
ETOPS	Extended Operations
FAA	Federal Aviation Administration
GUI	Graphical user interface
HHL	Heavy/hard landing
IPT	Integrated product team
IT	Information technology
IFSD	In-flight shutdown
LO	Local operator
LOV	Limit of Validity
MAC	Mean aerodynamic cord
MAUS	Mobile Automated Scanner
MEL	Minimum Equipment List
MLW	Maximum landing weight
MPE	Maintenance Programs Engineering
MRO	Maintenance repair and overhaul
MSD	Multiple site damage
MTOW	Maximum takeoff weight
NDE	Non-destructive evaluation
NDI	Non-destructive investigation
NDT	Non-destructive testing
OA	On-site assistant
OEM	Original equipment manufacturer
ONS	Onboard network server
PDM	Programmed depot maintenance

PoD	Probability of detection
QAR	Quick Access Recorders
RI	Remote inspector
RID	Remote inspection device
SCC	Stress corrosion cracking
SFPOF	Single flight probability of failure
SIP	Session Initiation Protocol
SME	Subject matter expert
SNR	Signal-to-noise ratio
SOW	Statement of Work
SPMS	Sensory Prognostics and Management Systems
VCS	Video Communications Server
WFD	Widespread fatigue damage

EXECUTIVE SUMMARY

Commercial airlines and the Federal Aviation Administration continue to develop strategies for decreasing aviation operational and support costs while maintaining flight safety. The availability of data collected from aircraft, support equipment, and maintenance information systems has created opportunities to reduce operation, maintenance, and certification costs. Using this data to monitor the health state of aircraft systems and subsystems for more efficient maintenance and certification will provide the lowest-cost solutions compared to solutions that require additional sensors, hardware, and wiring on the aircraft. In addition, shipside inspection support equipment produces material state data that, if collected, managed, and processed efficiently, can be used to assess the current and future state of the structure.

The Sensory Prognostics and Management System (SPMS) program identified and studied application areas that could use these data sources to reduce operation and support costs and potentially improve certification efficiency.

Major accomplishments of this program include:

- Metrics were identified for assessing the maturity of applications and the degree by which each application impacts: 1) operation and support cost savings, 2) operational reliability and maintainability, 3) certification cost reduction, 4) innovative use of data for certification, 5) improvements in existing certification methods, and 6) innovation in certification methods.

- A portfolio of high-priority SPMS applications with potential for near-term transition was identified. This portfolio includes heavy/hard landing (HHL) detection, remote non-destructive testing (NDT), remote tire inspection, corrosion condition-based maintenance (CBM), and operation with degraded structure.

- Case studies were identified and discussed in detail for three application areas: HHL detection, remote NDT, and remote tire inspection. Corrosion CBM and operation with degraded structure were also discussed.

When advanced HHL loads algorithms were applied to the same 500 historic landings, only 19 were incorrectly predicted, which resulted in a false call rate of less than 5%. This performance rate can be achieved with existing onboard data only. Additional information measured by structural sensors can be used if the cost-benefit analysis shows positive return on investment. The key to successful implementation of these algorithms is the accuracy of the models' ability to correlate flight parameters with response load information, which is influenced by the fidelity of the analytical landing model data used to develop the reduced-order loads algorithms and the accuracy and richness of this analytical training data. The SPMS HHL case study showed validation of these models by using hardware data collected from a landing gear drop test. In addition, these models were validated against measured flight-test data and proved to be universally conservative across main landing gear response loads.

The remote NDT case study involved a The Boeing Company 787 at a remote site experiencing a physical impact event in the fuselage that was self-reported, witnessed, or discovered. Three

specific remote NDT scenarios were defined that allowed the accept/reject decision to be made by a remote expert:

- Scenario #1—Remotely Assisted NDT: A remote expert guides an on-site operator of a remotely enabled NDT through an inspection in real time.
- Scenario #2—Simplified NDT: An on-site operator (unsupported), using an easy-to-operate tool, completes an inspection, and the data and test report are sent to the remote expert inspector for assessment and buy off.
- Scenario #3—Advanced Remote NDT: Positional information relative to aircraft structure is collected and used to integrate structural and NDT data for a more in-depth assessment by an expert in real time or post-inspection.

For all scenarios, Boeing Business Process Instruction (BPI)-2040 (see appendix A) is recommended to incorporate remote NDT into the NDT manual. The alternative approach is to incorporate remote NDT into the structural repair manual, because these manuals are accessible by non-NDT operators in remote locations.

Though the remote tire inspection case study showed significant technical barriers, the technologies, implementation requirements, and issues and certification were extensively discussed with subject matter experts and documented. Updates were made to a 737 maintenance manual tire inspection task to reflect the impact of remote tire inspection in maintenance manuals (appendix B).

Corrosion CBM technologies and implementation requirements were studied extensively. A case study was not selected to be further pursued because of the lack of infrastructure to collect and manage corrosion inspection data and the lack of validated analytical models to predict the growth of corrosion and impact on material strength.

Operating aircraft with degraded structure was considered a high-priority application for SPMS, because it allows for the ability to determine inspection intervals and predict the repair event, reducing maintenance costs. The SPMS program intended to examine Boeing-developed algorithms for military application and then restructure them for commercial use. Because of the lack of a parallel Boeing program, degraded structure was not pursued under SPMS II.

To move the SPMS technologies to the field, a close collaboration between original equipment manufacturers, operators, and regulatory agencies is required to address the technical and certification aspects of these technologies. The certification of SPMS for maintenance credit needs to address the adequacy and integrity of collected data and the validity of the algorithms and models. The SPMS algorithms can reside on the airplane if the data are collected from onboard systems; if the data are collected from a ground system, such as an aircraft health monitoring system, the SPMS algorithms can reside off the airplane. For onboard systems, software changes follow the guidance related to updates to modifiable aircraft software. For ground systems, assurance needs to be in place in terms of data integrity and quality of the transferred data to the ground. The second aspect of SPMS validation is in regard to the accuracy of algorithms for prediction of failure and enabling changes in maintenance practices. This will

require validation of algorithms through modeling, simulation, use of the hardware lab, and flight-test data.

Advances in capabilities and capacities of newer aircraft's onboard data collection and communication systems; ubiquitous availability of Web-enabled inspection devices; communication and storage infrastructure for storage; and analysis of NDT data present a future opportunity for taking advantage of the data for SPMS applications.

1. INTRODUCTION

Commercial airlines and the Federal Aviation Administration (FAA) continue to develop strategies for decreasing aviation operational and support costs while maintaining flight safety. Data acquired by airlines from Airplane Condition Monitoring Systems (ACMS), Quick Access Recorders (QAR), subsystem built-in-test reports, Central Maintenance Computers, and other onboard data collection systems could be used to help develop those strategies. Extensive information is also generated from flight tests, non-destructive testing (NDT), maintenance repair, overhaul, and maintenance records from suppliers. Though these data are plentiful, diverse, and readily available to airlines, they are not currently being used to their fullest potential.

Sensory Prognostic and Management System (SPMS) solutions could potentially facilitate the availability of more health management data in the future. However, there have been barriers to effective field use of these data due to operational and technical readiness issues. The operational issues stem from the fact that changing maintenance practices per assessment of SPMS-type systems requires extensive qualification and validation; situations of low technology readiness require additional maturation before SPMS capabilities can demonstrate effective results.

The SPMS II program investigated areas in which these data can be used and, in doing so, provided insights into technologies and the implementation and certification of selected applications. The program leveraged the results of the SPMS I contract. TÜÉ= SPMS I program focused on evaluating and defining various SPMS implementations and provided examples of how to integrate advanced diagnostic and prognostic capabilities into commercial aircraft. This initiative included gathering and communicating data from the continuous monitoring of aircraft systems, the observation of current system states, and the processing of these data to support proper maintenance and repair actions.

As a result of performing cost-benefit analysis, SPMS I recommended the following application areas:

- Engine lifing.
- Engine condition-based maintenance (CBM).
- Health monitoring of thrust reverser.
- Engine start.
- Tires and brakes.
- Environmental control system (pneumatics and air conditioning).
- Electrical power generator.
- Assessment of hard landing/structural loading.

These application areas, along with other areas included in the program's Statement of Work (SOW), were studied under SPMS II, as described in section 1.1.

1.1 SPMS II TECHNICAL APPROACH

The SPMS II program identified a set of high-priority SPMS applications and studied their benefits, technical specifications, and salient aspects of their qualifications and certification. Figure 1 shows the initial process for selecting application areas. The goal of the program was to review the health management applications presented in the SPMS I final report and investigate additional areas that could provide airlines with operational and safety benefits. Those applications that could be implemented using available data could then be identified and further refined with an emphasis on acceptance and certification methods. These additional areas, as listed in the program SOW, include:

- Relaxation of Extended Operations (ETOPS) and Minimum Equipment List (MEL) dispatch criteria.
- Realizing more life from systems with life-limited components.
- Exploitation of flexible maintenance intervals.
- Automating data acquisition and communications to reduce manual data inspections.
- Ensuring data integrity and security.
- Ramifications of the use of support-critical information for safety-critical systems.
- Maintenance quality assurance.
- Improving maintenance and reducing airline costs associated with non-value-added recordkeeping.

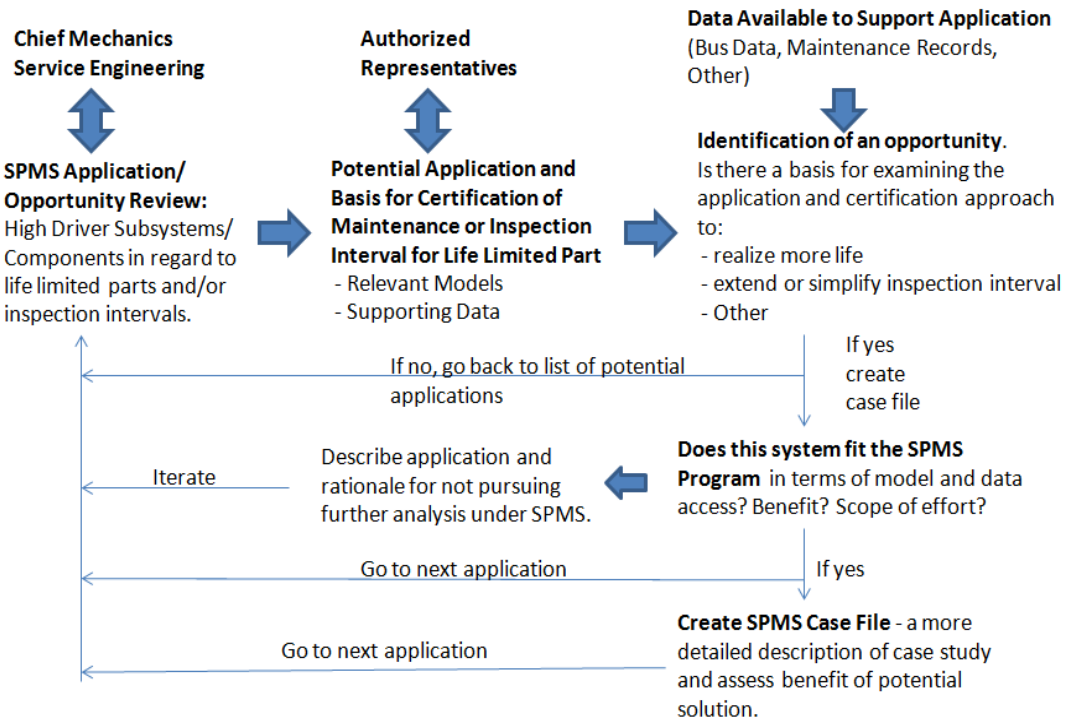


Figure 1. SPMS II application selection process

The first step in this process was to screen each SPMS I application to find if it could be implemented with existing data. A review/survey of the applications conducted with Boeing chief mechanics and service engineering was used to identify higher payoff opportunities to pursue. It was determined that most of these high-payoff opportunities were in the application areas of extending component life on wing, extending inspection intervals, and partially or fully automating inspections. Among the applications for which supporting data were available were the engine lifing, hard landing/structural loading, tires, and the thrust reverser. During this exercise, additional applications were recommended by chief mechanics and service engineering that were believed to offer benefits in terms of operation, maintenance, and certification. The description and process for review and down selection are described in section 1.2.

1.2 SPMS II APPLICATIONS EVALUATION

The overall objective of the SPMS II program was to identify SPMS applications and certification methods that would financially benefit airline operators using the data currently collected from aircraft. This involved evaluating applications beyond those assessed in SPMS I, including those that resulted in efficiency in certification and maintenance processes. Therefore, for SMPS II evaluations, additional metrics were used.

The following parameters were used to measure each application in terms of innovation and effectiveness in regard to the methods and technologies to implement and certify a health management application:

- Integrate with or leverage existing processes to support certification (e.g., using the maturation of a support-critical capability to collect data to establish the reliability of, and certify, this same capability at a higher level).
- Exploit the value or role of existing data in supporting certification.
- Identify technologies or modify certification methods to reduce cost.
- Incrementally enhance certification efficiency by leveraging ongoing or planned data collection.

The benefits of the SPMS II areas were assessed using the following metrics:

- Operational availability and reliability improvements—Contribution of SPMS application in reducing down time, thereby increasing the availability of aircraft. Examples include more efficient inspection, reduced troubleshooting, and reduced unscheduled maintenance.

- Maintenance and logistics cost reductions—Contribution of SPMS in reducing the cost of maintenance and logistics. Examples include life extension and prognostics for reduced logistics footprint.

- Certification cost reduction—Level or extent that the SPMS data can be used for supporting certification.

- Improvement in existing certification method—Quantitative and qualitative improvement compared to existing certification practices. This could be a higher level of confidence or qualitative endorsement by authorized representatives (ARs)/subject matter experts (SMEs).

- Certification method innovation—Degree of innovation pertaining to certification methods based on ARs'/SMEs' opinion.

- Innovative use of data for certification—Degree of innovation regarding the use of data for certification based on ARs'/SMEs' opinion.

1.3 IDENTIFICATION AND RANKING OF AREAS OF INVESTIGATION

Early in the program, it became clear that the use of a survey with defined questions would circumscribe opportunities for SMEs to add their input beyond the responses to the questions. In contrast, interviews provided opportunities for the SMEs to add any additional criteria or considerations. As such, the survey was replaced by semi-structured, in-person interviews.

Interviews started with the following topics:

- Given a baseline understanding of SPMS and health management in general, what areas do you see where this technology might be leveraged given current data access?
- Specifically, think in terms of reduced inspections, realizing more life from life-limited components or, in general, reducing maintenance, development/certification, and operational costs while maintaining or improving safety.
- Provide examples: ETOPS, structural inspections based on monitoring structural load.
- Do you think there are other applications of SPMS using available data that would improve maintenance processes and safety?

A number of personnel (chief mechanics, service engineering, ARs, and SMEs) were interviewed to generate ideas on SPMS applications. Table 1 summarizes the interview topics and position and background of the SMEs.

Table 1. Personnel interviews

Position/Background	Subjects
737 Chief Mechanic	Structural inspections, corrosion inspections, The Ugly List, inspection interval calculation
AR Tires and Landing Gear	Inspection of hail damage, remote tire inspection
Airplane Health Management SME	Integration of health management and fault isolation manuals, closed-loop maintenance practices
787 Landing Gear/Structures	Hard-landing inspections
Commercial Airplane Support Operations Center	Digitizing maintenance processes, E-log book improvements, transition from paper
Structural Health Management BR&T	Structural life and monitoring, hard-landing inspections
Structural Health Management BR&T	Structural life and monitoring, inspection interval calculation
Non-Destructive Testing BR&T	Measuring corrosion, corrosion CBM
Reliability and Maintainability Engineering	Airplane/airline data collection and databases

In addition, a number of other BR&T and Boeing Commercial Airplanes technologists were contacted to explore possible ideas such as engine health management, ETOPS, and remote inspection of aircraft fuselage and wing structure. The interviews resulted in the development of a portfolio of application areas that could be investigated and included their description, existing data, benefit, certification, and applicability to the SPMS program.

1.4 AREAS OF INVESTIGATION

The interviews with ARs/SMEs and analysis of the original SPMS I work resulted in selecting areas of investigation described in sections 1.4.1–1.4.12.

1.4.1 ETOPS and MEL Dispatch Criteria

1.4.1.1 Application Description

Meeting ETOPS dispatch criteria allows an operator to fly routes within a designated flight time from an airport. The primary focus of ETOPS has been two-engine flight over water, but the ETOPS concept applies to any route and number of engines.

This study investigated the use of available aircraft data to expand ETOPS by extending the range using prognostics capability or somehow improving the means of complying with ETOPS criteria. Similarly, MEL restrictions that can be obviated using accessible data would also be an application of interest.

ETOPS dispatch criteria or considerations include the following:

- Airframe/engine combination designed to fail-safe (Title 14 Code of Federal Regulations [CFR] Part 25) criteria.
- Maintenance and training program.
- Effect of operation with failed engine.
- Fuel management.
- Independent sources of AC power.
- Cargo fire protection system.
- Equipment cooling.
- Analysis of failure effects.
- In-service experience (world fleet).
- Manufacturer validation flight test.

A key ETOPS requirement was tracking ETOPS significant events such as engine in-flight shutdowns (IFSDs) and engine condition monitoring. For SPMS purposes, the focus was the use of current engine data to confirm or validate that the engine meets ETOPS requirements, specifically IFSD requirements.

1.4.1.2 Existing Data

Larger, later-model aircraft generate engine parameters such as temperatures, pressures, and speeds, plus control commands. This data can be used to estimate the health state of the engine, including failure precursors. However, precursors for major fault modes of concern, such as disk rupture or blade cracking, are best detected by combinations of more advanced technologies (e.g., time of arrival, vibration monitoring, and gas path monitoring, which requires external sensors).

1.4.1.3 Benefit

Feedback from SMEs indicates this is not a serious issue. Current technology supports ETOPS limitations that have been extended to four or more hours of flight time for polar or ocean routes. MEL relaxation was not identified as a significant benefit in the SPMS context.

1.4.1.4 Certification

The certification task would focus on showing the reduced probability of component failure by the SPMS assessment either through engine modeling or field experience. Because engine failure is a rare event in the field, engine modeling may be the better approach. The novel element of this application would be in determining the accuracy and reliability of SPMS assessments/predictions, which would be necessary for certification.

1.4.1.5 SPMS II Applicability

In the context of the SPMS analysis, the ETOPS and MEL dispatch criteria appeared to be a solved problem with little return.

1.4.2 Increased Engine Life Realization

1.4.2.1 Application Description

The ability to estimate engine life from an engine performance model that computes the engine component stress from engine temperatures, pressures, speeds, and control commands has been developed and is being tested. This application appears to provide good results, but further work is necessary to demonstrate and validate this approach.

1.4.2.2 Existing Data

A set of approximately 25 parameters that includes engine temperatures, pressures, and speeds plus control commands is available. The application would require continuous collection of these parameters any time the engine is in operation and the downloading of this data for analysis if the application is not implemented on board. Samples should be taken at a 10 Hz rate. It may be possible to get significant improvement with 3–5 Hz data sampling depending on the various parameters. Collection and management of this streaming data is a significant cost that would require additional infrastructure.

1.4.2.3 Benefit

The engine is typically the top driver in terms of maintenance costs. A 5% increase in life on wing would achieve significant savings depending on the type of aircraft. This application should also improve safety, given that it is more accurate than current cycle counting methods, and add confidence to reliability estimates, which are used as a basis for operational capabilities, such as ETOPS.

1.4.2.4 Certification

Certification of the new model would appear to follow the same approach as the current cycle counting method. The underlying models need to be validated with test and field data. The collected data would need to be handled appropriately to avoid any corruption. Mitigation methods for missing data would have to be developed.

1.4.2.5 SPMS II Applicability

Engine modeling and expertise and related design data reside with the engine original equipment manufacturer (OEM) and were not readily available for this concept in the context of the SPMS II program. Given this restriction, it was more productive to pursue analogous operations for structural components.

1.4.3 Thrust Reverser

1.4.3.1 Application Description

In the earlier SPMS program, the thrust reverser was identified as an application in which the data to monitor position were available on some airplanes at a rate that may support prognosis of fail-to-lock and binding fault modes.

1.4.3.2 Existing Data

Reverser actuator position data is collected via the engine control unit and made available via a 429 bus on some aircraft.

1.4.3.3 Benefit

Prognosis of degraded conditions would reduce schedule interruptions and produce a modest benefit for longer-haul aircraft that do not land often and have longer turnaround time, as long as this type of data is available.

1.4.3.4 Certification

The prognostic solution would be support critical (not safety critical), with the results used for maintenance advisory.

1.4.3.5 SPMS Program Assessment

Because of the support-critical nature of the application, it did not score well in regard to the SPMS II program objectives.

1.4.4 Corrosion CBM

1.4.4.1 Application Description

Corrosion CBM would build on the current non-destructive investigation (NDI) methods by adding the element of prediction based on data collected by NDI tools and operational data from aircraft. Corrosion would be measured with NDI equipment as it is currently performed, but the data would be stored, trended, and used to predict the time when the component would need replacement. It could also be used to recommend the time to perform repairs (blending) on pitted surfaces. Aircraft load and environmental factors could be considered in the calculations.

The result would be the condition-based treatment of corrosion inspection. If the method is used only for maintenance guidance for when to plan on removing the component, it would be support-critical. If it is used to recommend NDI intervals or recommend repair/blending, it would most likely be safety-critical, depending on the structure.

1.4.4.2 Existing data

The data of interest in this application are the images acquired from ongoing NDI tests as walk-up support equipment. Additionally, the operational and environmental conditions under which the aircraft was flown between inspections are used for predicting corrosion formation or growth. This information is available from the aircraft and operational databases.

1.4.4.3 Benefit

Because many of the structural components are not held in inventory, there would be reduced downtime waiting for a part to be manufactured and, therefore, increased aircraft availability.

The application could also save maintenance costs by eliminating unnecessary inspections or reducing collateral damage.

1.4.4.4 Certification

The quantitative measurement and characterization of corrosion/metal loss from the NDI images could support trending and prediction. Predictive models, including corrosion models for the material under study and operational and environmental condition, need to be verified and validated.

The application would build on current models and procedures that specify the placement and operation of the NDI equipment. However, the use of the SPMS data to schedule inspections or repair/blending is a new element introduced by corrosion CBM. If the application is used only for maintenance guidance, it would be support critical. Once ample operation data are collected and the system is refined and matured, it can be considered for certification for maintenance credit.

1.4.4.5 SPMS Program Assessment

The application was considered a good fit as a possible SPMS program focus given the inclusion of data acquired by means of support equipment.

1.4.5 Structural Fatigue Inspections

1.4.5.1 Application Description

The earlier SPMS investigation identified a number of possible structural fatigue inspection applications that primarily use monitored flight parameters to more accurately calculate the usage and fatigue of key inspection points. This will result in reduced inspection if the part or component is not exposed to maximum design loads. Though these applications can take advantage of available aircraft data, in some cases their accuracy can be enhanced by additional sensors in key locations. Some examples include:

- Heavy/hard landing (HHL)—Analysis has shown that landing loads can be modeled and estimated from aircraft flight parameters during landing. The result would be used to direct inspection and maintenance.
- Flap extension overspeed—The loading on the flap would be modeled based on air speed during flap extension and used to guide inspections in cases in which the flap is extended at high air speed.
- Operating with degraded structure/NDI—This application creates a methodology to estimate crack growth based on operational conditions and NDI data. The lifing methodology here is damage tolerance versus safe life, by which operation with a crack of any size is not permitted.

1.4.5.2 Existing Data

The data on the flight dynamics that are currently recorded on commercial aircraft would support all the applications. NDI technology to detect and measure crack growth may also be used to support the above applications.

1.4.5.3 Benefit

Based on SME inputs, hard landing appears to have the greatest payoff followed by operating with degraded structures. The flap extension overspeed has the least promise based on frequency of occurrence. An additional benefit of hard landing is the avoidance of fuel dumping, which is expensive and an environmental concern.

1.4.5.4 Certification

The models and processes that would be the basis for certifying these capabilities would be derivatives or extensions of current models. For the structural fatigue inspection applications, a likely strategy is to use sensors to validate models based on aircraft flight dynamics data. The operating with degraded structures based on NDI would likely represent the greatest challenge because material models need to be developed and validated with lab and field data for estimation of crack growth under various operating and load environments.

1.4.5.5 SPMS II Applicability

Hard landing and operating with degraded structures/NDI was rated to align with the SPMS II program criteria in providing benefit, availability of data, and being of interest in regard to certification.

1.4.6 Fuselage Hail/Damage

1.4.6.1 Application Description

This application would use a laser scanning device to automate the detection and measurement of damage to airline fuselage.

1.4.6.2 Existing Data

The data of interest is the scan information and the results generated.

1.4.6.3 Benefit

The application would save time and maintenance labor by automating the inspection process. However, any benefits would depend on the implementation of a scanning mechanism, which would have to be low-cost given the frequency of occurrence.

1.4.6.4 Certification

The certification interest would be in the ability of the system to acquire and process the scan data and correctly indicate the severity and density of the damage.

1.4.6.5 SPMS II Applicability

Given the maturity of this application, it was rated as a low-priority cost/benefit.

1.4.7 Digitizing Maintenance Systems

1.4.7.1 Application Description

Current maintenance practices frequently require paper signoffs from personnel who are physically separated for approvals at various steps in the processes. The application suggested here is to transition to electronic signoffs and records. This would include further digitizing maintenance inputs for actions taken and communication of data records over wireless media.

1.4.7.2 Existing Data

Paper documents associated with maintenance processes; maintenance manuals and specification; logistics; and supply chain data.

1.4.7.3 Benefit

Improved data quality, accessibility, management, and storage could result in significant benefits.

1.4.7.4 Certification

The automated maintenance management systems are taking advantage of advancements in information technology (IT) systems in other areas, such as finance. The issues that can be a certification concern, such as data integrity, loss of data, and data quality, are all addressed in other areas, and the technology is relatively mature. Steps should be taken to archive and back up data periodically so they are not lost or corrupted.

1.4.7.5 SPMS Program Assessment

Digitizing maintenance systems deviates from the intent of SPMS II in that it involves aircraft data use for reducing maintenance cost. There were not many challenges for certifying authorities in the use and deployment of IT systems for collection and management of maintenance data.

1.4.8 Remote Inspections

1.4.8.1 Application Description

This application would use a camera and high-speed communications for remote NDT of composite structures and tire inspections by qualified experts. Both types of remote inspection eliminate the need for an on-site qualified inspector.

Remote inspections would have a video and voice link to communicate on-site data. The voice link could be used by a person on-site with the camera, who could manipulate the camera per the instructions provided by the offsite qualified expert. The topic to be addressed in this case study is the criteria to substitute this capability for on-site inspection by a trained maintenance person.

1.4.8.2 Existing Data

The existing data would be the current documented inspection data and procedures for various types of equipment. The additional readily available data are video and voice from the remote inspection site.

1.4.8.3 Benefit

Absence of the specific certified Airframe and/or Powerplant maintenance technician (A&P) on-site can result in delayed inspection and flight delays. Remote inspection would expedite inspections and improve the dispatch rate.

1.4.8.4 Certification

The remote inspection method would have to be shown to work as well as or better than the current process. The images and data at the remote site should include all the features that are observed by a local inspector. The infrastructure for transmission of data should be validated to show that the quality of data and images are not degraded at the remote location. The recordkeeping and data storage requirements need to be determined before the system is fully matured during an introduction-to-service program. Training materials need to be developed for using these systems.

1.4.8.5 SPMS II Applicability

The application fits the SPMS charter because of the availability of data and the ability to address the certification aspects.

1.4.9 Maintenance Quality Assurance

1.4.9.1 Application description

This application uses aircraft data, fault indications, and maintenance and repair actions in electronic format to improve the quality and efficiency of maintenance procedures. This requires digitizing current processes so the results from analyzing the data can be integrated. Of specific interest are fault isolation manuals and the electronics logbook. Statistical models and data

mining approaches are used to analyze fault and maintenance data. Though not certified by the FAA, these documents can benefit by being integrated into a digital system to improve the procedures for efficient airplane maintenance.

1.4.9.2 Existing Data

Existing data include flight and performance data; fault indications; cautions; warnings and advisories; maintenance; and repair data.

1.4.9.3 Benefit

The benefits of the maintenance quality assurance application are more efficient and accurate maintenance, which results in reduced costs and improved aircraft availability and dispatch rate due to reduced time for fault isolation and repair.

1.4.9.4 Certification

This application does not present any certification challenges because the FAA CFR does not specify the format of maintenance documents. The application does not intend to change the scheduled maintenance, but rather improve the process for rectifying faults and unscheduled maintenance. Guidelines should be developed for handling data to avoid over-dependency on electronic media; another option is to ensure that a backup process is in place in the event servers or communication links fail.

1.4.9.5 SPMS II Applicability

This application is already being addressed by OEMs and airlines and does not directly involve certification considerations. This application was not rated a high-priority area.

1.4.10 Exploitation of Flexible Maintenance Intervals

1.4.10.1 Application Description

This application would exploit flexibility in current inspection schedules to more efficiently group a greater number of inspections into one maintenance session or check, which would reduce maintenance downtime and costs.

1.4.10.2 Existing Data

Existing data includes maintenance specifications related to periodic inspections and the outcome of inspections and flight and operational data.

1.4.10.3 Benefit

Benefits include improved availability of assets in high-value situations through flexible scheduling and reduced maintenance cost.

1.4.10.4 Certification

The certification of temporary inspection extension would depend on the criticality of the inspected part or location to determine how the maintenance credit can be obtained. Historical data and alternative means of compliance can be used for certification for lower-criticality components.

1.4.10.5 SPMS II Applicability

This application was considered a desirable capability for a maintenance system but not specifically aligned with SPMS II objectives because of the lack of data for the development of a case study.

1.4.11 Reduce the Amount of Data Needed to Achieve Certification or Maintain Service Management Plan

1.4.11.1 Application Description

This application suggests reducing the data required to support existing inspection procedures. The idea was to look at current certification methodologies and reduce the data that has to be collected to certify a new part or change to an aircraft.

1.4.11.2 Existing Data

To be defined for a specific application.

1.4.11.3 Benefit

To be defined for a specific application.

1.4.11.4 Certification

To be defined for a specific application.

1.4.11.5 SPMS II Applicability

This was a general goal or consideration that could be applied to specific applications. It did not fit within the scope of SPMS.

1.4.12 Collect and Handle Data Appropriately in Anticipation of Safety Critical Certification

1.4.12.1 Application Description

This application suggests collecting data in anticipation of it being used for health management purposes. In addition, data from support critical functions could be collected in anticipation of certifying a function to a higher level.

1.4.12.2 Existing Data

Existing data includes flight and subsystem (e.g., engine) data currently being recorded.

1.4.12.3 Benefit

The benefit would be in reducing the time required to collect data to certify the models related to the application(s).

1.4.12.4 Certification

The data would have to be handled and stored in accordance with the level of certification desired for the end system.

1.4.12.5 SPMS II Applicability

It was concluded that this was an aspect that should be considered for each application and that it cannot be studied as an individual application.

2. APPLICATION/CASE STUDY PRIORITIES

The research team studied the applications described in section 1.4 in terms of SPMS objectives and alignment with the program scope and grouped them into three priority levels.

The Priority I group was perceived to provide the most benefit; sufficient data were available for their use, and the applications were within the scope of the SPMS program (met both criteria).

The Priority I applications are:

- Structural fatigue inspections.
  - Airplane load monitoring.
  - Hard landing.
  - Flap extension overspeed.
  - Operating with degraded structures.
- Remote inspections.
  - Tire inspection.
  - Composite structure.
- Corrosion inspections/CBM.

The Priority II group had clear maintenance benefits, but sufficient data were not available or the applications did not fit the scope of the program (met only one criterion). The Priority II applications are:

- Increased engine life realization.
- Digitizing maintenance systems.
- Fuselage hail/damage.

The Priority III group provided low maintenance benefit or was not aligned with SPMS objectives and scope (did not meet either criteria). The Priority III applications are:

- Thrust reverser.
- ETOPS and MLE dispatch criteria.
- Maintenance quality assurance.
- Exploitation of flexible maintenance intervals.
- Reduce the amount of data needed to achieve certification or maintain service management plan.
- Collect and handle data appropriately in anticipation of safety critical certification.

The applications in the Priority I list were further studied based on their applicability to SPMS, maturity, cost benefit, and risk in the context of the SPMS program. The list was used as a basis for case study selection and development. Table 2 summarizes the outcome of this evaluation. Later in the program, during the case studies, it was determined that some of the ratings could be adjusted. For example, tire health monitoring, which was initially assumed to be a mature technology, was found to require more advancement to replace the on-site expert human inspection. This process resulted in the team focusing on the applications that are bolded in table 2. Some applications were eliminated because of low return on investment and high risk (e.g., flap extension overspeed and airplane load monitoring).

Table 2. Prioritization of SPMS II areas

Application	SPMS II Program Applicability	Maturity	Cost/Benefit of Base Application (Return on Investment)	Risk (SPMS II Program Context)
Airplane Load Monitoring	H	L	Unknown	H
Hard Landing	H	H	M	L
Flap Extension Overspeed	H	M	L	L
Operating with Degraded Structures	H	L	M	M
Remote Tire Inspection	M	H	H	L
Remote Composite Structure Inspection	M	M	M	L
Corrosion Inspections	H	M	H	M

H = high; M = medium; L = low

3. CASE STUDIES DESCRIPTION

Sections 3.1–3.5 include detailed descriptions of the selected higher-priority areas, including background information, technology, and implementation and certification aspects. These application areas include HHL, operating with degraded structure, remote tire inspection, remote NDI of composite material, and corrosion CBM. HHL and NDI were pursued as case studies in which the implementation and acceptance methods were fully analyzed and documented. A trial case study was performed for remote tire inspection, but because of low technology maturity, the case was not further pursued. The certification study was limited to survey results from experts and recommendations in regard to updates to aircraft maintenance manuals (AMMs). The corrosion CBM is another case in which the technology is not mature and readily available for transition; therefore, a case study could not be performed. The last case was the operation with degraded mode. For this application, the description of technology is included. The development of a case study could not be accomplished because there was no parallel Boeing program to be leveraged.

3.1 HHL

HHL detection technology fits the SPMS program criteria for the following reasons:

- It takes advantage of existing aircraft data.
- It provides a number of opportunities to take maintenance credit for waiving inspections above and beyond the capability offered by current systems in the field.
- Certified analytical simulation models and data are available on landing events and can be used to develop reduced order loads models, which can be integrated on board for rapid, near real-time evaluation.
- It has existing baseline models and approaches that can and should be improved.

The most important part of HHL is the landing load prediction model and system, which provides greater accuracy and results in a reduced number of false positives without compromising the ability to predict all hard landings. This accuracy improvement is related to a number of basic system design parameters:

- Topology and use of advanced algorithms to compute landing loads.
- Landing model development data fidelity and accuracy.
- Number of model development data sets and model optimization parameters.
- Comprehensive coverage of the data space used to develop loads models.
- Number and adequacy of validation cases to ensure model regularization.

3.1.1 Background

An HHL results in an airplane taken out of revenue service to inspect critical points along the aircraft fuselage and cabin; landing gear; engine; empennage; and wings (details provided in appendix C of the Boeing proprietary version of this report). A large percentage of Level 1 inspections (30%–85%, depending on the platform) result in no adverse findings. The economic

impact to the operator of a Level 1 inspection varies from $50,000–$200,000 per event (all costs, including maintenance and revenue loss).

The frequency (based on a fleet size of 170 aircraft) of reported HHLs is as follows:

- Fuel dump: 3–4 times per year.
- Overweight landing: 10–12 times per year.
- Hard landings: 4–5 times per year.

Aircraft land three times a day for 365 days, which results in 186,150 landings per fleet per year. Approximately one hard landing is reported every 41,366 flights. The immediate impact of implementing a solution in reducing this false call rate to a more reasonable percentage (e.g., 10%–15%) results in a more reliable aircraft with an increased operational efficiency and an overall positive net present value for the operator based on maintenance cost savings and reduction in lost revenue.

3.1.2 Current HHL Detection Approach

Historically, Boeing's philosophy on hard landings has been:

- The flight crew, with guidance from data if desired, determines the severity of a landing.
- When the flight crew reports a hard landing, an inspection is conducted in accordance with AMM procedures.
- No specific language exists that allows the maintenance crew to waive an inspection when a flight crew declares it.

Today, operators are trending toward more automated onboard hard-landing determination systems based on hard-landing reports generated by systems such as the Airplane Condition Monitoring Function (ACMF) and monitoring of QAR data. However, differences between these sources have led to conflicts and uncertainty in the recommendation for inspections. As a result of avionics memorandum AV-AMI-12-055, issued in 2012, these data sources were deemed unreliable for judging the severity of a landing and informing the need for inspection because the QAR is rated Design Assurance Level (DAL) D/E.

In the past, the ACMF hard-landing report was triggered by exceeding a vertical acceleration threshold on touchdown. When using this measurement against the threshold as the sole indicator of a hard landing, the result is numerous costly Level 1 inspections, most of which are unnecessary. A complex, dynamic event such as a landing cannot be accurately represented by one single data measurement. Landing is a multivariate problem because other additional flight parameters are also important and therefore must be considered for a thorough review of all mechanisms and structures.

In concept and practice, the pilot determines hard-landing severity. If a HHL is suspected, the following procedure is followed and outlined in the AMM:

- The Level 1 inspection is applicable when an Overweight, Hard, High Drag, or Side Load landing occurs.
- If the inspection during Level 1 does not show that damage has occurred, no more inspections are necessary.
- If the Level 1 inspection shows that there is damage, the Level 2 inspection is necessary.
- A High Drag or Side Load landing occurs if the airplane makes a landing with one or more of the following conditions:

  - The airplane made a landing farther than the prepared surface.
  - The airplane made a landing short of the prepared surface.
  - The airplane made a landing and two or more tires blew.

- If there was a High Drag or Side Load landing, perform the Level 1 inspection.
- If there was an Overweight landing and the landing was not a Hard, High Drag, or Side Load landing, the Level 1 inspection is not necessary.
- If the pilot wrote in the report that there was an Overweight or Hard landing, use flight parameter tables to find if an inspection is necessary:

  - Pull the maintenance page "ATA 51 Landing Conditions." Compare the values given for the specified landing on the maintenance page to the limits on the applicable table. If all of the values are between the limits on the applicable table, then no inspection is necessary. If a value is not between the limits on the applicable table then a Level 1 inspection is necessary.

If the measured sink rate, roll, gross weight, etc. exceed the flight parameter threshold tables in the AMM, the Level 1 inspection, which includes main landing gears, nose landing gears, fuselage check points, wing check points, and cabin, is conducted. If any damage is found during the Level 1 inspection, then Level 2 inspections, which involve a much more comprehensive examination, are conducted. After completing the inspection, the airplane is put back together in normal functioning order. These maintenance actions are time-consuming. The current assessments used to determine the need for these inspections are conservative thresholds so as to avoid missing a needed inspection, which results in room for improvement to the overall maintenance program.

3.1.3 Current HHL Detection System Limitations

The following is a list of major technology gaps that the current landing severity determination approach fails to address and which a newly proposed landing load prediction based method can successfully close:

- In general, the current hard-landing determination system is overly conservative to avoid missing a hard landing and, in turn, results in a 35%–45% false positive rate, depending on the platform. This means that 35%–45% of grounded airplanes should not have been grounded because they did not experience a hard landing. This conservatism is built into the system because of landing assessment fidelity that can be addressed with a higher-order model, such as a landing loads prediction algorithm. The current method is a linear threshold-based classification of a small number of flight parameters within a complex multidimensional and nonlinear data space.

- The AMM inspection determination method, as integrated today on the 777 and 787 airplanes, for example, requires too much time to determine if an inspection is warranted and what type of inspection is needed. The pilot makes the first call, which then flows down to the maintenance personnel to bring up a report of the flight parameters on landing. The information from this report is then manually applied to the look-up tables to determine if an inspection is required and, if so, what type of inspection (i.e., Level 1 versus Level 2), which details the inspection protocol.

- The current method does not provide any detailed information, only a go/no-go decision. Therefore, the inspection, if one is deemed necessary, requires too much airplane downtime because the inspection includes an overhaul of a large amount of airplane acreage that must be inspected in both Level 1 and Level 2. This translates into revenue lost that the airplane could have been generating for operators.

3.1.4 Advanced HHL Detection System

The key to the problem of HHLs is developing a cost effective solution that is both accurate (i.e., provides minimal false positive and zero false negative hard-landing indications) and reliable (i.e., does not rely solely on measurements from transducers that are non-redundant or susceptible to damage). Practical issues with instrumenting the landing gear directly present logistical roadblocks, increase costs, and affect reliability. Another key challenge is the many variables involved in a landing event. It is necessary to evaluate all of these variables in a combined sense to be able to accurately classify the severity of a landing.

The proposed HHL prediction system is a reduced-order algorithm that uses relevant aircraft flight parameters to predict pertinent and critical loads to evaluate the potential of damage. By providing accurate and reliable load information, this system will significantly reduce the number of hours a plane is grounded for inspection because of an HHL.

The loads algorithms are based on models that are developed using analytical methods (e.g., using a numerical simulation), experimentally (e.g., using flight-test data), or with a combination of both. Some of the advantages of this type of model (as compared to, for example,

a Finite Element Model [FEM]) are the ability to model considerably nonlinear phenomena with a fairly compact and efficient set of computations and the automatic handling of the "model validation" process (which can be extremely challenging, time consuming, and costly). Using analytically developed data sets reduces the amount of data required from flight tests, and using judiciously chosen flight-test data will both validate and increase the accuracy of the algorithm. The key to successfully designing an accurate, efficient, and robust loads model is the proper choice of model development data, model configuration, and model development method. Details describing the loads model and how it is developed can be found in appendix C of the Boeing proprietary version of this report.

In this newly proposed HHL prediction system, loads are computed at locations on the airplane that correspond to the AMM inspection points. These include locations such as landing gear struts, drag brace, truck beams, body loads, and engine links and locations for which their response has strong correlation with landing severity (i.e., most likely to exceed limit load on a hard landing), such as APU vertical acceleration and empennage acceleration. The input data set for each predicted load is a unique combination consisting of measured flight parameters on board, such as airspeed, sink rate, roll angle, roll rate, pitch angle, weight, and center of gravity (CG) (see figure 2).

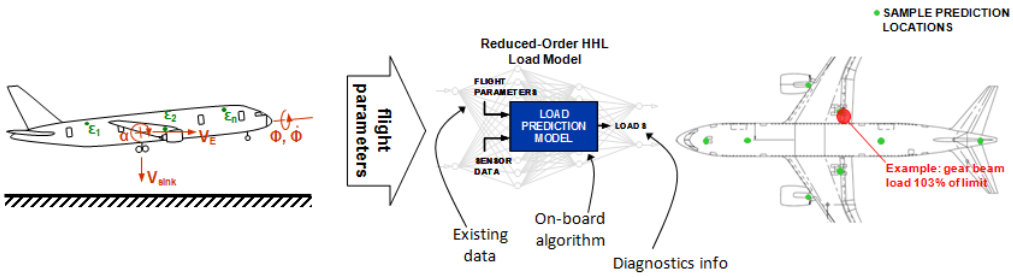


Figure 2. Advanced HHL loads model description

In addition to providing operators with the ability to reduce false calls, the HHL load prediction algorithm can also serve as a maintenance aid to guide maintenance personnel to the appropriate areas to be inspected when there is need for inspection. A HHL would still be determined by the pilot, and, at the discretion of the pilot, he may also use the predicted load information to help in the final determination of landing severity in addition to influencing appropriate maintenance actions.

Additional processing can provide a usage-based estimate of remaining useful life. This eliminates unnecessary inspections and reduces inspection times when they are prescribed, therefore reducing aircraft downtime and schedule interruptions. The method does not require the addition of sensors because the necessary data is already available from the flight instrumentation and control functions. Extending this concept with directly measured information such as strain or acceleration can increase the landing assessment performance rate and possibly allow for a method to provide a more accurate calculation of landing gear life.

3.1.4.1 HHL Technology Augmented With Sensor Data

Any approach based solely on flight computer data may suffer from the possibility that the data may not explicitly include information regarding the transient dynamic response of the structure to the landing impact. This transient response becomes increasingly complex as the size of the aircraft increases. One approach for enhancing the accuracy of load prediction to directly include the transient dynamic response effects is by using structural sensors.

Boeing studied the value of adding sensors to supplement the data provided to the HHL load prediction system. Examining the point dispersion allows for a quantitative measure of the benefit of adding each individual sensor (see figures 3 and 4).

DDZCG
roll angle
CG
sink rate
pilot normal accel
weight
pitch
KEAS
roll rate

	Inputs						False Positives						
	9	2	2	1	1	1	440	600	471	648	479	2638	
Rank / Description	Flight Params	Gear Beam	Struts	SG501	SG1389	DDZ APU	Real World Group	Pilot Call Group	Group #1	Group #2	Group #3 (training set)	Total False Positives	% False Positives
ALS 733	x						0	227	207	221	177	832	31.54
7	x						0	66	63	40	19	188	7.13
2	x	x					0	36	24	16	9	85	3.22
4	x		x				0	42	52	29	13	136	5.16
6	x			x			0	50	54	31	17	152	5.76
3	x				x		0	40	40	26	16	122	4.62
5	x					x	0	44	56	33	18	151	5.72
1	x	x	x	x	x	x	0	20	23	11	8	62	2.35
2+3	x	x			x		0	25	22	12	10	69	2.62
2+3+4	x	x	x		x		0	18	18	8	10	54	2.05
2+3+4+5	x	x	x		x	x	0	28	34	15	10	87	3.30
wing only	x	x	x				0	28	22	13	9	72	2.73
press vess only	x			x	x		0	49	48	29	19	145	5.50

Model fidelity and prediction accuracy increases with more inputs

Figure 3. Effect on HHL load model prediction as a function of adding structural sensor data

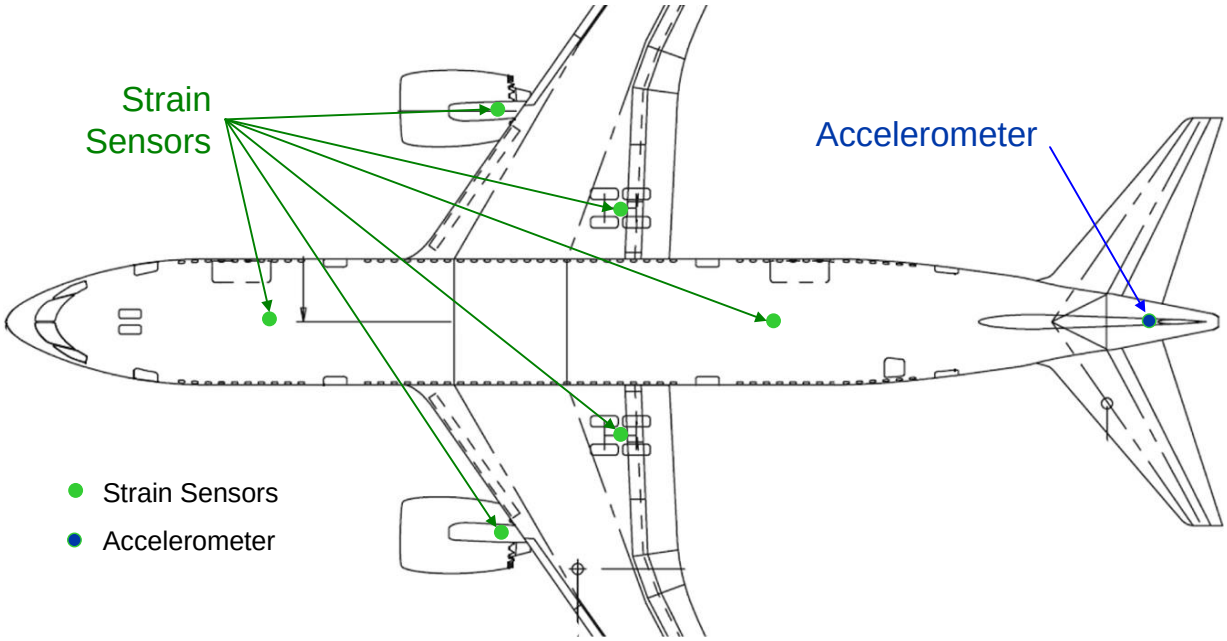


Figure 4. Sensor locations for augmented hard landing assessment system

Sensors that do not reduce the false call rate have minimal value. The Boeing study indicated that a small number of sensors provided an improvement in performance of the HHL system. Additional sensors resulted in diminishing returns in improved performance. The sensor topology that provides improved performance without diminishing return and increases in system cost and complexity as shown in figure 3 includes strain measurements at the gear and aft body crown. These locations are shown in figure 4.

The selected locations represent high-load areas on the engine pylons and near main landing gear trunnions. These sensors are most effective for computing load response at these specific locations, which improves the overall landing assessment performance (i.e. reduction in false call rate). The fuselage-mounted strain sensors would primarily improve detection of fuselage bending response, particularly on the fuselage crown. Ideally, the sensors would be located at the critical areas on the fuselage crown. However, it is likely that other less critical areas could be monitored instead and the results analytically transferred to the critical areas if it reduced the cost of the overall HHL system implementation. The accelerometer located in the tail region would also aid in the measure of the response of the fundamental fuselage bending modes. It could be located at nearly any convenient location in the tail.

The sensor locations shown in figure 4 were developed for a mid-size aircraft (767/787 class). For a smaller 737 class, the fuselage bending response is less significant; the number of sensors on the fuselage centerline could be reduced. A detailed study of a 737 aircraft would be required to define the value of the other sensors. For a larger 777/747 class aircraft, outer-wing structural dynamics may be important enough to justify additional wing sensors. It is estimated that no more than 2–4 additional sensors would be required.

Each of the sensors would need to have a sufficient bandwidth to capture the response of the major dynamic modes of the structure. The sensors would be active and capturing data only during landing.

3.1.5 HHL Case Study

The case study discussed in this section relates to the following routine scenario:

> The pilot of a 787 lands the fully boarded airplane at its intended destination with a sink rate of approximately 8 ft/sec, which may have resulted in a touchdown that exceeded design load limits. He judges this by the shock he feels from his seat, which is the result of energy transferred from the impact of the landing gear on the runway to the floor beams, his seat track, and finally his seat. Additional supporting data, such as airspeed and roll angle/rate on landing, can sometimes be made available to the pilots to help them make the decision to dispatch the airplane to maintenance for a hard-landing inspection. However, because it was a high sink rate landing and he experienced a jolt to his seat at touchdown, he decides to act with conservatism and call for a hard landing.

The approach in dealing with this type of scenario has evolved over recent years. Until recently (i.e., the introduction of the new 787 airplane), the pilot had the final call on issuing a full airplane inspection based on limited information, making this process a subjective, human-based decision. With the advent of the 787 and its new system technology offerings, an approach for determining a hard landing based on flight parameters was developed and offered for production use (note that not all commercial models use this technique). This system is the result of carving out thresholds in the flight parameter data space. Any landing that exceeds any of these predetermined thresholds would result in a hard-landing inspection. This approach is less subjective and, therefore, more accurately correlates with a hard landing. However, there is still room for improvement with this system because it is overly conservative due to its fundamental limitations.

3.1.5.1 Case Study Results: Landing Severity

This case study and a parameterized analytical 787 model data space varying in sink rate and roll rate show that 35% of hard-landing inspections under the current system are unnecessary. This means the pilot in the HHL case study has a 35% chance that the called-for hard landing was inaccurate and the inspection was unnecessary.

This current threshold classification approach is directly compared to the performance of the HHL load prediction algorithm; both were applied to a set of 479 total landings and evenly distributed across the span of sink rate and roll angle.

The threshold rules of the current hard-landing determination method were applied to each case, and the results that the current system would predict as either safe or hard are shown in figure 5.

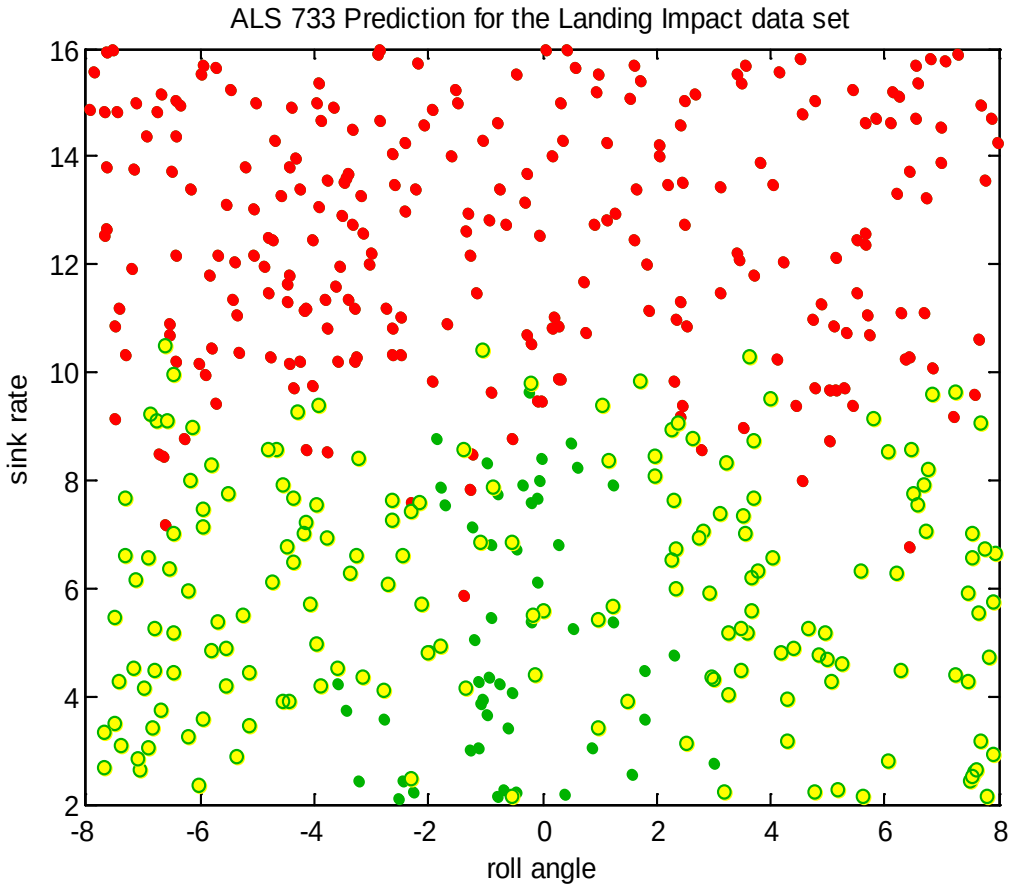


Figure 5. Landing severity prediction results by the current hard-landing model

The red data markers represent hard landings that the threshold model predicted correctly. The green markers are acceptable landings that the model also predicted correctly. The yellow markers are landings which the model predicted as hard but were acceptable. Of the 479 total landing cases, 250 hard landings were predicted correctly (zero false negatives) and 177 were incorrectly predicted as hard landings (false positives), resulting in a 35% false call rate. This false call rate was due to conservatism in the thresholds so that hard landings are not missed because the classification consists of linear, flat line demarcations through a complex and convoluted data space.

In applying the HHL load prediction method to the 479 landing cases, the model was used by applying the flight parameter inputs for each individual case. All resulting load predictions for each individual case were then compared to the respective limit value. If the occurrence of one or more of the loads exceeded its respective limit value, then a hard landing was determined and, therefore, the need for inspection. The results are shown in figure 6.

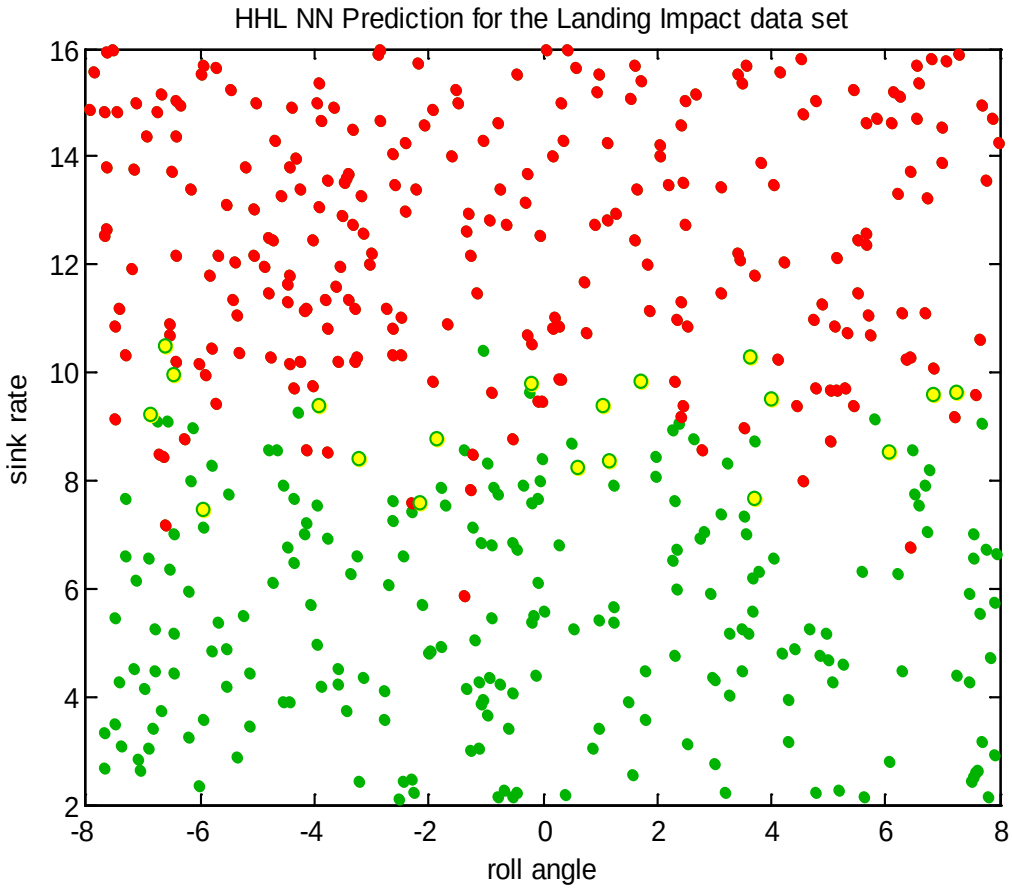


Figure 6. Landing severity prediction results by the newly proposed HHL load prediction algorithm (with flight parameter inputs only)

The red data markers represent hard landings that the HHL model predicted correctly. The green markers are acceptable landings that the model also predicted correctly. The yellow markers are landings that the model predicted as hard but were acceptable. For the 479 total landing cases, 250 hard landings were predicted correctly (zero false negatives) and 19 hard landings were incorrectly predicted (false positives), resulting in a 5% false call rate.

The false positive rate can further be reduced by using a limited set of information from structural sensors (e.g., landing gear strut strain, body crown strain, landing gear beam strain) as additional inputs to the HHL load prediction method on the 479 landing cases. All resulting load predictions for each individual case are then compared to the respective limit value. If the occurrence of one or more of the loads exceeds its respective limit value, then a hard landing is determined and, therefore, the need for inspection. The results are shown in figure 7.

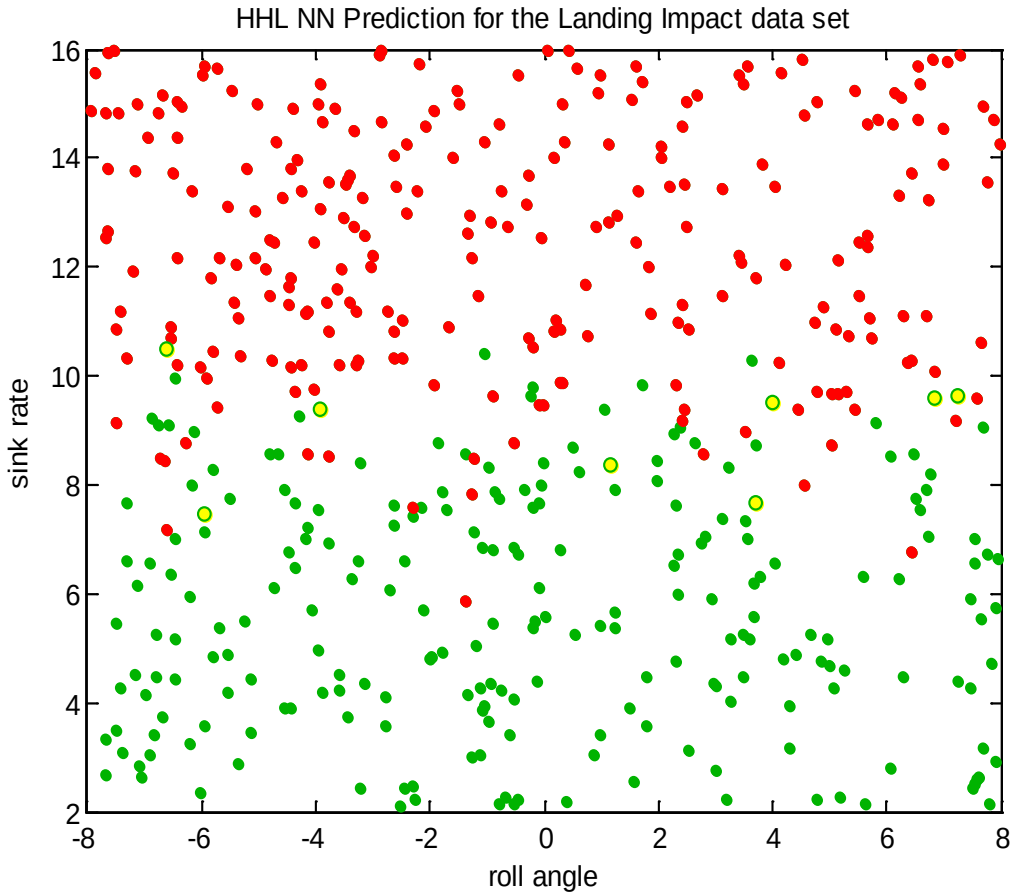


Figure 7. Landing severity prediction results by the newly proposed HHL load prediction algorithm (with flight parameter and structural sensor inputs)

For the 479 total landing cases, 250 hard landings were predicted correctly (zero false negatives) and 8 were incorrectly predicted hard landings (false positives), resulting in a 2% false call rate.

The HHL algorithm was developed using analytical flight parameter inputs and load outputs of real cases from the full-order landing simulation model. Once developed, the loads model uses relevant aircraft flight parameters from each landing case to accurately predict pertinent loads critical to evaluate the potential of damage.

The case study showed that the false call rate can be reduced by approximately 30% from the current approach. By providing accurate and reliable load information, this system will significantly reduce the number of hours a plane is grounded for inspection because of HHL.

3.1.5.2 Analytical Dynamic Landing Model Description

The HHL load prediction algorithm was developed using examples of inputs and outputs during landing. These data sets can be created analytically (e.g., using a numerical simulation), experimentally (e.g., using flight-test data), or with a combination of both. Using analytically developed data sets reduces the amount of data required from flight testing, and using judiciously

chosen flight-test data will both validate and increase the accuracy of the load prediction algorithm. The key to successfully designing an accurate, efficient, and robust loads model depends on the accuracy of the data used to develop the model and the proper choice of the development data, model configuration, and model development method. These model design parameters directly affect the level of accuracy with which the model predicts loads, which in turn affects the false-call rate.

The load prediction accuracy of the HHL system used in the case study is dictated by the fidelity of the analytical landing model because it is this model which is used to provide input and output data to develop the reduced-order HHL prediction model. Therefore, a discussion of the capabilities and accuracy requirements of the landing model is needed to understand some of the basic HHL system requirements.

Figure 8 shows the overall flow and capability of the aeroelastic model, which is used for dynamic landing analysis.

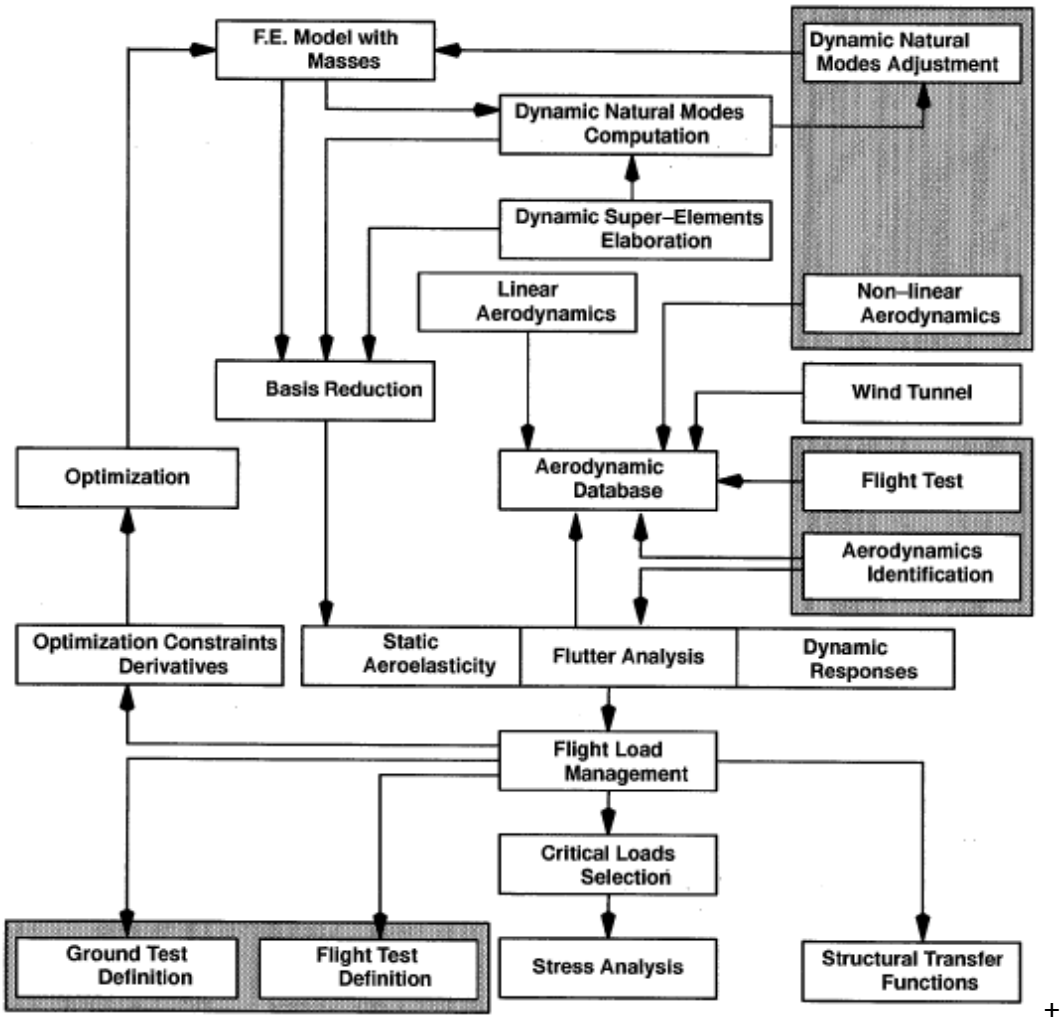


Figure 8. Overall aeroelastic model for dynamic landing simulation

This dynamic landing loads model is used by the airplane program for airplane design cycles and is governed by requirements outlined in 14 CFR 25. The data provided by the model demonstrates to regulatory agencies that the Boeing methods used are acceptable for showing compliance with the requirements. The landing analysis includes the appropriate amount of conservatism required to maintain safety margins for flight critical structures, such as the landing gear, to meet all CFR ultimate load and strength requirements.

Airplane geometry, stiffness, weight, CG, moments of inertia, ground coefficients of friction, and landing velocity data are all provided by program structural loads analyses, as governed by design load factors. Design criteria, aerodynamic data, and mass properties form the basis for the flight- and ground-loads analysis, including ground loads on the landing gear. The structural analysis configuration defines specific parameters of an airplane that are used for flight- and ground-loads analysis. These loads are then used for the design and stress analysis of all aircraft structural members. Landing simulations are run for a duration to include transient effects after touchdown so as to solve maximum peak load response information.

The design payload distributions analyzed for critical landing events are based on a series of load combinations in the fuselage derived to provide maximum forward and aft CG; maximum and minimum moments of inertia; maximum bending moments and shear at front and rear spar locations; and maximum vertical loads on the landing gear. Critical load combinations include maximum lateral unbalance and maximum and minimum % mean aerodynamic cord (MAC); sink rate; and roll angle and rate.

3.1.5.3 HHL Load Prediction Model Development

The data sets generated for the purpose of developing and training the HHL prediction algorithm were designed with the intent to provide a large number of cases with enough range in each parameter to regularize the full extent of the data space. In addition, these data sets are also meant to represent actual service history landing variation to specifically measure the prediction accuracy. Details describing the model development data sets can be found in appendix C of the Boeing proprietary version of this report.

3.1.5.4 Landing Model Validation

The dynamic landing model is validated and updated by landing gear drop testing, which characterizes modes, including any nonlinearities, frictional coefficients, and inherent structural and viscous damping in the system, thereby verifying the absorption characteristics in the strut. The measured data from drop testing is compared against the model by matching modes in the amplitude and phase frequency response plots of the strut. The model is updated with the measured information to reflect accurate mass, stiffness, and damping parameters in the landing gear elements. Additional validation may include sine sweep testing across a frequency range of interest, typically from 1–500 Hz. Energy absorption is verified and demonstrated in drop testing, with sink rates up to 10 ft/sec.

Drop testing includes a number of varying conditions, including level landing at design landing airplane weight; tail down at design landing weight; with and without tire spin-up; stowed truck landing; and takeoff mode landing.

In addition to landing gear drop testing, the model is validated by matching airplane modes frequency and amplitude (damping) from ground vibration testing. With modal energy captured and accurately represented by the model, it can be shown that the model is capable of computing an accurate transient dynamic landing response.

3.1.5.5 Landing Model Conditions

Critical design landing loads for landing gears are found by running parametric sweeps of inputs within the weight and payload distribution plots. An example of this envelope is shown in figure 9.

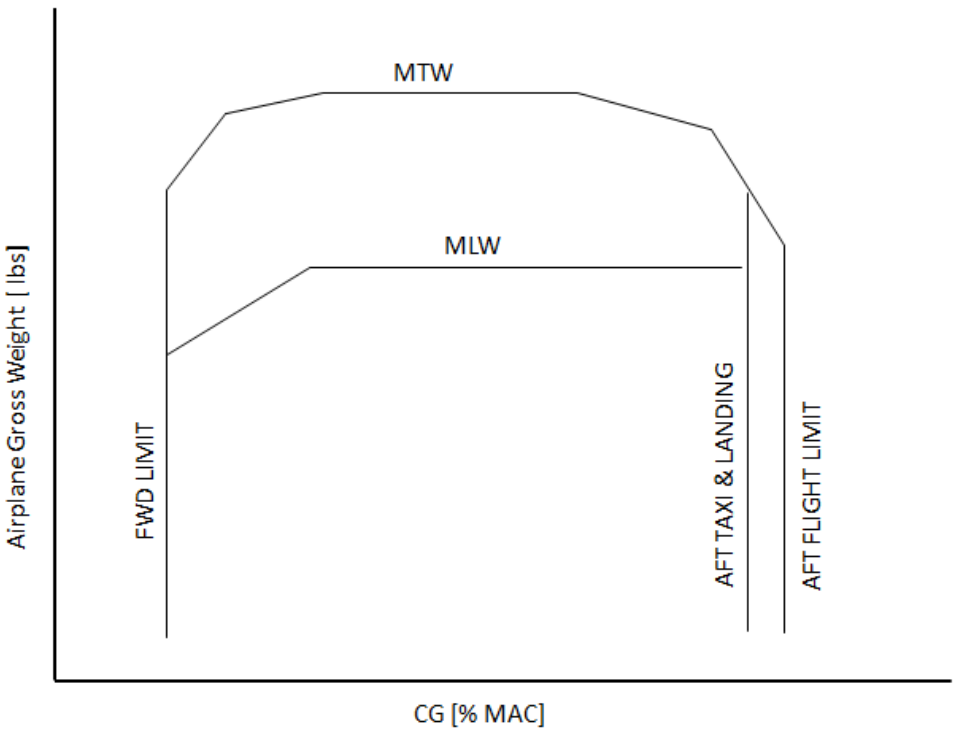


Figure 9. Airplane gross weight versus distribution envelope

3.1.6 HHL System Implementation/Concept of Operations

A typical in-service usage scenario of the landing loads prediction system would follow a chronological order of landing events:

1. Pilot lands and calls for a hard landing (sometimes uses data sent to cockpit; e.g., sink rate).
2. The data gather function is initiated (e.g., ACMF calls the data gathering application, or the Data Collection Algorithm calls data from the common data network bus) to get flight parameter inputs.
3. The data reduction algorithms are executed.
4. Input checking (input set boundaries, data fidelity).

5. Inputs are applied to HHL load models.
6. Model outputs are compared against respective limit loads.
7. Normalized load results are reported for final inspection determination.

The full benefit of the HHL load prediction system should be attained in less than 5 minutes, in which time the system rapidly generates and provides structural loads data to the maintenance crew who can make a landing severity determination and avoid airplane service interruptions.

When the pilot makes a hard landing call, the maintenance crew issues a request for the landing load report. The data-gather function accesses flight parameter inputs, and routines are executed for input data checking and landing load models used to obtain load information. Each load is normalized to its respective limit, and the normalized information is then reported to maintenance. If all normalized loads are less than 1, the inspection may be waived. If any one or more normalized results are greater than 1, then a Level 1 inspection is required at those locations.

3.1.7 HHL System Acceptance and Certification

The requirements of the landing monitor system reliability are dictated by the flight criticality of the system. The ability of a system to meet these requirements is addressed by a Fault Hazard Assessment (FHA), and the final determination on the appropriate use of data and systems in performing their basic function for the disposition of hard-landing inspections is made by systems and structures ARs. The sensor data and systems used to host and treat that data are analyzed for reliability, which is used as justification for the acceptance and certification of the hard-landing monitor function. In addition to the input data sourcing aspect, model validation and full functionality testing are required for certification of the hard-landing monitoring system.

With respect to systems design, avionics, and data sourcing, the HHL load prediction system acceptance methods will be similar in nature to the 777 Airplane Information Management System (AIMS) [1] Blockpoint Version 17A (V17A) software functionality update. The assumption is that the loads prediction algorithms will reside in the ACMS of the Common Core System and rely on the same data processed in the ACMS for general functionality. Therefore, the certification methods in this report will follow much of the same process and deliverables as proposed in the Certification Plan 14199, which addresses the update to the AIMS-2 platform [2]. The highlights to Certification Plan 14199, as relevant to ACMF updates, are outlined in section 3.1.7.3.

3.1.7.1 Software Certification Requirements

Use of airline modifiable software for dispatch relief whose erroneous output could cause failure to detect a potentially unsafe condition must be compliant with FAA CFR (i.e., FAA orders 8110.49 and DO-178). Refer to table 3 for the levels of design assurance.

Table 3. Airplane software certification requirements

Level	Failure Condition	Failure Condition Described
A	Catastrophic	Failure may cause a crash. Error or loss of critical function required to safely fly and land aircraft.
B	Hazardous	Failure has a large negative impact on safety or performance, or reduces the ability of the crew to operate the aircraft because of physical distress or a higher workload, or causes serious or fatal injuries among the passengers (safety significant).
C	Major	Failure is significant, but has a lesser impact than a Hazardous failure (e.g., leads to passenger discomfort rather than injuries) or significantly increases crew workload (safety related).
D	Minor	Failure is noticeable, but has a lesser impact than a Major failure (e.g., causing passenger inconvenience or a routine flight plan change).
E	No Effect	Failure has no impact on safety, aircraft operation, or crew workload.

Level B/C is the established level for dispatch-dependent information/data, and the 787 program uses EICAS Displays SW (Level B) for landing condition data. Digital flight data recorder (DFDR) data (Level D) has been deemed acceptable because Advisory Circular (AC) 20-141B requires the DFDR data to be validated on a regular basis.

Current AIMS options for the determination of maintenance actions include use of the Landing Condition Maintenance Page (i.e., Hard Landing Report) in AIMS Displays and use of DFDR data, which must be sampled at a minimum of 8Hz. If data are unavailable or are not at a sufficient rate, then a Level 1B inspection must be performed. The airplane can be dispatched for three days with the DFDR system message “Inoperable for Displays” if the cockpit voice recorder is fully functional. This option requires the DFDR manufacturer or third-party system to extract and decode data and requires an engineer to review the data to determine time of impact.

Use of QAR data is not feasible because QAR data is Level E. Use of onboard network server (ONS) data is not feasible because ONS is Level D/E. The AIMS airline modifiable information (AMI)/ACMF modified to Level C is not feasible because AMI is not airline modifiable.

Add-on options to the current system, such as an accelerometer or strain gage, to output flight data to the DFDR would require their own display/indication system. Installation would require power input and an additional card/box to perform data acquisition and contain logic to set the light/indicator system when the vertical acceleration exceeds a set limit. It also may require on-ground relays to filter out any in-air triggered events.

3.1.7.2 Landing Load CFR Requirements

The primary FAA regulations involved in landing overweight and fuel jettison include the following and are adhered to in making decisions to satisfy the load model requirements. A full list of certification requirements for AIMS based on CFR and Joint Aviation Requirements is listed in the certification plan [1 and 2]:

14 CFR 25.1519 — Requires the maximum landing weight, center of gravity, and weight distribution to be an operating limitation, per 25.23 through 25.27:

25.23 Load distribution limits.

1. Ranges of weights and centers of gravity within which the airplane may be safely operated must be established. If a weight and center of gravity combination is allowable only within certain load distribution limits (such as spanwise) that could be inadvertently exceeded, these limits and the corresponding weight and center of gravity combinations must be established.
2. The load distribution limits may not exceed—

(1) The selected limits;
(2) The limits at which the structure is proven; or
(3) The limits at which compliance with each applicable flight requirement of this subpart is shown.

25.25 Weight limits.

(a) *Maximum weights.* Maximum weights corresponding to the airplane operating conditions (such as ramp, ground or water taxi, takeoff, en route, and landing), environmental conditions (such as altitude and temperature), and loading conditions (such as zero fuel weight, center of gravity position and weight distribution) must be established so that they are not more than—

(1) The highest weight selected by the applicant for the particular conditions; or

(2) The highest weight at which compliance with each applicable structural loading and flight requirement is shown, except that for airplanes equipped with standby power rocket engines the maximum weight must not be more than the highest weight established in accordance with appendix E of this part; or

(3) The highest weight at which compliance is shown with the certification requirements of Part 36 of this chapter.

(b) *Minimum weight.* The minimum weight (the lowest weight at which compliance with each applicable requirement of this part is shown) must be established so that it is not less than—

(1) The lowest weight selected by the applicant;

(2) The design minimum weight (the lowest weight at which compliance with each structural loading condition of this part is shown); or

(3) The lowest weight at which compliance with each applicable flight requirement is shown.

25.27 Center of gravity limits.
The extreme forward and the extreme aft center of gravity limitations must be established for each practicably separable operating condition. No such limit may lie beyond—
(a) The extremes selected by the applicant;
(b) The extremes within which the structure is proven; or
(c) The extremes within which compliance with each applicable flight requirement is shown.

14 CFR 91.9 — Requires compliance with operating limitations

14 CFR 121.557 and 121.559 — Allow the pilot in command to deviate from prescribed procedures as required in an emergency situation in the interest of safety. In June 1972, the FAA issued Air Carrier Operations Bulletin No. 72-11 giving three examples of situations the FAA considered typical of those under which pilots may be expected to use their emergency authority in electing to land overweight:

- Any malfunction that would render the airplane unairworthy.
- Any condition or combination, thereof, mechanical or otherwise, in which an expeditious landing would reduce the exposure to the potential of additional problems which would result in a derogation or compromise of safety.
- Serious illness of crew or passengers which would require immediate medical attention.

14 CFR 25.1001 — Requires a fuel jettison system unless it can be shown that the airplane meets the climb requirements of 14 CFR 25.119 and 25.121(d) at maximum takeoff weight, less the actual or computed weight of fuel necessary for a 15-minute flight comprising a takeoff, go-around, and landing at the airport of departure.

To comply with 14 CFR 24.1001, the 747 and MD-11, for example, require a fuel jettison system. Some models, such as the 777 and some 767 airplanes, have a fuel jettison system installed, but it is not required by CFR. Other models, such as the DC-9, 717, 737, 757, and MD-80/90 do not require or do not have a fuel jettison system based on compliance with 14 CFR 25.119 and 25.121(d).

3.1.7.3 HHL Loads Algorithms Certification Plan

This section summarizes the acceptance and certification plan required for carrying through to service a new and enhanced HHL detection system, which allows the operators to safely and reliably waive inspections that other methods cannot waive, which maximizes airline customer revenue and Boeing airplane fleet availability.

This plan is divided into two parts. Section 3.1.7.4 includes the acceptance methods for ensuring the structural landing analysis methods used by the system comply with safety standards (i.e., 14 CFR 25). Section 3.1.7.5 includes the plan by which the system architecture from the

standpoint of network systems, measurements, signals, and software is in compliance with safety standards such as DO-178B, Order 8110.49, Change Order 1, DO-248B, and AC 20-115B.

3.1.7.4 Landing Load Algorithms in Service

Flight parameters (and limited sensor data, if the landing assessment system makes use of it) are recorded during the landing event. The sampled flight parameters and sensor data are processed to return their peak values. Note that, in some cases, both maximum positive and maximum negative values are used. This reduced set of sampled data is used as the input to the load prediction algorithm.

These flight parameters include (but are not limited to): pitch angle, roll angle, roll rate, CG vertical acceleration, airspeed, pilot seat acceleration, and weight. To maintain fidelity, these flight parameters must be recorded with appropriate sample rates to resolve proper peak values during landing. The current maintenance system requirements for equivalent software and systems would apply.

Computed strains and load factors can be used in a variety of ways. For example, all computed loads are to be compared to their limit values. One or more of the loads exceeding its respective limit value would signify a hard landing and, therefore, the need for inspection. This data could be used in a Boolean sense such that no actual load information is presented to the maintenance group, but rather just a “yes” or “no” answer to the question “did a hard landing occur?” Conversely, detailed information describing loads at a variety of locations around the aircraft could be presented to guide the inspection process. Because this decision is informed by data coming off the DFDR, the same certification rules that dictate the current system apply.

Error analysis must be performed to guarantee no false negative results are generated (i.e., a hard landing occurs and the system indicates that it did not occur). Also to be proven is whether DFDR sampling rates provide enough sampling to keep the system error limits to a minimum.

The landing loads algorithms development and usage include the following basic requirements for in-service acceptance:

- Compliance with 14 CFR 25.
- No undetected actual hard landings (i.e., the system shall have a hard-landing detection rate of 100%). This requires safety margins to cover all sources of uncertainty in the landing assessment, including analytical landing model uncertainty, flight parameter input error, and reduced-order HHL loads model uncertainty.
- Must predict at least the minimum set of loads at critical locations, which would fully cover any and all failures or damage found in Level 1 inspection.

The HHL load algorithms are built with Bayesian techniques that result in statistical distributions and, therefore, confidence intervals on the resulting load outputs. Bayesian probabilistic methods are used to rigorously apply safety margins while taking advantage of the model fidelity and resulting load prediction performance accuracy.

Because the load output computed by the loads model is statistical (i.e., mean and variance are represented based on a confidence interval), a conservative factor can be applied to the standard deviation and added to the mean value to ensure no false negatives (missed hard landings) occur. This must be statistically proven throughout the life of a given fleet.

3.1.7.5 Analytical Methods and Empirical Validation

The HHL load prediction model is an extension of the current AMM flight parameter threshold approach because it is a more complex classification method operating on the same basic flight parameter input data. Therefore, similar requirements will remain the same with regard to the certification methods for the structural model itself.

3.1.7.6 Dynamic Landing Model Means of Compliance

The flight parameter-based threshold approach is certified through a series of internal communications with structures and maintenance ARs. Reports are issued to address the following and to ensure structural airworthiness in satisfying the CFR with respect to landing:

- Flight parameter data space delineations to distinguish normal/hard landings.
- Rationale for determining critical flight parameters used for assessment.
- Acceptable methods to measure uncertainty for these estimations and safety margins required to cover uncertainty.

For structures, airplane program loads and dynamics engineers send and receive internal concurrence from the loads and structures AR via coordination sheets to the AMM group. These contain instructions on how to revise the AMM.

One example coordination sheet is referenced in a Boeing proprietary memorandum [3]. This memorandum presents the hard landing limits to be used in the planned revisions to the AMM hard and overweight landing inspection procedures for all Boeing heritage models (except the 787). The analysis methodology to determine the hard landing threshold as a function of roll angle for all models is outlined in this referenced coordination sheet.

Landing loads are one of many design constraints for the landing gears and their supporting structures. A landing that exerts an excessive load above a certain threshold to the airplane due to a high sink rate at touchdown is considered a hard landing. In addition to high sink rate touchdown cases, landings with weight beyond maximum landing weight (MLW) may be another cause of excessive landing loads. These are called overweight landings. The requirements for hard landings originate from FAA regulations and Boeing requirements. Refer to appendix C in the corresponding proprietary Boeing report for detailed requirements.

The most critical landing load requirements can be summarized as follows:

- The airplane shall be designed for a limit descent velocity of 10 ft/sec at the design landing weight. Refer to 14 CFR 25.473 (a)(2).
- The airplane shall be designed for a limit descent velocity of 6 ft/sec at the design takeoff weight. Refer to 14 CFR 25.473 (a)(3).
- The prescribed descent velocities may be modified if it is shown that the airplane has design features that make it impossible to develop these velocities. Refer to 14 CFR 25.473 (a)(4).
- The landing gear may not fail in a test, demonstrating its reserve energy absorption capacity, simulating a descent velocity of 12 ft/sec at design landing weight, assuming airplane lift not greater than airplane weight acting during the landing impact. Refer to 14 CFR 25.723 (b).

The first and second requirements provide the design limit sink rates for MLW and maximum takeoff weight (MTOW), which can be exerted to airplane structures without safety issues. The total energy or linear momentum changes during a landing are good measures for the load exerted to the structure, and their limits can be fairly accurately expressed with the sink rate at touchdown. In general, the limit descent velocity for MLW (10 ft/sec) is a more severe condition compared to that of MTOW (6 ft/sec) in terms of energy. Therefore, there is an opportunity to allow airplanes to land safely with a certain level of sink rate limit for the MLW or above.

The third requirement does not provide information for the sink rate limits or load limit related to the hard landings, but it includes important information for potential hard landing protection functions, which can be developed in conjunction with the sink rate monitor function described in this document. Title 14 CFR 25.473(a)(4) states that airplanes cannot take advantage of a hard landing protection function for the load credit unless the protection function guarantees the sink rate will be limited to 10 ft/sec in all landing cases. This requirement is strict compared to other load requirements for other load alleviation functions, such as maneuver load alleviation and horizontal tail load alleviation. The other requirements allow the function availability in terms of flight hours (i.e., defined useful life). The hard-landing monitor development is not impacted, but this is a critical roadblock for the hard-landing protection function. This topic will be discussed in a separate report.

The fourth requirement defines the landing gear energy absorption capacity. In some cases, this may be considered the most strict load condition for the landing gear hydraulic system. However, the total load to the landing gear and overall supporting structure must be considered in light of all requirements together, especially with the first requirement stated above. Title 14 CFR 25.723 states that the certification drop tests must be performed to substantiate energy absorption capability and validate the dynamic model. This test is normally required only for certification of a new shock strut design. Boeing has not scrapped or overhauled landing gears based on in-service known or assumed high loads. Few 777 hard landings are reported, but no gear damage has been reported. For numerous hard landings on the 747, 767 with resulting loads in excess of 3 g, no landing gears have been scrapped as a result. Records for the past 20 years show hard landings have only caused a few nose gear axles to bend and less than 12 main

landing gear fuse pins to crankshaft. Anecdotally, there was an incident in which a 747 landed so hard that seven aft fuselage skin panels required replacement. There was no damage to the gear. Landing loads on the gear (including hard landings) are not ultimate loads.

The load factors presented in the new methodology are for the purpose of allowing the operators an option to waive portions of the hard and overweight landing inspections, provided the load factor is below the threshold and meets the criteria stipulated in the AMM. These load factor thresholds may only be used for normal landings on the main gear; they may not be used for bounced landings or for hard nose gear landings (the nose gear inspection may be waived only if the pilot specifically states that the landing was not a hard nose gear landing).

The basic approach was to maintain the load factors in the current AMM hard-landing inspections for the range of 0–2 degrees of roll and to extend the limits to 6 degrees of roll using the results of the dynamic rolled landing analyses to determine a conservative threshold based on limit landing gear loads. The overweight landing inspection threshold is based on a similar approach, but the threshold line is constant from 0–1 degree of roll, then linear from 1–6 degrees of roll.

The load factor trends used to generate the thresholds presented in this report are based on dynamic landing analyses of several models (737-800, 787-8, 747-8, and 777-300ER) at various sink rates, roll angles, roll rates, and landing weights. The threshold limits represent lines of equivalent main gear maximum vertical load during the landing simulation. The hard landing AMM threshold is based on a landing weight of MLW, and the overweight landing AMM threshold is based on a landing weight of MTOW (to be used for landing weights above MLW+Δ).

The assumptions used to determine the generic normalized function are:

- For landing weights up to MLW+Δ, the value at 0-degree roll angle is equal to the current AMM value, which represents the load factor for a 10 ft/sec landing at MLW with no roll angle and no roll rate.
- For landing weights up to MLW+Δ, the value at 2-degrees roll angle is the same as that for a 0-degree roll angle to be consistent with the current hard landing AMM wording, which defines a constant load factor valid up to 2 degrees of roll.
- For landing weights above MLW+Δ, the incremental load factor ratio is 90% of the weight ratio discussed above and is constant from 0 to 1 degree of roll (the resulting incremental load factor is rounded to two significant figures for each model).
- The value at 6 degrees of roll is based on achieving an equivalent vertical gear load assuming a roll rate of 3 deg/sec, at a reduced sink rate (this value is 50% of the incremental value at a 0-degree roll angle).

Table 4 lists the means of compliance with regard to use of the analytical landing model for purposes of classifying hard landings from normal landings. Analysis methods are proven by the list shown to ensure conservatism, accuracy, and compliance with the requirements listed in the last column of the table.

Table 4. Dynamic landing model and analysis means of compliance

Dynamic Landing Model and Analysis		
Calculation/Analysis	All data sheets, critical landing cases, analytical models, and the Certification Summary will be analyzed and reviewed to verify that compliance is shown for structural design features relative to the regulation and requirements listed in the certification plan. Airplane geometry, stiffness, weight, CG, moments of inertia, ground coefficients of friction, and landing velocity and sink rate data are provided by program-integrated product teams to determine landing case envelopes. Landing gear model element resolution and idealized assumptions must be adequate to capture the accurate characterization of transient effects associated with landing. Adequate modal resolution must be accounted by the model to represent energy absorbed by the gear, body, and wings on landing. Design payload distributions analyzed for critical landing events are based on a series of load combinations in the fuselage derived to provide maximum forward and aft CG; maximum and minimum moments of inertia; maximum bending moments and shear at front and rear spar locations; and maximum vertical loads on the landing gear. Critical load combinations include maximum lateral unbalance and maximum and minimum % MAC, sink rate, and roll angle and rate. Program structures team defines a list of all load locations, which have greatest probability of failure in the event of a landing, (i.e., minimum set of loads at critical locations which would fully cover any and all failures or damage found in Level 1 inspection). At these locations, allowable design margin is included to account for structural yield and uncertainty in the stress analysis. Landing simulations are run for a solution time length after touchdown and time step size to accurately compute all maximum dynamic loads of all critical structures listed above.	CFR 14 Part 25 CFR 25.23 Load distribution limits CFR 25.25 Weight limits CFR 25.27 CG limits CFR 25.1519 MLW, CG, and weight distribution to be an operating limitation
Oversight	The Structures AR's will review the data in the landing analysis and margins used to ensure that it complies with CFR 25.	
Empirical Validation	Model validation is performed by comparison of model results to landing gear drop testing with varying input conditions to ensure the model accurately characterizes structural and viscous damping and energy absorption in the landing gear. Modal test results confirm model accuracy across a frequency range dependent on representing accurate characterization of transient effects associated with landing maximum critical loads.	

3.1.7.7 Reduced-Order HHL Algorithm Means of Compliance

The reduced-order loads models are developed by correlating landing case inputs to peak output load information provided by the full order dynamic landing model. To prove the reduced-order HHL load algorithms meet the same set of requirements, the following means of compliance are performed and verified, as listed in table 5.

Table 5. HHL reduced-order model and analysis means of compliance

Dynamic Landing Model and Analysis		
Calculation/Analysis	All data sheets, critical landing cases, analytical models, and the Certification Summary will be analyzed and reviewed to verify that compliance is shown for structural design features relative to the regulation and requirements listed in the certification plan. No actual hard landings shall go undetected (i.e., the system shall have a hard-landing detection rate of 100%). Safety margins on load outputs are sufficient to account for reduced-order model uncertainty, landing model uncertainty, onboard input signal fidelity due to frame rates, filters, and trigger sample delays. Safety margins fully account for landing model data uncertainty because this information is used for development of HHL algorithms. Landing model data input sets used to develop the HHL algorithms represent the full extent of worst case landings and fill the envelope with adequate resolution for accurate model interpolation. Validation cases used to ensure model regularization (accuracy without overfitting) spans the data space of normal operation. Safety margins fully account for sources or error in the reduced-order model based on a P90/95 basis. Safety margins account for error in signal fidelity (i.e., flight parameter measurement frame rate, sample delay, and signal latency) for all model inputs. Safety margins account for applying one universal landing model to predict landing loads on all unique aircraft throughout the fleet. Input limit checking is required to ascertain the ability of the model to accurately predict loads. If any input is outside the bounds of data used to develop the models, this HHL system is not used. Example cases include high crab angle and roll conditions, bounced landings, and nose pitch-over cases.	CFR 14 Part 25 CFR 25.23 Load distribution limits CFR 25.25 Weight limits CFR 25.27 CG limits CFR 25.1519 MLW, CG, and weight distribution to be an operating limitation DO-178B RTCA/DO-248B FAA Order 8110.49
Oversight	The Structures AR's will review the data in the landing analysis and margins used to ensure that it complies with CFR 25.	
Empirical Validation	Model validation is performed by comparison of model results to landing gear drop testing with varying input conditions to ensure the model accurately characterizes structural and viscous damping and energy absorption in the landing gear. Modal test results confirm model accuracy across a frequency range dependent on representing accurate characterization of transient effects associated with landing maximum critical loads.	

3.1.7.8 System Architecture

For purposes of this certification plan, the assumption is made that the loads prediction algorithms used for HHL inspection determination reside in the ACMS of the common core system (or equivalent or higher DAL) and will rely on the same data processed in the ACMS for general functionality. Therefore, the certification methods in this report will follow much of the same process and deliverables as proposed in the Certification Plan 14199, which addresses the update to the AIMS-2 platform on the 777.

The systems and software certification level required to waive an inspection remains a controversial topic; however, in this report, the assumption is that Level B software and Level C system and incoming signals are required, because these levels represent the existing practice.

The assumption in this report is that the HHL system is hosted by the Airplane Health Monitoring (AHM) system, including software that resides in the ACMS. The ACMS is comprised entirely of software that executes in the Common Core System and is used to monitor, process, and store data from airplane systems for report generation [4]. ACMS reports are used for routine operations and to monitor engine, APU, and other airplane systems and overall airplane performance. Specifications for ACMS display screens, access security, monitored data, report generation, and logic modules to trigger those reports are entered using the Ground-Based Software Tool customized by the airlines. ACMS provides the ability to record data based on AMI-defined trigger conditions and has a high sample rate mode.

The process flow for HHL inspection determination includes the measurement of raw instrumentation measurements, algorithms used to compute single value peak parameters to be input to the HHL model, signal path to ACMS, software that executes the HHL routines on the ACMS, outputs load information, comparisons of each load to its respective limit, and maintenance action directions displayed to the maintenance crew on the landing condition maintenance page. The affected integrated product teams (IPTs) for carrying out this process include systems, avionics, displays, flight manuals, flight controls, structures, and maintenance.

The automated maintenance computer accesses accurate flight parameter data with high-integrity software per 14 CFR 8110.49. Software updates guided by the system function requirements are necessary for the insertion of HHL load prediction algorithms.

Flight parameter data bandwidth must be proven adequate to reliably and accurately predict structural loads.

Data reduction must be reliably performed by onboard software and the processes and proven repeatable.

The following flight parameters accessed and received by the ACMF is the minimum list of information required for landing severity determination by the HHL system. These flight parameter inputs shall be reported in engineering units, as listed in table 6.

Table 6. HHL load prediction model input parameters

HHL LOAD MODEL INPUTS		
NAME	DESCRIPTION	UNITS
SINK RATE	airplane vertical sink rate	ft/s
ATTITUDE	airplane pitch attitude	deg
ROLL ANGLE	airplane roll angle (positive right gear down)	deg
ROLL RATE	airplane roll rate (positive right gear down)	rad/s
SINK ACCEL	initial sink acceleration (positive down)	g
GROSS WEIGHT	gross weight	lb
CG	CG	%MAC
+BAPILOT	maximum vertical load factor at pilot seat	g
+BACG	maximum vertical load factor at CG	g
KEAS	equivalent air speed	knots

The architecture and data flow management for such data to be used for landing inspection assessment is shown in figure 10.

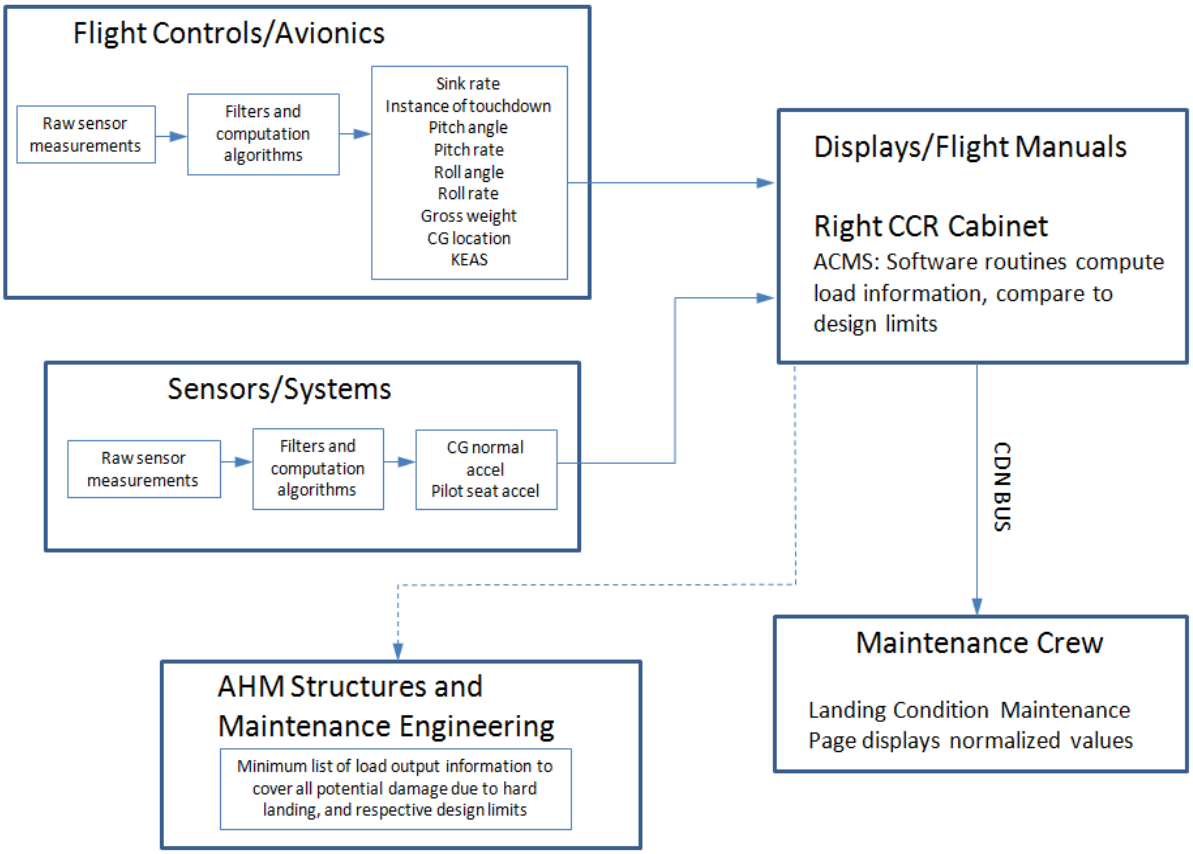


Figure 10. HHL system level data flow

The current process by which flight parameter information is used to make an informed maintenance decision once the pilot makes a hard-landing call is performed by displays/flight manual teams, which includes determination of measured flight parameters and comparing each to predetermined respective limits:

- Reference the aircraft weight.
- Reference the maximum (structural) landing weight of the aircraft.
- Prior to touchdown, reference CG sink rate.
- Prior to touchdown, reference pitch attitude.
- Prior to touchdown, reference crab angle.
- Prior to touchdown, reference roll attitude.
- Prior to touchdown, reference body roll rate.
- Prior to touchdown, reference CG normal acceleration.
- At touchdown, reference peak CG normal acceleration.
- At touchdown, reference body pitch rate.

The new HHL technology takes this information one step further and passes the flight parameters through a routine that includes a number of linear and nonlinear mathematical operations for the computation of landing loads. This process is described in detail in appendix C of Boeing's proprietary version of this report.

3.1.7.8.1 Core Software Discussion

The AIMS core consists of eight software partitions that will be hosted in the AIMS cabinet. The feature modifications for HHL determination are to be developed and verified by the software supplier.

All AIMS core software, including HHL software, will comply with DO-178B, RTCA/DO-248B, and FAA Order 8110.49 Change Order 1.

3.1.7.8.2 ACMF Software Discussion

AIMS ACMF application software will comply with DO-178B and RTCA/DO-248B, with only the errata sections of RTCA/DO-248B applying, and FAA Order 8110.49 Change Order 1.

The ACMF AMI software is considered user-modifiable software as defined in FAA Order 8110.49 Change Order 1. An ACMF AMI built for the left ACMF partition will be incompatible with the right ACMF partition, and an ACMF AMI built for the right ACMF partition will be incompatible with the left ACMF partition.

3.1.7.9 Systems/Software Means of Compliance

The means of compliance to ensure that the onboard loads software and the system in which it resides meets certification requirements are shown in table 7.

Table 7. HHL load inspection determination outputs

Avionics-AIMS		
Calculation/Analysis	All pertinent engineering drawings, data sheets, System Description Documents, and the Certification Summary will be analyzed and reviewed to verify that compliance is shown for design features relative to the regulation and requirements listed in the certification plan. Analysis is used for the Similarity Analysis deliverable to verify models not covered in the ground- and flight-test deliverables remain in compliance with the applicable regulations with new software.	DO-178B RTCA/DO-248B FAA Order 8110.49
Software	The System AR will review the data in the software documents to ensure that it complies with systems-related aspects.	
Software-Lvl_A_C2_L_Special_IMA_Platform Software-Lvl_D_C2_L_Special_IMA_Platform		
Software	The Software AR will review the data in the document to ensure that it complies with all the applicable requirements of DO-178B, Order 8110.49 Change Order 1, and errata to DO-178B in DO-248B for the appropriate software level, and will review the supplier's records to ensure that there is evidence that the software activities conformed to those requirements. DO-178B is the FAA-approved means of compliance per AC 20-115B.	DO-178B Order 8110.49 Change Order 1 errata to DO-178B in DO-248B AC 20-115B
Software-Lvl_B_C2_B_Electronic_Equipment/Systems Software-Lvl_B_C2_F_Navigation_Systems/Antennas		
SW - Software	The Software AR will review the data in the document to ensure that it complies with all the applicable requirements of DO-178B, Order 8110.49 Change Order 1, and errata to DO-178B in DO-248B for the appropriate software level, and will review the supplier's records to ensure that there is evidence that the software activities conformed to those requirements. DO-178B is the FAA-approved means of compliance per AC 20-115B.	DO-178B Order 8110.49 Change Order 1 errata to DO-178B in DO-248B AC 20-115B

Table 7. HHL load inspection determination outputs (continued)

Avionics-DISPLAYS		
Calculation/Analysis	All pertinent engineering drawings, data sheets, System Description Documents, and the Certification Summary will be analyzed and reviewed to verify that compliance is shown for system design features relative to the regulation and requirements listed in the certification plan. Analysis is used for the Similarity Analysis deliverable to verify that models not covered in the ground- and flight-test deliverables remain in compliance with the applicable regulations with new software.	DO-178B Order 8110.49 Change Order 1 errata to DO-178B in DO-248B AC 20-115B
Safety Assessment	A System Safety Assessment, including failure modes and effects analysis and a fault analysis, will be used to show that any failures of the system changes will not contribute to a Hazardous or Catastrophic condition to the aircraft or to any interfacing system. The results of the analysis will be documented in a Boeing Airplane Information System Safety Analysis document. Updates to the Safety Analysis for the Displays/Central Maintenance Computing Function changes are limited to category Minor (2) or Major (3) conditions, and show there are no upgrade changes affecting category Hazardous (4) or Catastrophic (5) conditions.	AC 23-1309
SW - Software	The System AR will review the data in the software documents to ensure that it complies with systems-related aspects.	
Avionics-ACMS/DMU		
Calculation/Analysis	All pertinent engineering drawings, data sheets, System Description Documents, and the Certification Summary will be analyzed and reviewed to verify that compliance is shown for system design features relative to the regulation and requirements listed in the certification plan. Analysis is used for the Similarity Analysis deliverable to verify that models not covered in the ground- and flight-test deliverables remain in compliance with the applicable regulations with new software.	DO-178B Order 8110.49 Change Order 1 errata to DO-178B in DO-248B AC 20-115B
Software	The System AR will review the data in the software documents to ensure that it complies with systems-related aspects.	

Table 7. HHL load inspection determination outputs (continued)

Avionics-CENTRAL MAINT COMPUTER		
Safety Assessment	A System Safety Assessment, including failure modes and effects analysis and a fault analysis, will be used to show that any failures of the system will not contribute to a Hazardous or Catastrophic condition to the aircraft or to any interfacing system. The results of the analysis will be documented in a Boeing Airplane Information System Safety Analysis document. Updates to the system Safety Analysis for the Displays/Central Maintenance Computing Function changes are limited to category Minor (2) or Major (3) conditions. There are no system changes affecting category Hazardous (4) or Catastrophic (5) conditions.	DO-178B Order 8110.49 Change Order 1 errata to DO-178B in DO-248B AC 20-115B
Calculation/Analysis	All pertinent engineering drawings, data sheets, System Description Documents, and the Certification Summary will be analyzed and reviewed to verify that compliance is shown for system design features relative to the regulation and requirements listed in the certification plan. Analysis is used for the Similarity Analysis deliverable to verify that models not covered in the ground-and flight-test deliverables remain in compliance with the applicable regulations with new software.	
Software	The System AR will review the data in the software documents to ensure that it complies with systems-related aspects.	
Software-Lvl_D_C2_B_Electronic_Equipment/Systems Software-Lvl_D_C2_J_Flight_Data/Voice_Recording		
Software	The Software AR will review the data in the document to ensure that it complies with all the applicable requirements of DO-178B, Order 8110.49 Change Order 1, and errata to DO-178B in DO-248B for the appropriate software level, and will review the supplier's records to ensure that there is evidence that the software activities conformed to those requirements. DO-178B is the FAA-approved means of compliance per AC 20-115B.	DO-178B Order 8110.49 Change Order 1 errata to DO-178B in DO-248B AC 20-115B
Flight Test-Flight Analyst Flight Test-Flight Test Pilot		
Flight Test	A flight test will be conducted to demonstrate proper performance of the system changes in flight to show compliance with the applicable regulations/requirements listed in this certification plan.	

These compliance standards are carried through to implementation of newly added software and followed by functionality testing to verify they meet the reliability targets outlined in the DAL definitions, as advised by the flight-hazard assessment.

3.1.8 HHL Summary and Conclusions

HHL as an SPMS example uses existing data from the aircraft and provides information regarding the aircraft's exposure to load and stress environments. This information can be used to more accurately assess the current aircraft structural condition, resulting in a more efficient inspection process. Though, theoretically, more data and information (of sufficient quality) can

enhance the ability to evaluate the structural condition, there are challenges when trying to make autonomous decisions with these additional data and information. For example, current HHL maintenance procedures are initiated on a decision from the pilot. Individual differences in pilot sense of feel and differences in airline-to-airline policies are some factors that can affect the acceptance of autonomous technologies. An overall reluctance to shift decision authority from the pilot to an autonomous system has been met with significant resistance; however, airlines believe it to be the appropriate direction for discerning landing severity.

To this end, the nearest-term technology implementation strategy for automated HHL determination has been initially focused on using it as a "maintenance aid." That is, the HHL system would be used after the pilot declares a hard landing to aid the maintenance personnel in determining the severity of the landing and/or indicate which structural details experienced the highest loads during the event. The proposed method for predicting HHL loads could be thought of as the first step toward CBM for landings. The advantage this technology offers is that it can add operational capability by knowing usage loads determined by existing onboard data, with the algorithm as the centerpiece.

The landing load algorithm offers increased accuracy and capability in fitting a multidimensional and nonlinear data space that describes a complex dynamic event, thereby resulting in an approximately 30% reduction in false call rates. Furthermore, because of the computational efficiency, the loads algorithms can reside on board the aircraft and provide the operators near real-time assessments, which is useful and more reliable and repeatable than manual methods.

The natural evolution of the HHL system may allow a prognostic capability to determine the residual life of aging structures. Currently, statistical models are used, which are based on cycles and stress on a part to infer its remaining life. Structural design limit criteria are based on a life model consisting of expected cycles and stress the part will experience throughout its life. However, these statistical models are conservative estimates in comparison to the actual loads and cycles a part will experience over its life and therefore may result in the premature retiring of that part. With new approaches like the HHL load-based method, in which actual loads and cycles are monitored and recorded, a purely statistical model may no longer be solely relied on and conservatism can be reduced, thereby allowing airlines to operate the airframe for the full duration of its actual life and maximizing airline investment. For the HHL method to be realizable for such an application, landing loads should be recorded for every landing across the fleet throughout the life of the airframe. This information is used to update the life model and extend its use past original design curves for each respective part.

This technology can also be extended to enhance additional capability for benefits across the flight regime. Implementation and operational use of HHL loads-based methodology on a commercial platform can result in the adoption of other structural health management technologies. For example, in-flight loads monitoring across additional load cases and flight regimes, such as gust and flight-critical maneuvers, could be used to influence maintenance and operations, structural life extension, and structural design in the future.

To be realized as a fielded technology, these loads algorithms are challenged by certification and acceptance across the industry. HHL software implemented as modifiable software for dispatch

relief whose erroneous output could cause failure to detect a potentially unsafe condition must be compliant with FAA CFR (i.e., FAA order 8110.49 and DO-178). The required software level is Level B/C, which is the established level for dispatch-dependent information/data. With respect to systems design, avionics, and data sourcing, the HHL load prediction system acceptance methods will be similar in nature to a software functionality update to an onboard maintenance information management system. Therefore, the certification methods developed in this report as they pertain to software and systems follow much of the same process and requirements as proposed for certification plans for fielded systems.

With regard to model validation, all data sheets, critical landing cases, analytical models, and certification summaries will be analyzed and reviewed to verify that compliance is shown for structural design features relative to the regulation and requirements listed in the certification plan. Airplane geometry, stiffness, weight, CG, moments of inertia, ground coefficients of friction, and landing velocity and sink rate data are provided by program IPTs to determine landing case envelopes. Landing gear model element resolution and idealized assumptions must be adequate to capture the accurate characterization of transient effects associated with landing. Adequate modal resolution must be accounted for by the model to represent energy absorbed by the gear, body, and wings on landing. Design payload distributions analyzed for critical landing events are based on a series of load combinations in the fuselage derived to provide maximum forward and aft CG; maximum and minimum moments of inertia; maximum bending moments and shear at front and rear spar locations; and maximum vertical loads on the landing gear. Critical load combinations include maximum lateral unbalance and maximum and minimum % MAC; sink rate; and roll angle and rate. A program structures team defines a list of all load locations, which have greatest probability of failure in the event of a landing (i.e., minimum set of loads at critical locations which would fully cover any and all failures or damage found in Level 1 inspection). At these locations, allowable design margin is included to account for structural yield and uncertainty in the stress analysis.

Landing simulations are run for a solution time length after touchdown and time step size to accurately compute all maximum dynamic loads of all critical structures. The structure AR will review the data in the landing analysis and margin analysis to ensure that they comply with 14 CFR 25.

Lastly, model validation is performed by comparing model results to landing gear drop testing with varying input conditions to ensure the model accurately characterizes structural and viscous damping and energy absorption in the landing gear. Modal test results are also used to confirm model accuracy across a frequency range to represent accurate characterization of transient effects associated with the dynamic landing event. With limited flight-test validation, the technology can be inserted as part of the overall routine for landing severity assessment as an in-service aid alongside the current methods. With time, confidence in the assessment will be gained, and loads-based algorithms, such as the one described in this report for HHL, will lead the industry for future evolution of maintenance and operations capability.

3.2 REMOTE NON-DESTRUCTIVE TESTING

3.2.1 General Description of the Problem/Objective

Composite materials are increasingly common on large commercial aircraft and, as heralded by the Boeing 787, will soon become the predominant material. Like any material on these aircraft, composite materials are subject to damage in service. However, unlike some other materials, permanent repair methods can be quite involved and are normally undertaken only at heavy maintenance facilities. This leaves the problem of what to do when damage to an airplane is caused or discovered at the airport loading gate. If repair equipment is not available or if the repair would take too long, the flight is cancelled. The airplane could even be grounded and ferried to a maintenance base, resulting in even greater economic loss to the airline.

In an effort to address this problem, rapid low-tech repair schemes have been proposed in the industry. Boeing is actively at work on some of these concepts. They would involve the application of a “temporary structural repair” that would restore the damaged structure, but only until the next heavy maintenance visit. It would be applied over the damage instead of removing the damage. However, this concept raises the questions of how to determine, in an airplane gate situation, the extent of damage and, without knowledge of the depth and extent of the damage, how to determine if a temporary repair patch can restore the structure.

The objective of this SPMS application study is to describe the technology for efficient inspection and assessment of damage and implementation, concept of operation, requirements for practice, and acceptance and validation of procedures.

3.2.2 Unique Problem Characteristics

For thin-skinned honeycomb sandwich structures, industry data shows that an audible tap test is sufficient to determine the extent of subsurface damage. However, newer airplanes incorporate large honeycomb sandwich elements with thick face sheets, such as flaps, landing gear doors, and raked wing tips. Tap testing is generally inadequate for detecting skin delamination beyond several plies in depth.

For solid laminate structures, which represent the majority of the external surface of the 787, the same situation exists. Tap testing has been shown to be inadequate on solid laminates.

Therefore, there is a need for a fast and reliable method to disposition an airplane that arrives at the gate with known or suspected impact damage on composite structures. The damage must be categorized as one of the scenarios shown in figure 11. Visual and tap test inspections cannot determine the full extent of damage, so a decision on flying the airplane cannot be made. The airplane must be grounded until skilled NDT personnel can arrive from a maintenance base, often in another city or state.

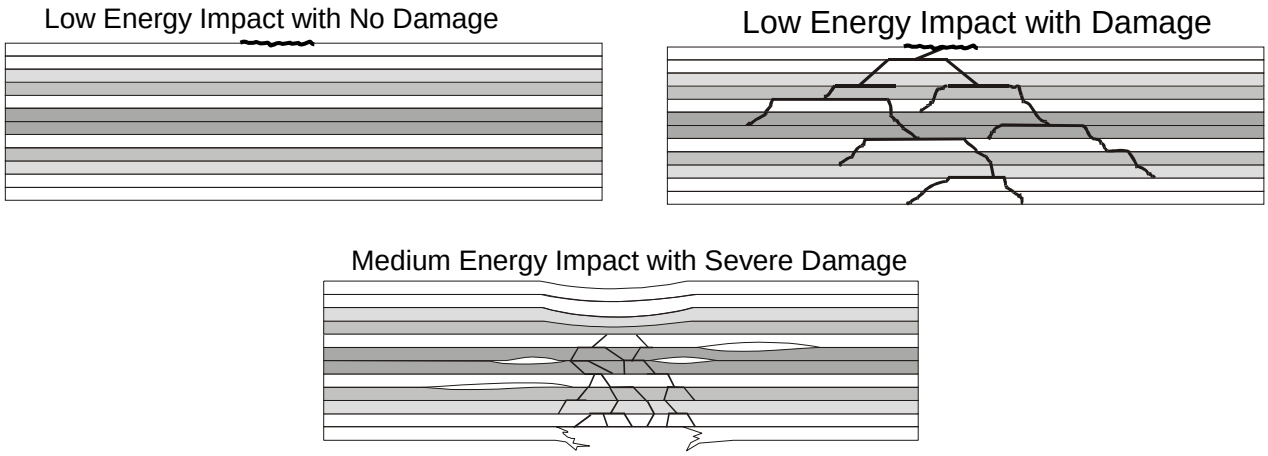


Figure 11. Damage scenarios in which interim repairs are considered; visible surface indications may or may not be associated with subsurface damage, and ultrasonic inspection is required to determine damage extent

3.2.3 Methods and Devices

Currently, visual inspection is envisioned to be the primary means of dispositioning damage. Measurements of damage width, length, and depth will be correlated with engineering data showing an assumed, conservatively drawn subsurface damage distribution. This represents the "allowable damage limits." For certain structures, a second set of allowable damage limits will be available. These will be less conservative and will enable the operator to dispatch more airplanes. They will be based on the presence and use of NDT to precisely map the subsurface damage or establish its absence.

Low-skill NDT devices have been conceived that bring a non-destructive test capability to the airport dispatch environment. Each has a particular scope of application. The solutions suffer from the following limitations:

- Visual inspection cannot discern subsurface damage, so the more generous set of allowable damage limits (based on NDT) cannot be exploited for improved dispatch rates.

- The simplified NDT devices are easily confused by complex structures. They are generally designed as "screening" devices, responding with a red light to any change in structure that cannot be identified. The red light signals a need to advance to the next step, which is full-fledged NDT with a trained technician. Unfortunately, trained technicians are often not available near an airport loading gate and must be brought in; flight cancellation is an inevitable consequence. Dispatch-rate enhancements enabled by simplified NDT devices could be further improved if skilled NDT interpretation were available on the scene.

3.2.4 Remote NDT for Composite Aircraft (U.S. Patent 8255170)

A new approach involves a method of bringing skilled NDT interpretation to line maintenance by using transmission and remote interpretation of the results obtained by local maintenance personnel. Decisions could be made hundreds of miles from the scene in time to dispatch an airplane with minimal delay or remove it from service for repair. This approach takes advantage of wireless data transmission and Internet technology already developed but never applied to the NDT arena in airplane line maintenance.

It is anticipated that the necessary data will be transmitted through commercial wireless networks; however, a dedicated wireless hub could be installed to connect a particular airport area with the aircraft operator's computer network. The process is intended to link the airport gate personnel to skilled industry NDT personnel.

Real-time data transfer will be critical. An example of an NDT technology that will be ideal for remote line maintenance NDT is the AcoustoCam™, made by Imperium, of Silver Spring, Maryland. Photographs of a recent model (i600) of the AcoustoCam are shown in figure 12. The system was developed with technical guidance, testing, and feedback from Boeing and has been investigated for finding damage in 787 fuselage structure with a backside hat stiffener. A computer screen can be viewed at a remote site by an NDT expert while the on-site operator is using it. In addition, other data can be fed to the technician, such as an optical video (using a video camera mounted on the instrument or on a tripod next to the operator); ultrasonic C-scan and A-scan data; and location information. An example of a graphical user interface (GUI) that supports remote NDT is the AcoustoCam interface, shown in figure 13.

(a) (b)

Figure 12. The (a) AcoustoCam End Effector and (b) AcoustoCam system

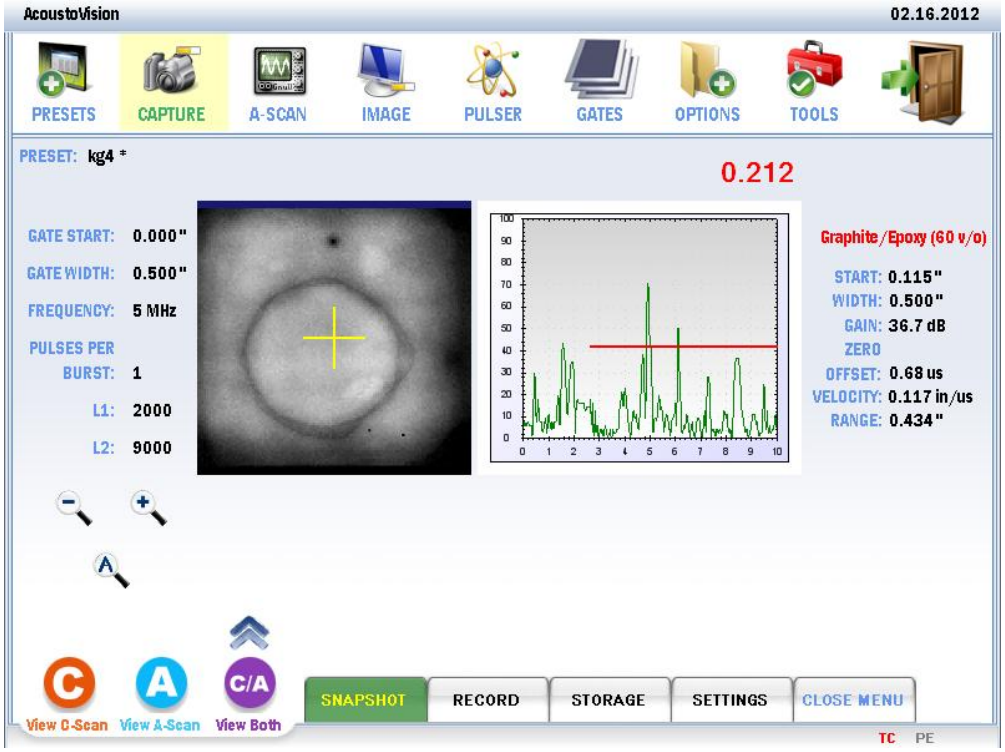


Figure 13. AcoustoCam's GUI, available on-site and remotely, showing a live video pulse-echo C-scan image on the left and live A-scan representation of the waveform at the center of the C-scan image (at the cross hairs)

If a video camera is also used, a real-time video image of the actual inspection (not shown) can also be available to the NDT expert interacting remotely with the on-site AcoustoCam operator.

3.2.5 Remote NDI Concept of Operation

Schematics for the remote NDT process for addressing composite impact damage, including data flow, hardware, and decision-making, are shown in figures 14–16. The real-time wireless data and video interfaces will enable rapid decision-making in situations in which time is critical.

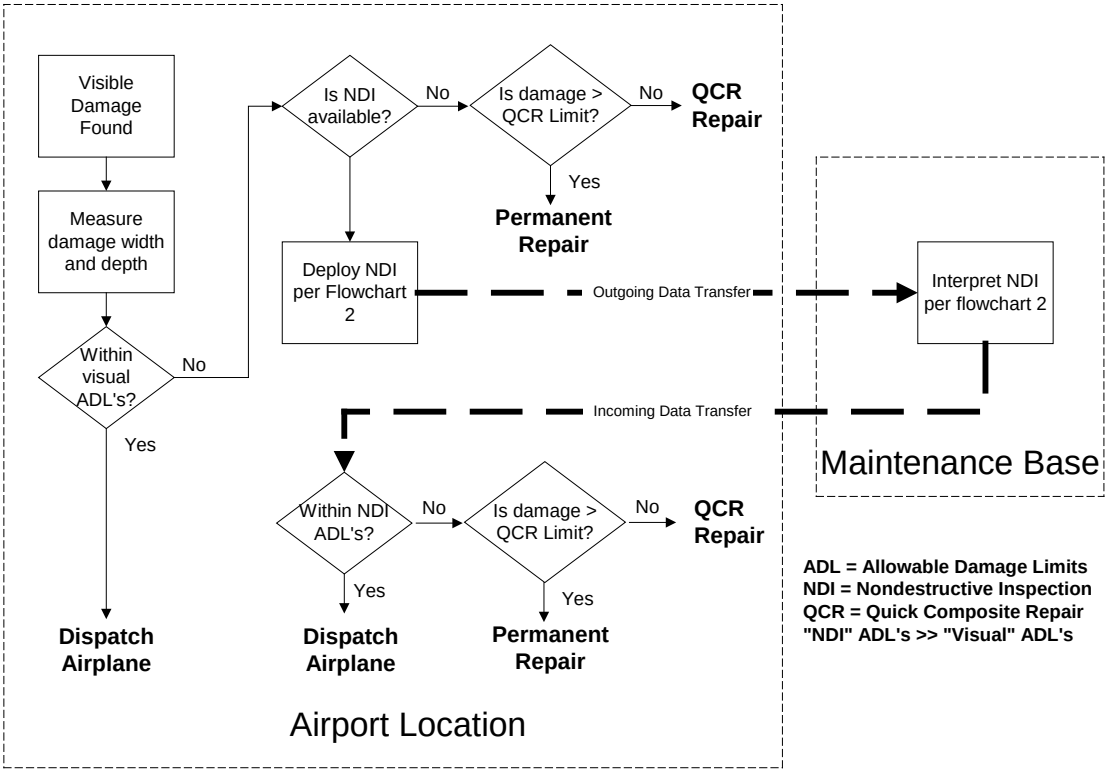


Figure 14. Flowchart showing damage evaluation/repair decision sequence

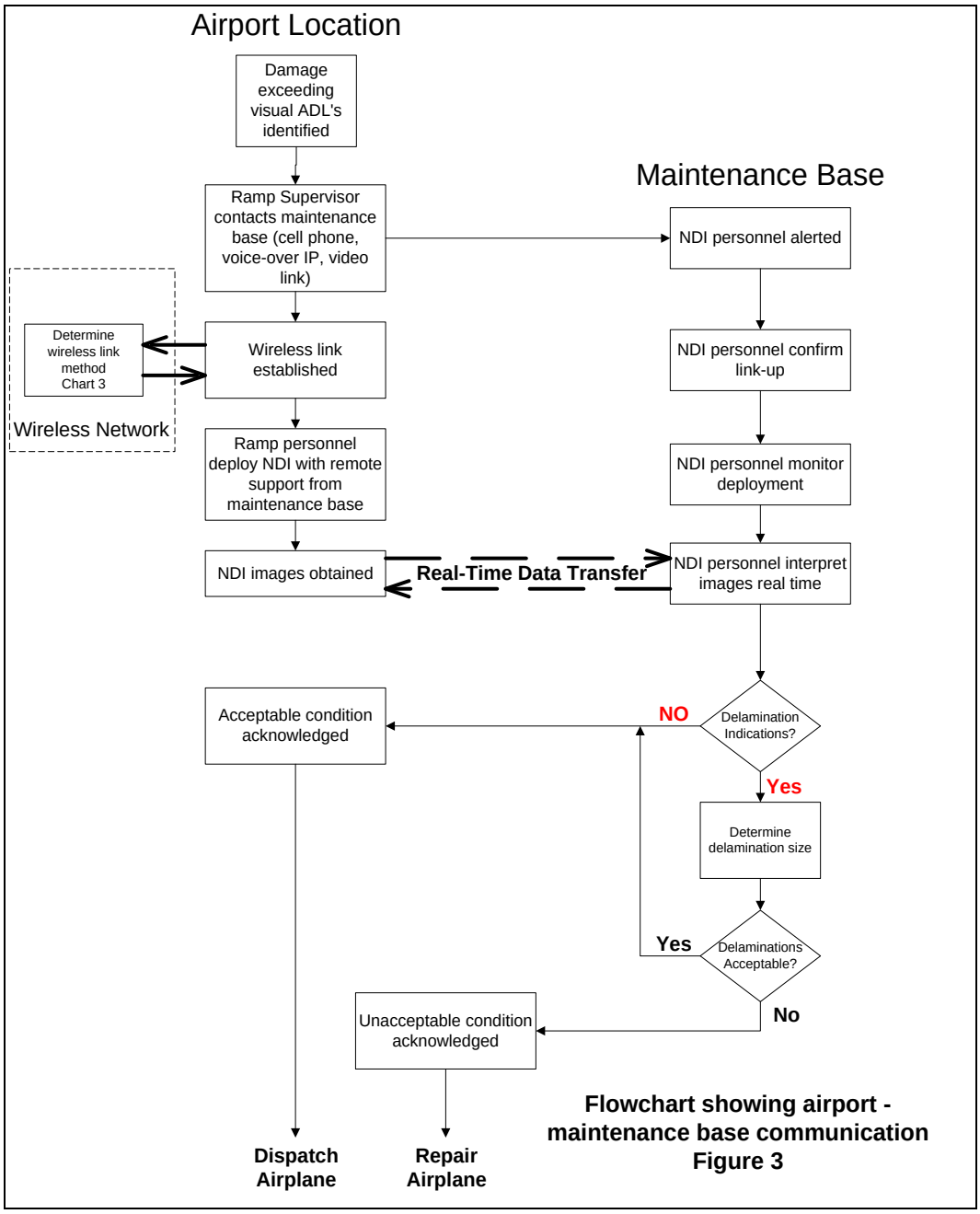


Figure 15. Flowchart showing airport–maintenance base communication

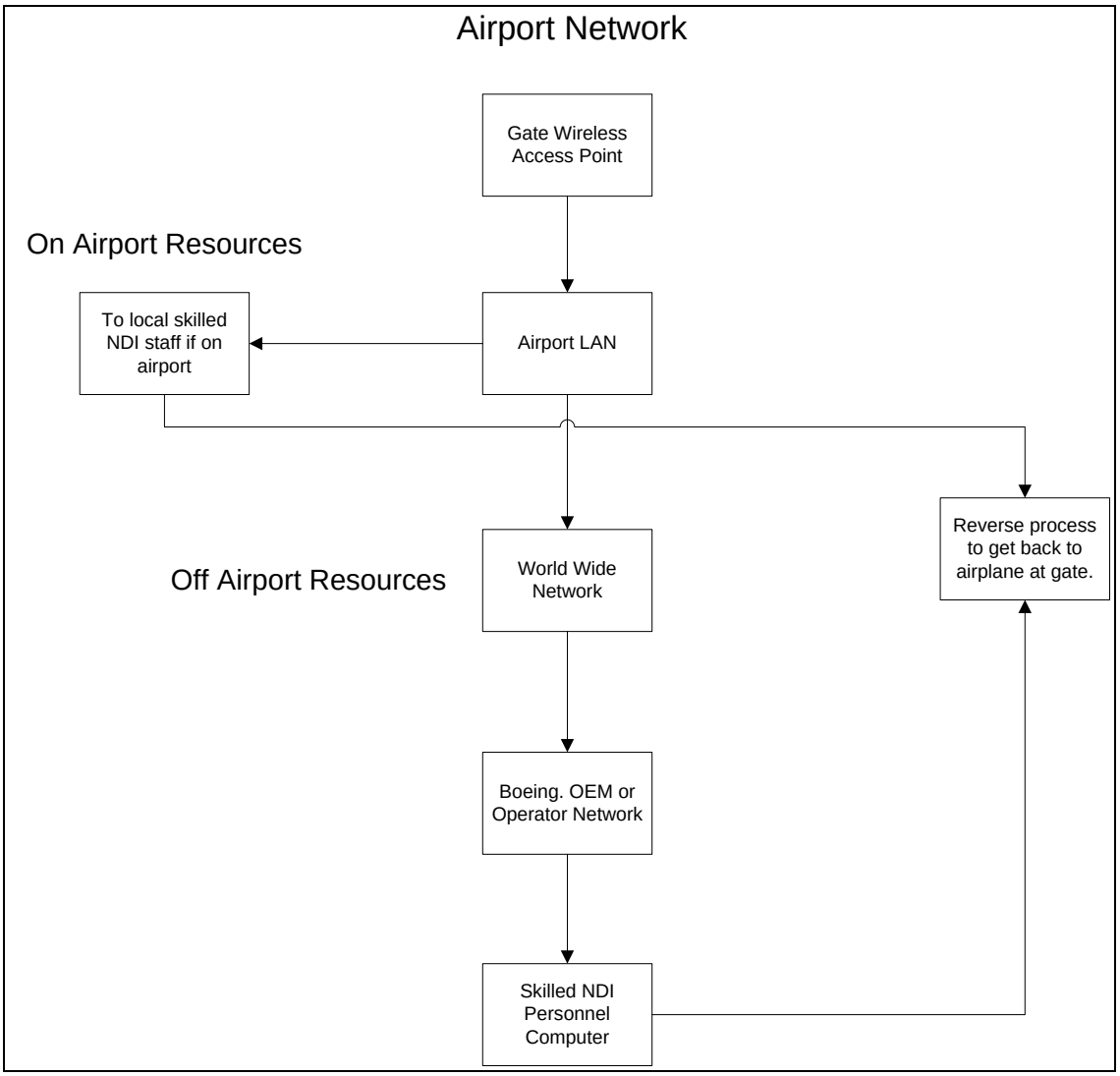


Figure 16. Flowchart showing computing infrastructure

If available for the 787 and other composite aircraft inspections, this methodology would:

- Provide rapid disposition of potential impact damage (fly as is, quick repair and fly, pull out of service and repair), including flight operations modifications in a timely manner.
- Reduce the cost and time required to perform impact-damage inspection.
- Decrease the number of inspections requiring experts at the aircraft.
- Optimize the use of skilled NDT personnel.
- Reduce training requirements for field evaluators.
- Provide permanent, verifiable, and accurate records of remote inspections, if desired.

With the increasing use of composite primary structures in the commercial aerospace industry, there is a critical need for rapid NDT approaches that minimize the requirements for trained NDT expertise at every airport. NDT is essential for commercial airline operators to effectively

maintain in-service fleets. However, the current state is not well matched to the growing use of composite aircraft structures because:

- Operators currently rely on the costly and sometimes time-consuming deployment of certified inspectors.
- The current state requires extensively trained and highly skilled inspectors.
- Most inspections are on familiar metal structures using mature techniques.
- Atypical indications encountered in the field call for higher-level experts and the use of more sophisticated equipment.
- There is currently no central database of inspection information/history, no common format on data files, and no capability to transmit high-fidelity non-destructive evaluation (NDE) images and signals over a network.

Composite commercial aircraft, like the 787 Dreamliner, will challenge the operators because:

- The existing inspector base is unfamiliar with the advanced composites used.
- Equipment designed for inspecting metal structures may not be optimal.
- Composites require a greater degree of experience-based interpretation.
- Customers will require assistance in inspecting indications to determine airworthiness as they are encountered at line stations around the world.

3.2.6 Remote NDT Case Study

The three scenarios described in sections 3.2.6.1–3.2.6.3 were demonstrated as part of the remote NDT case study as viable embodiments of remote NDT for commercial applications.

3.2.6.1 Scenario #1: Remotely Assisted NDT

The following are the details of Scenario #1:

- 787 at a remote airport.
- Impact event was heard or witnessed.
- A local non-NDT user is operating the instrument with prompting from an NDT expert at a maintenance base.
- The accept/reject decision was made by an NDT expert.

When a possible damage incident occurs, an on-site person contacts a remote NDT expert to assist with the inspection of the potentially damaged area. The operator of a networkable NDT tool is summoned to the aircraft and connects with the remote NDT expert through an online collaboration tool such as WebEx. A webcam is set up to show the damaged area and the operator's scanning movements. The NDT expert verbally instructs the on-site person as he sets up the NDT tool with settings appropriate to the structure in the suspected damage area.

The NDT data is captured by the on-site person while the expert guides their scanning motion and observes the inspection results in real time. Using the Webcam imagery, the expert is able to verify that the on-site person is scanning the inspection area correctly and with the correct

system settings. The expert saves the report after the data is collected and ensures the report is complete. The report includes, as a minimum, the aircraft tail number, damage location, NDT data, system settings, a photograph of the damage (with a scale to show size), a photograph of the damage relative to surrounding features (to document and verify the specific damage location), operator name, expert name, and date/time of the inspection. The accept/reject decision is made by the certified expert who has remotely supervised the entire inspection. The expert is able to validate the data, accept the result, and verify the report as being accurate and complete. This report, minus the NDT device data, would typically be retained in practice, as it is today, per regulatory agency requirements. An operator might also consider saving the NDT data for the first several years of practicing remote NDT as part of its introduction to service. After remote NDT is matured and confidence is built in the method and remote NDT devices, only the results of the inspection would likely be saved for the life of the aircraft. However, the bonded repair size limits (BRSL) policy that is coming out recommends keeping records for in-service repair for the life of the aircraft.

Note: A slight modification of Scenario #1 is for the expert to take control of some or part of the inspector's NDT tool, using remote-enabling software such as Lync. This eliminates the need for step-by-step verbal instruction. In this scenario, the on-site operator is responsible only for the powering-up and movement of the inspection device.

3.2.6.2 Scenario #2: Simplified NDT by On-Site Operator

The following are the details of Scenario # 2:

- 787 at a remote airport.
- Impact event was heard or witnessed.
- A local non-NDT user downloads a setup file designed by an expert user for this specific situation.
- Local user performs inspection unsupported.
- The accept/reject decision is made by the remote expert who receives the report from the local user.

When a potential damage incident occurs, an on-site person contacts a local person who has been given the basic training for using a simplified NDT tool. The local operator (LO) selects the appropriate inspection scenario from an online library and downloads an interactive, sequential procedure onto the NDT tool. He then follows the step-by-step instructions for performing an inspection, including scanning a reference standard and comparing it to the digital image provided.

The operator conducts the actual inspection unsupported. The NDT data is captured and a report is generated as the operator follows the steps he is given. The operator cannot advance to any step without completing and documenting the previous step. At the end of the inspection, the operator sends the inspection report to the remote NDT expert. The report includes, as a minimum, the aircraft tail number, damage location, NDT data, system settings, a photograph of the damage (with a scale to show size), a photograph of the damage relative to surrounding

features (to document and verify the specific damage location), operator name, date/time of the inspection, and space for a remote NDT expert to sign off after a review.

The expert examines the NDT data, reads the report that is compiled from the data collected, and ensures the report is complete. The operator is still present at the aircraft during this review and the opportunity to engage in dialog and ask questions is available. An accept/reject decision is made by the certified expert once he is satisfied with the results of the inspection. This report, minus the NDT device data, would typically be retained in practice, as it is today, per regulatory agency requirements. An operator might also consider saving the NDT data for the first several years of practicing remote NDT as part of its introduction to service. After remote NDT is matured and confidence is built in the method and remote NDT devices, only the results of the inspection would likely be saved for the life of the aircraft. However, the BRSL policy that is coming out recommends keeping records for in-service repair for the life of the aircraft.

3.2.6.3 Scenario #3: Advanced Remote NDT Using Local Positioning System and Integrated Visualization Tool

The following are the details of Scenario #3:

- Aircraft in a depot maintenance hangar, maintenance repair and overhaul (MRO), or remote location.
- A local non-NDT user is guided through a sophisticated inspection by a remote expert.
- Results are captured and placed in structural context.
- The accept/reject decision is made by a remote NDT expert.

When a damage incident occurs that will require a repair, the aircraft is taken offline and moved to a depot maintenance hangar or MRO (in the rare case the aircraft cannot be moved without at least a temporary repair, a remote inspection may be performed wherever the aircraft has landed). An on-site person contacts a remote NDT expert to collaborate on an inspection of the damaged area. A network connection is established through the local wireless hub so that visual situational awareness, audio interaction, and remote position indexing and scanner control can all be completed in real time.

An NDT tool capable of collecting NDT data of the damaged area (such as the Boeing Mobile Automated Scanner [MAUS®]) is brought to the aircraft. The remote expert guides the on-site operator in setting up the system. A positioning system, such as the Boeing Local Positioning System (LPS), is also brought in and set up by the on-site personnel, with guidance from the remote NDT expert. The positioning system is guided in real time by the remote expert to tie both the damage and the NDT scanner into the aircraft coordinate system. The NDT data is then captured while the expert observes the inspection. The expert is able to verify that the scanner is performing the inspection correctly, with the correct system settings, in the correct location.

The remote NDT expert compiles the inspection report after the data is collected and ensures the report is complete. The report includes, as a minimum, the aircraft tail number, damage location, NDT data, system settings, a photograph of the damage (with a scale to show size), a photograph of the damage relative to surrounding features (to document and verify the specific damage

location), operator name, expert name, and date/time of the inspection. When a positioning system is used, damage location verification can also include location information in actual aircraft coordinates, video documentation of the damage in context, and the inspection itself. The expert is able to validate the data, accept the results, and verify the report as being accurate and complete. This report, minus the NDT device data, would typically be retained in practice, as it is today, per regulatory agency requirements. An operator might also consider saving the NDT data for the first several years of practicing remote NDT as part of its introduction to service. After remote NDT is matured and confidence is built in the method and remote NDT devices, only the result of the inspection would likely be saved for the life of the aircraft. However, the BRSL policy that is coming out recommends keeping records for in-service repair for the life of the aircraft.

In this "advanced" remote NDT scenario, the additional capability provided enables a remote repair analyst to immediately begin analyzing the damage and designing the appropriate repair. The positioning system controlled remotely by the expert creates a positional correspondence of the 2-D NDT scan registered in the coordinate system of a 3-D computer-aided design (CAD) model visualization environment. The 3-D CAD model environment may be the Boeing Integrated Visualization Tool or something equivalent, which enables visualization and interaction with the data in 2-D and 3-D analysis software. The damage location, size, and geometry relative to previous damage and repairs and structural features are provided to the repair analyst, who has interactive computer control of both the NDT data and the 3-D model of the structural environment.

Though the repair must be undertaken by on-site personnel certified to conduct and accept the repair, the design can be completed remotely using the information provided by the advanced remote NDT method. Post-repair inspection can be performed using the same or similar scan system, guided by the remote NDT expert.

3.2.7 Remote NDT Inspection Validation and Certification

The validation and certification of remote NDT can be discussed with regard to various aspects of remote NDE, such as equipment, infrastructure, practices, procedure, and training for use.

3.2.7.1 Instrument Validation and Training

Verification and validation of remote NDT instruments would be performed as they are currently for any NDT instruments. Testing on reference standards is typically performed to ensure a 3-to-1 signal-to-noise ratio (SNR) for all flaws that must be found. Following these laboratory tests, a final validation is performed on actual structure.

If time, funding, and resources are available, a full or partial probability of detection (PoD) study is completed to validate an instrument for specific applications. Remote NDT instruments will also need to be tested in a remote mode to ensure the SNR or PoD requirements are met using remote personnel.

Training methods will be similar to those performed today on NDT instruments and incorporate the additional feature of the remote aspect of the procedure. In addition to learning how to use

the instrument and how it works, trainees will need to learn protocol and procedures for remote interaction with personnel and remote instruments. As part of a training class, a remote scenario with several individuals could be set up and performed as part of a practicum. For example, an expert and an operator could be interacting from separate rooms while conducting a defined set of inspection scenarios.

The DolphiCam®, manufactured by Dolphitech, is used for the demonstration of Scenarios #1 and #2 in the present case study. Boeing has been working with Dolphitech to modify the DolphiCam software to improve its usefulness for remote NDT scenarios on commercial aircraft. Boeing is currently considering a new or modified DolphiCam procedure to enable real-time remote NDT support per Scenario #1. The procedure would not be an NDT manual procedure but would be incorporated into the SRM using the process outlined above.

The new procedure will include use of networking software, a webcam, and real time communications between a qualified NDT expert and the user as mandatory requirements. Dolphitech is considering development of training classes and/or a training video for non-NDT users guided by experts.

3.2.8 Requirements for Remote-Expert NDT Practices

The quality of Web-based technology and enabling networkable NDT tools (such as the Dolphitech DolphiCam and Boeing LPS) are reaching the threshold required for remote-expert NDT to begin to make cost-savings inroads into traditional on-site inspection scenarios. For safe, consistent, and effective use of remote-expert NDT for commercial in-service aviation, a set of requirements is needed for inspection validation. This report describes these requirements.

3.2.8.1 Real-Time Remote-Expert NDT

The following set of requirements is recommended by Boeing as necessary and sufficient for buy off of a remote inspection:

- Remote ambient lighting level must be sufficient for all remote imaging requirements, including verification of the correct test location; appropriate tool and test setup; proper procedure; full coverage of the inspection area; and general situational awareness. The clarity of the site location tools and setup should be verified by the expert away from the test site.

- The phone audio level and quality should be sufficient to enable error-free communication between the expert and remote tool operator.

- The remote tool operator should repeat back to the remote expert any instructions so that the remote expert can verify he was heard correctly. This is the best method to continually verify the audio is sufficient for the high-quality communication necessary for real-time remote-expert NDT.

- For noisy environments or documentation of verbal communication, a speech-to-text application should be used. Remote visual capability with both far-field and near-field views of the inspection region is required. The far-field imaging ensures an understanding of context, provides situational awareness, and generally improves communication between expert and operator. The near-field imaging ensures high-quality expert monitoring and feedback for the remote tool operation and data collection. The two-field requirement can be met by using two separate cameras or by using a high-zoom camera that can be zoomed in and out by the expert during the inspection. This camera can be remotely controlled by the expert, but this is not required if the on-site person can control it under the expert's guidance.

- The far-field image (whether from a separate or zoomed-out camera) must have sufficient spatial resolution to allow the expert viewing remotely to read the 20/40 line of a full-size Snellen (see figure 17), Rosenbaum, or Jaeger eye chart placed on the structure adjacent to the inspection region. At the same time, the field of view must be larger than 10′ across in the longest dimension to ensure sufficient situational awareness for the remote expert. If the expert cannot correctly read the entire 20/40 line, the camera can be moved closer or zoomed in as long as the field of view meets the 10′ minimum requirement. The remote inspection cannot be performed if these conditions are not all met.

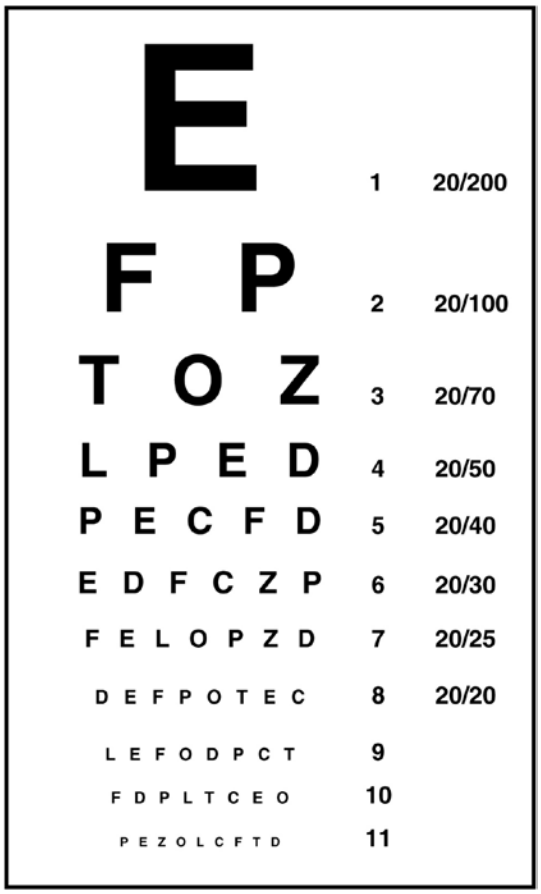


Figure 17. Snellen eye chart

- The location of the inspection area should be visually marked by the on-site remote tool operator so that it is clearly visible in the far-field image to the remote expert.

- The on-site inspector cannot block the far- or near-field camera views in any way during the inspection. If the remote expert is unable to view the entire inspection area at any time, the on-site inspector must adjust the camera position and his position and perform the inspection again.

- For instances in which accurate position verification of the inspection area relative to the aircraft coordinates is required, a positioning system such as the Boeing LPS should be used. The LPS can be operated remotely by the expert after giving any needed setup guidance to the on-site personnel. A calibration of the positioning system to the structure under inspection should be completed to verify accuracy before taking any measurements. The calibration procedure and results should be documented and included in the data that will be saved with the inspection results

- The computing system used for remote-expert NDT must have camera connections for the far- and near-field cameras and have Lync software (or equivalent) to enable remote communication between the expert and remote tool operator

- NDT data must be taken and displayed in a format that allows the remote expert to make a definitive assessment of the damage. Figure 18 shows a screenshot example of what a remote expert would see on his computer screen in real time (note that the camera here is currently pointed at the on-site inspector; the image should be switched to a view of the inspection area as the data are collected). The DolphiCam ultrasonic testing data of several back-drilled holes are being collected and displayed on the screen in B-Scan, C-Scan, and 3-D formats.

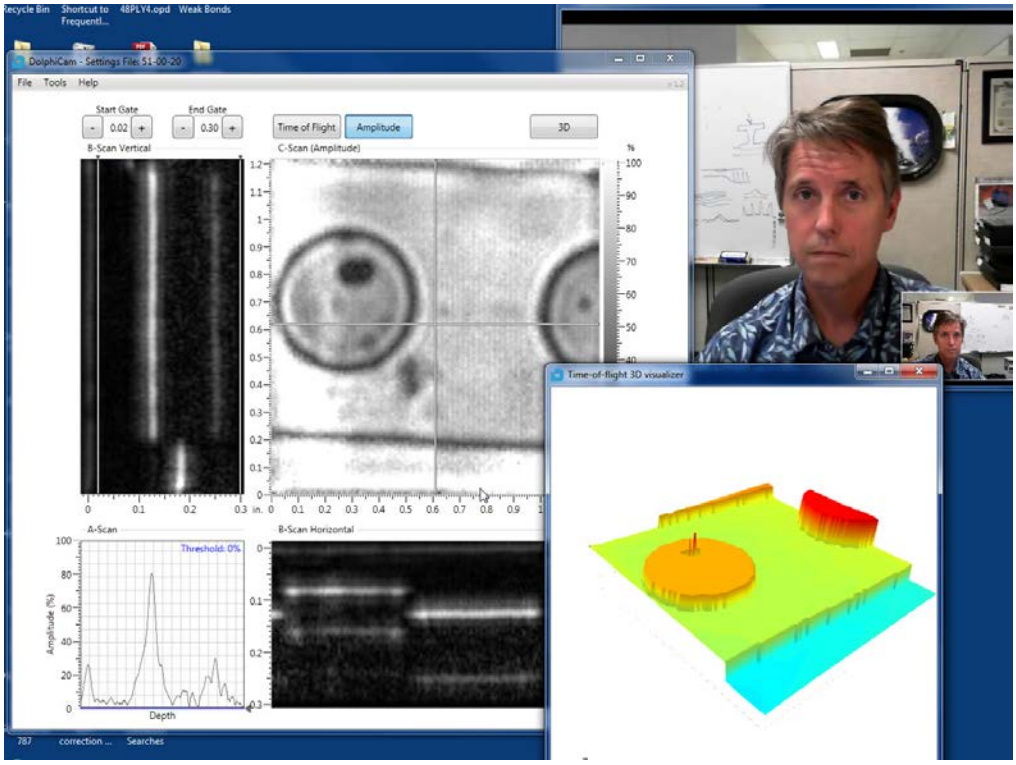


Figure 18. NDT remote display

- Expert remote control capability for the on-site tool is not a requirement but is an option that may be the chosen method in certain situations. For example, when a relatively complex change of the tool settings is needed, the remote expert can take control and make the changes himself rather than guide the on-site tool operator.

- Digital still images of the inspection should be taken and included with the rest of the NDT data. These may be screen captures from the video feed. The images should include up close details and larger fields of view that show context relative to the location on the structure. At least one image each that generally represents the camera views should be included.

- The minimum length of time to preserve the NDT data and related documentation is 2 years. This requirement does not eliminate the current record-keeping practice of the organization conducting the remote-expert NDT. Whichever is the longer requirement should be followed. An organizational system should be used, with access provided to appropriate individuals responsible for retaining inspection records.

- In addition to the data and accompanying photographs, the following information should be stored for later review should questions or issues about the remote inspection arise:

  – Name of inspection and structure under inspection.
  – Date and time.
  – Tail number and section.
  – Aircraft model.
  – On-site inspector ID.

- The remote expert will make the assessment of the NDT data, issue his test report per standard practice, and follow disposition procedures as he would with any non-remote inspection. With the NDT test and data viewed and analyzed in real time, the remote expert will perform standard buy-off procedures required of a non-remote inspection. Decisions such as initiating a quick temporary repair, a permanent repair, or the release of the aircraft for flight are based on pre-established specifications that apply to both remote and non-remote inspections.

- The Internet connection speed must be sufficient to allow for minimal latency between audio, test data, and visual transmission. If the lag time between any two of these exceeds 2 seconds, real-time remote expert NDT should not be performed and the near real-time remote expert NDT method must be selected instead. The requirements for this method are described in section 3.2.8.2.

3.2.8.2 Near Real-Time Remote-Expert NDT

If the expert is not guiding the non-expert remote tool operator in real time, the method is considered near real time (also called remote post-test assessment) and has some specific requirements (note that the current situation is that OEMs often perform NDT expert support of a qualified NDT user, as in a second opinion or a consult; these requirements are not needed for consultations between experts):

- The remote tool data collection settings must be pre-set by an expert.

- A “user lockout” feature must be available and set on the remote tool before the non-expert operator uses it. This feature eliminates the possibility of the on-site operator of the tool making intentional or inadvertent changes to any settings that would adversely affect the inspection.

- A clear and simple set of test instructions must be followed by the operator.

- The inspection data transmitted to the remote expert must be sufficient to properly interpret the results and allow for disposition to the acceptance criteria. It must include all the forms of analysis (i.e., A-scan, B-scan, C-scan) that an on-site qualified user would use in making the same assessment.

- The bounds of the inspection area; start and endpoints of the scan; and scan direction should be clearly marked; in addition, a photograph of the markings should be taken.

- Photographs (or video frame captures) of both far- and near-field images must be included in the report to the expert. The images must include the photograph of the markings, the inspection area relative to the larger structure, and the tool being used on the structure.

- In addition to the data and accompanying photographs, the following information should be sent to the remote expert for assessment and disposition:

  – Name of inspection and structure under inspection.
  – Date and time.
  – Tail number and section.
  – Aircraft model.
  – On-site inspector ID.

- The remote expert will make the assessment of the NDT data sent to him, issue his test report per standard practice, and follow disposition procedures as he would with any non-remote inspection. With the NDT test and data viewed and analyzed post-test, the remote expert will perform standard buy-off procedures required of a non-remote inspection.

- Decisions such as initiating a quick temporary repair, a permanent repair, or the release of the aircraft for flight are based on pre-established specifications that apply to both remote and non-remote inspections.

- The minimum length of time to preserve the NDT data and related documentation is 2 years. This requirement does not eliminate the current recordkeeping practice of the organization conducting the remote-expert NDT. Whichever is the longer requirement should be followed. An organizational system should be used, with access provided to appropriate individuals responsible for retaining inspection records.

3.2.8.3 NDT With Simplified Tools and Local Decision-Making

If the expert is not guiding the remote tool operator in real time or in near real time, the method is considered an unsupported inspection, with expert knowledge embedded in the operating characteristics of the equipment. The specific requirements follow:

- The inspection process must be fail-safe in the sense that situations that could lead to a missed defect will not occur when the instrument is used properly by an appropriately trained user.

- The remote tool data collection settings must be pre-set by an expert and embedded in the operating characteristics of the instrument.

- A “user lockout” feature must be available and set on the remote tool before the non-expert operator uses it. This feature eliminates the possibility of the on-site operator of the tool making intentional or inadvertent changes to any settings that would adversely affect the inspection.

- A clear and simple set of test instructions must be followed by the operator.

- The bounds of the inspection area; start and endpoints of the scan; and the scan direction should be clearly marked, and a photograph of the markings should be taken.

- In addition to the inspection results and accompanying photographs, the following information should be documented and retained:

  – Name of inspection and structure under inspection.
  – Date and time.
  – Tail number and section.
  – Aircraft model.
  – On-site inspector ID.

- The local user will make the assessment of the NDT data collected, issue his test report per standard practice, and follow disposition procedures. The user will perform standard buy-off procedures required of a non-remote inspection.

- Decisions such as initiating a quick temporary repair, a permanent repair, or the release of the aircraft for flight are based on pre-established specifications.

- The minimum length of time to preserve the NDT data and related documentation is 2 years. This requirement does not eliminate the current recordkeeping practice of the organization conducting the remote-expert NDT. Whichever is the longer requirement should be followed. An organizational system should be used, with access provided to appropriate individuals responsible for retaining inspection records.

3.2.9 Remote NDT Procedure Validation

If remote NDT technology and methods are going to be used for commercial aviation, a method must be in place for documenting, validating, and controlling procedures. At Boeing, Business Process Instruction (BPI)-2040 is the controlling document that establishes how a new method gets approved, published, and used by commercial airlines (see appendix A).

The purpose of BPI-2040 is to establish the process for in-service NDT inspection techniques to be published in the referenced in-service NDT manuals. It defines the process of applicable organizations and establishes methods for developing NDT techniques for all heritage Boeing commercial airplanes.

BPI-2040 describes the process for establishing NDT techniques from the initiation of NDT inspection requests to publication of the techniques in the appropriate format (NDT manual, service bulletin, etc.).

A list of the process steps, with roles in parentheses next to the step, follows:

1. Initiate NDT support requests (stress engineer, service bulletin, engineering personnel, customer).
2. Oversee evaluation (service engineering focal).
3. Complete evaluation (BR&T technology development personnel).
4. Incorporate maintenance information (Maintenance Programs Engineering [MPE] focal).
5. Incorporate NDT data (service bulletin engineering personnel).
6. Investigate procedures (BR&T technology development personnel).
7. Approve procedures (service engineering focal).
8. Release NDT procedures (service engineering focal).
9. Publish and maintain NDT manuals (maintenance and ground operations systems focal).
10. Publish maintenance planning data and supplemental structural inspection document (MPE focal).
11. Publish service bulletins (service bulletin engineering personnel).
12. Maintain process (BR&T technology development personnel).

The BPI-2040 process can be used to incorporate remote NDT (using various scenarios and instruments) into the NDT manuals and accepted industry practice. However, there is an alternative approach that has some precedence, which is to incorporate remote NDT into the Structural Repair Manual (SRM), as discussed in section 3.2.9.1.

3.2.9.1 Remote NDT in the SRM

In situations that involve non-NDT operators, it is desirable to place inspection procedures in the SRM instead of the NDT manual because local non-NDT personnel in remote locations do not typically have access to the NDT manual. For example, the Boeing ramp damage checker is an inspection procedure intended for non-NDT users that was previously released for industry use through the SRM.

If a remote NDT procedure is to be placed in the SRM (in a similar manner as the Boeing ramp damage checker), the process would generally be as follows:

- Develop the procedure with concurrence of service engineering or at their request.
- Submit the developed procedure to service engineering NDT focal using the BR&T memorandum system. Copy the memorandum to the appropriate Boeing ARs.
- Service engineering NDT focal approves the procedure in coordination with Boeing ARs.
- The approved procedure is submitted to the SRM group.
- The SRM group submits the procedure for publication in SRM.

As in the NDT manual development process, remote NDT acceptance would stay within the framework outlined, and remote NDT should not change it.

Boeing believes no major changes are needed to accommodate the remote aspect of NDT if BPI-2040 processes can be followed or the procedures are published in the SRM.

3.2.9.2 Remote-Expert NDT Training

For real-time and near real-time support, it is assumed that the remote expert holds the appropriate NDT certification for the inspection method to be conducted remotely. However, both the remote expert and the on-site remote tool operator will require some specific training before they can conduct remote-expert NDT, whether real time or near real time.

A Web-based remote training module/remote-expert NDT training course that is approved by the organization's Level III NDT technician would be required. The training can be completed in a classroom taught by an on-site instructor. It may also be pre-loaded Web-based training provided by Boeing or a remote NDT tool supplier, such as Dolphitech. This could be finished at the student's pace, with guidance for hands-on practice and a test at the completion of the training. The third option is for a point-of-use type training, in which the learning is completed prior to the actual remote-expert NDT inspection. One or both of the "expert" and "non-expert" students can be led through an online or pre-packaged training course. A step-by-step set of procedure instructions for the actual remote-expert NDT inspection can also be provided. This subset of the larger training package can be used as part of a first-time training curriculum, an "every-time" guidance tool, or as an optional "refresher" for those who have not performed remote-expert NDT inspections in a while.

The course should cover the following elements:

1. Remote-expert NDT definitions and practices—The definitions of real-time and near real-time remote-expert NDT should be given with an explanation of the general usage, advantages, and disadvantages of the approaches. Example remote-expert NDT scenarios should be taught and practiced, with attention on the proper requirements and methodology of an approved test. Obtaining remote access using Lync (or equivalent) software and setting up and operating interfaced video cameras should be demonstrated to and practiced by the students.

2. Remote NDT tools—The various remote NDT tools in use in the aerospace community should be described. The specific remote NDT tools that the student's airline, MRO, or OEM have chosen to use should be described in detail. Hands-on training with the instruments in remote (separate room) scenarios should be completed for both expert and non-expert (specific, more in-depth training for the expert is assumed). At a minimum, every expert student should guide a series of trial inspections, evaluate the data, and make determinations of damage and repair assessment scenarios that correspond to the type of assessments they will be doing. He should also show proficiency in taking control of the instrument remotely (if the particular device has that capability). Non-expert students taking the course should show hands-on familiarity with the selected instruments and remote-expert NDT methodology and be successfully guided through the inspection of various damage and repair assessment scenarios.

3. Inspection buy off—In this section, it should be emphasized that buy off of an inspection can only be performed by a remote expert (certified Level II or III in the method used, who has also passed the referenced remote-expert NDT training course). The buy off is completed by the remote expert who views and analyzes the NDT test and data either in real time or post-test and then performs standard buy-off procedures required of a non-remote inspection.

4. Data handling and storage—In addition to the requirements listed in this document, the organization's specific practices should be defined for the students.

5. System and method requirements—The current requirements document should be provided to course attendees, with each point covered by the instructor and discussed by the class.

6. Passing the course—Students should be tested for mastery of the course material. They can be graded pass/fail based on a combination of hands-on and written; online; or Web-based software tests that are specific to the expert and non-expert students. The organization's Level III must approve the test as being representative of the knowledge required to conduct remote-expert NDT. The Level III NDT technician would have various options for the course, including a classroom, Web-based, point-of-use approaches, or they could assemble and approve their own version.

For NDT with simplified tools and local decision-making, it is assumed that the optimum instrument settings are embedded in the instrument and are not available to the operator. However, the on-site tool operator will require some specific training on how to scan properly before they can conduct unsupported inspections.

3.2.10 Remote NDT Summary and Conclusions

Remote-expert NDT is an emerging concept and method that is taking advantage of data collected from the aircraft using networkable NDT tools and advanced Web-based communication technologies to transfer the information to a remote site where experts are available to assess the condition of composite structures. This provides airline operators with the benefit of rapid on-site inspection support for commercial aircraft, which results in increased dispatch rates.

Though there are situations in which remote-expert NDT might be needed at a manufacturing facility to perform an inspection (e.g., after a tool drop on a structure), the primary application for remote NDT is to quickly check an in-service airplane that has experienced a potential impact damage scenario for which timely assessment is needed.

To perform remote NDT, a non-expert at the remote event site (such as a remote airport location) uses an NDT tool with a simplified user interface to conduct an inspection while being guided by an NDT expert in one of three ways:

1. In real time, with immediate and direct two-way remote communication, verification, and NDT data transfer to the expert.
2. In near real time, with timely remote transfer of the inspection scenario, inspection process, and results, to be bought off by the expert afterward.
3. With a simple procedure guided and verified by a "smart" instrument, with the process and results subsequently documented by the on-site operator.

With each of these remote-expert NDT approaches, the appropriate level of training for both the expert and non-expert would be required. Options for training approaches were described in section 3.2.9.2. Requirements for a well-defined and controlled remote-expert NDT process have also been recommended to ensure the inspection is conducted properly every time. Remote-expert NDT can be used to support composite commercial aviation as long as there is a method for operators to document, validate, and control the process.

Some commercial airlines appear ready to begin using remote-expert NDT, especially as their fleets become more composite-oriented. NDT equipment manufacturers are offering simplified networkable NDT tools that will enable airlines to start remote-expert NDT. The time appears right for a broader industry discussion, perhaps at an FAA-led session at the Airlines for America (A4A) NDT Forum or a similar venue such as the Airworthiness Assurance Conference. The FAA has a window of opportunity to promote and guide the emergence of remote-expert NDT as a significant advancement in commercial aviation maintenance practices.

The validation and acceptance of remote NDT requires addressing aspects related to NDT instruments; infrastructure for transmission and management of data; and procedures and training for use of the equipment.

The verification and validation of remote NDT instruments would be completed essentially as they are currently for any NDT instruments. Testing on reference standards is typically conducted to ensure a 3-to-1 SNR for all flaws that must be found. Following these laboratory tests, a final validation is performed on actual structures.

For real-time and near real-time support, it is assumed that the remote expert holds the appropriate NDT certification for the inspection method to be used remotely. However, both the remote expert and the on-site remote tool operator will require some specific training before they can conduct remote-expert NDT, whether real time or near real time.

The training course should cover the following elements:

- Remote-expert NDT definitions and practices.
- Remote NDT tools.
- Inspection buy off.
- Data handling and storage—system and method requirements.
- Passing the course.

For NDT with simplified tools and local decision making, it is assumed that optimum instrument settings are embedded in the instrument and are not available to the operator. However, the on-site tool operator will require some specific training on how to scan properly before he can conduct unsupported inspections.

At Boeing, the controlling document that establishes how a new method gets approved, published, and used by commercial airlines is BPI-2040 (see appendix A). The purpose of BPI-2040 is to establish the process for in-service NDT inspection techniques to be published in the referenced in-service NDT manuals. This BPI defines the process of applicable organizations and establishes methods for developing NDT techniques for all heritage Boeing commercial airplanes.

In situations that involve non-NDT operators, it is desirable to place inspection procedures in the SRM instead of the NDT manual because local non-NDT personnel in remote locations do not typically have access to the NDT manual.

As in the NDT manual development process, remote NDT acceptance would stay within the framework outlined, and remote NDT should not change it.

It appears that no major changes need to be made to accommodate the remote aspect of NDT if BPI-2040 processes can be followed or the procedures are published in the SRM.

3.3 REMOTE TIRE INSPECTION

3.3.1 Introduction

Aircraft tire inspection is a relatively straightforward example of routine aircraft inspections performed on a regular basis. Currently, tire inspections at the gate require the presence of expert mechanics. The unavailability of qualified mechanics can delay aircraft dispatch, resulting in financial consequences for the airline operator. This issue can be addressed through the development of a remote inspection capability that eliminates the need for the presence of a local expert by providing remote expert support. Given sufficient technology and guidance, it is anticipated that a remote inspector (RI) could guide a LO to collect and transfer the needed data without the delay or expense of bringing an inspector on site.

The ubiquitous use of network-enabled cameras and sensor technologies provides an opportunity to examine their use for remote tire inspection. Camera and communication technologies with video and voice link for remote tele-collaboration are available and are being investigated for use in conducting general aircraft inspections. Image data acquired by cameras from the tire’s

surface and other data acquired by sensors (if available) can be transferred to a remote inspection site over the Internet. Under this SPMS program, these technologies and capabilities were further studied for use in remote tire inspection. A range of approaches—from simple to sophisticated—were studied in terms of technology maturity, requirements, barriers to implementation, and impact on maintenance operation. Finally, the focus was directed to more mature technologies that could potentially be transitioned to the field in the near future.

3.3.2 Remote Tire Inspection Technologies

To assess the effectiveness of available technologies for application to remote tire inspections, the technologies were mapped to each maintenance task related to 737 aircraft tire inspections. Each technology was examined against all the tasks in the list (see table 8) and whether the technology could provide required data for the maintainer to achieve the goals of the specific task. Tire Pressure Monitoring Systems (TPMS), cameras for visual inspection, and Light Detection and Ranging (LIDAR) for measuring the depth of grooves and cuts were considered to be viable options for supporting multiple inspection tasks. Other sensors, such as acoustics, mesh, and infrared, could support only one or few inspection tasks. Mesh sensing was anticipated to be achieved through one of several techniques that might include active fluorescence or multi-spectral active illuminated sensing. Metallic reinforcements might be sensed using radio frequency, magneto-restrictive, or inductive techniques.

Table 8. Tire inspection tasks and technology mapping

Tire Inspection Task	TPMS	Camera	LIDAR	Other sensors	Notes
Examine the tires for air leaks, abrasions, unusual worn areas, cuts, and flat spots.	HE	HE	HE	Acoustic	Imaging and sensors can provide features for detecting these anomalies.
Examine the tires for the presence of contaminants.		E		TBD	Need to determine a list of possible contaminants and signatures on the tire and then determine the method of detection.
Determine if the surface of the tire appears soft, spongy, or if there are bulges present.		E			Depends on the level of bulges. It appears there is a need for a sensor that can sense the toughness of a tire.
Cuts or weather cracks in the grooves, the tread, shoulders, or sidewalls that exceed the limits.		E	HE	Mesh Sensor	Need a method to quantify extent of damage.
Blisters, bulges, or other signs of ply separation in the tread, shoulder, or sidewall area.		HE	HE	Infrared sensor	Rubber temperature sensing? Look for temperature spikes indicating imminent loss of tread.
Tires with a flat spot that shows the tread reinforcement ply (bias) or cut protector (radial).		E	E	Mesh Sensor	
Measure the depth of the tire tread groove at three points that are equally apart. If the average depth of any groove is 1/32″ (0.79 mm) or less, the tire must be replaced at the next convenient maintenance opportunity.			HE		Need a method to measure the depth. Need to ensure the measurements are taken at the correct distance.
If the tread belt ply (radial) or carcass ply (bias) shows at any location, the tire is not serviceable and must be replaced.		E	HE		
If the tread is worn so that the cut protector (radial) or tread reinforcement ply (bias) shows at any location, the tire must be replaced at the next convenient maintenance opportunity.		E	HE		
Examine the tire for circumferential cuts.		E	HE		
Examine the tire for transverse cuts.		E	HE		
Examine the tire for punctures.	HE	E	E		
Examine the tire for rib undercuts.		E	E		
Examine the tire for groove cracks.		E	E		
Examine the tire for circumferential sidewall cuts.		E	HE		

HE = highly effective; E = effective

Table 8. Tire inspection tasks and technology mapping (continued)

Tire Inspection Task	TPMS	Camera	LIDAR	Other sensors	Notes
Examine the tire for radial sidewall cuts or cracks.		E	E		
Examine ozone/weather cuts or cracks.		E	E		
Examine the tire for flaking, chipping, or chunking.		E	E		
Examine the tire for any open tread splice.		E	E		
Examine the tire for thrown tread.		E	E		
Examine the tire for peeled rib.		E	E		
Examine the tire for chevron cuts.		E	HE		
Examine the tire for tread flat spots.		HE	E		
Examine the tire for flat spots.		HE	E		
Examine the tire for ice skid burn/tread rubber reversion.		HE	E		
Examine the tire for sidewall separation.		E	E		
Examine the tire for tread separation.		E	E	Mesh Sensor/ Infrared sensor	Rubber temperature sensing. Look for temperature spikes indicating imminent loss of tread.
Examine the tire for shoulder wear conditions.		HE	E		

HE = highly effective; E = effective

As summarized in table 8, this exercise showed that cameras provide the best coverage in terms of applicability to all the tire inspection tasks. These cameras are required to provide a clear and high-resolution image with network capability to facilitate the transfer of image, voice, and video communication. For the SPMS remote tire application area, we used the Librestream camera. This camera is currently being evaluated in the industry for general inspection tasks. The concept of using cellphone technology both as a video and voice link and as an interface platform for additional sensing capabilities is discussed to indicate the potential for future use. This system is at a concept level and requires more development and maturation before it can be used in the field.

3.3.2.1 Librestream Camera

The Librestream Onsight camera has one-way video and two-way voice links and annotation capabilities. The camera weighs 1.5 lb, has a removable rechargeable battery, and is registered to a proxy server, Librestream Video Communications Server (VCS), (see figure 19) for internal and external call routing. It can be used as a wireless (802.11b/g) or wired network device and supports Wireless Protection Access enterprise wireless security. It has optical zoom and macro functions.

Additional features that may be needed include camera orientation, distance from the tire, and the ability for orientation and distance to be controlled by the RI.

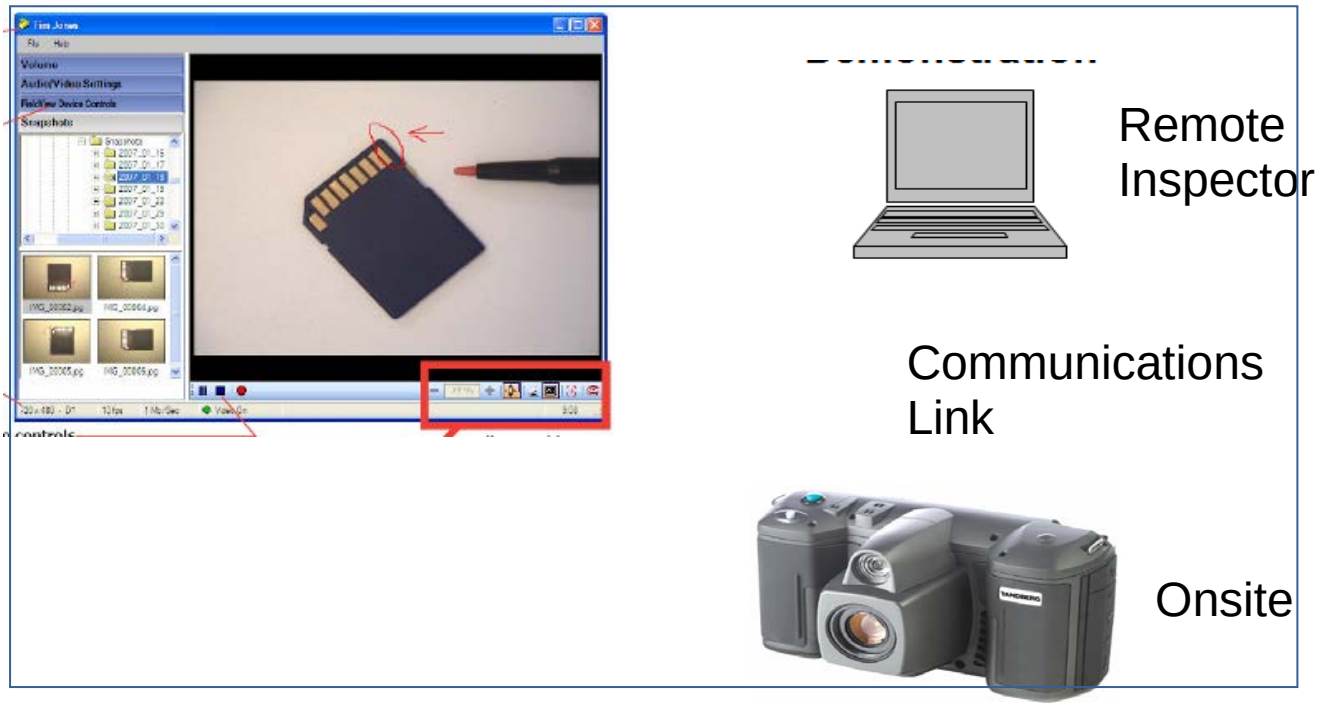


Figure 19. Librestream Onsight camera and computer interface

The camera supports a computer interface that allows for RI control. The control features include:

- Control stream quality, zoom, focus, and light.
- Create custom streaming configurations.
- Initiate or receive calls.
- Freeze image and annotation.
- Record still or motion images.
- Browse and playback archived sessions.
- Computer clients can also stream, talk, and annotate recorded sessions with each other.

A more detailed picture of the computer interface, including camera controls, is shown in figure 20.

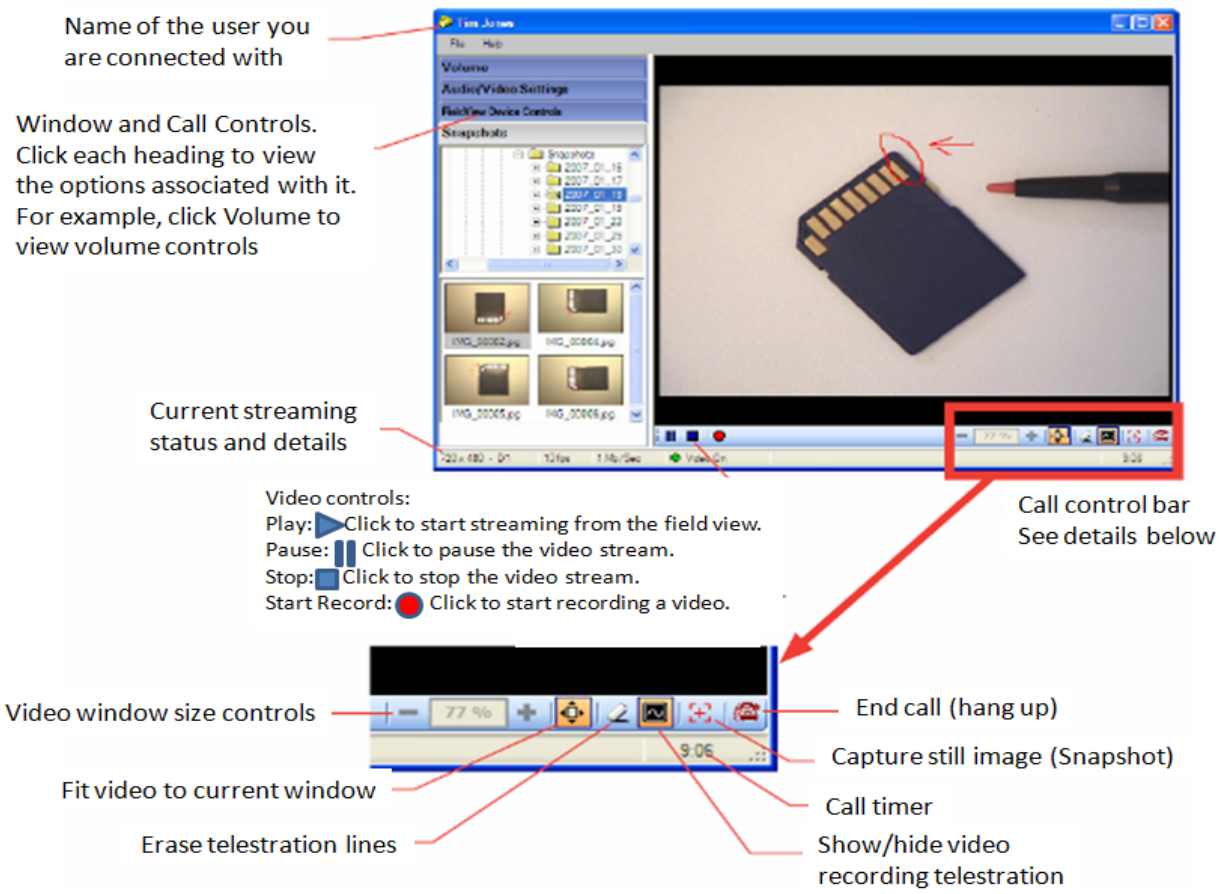


Figure 20. Computer interface to control camera from remote site

The communication link between the camera and the RI has the following properties:

- Protocol: Session Initiation Protocol (SIP).
- Network Bandwidth:
  - Widely variable, depending on available bandwidth.
  - Video stream rates from 64 kb/sec to 2.5 mb/sec.
  - Audio stream rates from 13 kb/sec to 64 kb/sec.
  - Total maximum bandwidth required $\leq$3 mb/sec.
  - Typical high-quality setting = 1.5 mb/sec.
  - Acceptable down to 400 kb/sec, with lower frame rate and higher compression.
- Security:
  - Registered to VCS SIP proxy.
  - Client device or application must be on VCS allowed list and have correct authentication username and password.
  - Transport Layer Security registration requires x.509 device or personal certificate (www.iana.org).
  - Media streams are encrypted at 128 bit Advanced Encryption Standard (AES) level (www.nist.gov).

3.3.2.2 Cellphone Technology Concepts

The use of smartphones and supporting accessories for low-cost remote tire inspections is being investigated in the industry. The motivation is to take advantage of widespread cellular connectivity, the abundant use of smartphones, and the ease of handling and use due to their small and compact size (see figure 21). The baseline concept is to use a smartphone case as a sensor interface platform that adds the capability to examine the status of the tire for conditions that cannot be accurately detected visually through the examination of the image by a RI.

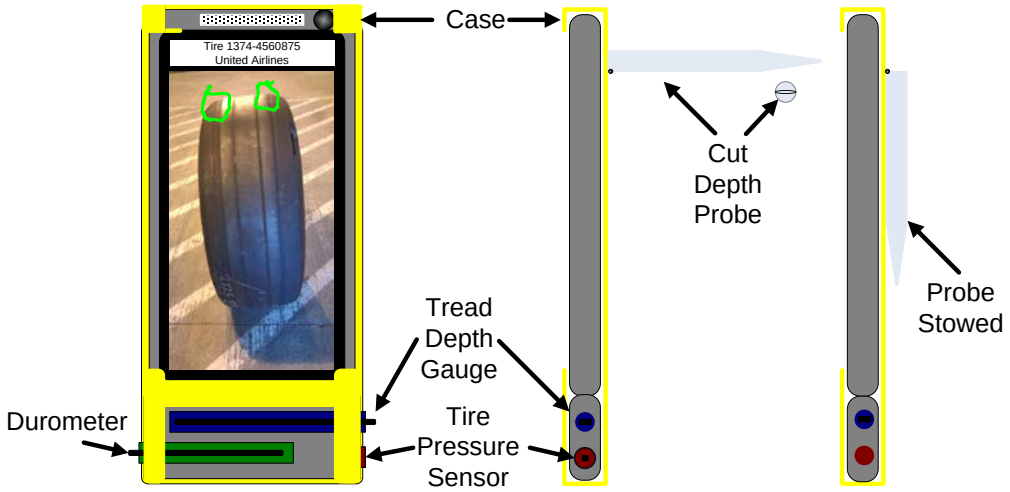


Figure 21. Cellphone and accessories to support remote tire inspections

The following features and sensors, if interfaced to a smartphone, can provide additional information related to tire wear, damage, and condition that cannot be clearly identified in the image at the remote site:

1. Cut-depth probe—A lighted optical probe accessory to inspect cut depth that swings into the camera's field of view. This might include optical fibers for delivering light from the phone's light emitting diode and a macro borescope capability. An optional probe position outside the field of view provides a fixed standoff distance and calibration metric for scale determination of defects.

2. Tire pressure sensor—A pressure gauge connected to the USB port to read the tire pressure.

3. Durometer—To determine if soft spots are in tolerance, with advisory software using tire pressure as a possible correction factor.

4. Tread-depth gauge—A tread-depth gauge that can be electronically read and readily imaged, with software to allow for capture of the often uneven wear patterns that are seen on the outer and center tire sections.

5. A smartphone application that uses the sensor and accessory set data and provides additional key capabilities for inspections, including voice and text chat; annotation; and metrics data capture and transfer.

Because smartphone accessories and sensor interfaces were not mature at the time of this project and there was not a parallel Boeing internal development program, the above smartphone system and accessories were not assessed as a case study under SPMS.

3.3.3 Tire Inspection Implementation

There are a range of methods with a wide spectrum of capabilities that might be considered and used for remote tire inspection. The implementation barriers are different depending on the level and degree of remote capability use:

- Physical remote inspection—Using current inspection methods with limited change except for moving the inspector offsite and having a local aide. The camera and infrastructure for communication and transmission of image data are required. There is no requirement for data storage.

- Enhanced remote inspection—Enhancing the robustness of the inspection process and artifact storage in some middle-ground fashion. There is limited added data persistence at this level/philosophy.

- Advanced remote inspection—Significantly changing current inspection methods through the rigorous processes enabled by the technologies for which data capture, storage, and long-term analysis become possible. Robust added data persistence would exist with this method. Advanced image and signal processing and tools can be used as decision aids.

Depending on the level, the following considerations should be given to the end-to-end data collection, transmission, storage, handling, and use of data:

- On-site data collection—For visual inspection of tires, still and video cameras are used to capture images. The collected images can be sent raw to the remote central location for an expert maintainer to review and assess the condition of the part based on maintenance specifications and his own expertise.

  - One issue that will need to be addressed is the storage of images and videos that contain information beyond what is currently captured by tire inspection, such as peripheral sites and personnel. This stored data can potentially cause liability, which will result in resistance from the operators. One possible solution is to reduce and eliminate unnecessary background information from the inspection site before the data is stored at the remote site. The raw data would be sent to the remote site and reviewed by the expert maintainer. The images and data could then be edited, as necessary, and stored in the archive. In addition, the video and still camera could be used to identify the inspection location, per maintenance manuals. This would help a less skilled maintainer to properly position the camera and capture the key inspection points. However, no local data storage without expert maintainer input and context is recommended. Depending on operator preference, data storage can be performed at the local site after review by a remote expert. The tire case study should retain certain types of data—for example, any information on the condition of the tire under inspection such as tire pressure and pictures of areas identified in the maintenance manual that can be referred to in future investigations.

- In some tire inspections, the on-site inspection system possesses imaging equipment (still or video camera) for ensuring accurate installation and operation of measuring equipment by less-skilled operators. In this scenario, images of the operator are captured. As current on-site inspections do not capture these images—only the outcome of the inspection is stored, without retaining the raw data that led to the expert maintainer's conclusion—this development could again incur resistance from operators and maintainers whose images present the possibility of future liability. However, there are valid reasons to retain the data for a limited time at the introduction of the remote inspection into service. The retained data can be used for process improvement and training until the system is fully matured and has gained sufficient confidence and history such that it can be certified for maintenance recommendation.

- Remote site data—The remote site needs to have a facility with the capability to connect to the field and acquire, store, and render the information to the expert inspector. Given the state of data storage technology, cloud computing, and distributed databases, this should not present a technical bottleneck for the fielding of the system. Data and image compression techniques can be applied to data for file size reduction. Guidelines need to be developed regarding the length of time the data are archived. The size of the images and videos that are captured during periodic inspections can be large and the cost of managing and archiving should be a consideration.

- Other issues that need to be addressed are the policies related to the ownership of data, specifically whether the data belongs to the operator or the OEM. Though it would make sense for the operator to have control over this data in case a need develops for further investigation, the data should be shared with OEMs for repair and maintenance engineering analysis and with certifying authorities during accident investigations.

- Inspection sign off—Inspections will be signed off by the RI. With the current state of information technology and automated logistics and maintenance management systems, the sign off can be done electronically. The remote operator signature is logged in from a remote site and stored in a central maintenance management system. Network connectivity is assumed to not be an issue.

Near-term implementation of remote tire inspection with network-enabled cameras to replace human visual inspection appears to be a viable option. Two aspects of remote tire inspection implementation—the approach for developing camera usage procedures and the impact of remote inspection on current maintenance tasks—were studied under the SPMS program.

3.3.3.1 Procedures for Use and Operation of Camera

Procedures and guidelines for the local inspector need to be developed to ensure the features related to a specific tire condition are captured and communicated to the remote expert clearly and accurately. The following is one approach for developing these procedures.

In the first step, an SME performs the remote inspection process by directing an on-site maintenance person and video recording his movements and camera angles. The on-site maintainer would use the camera as his pair of eyes, inspecting the tires as he does normally but also using the camera in conjunction with his visual inspection. The collection of video would generate specific camera-holding procedures. This step should result in the following initial set of requirements and instructions:

- Camera resolution.
- Distance from tire surface.
- Angle of camera to the tire surface.
- Surface lighting.
- Direction and sequence of tire inspections.
- Measurement of damage/wear features.
- Instructions for indeterminate inspection result.

The second step is to have a trained on-site maintainer use and verify these requirements and make appropriate updates through repetition until he has gained confidence in and validated the process.

The third step is for the validated procedure to be tested by a pilot or non-A&P-certified person using the camera/sensing equipment and audio to provide a view with annotations to the RI. In this case, the RI would be a certified airplane mechanic and could inspect any number of airplane tires from his remote location. The same or another inspector could inspect the tire locally and compare his results with the remote results. This process would also discover any potential indeterminate conditions for which additional procedures would need to be generated.

3.3.3.2 Remote Tire Inspection Maintenance Manual Updates

The second vital aspect of implementing remote tire inspection is updating current maintenance manual tasks to account for new capabilities and limitations that remote inspection imposes to the operator. The exercise presented here sought to establish the basis for updates to the current maintenance manuals that are designed for on-site expert tire inspectors (see appendix B). The inspection item, 737 maintenance manual diagrams, and manual inspection description were primary sources of information used for the purposes of the exercise. The approach for developing specific recommendations and instructions for remote tire inspections was to identify various tire degradations and directions for the related manual inspection of each of these modes, as shown in figures 22–24.

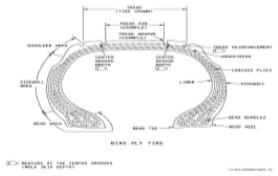
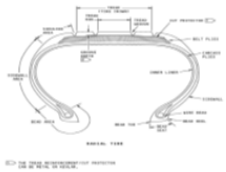
Inspection Item	Image	Manual Inspection	Remote Inspection	Criteria
Tire Tread		The crown of the tire that is visible is viewed.		If the average depth of any groove is 1/32 inch (0.79 mm) or less, the tire must be replaced at the next convenient maintenance opportunity.
1) Measure the depth of the tire tread groove at three points that are equally apart.		The tire tread measured at three distinct equally spaced points.		
2) If the tread belt ply (radial) or carcass ply (bias) shows at any location, the tire is not serviceable and must be replaced.		When inspecting the tire crown the tread belt ply (radial) or carcass ply (bias) shows in any location the tire is not servicable and must be replaced.		
3) If the tread is worn so that the cut protector (radial) or tread reinforcement ply (bias) shows at any location, the tire must be replaced at the next convenient maintenance opportunity		4) If the tread is worn so that the cut protector (radial) or tread reinforcement ply (bias) shows at any location, the tire must be replaced at the next convenient maintenance opportunity	The remote inspection equipment includes a camera device that provides sufficient illumination and resolution to permit identification of cut protector or tread reinforcement to be visible and readily identifiable.	No visible cut protector or tread reinforcement

Figure 22. Tire inspection requirements (part 1)

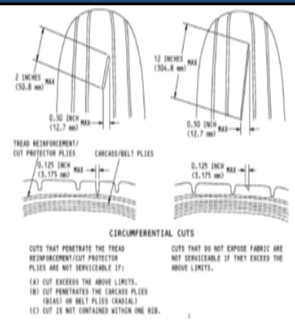
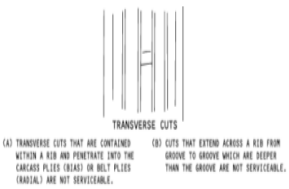
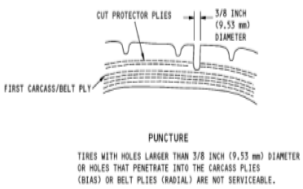
Cuts				
Circumfential Cuts the are within two treads must not exceed the prescribed limits in length, angle to tread and depth limitations.		The tire inspector has a measuring linear and angle measuring devices and inspects the crown for cuts and checks to assure that any such cuts do not exceed the limits shown in Column B.	The remote inspection equipment includes a camera device that provides orientation and scaling information in remotely shared images. Accessory appendages or tools that permit safely viewing, without degradation, the flaw depth such as integrated tooling, illumination, imaging and depth scaling are required to accomplish this task. The remote inspection equipment includes a camera device that provides sufficient illumination and resolution to permit identification of cut protector or tread reinforcement to be visible and readily identifiable.	
Transverse cuts		In inspecting the tire crown, the inspector identifies any transverse cuts (cuts perpendicular to the tread). Cuts within a rib that penetrate to the carcus must be replaced. If there is a cut across the more than one rib deeper than the tire tread grove, then the tire is not servicable.		
Holes or Punctures		In inspecting the tire crown, the inspector looks for any puncture holes. If any puncture holes penetrate into the carcass plies or belt plies the tire is not servicable.		

Figure 23. Tire inspection requirements (part 2)

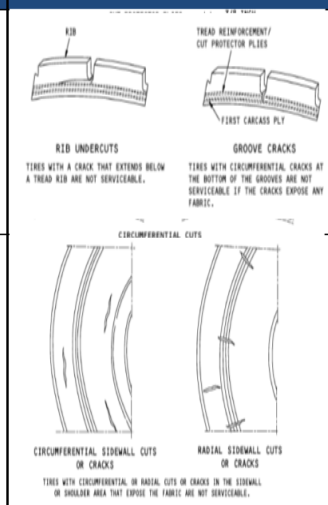
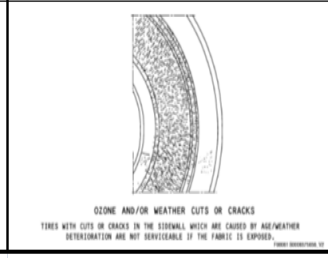
Cuts				
Rib Undercuts and Groove Cracks		In inspecting the tire crown, the inspector looks for any rib undercuts and groove cracks. Tires with a crack or cuts below the tread are not servicable. Tires with circumferential cracks at the bottom of the grooves are not serviceable if the cracks expose any fabric.	The remote inspection equipment includes a camera device that provides orientation and scaling information in remotely shared images. Accessory appendages or tools that permit safely viewing, without degradation, the flaw depth such as integrated tooling, illumination, imaging and depth scaling are required to accomplish this task. The remote inspection equipment includes a camera device that provides sufficient illumination and resolution to permit identification of cut protector or tread reinforcement to be visible and readily identifiable.	
Circumferential or Radial sidewall cuts or cracks		The tire inspector views both sides of the tire and identifies any cuts or cracks. If circumferential or radial sidewalls cuts or cracks expose fabric the tire is not servicable.		
Ozone and/or weather cuts or cracks		The tire inspector views both sides of the tire and identifies any ozone or weather cuts and cracks. If the cuts and/or cracks caused by ozone or weather expose fabric the tire is not serviceable.		

Figure 24. Tire inspection requirements (part 3)

The terminologies used in performing remote inspections are as follows: Remote Inspection (RI), remote inspection device (RID); and on-site assistant (OA).

For each case, the approach for using remote inspections for the specific degradation was studied and documented. One example is the inspection of tire tread. The inspection item is the depth of the tire thread groove at three points. The manual inspection task is described as

> The tire tread is measured at three distinct equally spaced points, using a ruler or depth gauge. If the average depth of any groove is 1/32 inch or less, the tire must be replaced at the next convenient maintenance opportunity.

In this case, the recommended procedure for remote inspection would read as follows:

> 1. The RID is used to scan the tire crown that is visible. Unusual or potential damaged areas can be captured and designated for additional inspections.
>
> 2. The tire tread is measured in three equally spaced points by OA as directed by RI. The measured depths are recorded and sent to RI. The RI has the ability to direct the OA in setting the camera location and orientation. The RI can also identify additional inspection locations, if necessary.

3.3.4 Remote Tire Inspection Initial Assessment

Remote tire inspections appear to be technically feasible. The major hurdle appears to be inspector acceptance and the willingness to support inspectors' judgment calls regarding tire condition.

Some considerations in regard to remote inspections include:

- Additional quantitative tools may provide information that can support improved decision-making; however, they may slow down/complicate the inspections.
- The cost must result in a positive return on investment.
- The ability to record data related to the inspection may have consequences in regard to inspector acceptance.
- Initially, and before sufficient confidence is gained, remote tire inspection may drive a conservative approach to tire removal, resulting in more removals.

Because remote tire inspections appear technically possible and do not require major changes in maintenance procedures, it was chosen for the development of an SPMS case study.

3.3.5 Remote Tire Inspection Case Study

Boeing has completed a case study covering remote tire inspections on aircraft such as the 737 and 787 (see figure 25), driven by the following goals:

- Identify one or more prototype implementation technology approaches.
- Identify other barriers outside of the technical arena that might compromise development.
- Describe the anticipated future state in which remote tire inspections are the norm, with a physical presence only required when a remote inspection cannot be accomplished for reasons determined by the responsible remote inspection authority.

Figure 25. 787 main landing gear

3.3.5.1 Background Activities

Before performing the remote tire inspection case study, the following background work was completed:

- Identified the Boeing 737 tire inspection tasks from the maintenance manual.
- Interacted with customer support engineers with direct support roles requiring interaction with the tire inspection topic.
- Obtained a light aircraft tire and performed notional inspection using the Librestream Onsight camera, a Blackberry smartphone, HTC EVO 4G smartphone, and a low-cost borescope camera.
- Used various inspection aids for opening and viewing cuts, slits, soft spots, and other defects.
- Established the communication link between Seattle and St. Louis for the remote inspection of a dismounted 737 tire (see figure 26).
- Revised the 737 tire inspection procedures, which required minimal changes. Primarily, statements regarding the incorporation of remote inspection had to be added. The philosophy was that a current inspection is left to the discretion of the inspector. The procedure adds the remote capability while allowing the RI to pass, fail, or deem the inspection incomplete. In the event of an incomplete inspection, alternate arrangements are required to complete the inspection by performing another remote inspection or traditional local inspection. The procedure was circulated to a group of expert advisors for review. Comments were collected. There were no edits suggested, as the philosophy resonated with the experts and users that reviewed the alterations to the baseline procedure.

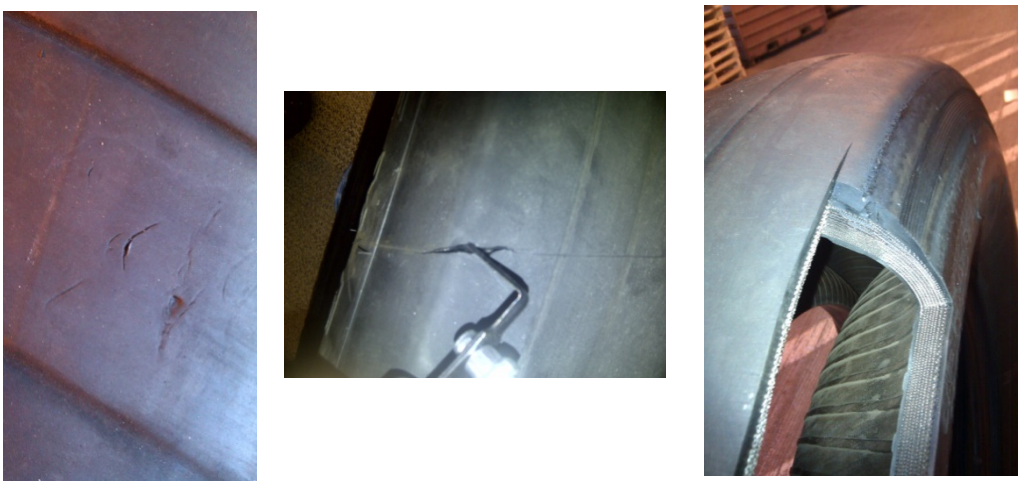


Figure 26. Examples of dismounted 737 tire captured images

3.3.5.2 Case Study Procedural Trials

Boeing arranged and visited the San Antonio 787 retrofit facility, where a 787 remote tire inspection case study was performed. The aircraft was in heavy modification and was surrounded by scaffolding and tooling, modestly impeding Boeing's activities but not preventing successful access. The tires installed (left main gear) were temporary ramp tires that were deemed flightworthy by our inspectors using conventional inspection techniques, though they were labeled "Remove Before Flight." The hangar lighting was generally obscured by the aircraft and the modification situation, necessitating local illumination. Inspectors noted that even on a typical day on the flight ramp, the use of a flashlight is required to backfill shadows and overcome lighting variations.

The following were the steps taken to perform the case study:

1. Performed a manual inspection with inspector A; inspector B was isolated from the aircraft. Inspector A documented the condition of the tires and wheels with the conventional rigor.
2. Performed a remote inspection with inspector B using selected available technologies; the on-site inspector was not a qualified inspector. Because this was a case study rather than an experiment, scientific controls were not in place.
3. Alternated the roles for inspector A and inspector B to permit direct witness of the opposite viewpoint and condition of the tires and wheels.

The hardware available for the trial included the Librestream Onsight, Galaxy S4 Active, HTC EVO 4G, and Blackberry Bold.

The trials provided a notional study of the videoconferencing on the Onsight and offered an opportunity to mimic the Onsight functions in still and video modes on the other devices. Streaming video and capture software (e.g., Skype) were not available for these trials because software and site network access permissions were not in place.

3.3.5.3 Procedural Trials Setup and Execution

Setup was limited to mimic local inspections. The primary setup was a procedural walkthrough prior to any remote inspection activities performed in virtual videoconference fashion to mimic a novice OA on-site supporting an experienced and qualified RI expert. The test articles were worn shop tires used for production transport and storage but deemed to be flightworthy, per the expert inspector's assessments.

The trials were performed with two experienced aircraft mechanics qualified as tire inspectors. The process was followed despite technology setup issues and sporadic personnel availability, developments which were illuminating and realistic elements of the effort (see figures 27–28).

Figure 27. Remote tire inspection procedural trial

Figure 28. Various images of tire and Onsight camera taken with a Galaxy S4 Active

Table 9 summarizes the results of the remote tire case study procedure trials.

Table 9. Case study tire inspection procedure trials results summary

Segment	Result	Comment	Notes
Remote Inspection Mechanic #1	Inspector #1 was at the remote inspection application on a laptop approximately 100′ from the aircraft in the hangar. Inspection was attempted with limited success. A non-inspection was declared.	The real-time operation was challenged because of a lack of RI context for crack location, scale, and difficulties in assessing certain features, such as flat spots on the tire.	The author acted as the on-site operator of the Librestream Onsight camera for this procedure trial, attempting to provide the best video and most informed responses to requests.
Remote Inspection Mechanic #2	Inspector #2 was at the remote inspection application on a laptop approximately 100′ from the aircraft in the hangar. Inspection was attempted with limited success. A non-inspection was declared.	Lighting direction, angle, and intensity were found to be key to providing some insights into crack depth because typical integrated lens-aligned camera lighting is meant to minimize shadows. Even with independent lighting from an angle, scale is difficult to determine at the remote operator station.	Inspector #1 acted as the on-site operator of the Librestream Onsight camera for this procedure trial, attempting to provide the best video and most informed responses to requests.
Interactive Remote Inspection Discussions	Inspectors #1, #2, and the author gathered at the landing gear, with both the Librestream Onsight and the smartphones. The separate lights were used to illuminate the tire from an independent position from the camera and noted that a moving angle created shadows that gave insight into crack depth, though the scale of the scene is still missing in 2-D images.	Remote tire inspection technology needs to advance in terms of integrated capabilities that will provide the data necessary to achieve remote tire inspections worthy of FAA approval. Tire inspectors would likely have near 100% “non-inspection” declarations with the current technology.	Technology advancements and procedural techniques that provide mitigation of some issues are required and are likely out of scope for this research.
Standard Manual Inspection	Both experts agreed (after the fact) that the tires on this aircraft are worn, but in flight-worthy condition.	The qualified local human expert has the stereo vision, dexterity, maneuverability, and a sense of context to achieve an inspection. Touching the tire appears to matter.	The installed tires are temporary ramp use tires labeled “REPLACE BEFORE FLIGHT.”

3.3.5.4 Remote Tire Inspection Technology Assessment

The primary requirement for successful remote inspection of aircraft tires, whether performed interactively in real time or recorded and played back later, is that a RI needs to have sufficient data quality to assess the condition of tires. Based on this case study procedural trial, Boeing concluded that the imaging technology maturity and the process for its use do not provide reliable remote tire inspection capability. The technologies did not appear to be far off, however, and the procedural trial can help determine the steps necessary before this capability is ready for acceptance, approval, and certification.

The primary technology constraints identified in this trial effort were visualization of scale, illumination for defects characterization, and provision of tactile feedback alternatives for flat/soft spots. There were other lesser technology constraints identified and operational uncertainties that further weaken the case for immediate acceptance of remote tire inspection. These lesser items tend to make the likelihood lower from a productivity standpoint rather than from a fundamental capability standpoint. They include noise cancellation, autonomous smart software, and the skillset requirements that become an issue in training the LO. At a certain

point, training the LO to perform remote inspection becomes as difficult as qualifying them as tire inspectors capable of locally performing the inspections themselves.

Human stereo vision provides a "calibrated" experience for dimensional estimation. Human hands can feel for flat spots and soft spots, which allows for rapid inspections. Humans also have innate feedback for head position and body position relative to a tire and landing gear. Technology needs to approximate these functions before remote tire inspections can replace current practices that rely on these on-site human capabilities for assessing tire condition.

3.3.5.5 Implementation Issues/Challenges

The case study implementation and other aspects of this effort were reviewed by Boeing SMEs with a view toward capturing the technical and operational issues and challenges foreseen in the regulating agencies (FAA/government), industry, and contractor communities, as summarized in table 10.

Table 10. Case study issues and challenges

Type	Issue	Mitigation	Expectations/Notes
Technical	Display of image scale	Image scaling via ranging	Autofocus sensors might provide enough data
	Illumination adaptations	Separate lighting or other mods	Kitted inspection tools
	Tactile feedback adaptation(s) for flat spot identification and scaling	Lighting, ranging, and image processing to present an annotated view of a flat spot in "target recognition fashion"	Algorithms and 3-D model extractions may be needed to replace tactile feedback; tactile displays are in development, but scaling would remain an interesting element
	Remote operator visualization context	Oriented picture-in-picture	CAD model of landing gear and tires moving using accelerometer and gyroscope data in inspection device would satisfy this item
Operational	Availability of sufficiently trained on-site operators and technology	All remote tire inspection enabled airports should have an equipment set that has been tested and qualified for the remote tire inspection application.	Possible qualification processes include the FAA, National Highway Traffic Safety Association, Aircraft Manufacturers Association, and aircraft manufacturers. A percentage threshold in independent tests for completed inspections is a good measure.

3.3.5.6 Procedure Trials Feedback

Table 11 summarizes characteristics of a prototype solution and SME comments as a result of the procedural trial.

Table 11. SME comments regarding remote tire inspection procedures

Characteristic	Description	Comments
Lighting	Secondary light source is required for effective split, cut, and wear depth assessments; alternating light sources and motion would add value	It was noted that movement of an independent light source on various angles offset from the camera line of sight offer advantageous shadowing to the viewer.
Brightness	Auto-iris function for tire inspection may require specific settings and even an advanced, automated algorithm.	Washout was apparent in some images because of the lack of contrast on the black tire.
Focus	Focus appears to vary depending on scene content and the material being imaged.	Rubber appears to absorb the autofocus energy and limit the sharpness of the image
Sound	Excellent noise cancellation technology is required	Ramp and hangar noise levels are significant.
Lens/Optics	Lenses need to be capable of macro to wide field of view	Human vision (corrected and aided) equivalency
Probes	A method to provide insight into scale and characteristics of the material defects under inspection. (e.g., cut depth/cord)	Expand a cut to visualize depth or add light to the defect
Sensors	Pressure, durometer, tread depth, etc.	External sensor to complete the desired inspection
Orientation	Accelerometer and gyroscope data can give orientation and the potential use of model-based characterizations.	RIs need to know what they are seeing to maintain a coherent assessment of the tire quality.
Metrology	Ranging sensors (possibly autofocus) could provide some ranging data and the potential use of model-based characterizations.	Without scale and orientation, an RI has no clear sense of scale.
Automation	Target (defect) recognition, model-based comparison, pseudo-stereo from motion	Tire/wheel specific variations of these technologies would make speedy and effective inspections practical.

3.3.6 Implementation Issues and Challenges Survey

A survey was prepared to gather perceived issues and challenges related to this effort from an affiliated community. Table 12 shows the types of data sought from the survey to capture a condensed view of the obstacles associated with an operational transition to remote tire inspections.

Table 12. Preliminary remote tire inspection survey

Category	Survey Question	Expectations
Safety	Will remote inspection ever cause decreased safety or will it always increase safety? For example, might a poorly performed remote inspection ever cause a mishap?	It is anticipated that the inspector, unless he feels there is high-quality data, will call an incomplete and require another inspection.
Cost	Will remote inspection ever cause increased costs or will it always save money? For example, could a poorly performed remote inspection raise costs?	Costs for inspection equipment should be nonrecurring and save on labor and operational delays over time.
Schedule	Does remote inspection always save time? Can there ever be a situation in which remote inspection adds delays?	Remote inspection should not ever add to delay.
Organizational	Are there operator, support, supplier, and/or government/regulatory organizational issues that inhibit or prohibit the remote inspection regime?	This is an area that is anticipated to have potential cost increases that are dependent on future government regulations.
Labor	Are there organized labor issues that would inhibit remote inspections from deployment and acceptance? What power and authority do they have to influence the acceptance or denial of such change as remote inspection represents to them?	This is an area of anticipated challenge. There will be a perception of job and work loss to overcome with labor unions once they become aware.
Legal	Are there liabilities or other legal aspects that are concerns?	Yes, but this can and should be mitigated through low-persistence approaches initially. Over time, a transition to more persistence in storing data will likely evolve as justified.
Administrative	Are there administrative details of other varieties that might be a problem related to remote inspection acceptance?	There may be other issues that are not yet anticipated.
Operational	What operational elements of remote inspection activities are concerns? Would people be reluctant to be imaged? Other aircraft? What if an event occurs in the background? Is the data persistence or deletion an issue?	Elements of remote inspection, such as inadvertent imaging of unrelated activities; permissions to image individuals or other aircraft; and other operational factors, are a possible hindrance.
Retention	Do artifacts get saved? How long? When and who accesses them?	This report's approach and philosophy is that the retention of artifacts will not change, even if they are created in the process.
Infrastructure	Does the network and communications infrastructure support the remote inspection needs in most places? Does WiFi exist where needed? Can cellular telephone wireless networks be used effectively?	This is expected to be a reasonable assumption for most locations or could be added at reasonable cost.
Reliability	Are the systems and processes involved reliable and useful in the long run?	This is not expected to be a problem, though the degree of usage will depend on the answer.

The survey was distributed to relevant personnel within Boeing to acquire their input on the topic of remote tire inspections. Table 13 shows survey respondent #1 in the airworthiness certification group, who is involved in the advocacy for and evolution of remote inspection as a business efficiency measure for Boeing.

Table 13. Survey respondent #1

Category	Survey Question	Responses
Safety	Will remote inspection ever cause decreased safety or will it always increase safety? For example, might a poorly performed remote inspection ever cause a mishap?	The safety of the inspection will depend on the video operator and the RI, not the technology.
Cost	Will remote inspection ever cause increased costs or will it always save money? For example, could a poorly performed remote inspection raise costs?	I believe at the worst possible case, the costs would break even. There may be situations when money is saved. The quality of the inspection will determine to a large extent whether a re-do is required. The initial costs to implement this technology may be greater to make sure the inspection is performed correctly. I am sure there will be lessons learned on how to improve inspections.
Schedule	Does remote inspection always save time? Can there ever be a situation in which remote inspection adds delays?	This is subject to debate. The use of video as a communication tool should only be used when there is a direct benefit. This will vary for each inspection and the requirements to perform the inspection.
Organizational	Are there operator, support, supplier, and/or government/regulatory organizational issues that inhibit or prohibit the remote inspection regime?	MROs are fairly sensitive to this issue. Union personnel and other site personnel feel there is a potential liability issue for the work performed and any aircraft mishap that may happen in the future. If the video is stored, the FAA may want to reference the video as evidence of incorrect routine maintenance, inspections, repairs, and alterations. From a certification perspective, the FAA does not like change. The FAA is not likely to approve video remote inspections in the near future.
Labor	Are there organized labor issues that would inhibit remote inspections from deployment and acceptance? What power and authority do they have to influence the acceptance or denial of such change as remote inspection represents to them?	
Legal	Are there liabilities or other legal aspects that are concerns?	
Operational	What operational elements of remote inspection activities is a concern? Would people be reluctant to be imaged? Other aircraft? What if an event occurs in the background? Is the data persistence or deletion an issue?	
Administrative	Are there administrative details of other varieties that might be a problem related to remote inspection acceptance?	Boeing, the customer, and the FAA may require additional requirements for the use of video technology.

Table 14 shows the response from a commercial aircraft technical support specialist with responsibilities that include landing gear and tires.

Table 14. Survey respondent #2

Category	Survey Question	Responses
Safety	Will remote inspection ever cause decreased safety or will it always increase safety? For example, might a poorly performed remote inspection ever cause a mishap?	I would expect that remote inspection has a higher potential to miss a flaw in the tire than a direct inspection. However, tire failures are normally considered to be "not safety," so remote inspection probably would have a minimal impact on safety.
Cost	Will remote inspection ever cause increased costs or will it always save money? For example, could a poorly performed remote inspection raise costs?	I would expect that it has the potential to save money, especially if the airplane is at remote airports when the inspection needs to be performed.
Schedule	Does remote inspection always save time? Can there ever be a situation in which remote inspection adds delays?	I do not see a time advantage for remote inspection.
Organizational	Are there operators, support, supplier and or government/regulatory organizational issues that inhibit or prohibit the remote inspection regime?	Not aware of anything that would prohibit remote inspection.
Labor	Are there organized labor issues that would inhibit remote inspections from deployment and acceptance? What power and authority do they have to influence the acceptance or denial of such change as remote inspection represents to them?	Unknown.
Legal	Are there liabilities or other legal aspects that are concerns?	Not that I am aware of.
Administrative	Are there administrative details of other varieties that might be a problem related to remote inspection acceptance?	
Operational	What operational elements of remote inspection activities is a concern? Would people be reluctant to be imaged? Other aircraft? What if an event occurs in the background is the data persistence or deletion an issue?	The only thing I can envision is that the quality of any images (e.g., lighting, percent coverage, etc.) might take away from a direct visual exam.

A theme that was brought up repeatedly by SMEs in regard to the implementation of remote tire inspection was that human judgment plays a significant role in tire inspection. Tire inspections are performed rapidly, and not all of the steps involved in maintenance task specifications are followed.

The following is a summary of SME feedback:

1. Generally, tire inspection is performed visually and takes approximately one minute per tire. The general scan is used to identify any perceived tire damage.

2. The published inspection procedure serves as a guideline for tire inspection. Tire wear is seldom as even or as stylized as described in the procedure. For example, tread depth may vary greatly around and across the tire. There is considerable judgment that will vary by expert and airline as to when to remove the tire.

3. Determining the depth of a cut and whether it penetrates to the fabric often presents a "catch 22," because inspectors are discouraged from using tools (e.g., screwdriver) to probe the cut because of concern for triggering a blowout. Therefore, the depth of a cut can be left to the judgment of the inspector.

4. Providing technology to generate data in such instances could be helpful.

5. The ability to record data may trigger more conservative behavior by inspectors because their decisions could be reviewed.

3.3.7 Remote Tire Inspection Acceptance

Because of gaps in technology and a lack of solid results from the case study trial, the details of remote tire inspection acceptance could not be further developed. A high-level process and general plan for acceptance by the FAA is shown in table 15.

Table 15. Steps for FAA acceptance of remote tire inspection

Deliverable	Prerequisite to Practical Implementation	Exit Criteria
Describe a future plan for progressive, iterative manufacturer, airline, and FAA reviews as an approach to a remote inspection preliminary FAA acceptance process	Technology must mature to a state in which the items in table 10 are addressed prior to a set of reviews to begin.	Technology appears mature, review plans are in place to compare remote versus local tire inspections to ensure equivalence.
Describe a contingent approval trial period, with feedback from users advising a procedural update	Remote tire inspection reviews are completed and accepted by the interested parties, manufacturers, airlines, and the FAA.	A plan for a contingent approval trial period is in place and record keeping mechanisms for the trial period are established.
Describe the final approval process for which the FAA formally acknowledges remote inspection as a operationally viable alternative	The contingent approval trial period is completed, data is reviewed, and all parties accept that there is a safe and practical way forward.	The FAA reviews the results of the contingent approval trial period and agrees that the results warrant final acceptance of remote tire inspections.

3.3.8 Remote Tire Inspection Summary and Conclusion

Aircraft tire inspection is an example of a routine inspection that requires the presence of an expert mechanic. The unavailability of qualified mechanics results in dispatch delays and financial consequences for the operator. This challenge can be addressed through the development of a remote inspection method that eliminates the need for the presence of a local expert. Instead, a RI could guide a LO to collect and transfer the needed data without the delay or expense of bringing an expert inspector on-site.

The primary challenge for remote inspection of aircraft tires is that a RI needs to have data of sufficient quality to accurately assess potential tire problems. Based on this initial study, the technology and the processes for its use are not yet mature enough to facilitate reliable remote tire inspections. The primary technology constraints and challenges identified in this trial effort were visualization of scale, illumination for defects characterization, and provision of tactile feedback alternatives for flat/soft spots. Other lesser technology constraints and operational uncertainties were also identified that further weaken the case for immediate acceptance of

remote tire inspection. These lesser items tend to affect productivity rather than feasibility. They include noise cancellation, autonomous smart software, and the skill set required of the LO.

The authors of this report anticipate that, in the not-too-distant future, technological advances will make remote tire inspection a viable option. It is also likely that technology will find its way into the tires and wheels themselves to enhance the ability of external devices to assess their remaining life, component by component. Once remote tire inspection technologies mature, the SPMS recommended updates to maintenance manuals (see appendix B) can be incorporated.

3.4 CORROSION CBM

3.4.1 Background

Currently, most inspections are performed visually either by the naked eye or with the assistance of borescope technology. In cases in which corrosion is found, the component will require an assessment to determine if any material thinning is present. Inspectors will typically perform the thickness inspections using either ultrasonic or eddy-current inspection depending on the number of layers that are present. These inspections in which visual inspection triggers a more detailed NDE investigation are called analytical conditional inspections (ACI). In most ACI cases, the data is not stored. However, for some ACI in which semi-automated scanning systems are used (e.g., MAUS), operators will archive the C-scans for future reference. These methods and equipment aid in a more effective diagnostics and repair process, with no ability to provide guidance on the future operational state of corroded material.

Corrosion CBM can potentially reduce the cost of periodic inspections, enable optimum repair, and enhance the availability of aircraft. Corrosion CBM can be viewed from several perspectives depending on the maintenance philosophy and the approach in using corrosion inspection.

If “condition” is assessed based entirely on the simple “presence” of corrosion, then inspection is the critical element and the methods used require only the capability to detect corrosion.

If “condition” is linked to specific criteria (e.g., maximum thickness loss, pits per square area, etc.), then resolution of the inspection method and a more detailed inspection procedure used must be considered.

If “condition” requires future inspection intervals and a prognostics element, then a damage tolerance model for corrosion and an acceptable inspection process must be in place.

3.4.2 Corrosion CBM Technologies

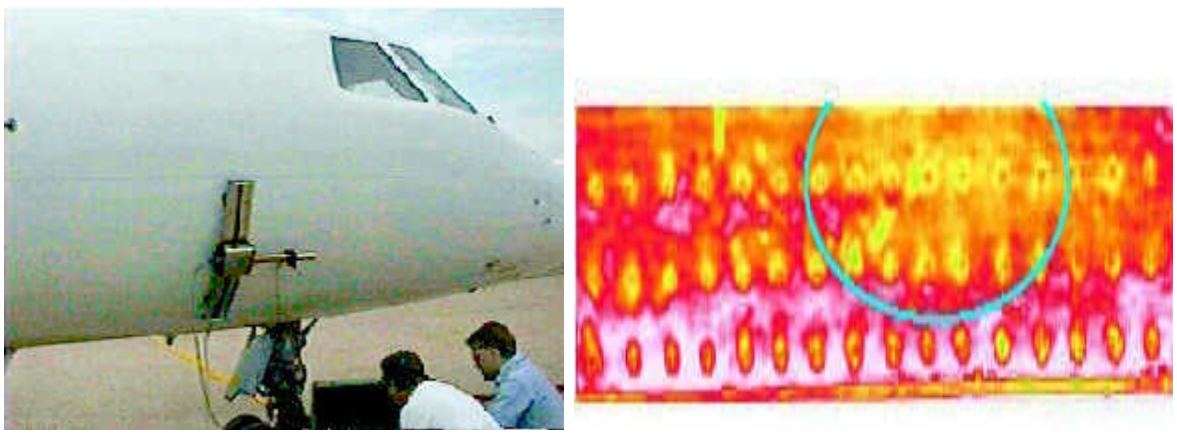
NDE is the common thread for corrosion CBM and is a required capability independent of maintenance philosophy. However, a key gap for cases that require prognostics is the existence of an accepted damage tolerance model for corrosion and infrastructures for collection, management, and analysis of historical NDE data. A description of various NDE technologies and damage tolerance models are provided in sections 3.4.2.1–3.4.2.3.

3.4.2.1 NDE Technologies

The most common and established NDE technologies as applied to corrosion are ultrasonic and eddy current. There is a newer radiologic-based approach (backscatter x-ray) that is currently being evaluated as a corrosion NDE tool, especially for pre-programmed depot maintenance (PDM) inspections to help minimize the extent of unscheduled maintenance during the PDM process.

3.4.2.2 Ultrasonic Methods

Ultrasonic methods use high-frequency mechanical stress waves (500 kHz–10 MHz) reflected from anomalies and interfaces to identify flaws. Ultrasonic inspections performed on in-service aircraft are typically performed in pulse-echo mode using a transducer applied to the part surface, with ultrasonic waves transmitted and received using the same transducer. The interpretation of ultrasonic data is performed using either A-scan (rectified waveforms on a CRT display) or C-scan (areal map of internal structure) formats. Key advantages of ultrasonic methods are the superior spatial resolution and the ability to resolve small flaws. One key disadvantage is the need for a coupling medium (e.g., water, silicone gel) to couple the energy into the part. Ultrasonic waves reflect from interfaces where there are differences in acoustic impedance. Because of this, inspections of multi-layer structures are typically limited to the first layer unless faying surface sealant or other material is present to couple the sound through multiple layers (see figure 29).



(a) (b)

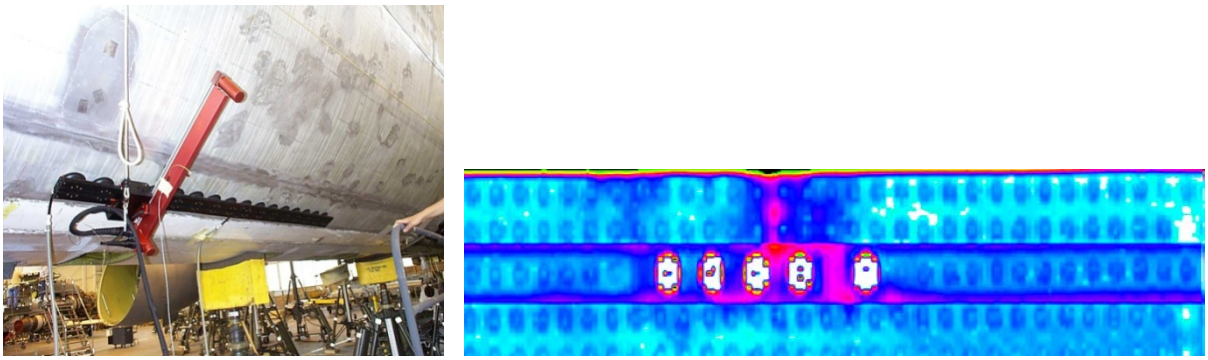
Figure 29. The (a) semi-automated ultrasonic inspection of fuselage lap seam and (b) ultrasonic pulse-echo C-scan showing areas of corrosion

3.4.2.2.1 Eddy-current methods

Eddy-current methods are based on the principles of electromagnetic induction. In conventional eddy-current testing, a circular coil carrying current is placed in proximity to the test specimen (which must be electrically conductive). The alternating current in the coil generates a changing magnetic field that interacts with test specimens and generates eddy currents. Variations in the phase and magnitude of these eddy currents can be monitored using a second “receiver” coil or

by measuring changes to the current flowing in the primary “excitation” coil. Variations in the electrical conductivity or magnetic permeability of the test object, or the presence of any flaws, will cause a change in eddy currents and a corresponding change in the phase and amplitude of the measured current.

The interpretation of eddy-current data is performed using either an impedance plane display, commonly included in portable systems, or a C-scan display, which is similar to that used in ultrasonic inspection. Eddy currents do not reflect from interfaces, so it may be used for the inspection of multi-layer structures. However, the depth of penetration is limited and is driven by the probe frequency and the conductivity of the material. In addition, unlike ultrasonic, a coupling medium is not required (see figure 30).

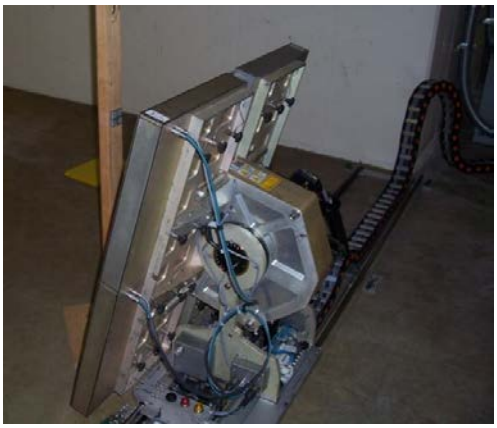


(a) (b)

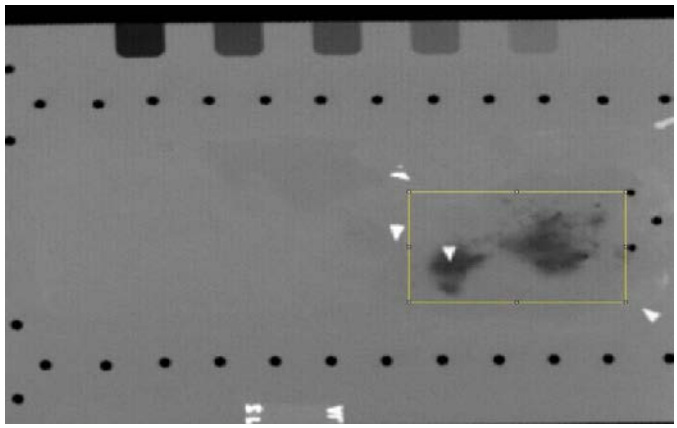
Figure 30. The (a) semi-automated eddy current inspection of fuselage lap seams and (b) eddy current C-scan showing areas of corrosion

3.4.2.3 X-Ray Backscatter

Traditional x-ray machines detect hard and soft materials by the variation in transmission through the target. In contrast, the backscatter x-ray detects the radiation that reflects from the target. It has potential applications on components for which less-destructive examination is required and can be used if only one side of the target is available for examination. Backscatter technology is based on the Compton scattering effect of x-rays, a form of ionizing radiation. The backscatter pattern is dependent on the material property and is good for imaging organic material. Digital x-ray images are produced that show the amount of energy reflected back to the detector. Although most x-ray-based methods are typically not desirable for maintenance operations because of safety considerations, backscatter methods are advantageous because of much smaller radiation impact zones (see figure 31).



(a)



(b)

Figure 31. The (a) x-ray backscatter source/detector and (b) backscatter image of material thinning/pitting in fuselage skin

In addition to these conventional NDE approaches, more advanced in-situ approaches that use permanently mounted sensors may also be used. Two mounted sensor-based approaches include piezoelectric wafers and fiber optic Bragg grating sensors. Both of these approaches have been demonstrated for corrosion detection applications; however, neither is currently used as part of a qualified maintenance and inspection process.

3.4.3 Damage Tolerance Models

A key technical capability for corrosion prognostics is the acceptable damage tolerance models that can support the prediction of material strength degradation under certain loading and environmental conditions.

Conventional damage tolerance analysis is based on crack-length predictions as a function of fatigue cycles with structural inspection intervals and maintenance actions programmed accordingly. The length of the longest crack is assumed to be just below the threshold of the inspection system, and then crack growth at the next scheduled inspection is predicted based on the airframe loading cycles. Appropriate NDE is applied to the airframe at inspection intervals programmed for half the cycles necessary to grow from the minimum detectable crack length to the known critical crack length. Corrosion damage tolerance analysis parallels this process with suitable NDE used to estimate corrosion damage in the airframe at some future inspection time.

Several different corrosion mechanisms occur in aircraft structures that result in different damage effects to the structure. It will be important to analyze the structural effects of these corrosion damage mechanisms, similar to how different crack growth mechanisms are treated in different structural members and materials.

A well-organized discussion on corrosion damage tolerance as applied to the C/KC-135 program was provided by Whaley [5]. Structural assessment and NDE should complement each other for effective damage tolerance analysis [6]. The effect of corrosion on residual strength and crack growth must be assessed in support of corrosion damage tolerance analysis [7]. According to

Goranson [8], damage tolerance analysis is used to achieve aircraft structural operating safety based on timely damage detection. The damage detection period can be significantly reduced in the presence of corrosion, and the random nature of corrosion makes it impossible to establish typical damage growth patterns [8].

In summary, models must be developed first to fully characterize the effect of corrosion damage on structural durability. Second, corrosion growth as a function of geographical location and external conditions must be developed. Finally, models are required to accurately predict when corrosion will increase the danger of multiple site damage (MSD).

Key elements needed for the development of a corrosion damage tolerance model for material thinning in aluminum skins include:

- Chemical analysis of corrosion byproducts and atmospheric data at geographic locations.
- Corrosion damage growth rate as a function of geographic location.
- Residual strength correlation to thickness loss.
- Crack growth correlation to thickness loss.
- Corrosion damage quantification using one or more NDE methods.
- Identification of appropriate corrosion damage metrics.

3.4.4 Corrosion CBM Implementation Requirements

To implement corrosion CBM, it is important to show that the desired level of safety is not compromised as the result of change in inspection intervals.

There are three elements of equal importance for achieving this goal: 1) allowable damage as specified by the residual strength, 2) damage accumulation by crack growth, and 3) damage detection through an inspection program [8]. An accurate assessment of residual strength and crack growth based on fracture mechanics has always been critical for achieving flight safety. It will be just as critical to evaluate the residual strength and crack growth of corrosion-damaged structures. This section includes detailed discussions of the three elements of corrosion damage tolerance analysis: 1) assessment of corrosion damage by NDE, 2) corrosion damage growth modeling, and 3) critical corrosion damage condition.

Quantitative NDE data can be used to support lifing/prognostics that would allow for CBM. Historically, most corrosion evaluations for both commercial and military aircraft have been performed visually, without the capture of any quantitative data. In the early 2000s, the U.S. Air Force began to implement more quantitative methods for evaluating corrosion to reduce the amount of unscheduled maintenance during PDM operations. For example, KC-135 maintenance operations included the visual inspection of all fuselage lap seams. Detection of pillowing or corrosion product emanating from the laps resulted in the removal of panels to determine the extent of corrosion. In many cases, the corrosion was limited to small areas and pitting was not yet evident. It was then determined that a more quantitative NDE method would help determine the extent of corrosion such that more informed maintenance/repair/replace decisions could be made. As a result, the Air Force Research Laboratory and Oklahoma City Air Logistics Center engaged in a number of research and development programs that led to the implementation of

large-area inspection processes using both eddy current and ultrasonic modalities to quantify the extent of corrosion. Most of these quantitative methods were implemented as ACI prompted by the visual detection of corrosion. However, several inspections were implemented in the PDM work package to be performed at every PDM interval due to the frequency of findings in these locations. These methods generated C-scan formatted data as a function of aircraft tail number and were archived for future historical and trending analysis.

From the commercial side, an airline (Airline A) was operating a large fleet of DC-9 aircraft during this same period. Many were experiencing corrosion issues in the belly skins. Much like the U.S. Air Force, Airline A experienced significant aircraft downtime due to unnecessary corrosion maintenance derived from visual inspections. Airline A followed suit with the U.S. Air Force and implemented large-area scanning processes for inspection of the belly skins. Using more quantitative data to determine the extent of corrosion also helped Airline A make better maintenance/repair/replace decisions; as a result, it saved the airline several million dollars each year the DC-9s remained in operation.

NDE is a key technology in developing a CBM approach. However, with regard to prognostics, several other key elements must be developed. NDE provides a quantitative, present-day assessment of the structure that includes area of damage, thickness loss, and presence of pitting/stress corrosion cracking (SCC). However, these alone are inadequate corrosion metrics. The influence of corrosion damage on structural durability must be modeled and determined.

3.4.4.1 Corrosion Damage Tolerance Models

The most critical component for structural integrity assessment is a validated method for the prediction of damage accumulation [9]. It has been known for a long time that even slight corrosion combined with with fatigue significantly decreases fatigue life [10]. The number of fatigue cycles required for crack initiation decreases by a factor of two or three when corrosion pits are present [11]. The threshold stress intensity also decreases by approximately 50% in the presence of corrosion pits. Severe corrosion regions may tunnel into the matrix of the material beneath the surface, resulting in significantly more complicated damage than simple thinning [12]. Finally, corrosion pillowing is known to significantly increase the stress in fuselage lap joints [13]. Most researchers assume that crack growth is the corrosion fatigue damage mechanism and that cracks grow from some corrosion-induced flaw [14– 15]. In the presence of corrosion, small cracks may grow much faster than large cracks [16]. In addition, the effect of corrosion on widespread fatigue damage (WFD) is not known. WFD is a dangerous condition in aging aircraft that is characterized by multiple cracking that decreases the airframe residual strength below the damage-tolerant requirement. Swift described two types of WFD [17]. First, MSD is characterized by simultaneous cracks in the same structural element. Second, the presence of fatigue cracks in adjacent structural elements is called multiple element damage. MSD is characteristic of fuselage structures and multiple element damage is characteristic of wing structures. MSD coupled with material thickness reduction by corrosion leads to a dangerous scenario [18]. The critical crack length with MSD decreases and the crack growth rate increases [19]. MSD might reduce residual strength and critical crack length substantially [20]. The nature of corrosion damage accumulation in fuselage lap joints suggests a fundamentally different character of the crack population. Traditional deterministic damage tolerance analysis is based on a single crack, usually assumed the largest crack. Corrosion damage accumulation

occurs randomly. Because corrosion pits are a site for crack initiation, corroded materials with many corrosion pits would likely have many cracks initiating [11]. Some of the corrosion pits or cracks may link up to form larger damage regions [9]. MSD influenced by corrosion damage may occur in the C/KC-135 fuselage lap joints as the airframes continue to accumulate fatigue cycles [21]. The possibility of MSD is a significant technical challenge to NDI systems. MSD could occur with very small cracks under rivet countersinks in lap joints [22]. This will require NDI systems to detect much smaller cracks in the presence of corrosion and under the rivet heads in lap joints. NDE equipment needs to have significantly higher PoD, an order of magnitude smaller than current practice. Furthermore, NDI equipment needs to provide information on size, location, and geometry of damage. Cracks of one or two millimeters (0.040″–0.080″) might degrade the fail-safe capability of the airframe [23]. Therefore, NDE systems must be capable of detecting very small cracks in the presence of corrosion for airframes that have accumulated a lot of fatigue cycles [24–25].

3.4.4.2 Corrosion CBM Infrastructure

Information is required to mature and evolve corrosion CBM and for the validation and certification of corrosion CBM infrastructure for the collection and archiving of historical NDE data and other relevant maintenance and operations. Issues such as data storage requirements, data access, and the duration for which data is required to be maintained have not been addressed; these issues need to be in the forefront when corrosion CBM is given consideration. Given the state of information technology, the infrastructure—including data collection, transmission, security, and management—is not a hurdle from a technical point of view. The barriers to implementation are the business considerations in terms of the ramifications of the storage of historical data that have not been available previously and the impact on liability and issues related to business operations.

3.4.5 Certification of Corrosion CBM

In 2011, the FAA issued AC 120-104 defining the establishment of a Limit of Validity (LOV) and how to use engineering data to support the structural maintenance program for commercial airplanes [26].

LOV is the total number of flight cycles/hours during which no WFD will occur. AC 120-104 also defines how to address maintenance actions incorporating LOV into airline operators' continued airworthiness maintenance programs. The ultimate goal of this document was to prevent WFD in the transport aircraft fleet up to the LOV. In response to this AC, Boeing responded with document D6-84678 in compliance with 14 CFR 26 Subpart C (Amendment 26-5) [27]. This document defines Boeing's WFD methodology, including the establishment of LOV and requirements for both service and maintenance actions.

It is apparent that the issuance of AC 120-104 and the establishment of LOV was not a reaction to corrosion [28]. The emphasis is clearly on the classic definition of WFD, which is a distribution of small cracks that, individually, are below the detection threshold relative to NDE systems. However, as a whole, the cracks can seriously degrade structural integrity.

Though corrosion itself may not apply to the establishment of an LOV, it is possible that certain SCC scenarios may apply. SCC is cracking induced through the combined influence of tensile stresses and a corrosive environment [29]. The required tensile stresses may be in the form of directly applied stresses or in the form of residual stresses. The stress of aircraft components may be residual within the part as a result of the production process or externally applied cyclic loading. Press-it bushings, tapered bolts, and severe metal forming are examples of high-residual tensile stresses that can lead to stress cracking.

A number of research and development programs were funded in the late 1990s through the mid-2000s addressing several of these items. Boeing was funded by the U.S. Air Force to investigate corrosion kinetics, including pit formation, and by the U.S. Navy to assess the impact of corrosion fatigue on structural integrity. In addition, Boeing received significant funding from the U.S. Air Force to develop NDE systems and processes to address corrosion during PDM operations. Some of these processes were eventually implemented into the KC-135 PDM work statement. The U.S. Air Force also put significant funding into development of a corrosion damage tolerance model, with elements worked primarily by Aeronautical Radio, Incorporated and S and K Technologies. Though no model has been implemented to date, this research shed light on the difficulties involved in developing an accepted model with so many variables involved. This resulted in the conclusion that the key capabilities for fielding of corrosion CBM are not available, and, therefore, it is too immature to address the certification of this capability.

3.4.6 Corrosion CBM Assessment Summary and Conclusion

Corrosion CBM can potentially reduce the cost of periodic inspections, enable optimum repair, and enhance the availability of aircraft.

NDE, which is currently used for corrosion detection, is a required capability for corrosion CBM. The most common NDE technologies are ultrasonic and eddy current. A newer, radiologic-based approach (backscatter x-ray) is being evaluated for corrosion detection.

For cases that require prognostics, key gaps as it relates to implementation and certification of corrosion CBM include:

- Corrosion damage tolerance—This equates to a credible model that can guarantee a safe margin of strength based on crack-growth prediction.
- Usage or environment model for the growth of corrosion to support the prediction of corrosion growth under various loads and environmental conditions.
- Collection, management, and availability of historical quantitative NDE data on corrosion growth to support the development of ultrasonic, eddy current, and backscatter x-ray technologies.

The conclusion is that corrosion CBM technologies and supporting infrastructure are not mature. The last gap, the collection of data, could be partially addressed by the collection of NDE data once the requirements for data collection are clearly identified and mandated.

There is currently no requirement for a commercial carrier to archive data from corrosion inspections or to report such information to Boeing or any other participant. The only requirement is documentation that an inspection had been performed. A cooperative relationship would need to be established with the carriers to encourage data collection, management, and sharing toward the goal of improving the certification process and reducing costs. The benefits would have to outweigh the costs.

Based on the above, corrosion CBM was not chosen for the development of an SPMS case study. The technology, implementation gaps, and related regulatory guidance were studied and documented for this report. In the future, once these gaps are addressed, a case study can be developed through which the certification of the corrosion CBM could be studied in further detail.

3.5 OPERATING WITH DEGRADED STRUCTURES

The concepts behind the operating with degraded structures application are based on work completed by Boeing on a U.S. Air Force Research Laboratory condition-based maintenance plus structural integrity (CBM+SI) demonstration program. The SPMS application would adapt the CBM+SI concepts to the commercial aircraft environment.

The objective of the Operating with Degraded Structures application, similar to the corrosion application, would be to determine inspection intervals and predict the repair event. The general flow from data to the decision support is shown in figure 32. The CBM+SI program investigated several levels of data inputs, including configurations that were composed of onboard sensor data.

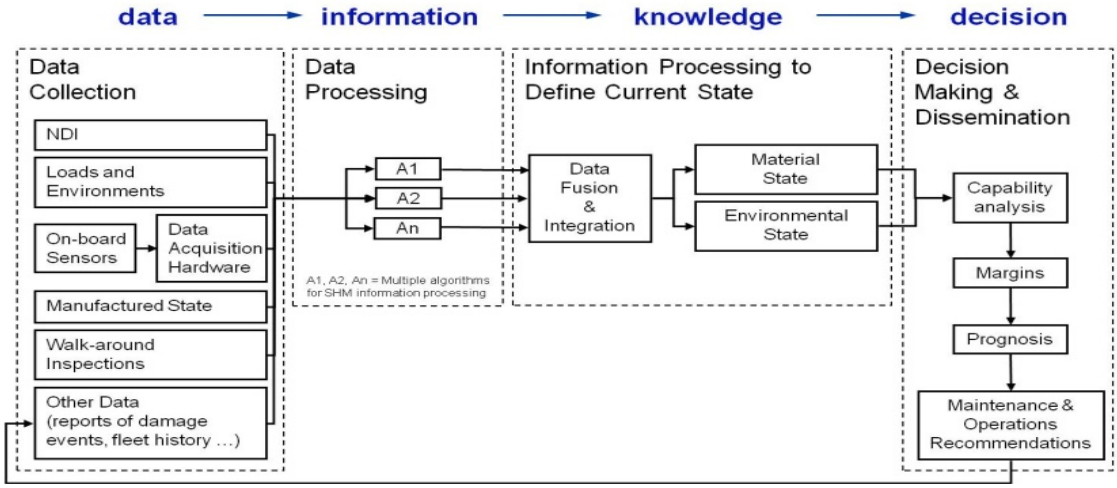


Figure 32. CBM+SI system elements

The key element of any prognosis structural health is a mechanism to estimate crack growth and associated confidence levels. In the CBM+SI program, a proprietary Boeing algorithm was used to perform this estimation on an F-15 structural component. A cost/benefit assessment was performed on concepts that involved several configurations of sensors/NDE technology and periodic and continuous monitoring strategies (see figure 33).

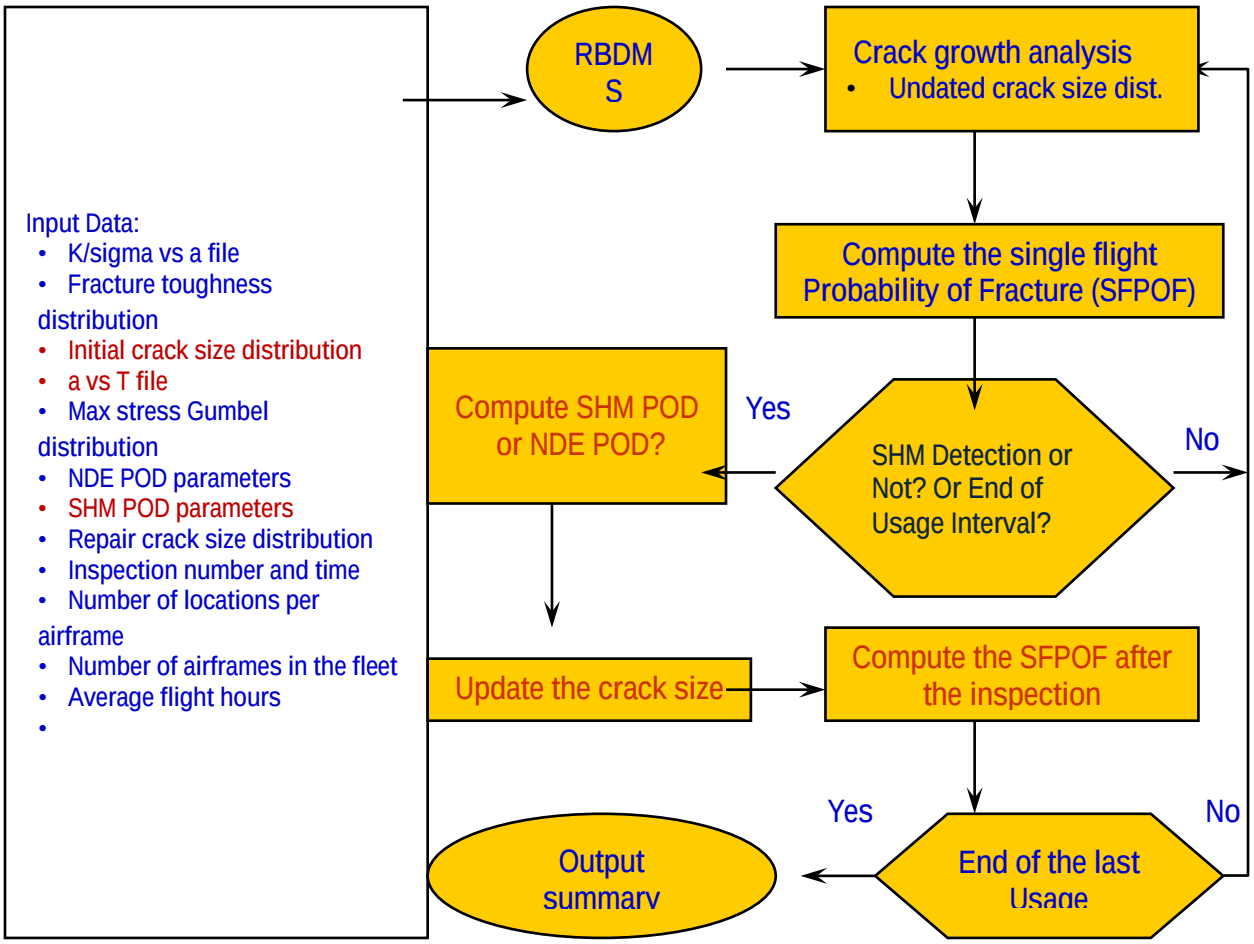
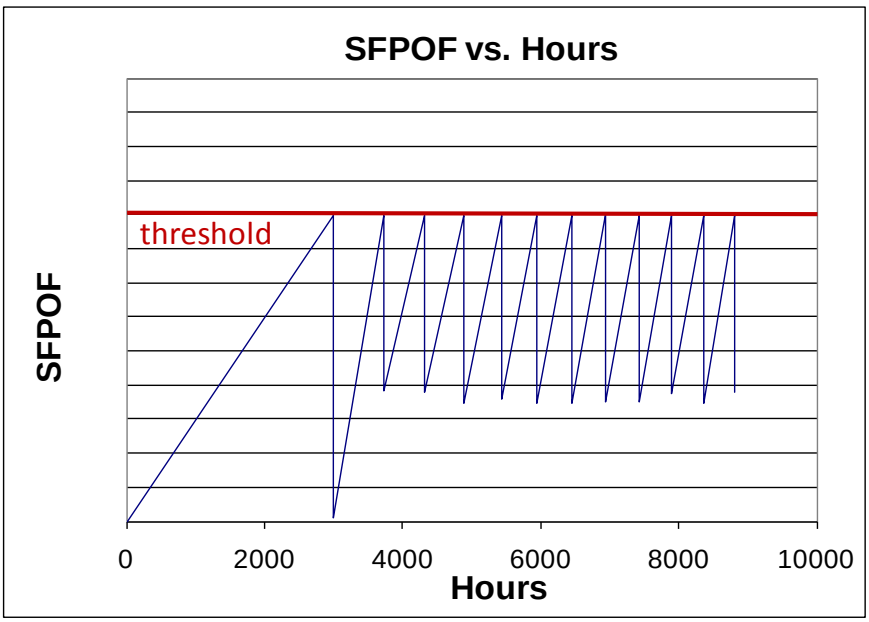


Figure 33. Probabilistic risk assessment

The process was risk-based using a single flight probability of failure (SFPOF). A plot of risk versus hours for the baseline traditional NDE approach with risk threshold is shown in figure 34.



Single Flight Probability of Failure (SFPOF) vs. Hours

Figure 34. Inspection intervals for baseline traditional NDE approach

This SPMS application was intended to be restructured to address the commercial aircraft environment and regulations. However, because of the lack of an internal Boeing program and leveraging opportunity for SPMS, this application was not pursued.

4. PROGRAM SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The availability of large amounts of data collected from airplanes, support equipment, and maintenance information systems presents a substantial opportunity to reduce operation, maintenance, and certification costs. Use of this data could provide lower-cost solutions than those that require the installation of sensors, hardware, and wiring on the aircraft. The addition of sensors to aircraft subsystems for collecting purely health-related data faces tremendous resistance due to the weight, cost, reliability, and complexity they contribute to the aircraft. SPMS health-monitoring applications use aircraft data to predict or provide early indications of failure, resulting in reduced unscheduled maintenance and improved availability. In addition to onboard data, data collected at the aircraft can be used for the same benefit. If the data generated by inspection support equipment is stored, collected, processed, and managed efficiently, it could be used to assess the current and future state of the structure. Furthermore, the transfer of this data to a remote site where an expert can view and perform the assessment would result in more efficient inspection by reducing reliance on the presence of a local inspector. This would expedite dispatch when a local expert is not present.

The SPMS program studied five applications that can take advantage of these data and potentially present the best return on investment. The extent and detail with which each area was studied depended on the maturity of the technology, availability of a Boeing parallel program, and the availability of leveraging opportunities:

- HHL detection.
- Remote NDT.
- Remote tire inspection.
- Corrosion CBM.
- Operating with degraded structure.

4.1 CONCLUSIONS

4.1.1 Heavy/Hard Landing Detection

Currently, when a pilot reports a heavy/hard landing (HHL), a complete set of inspections is required, many times resulting in unnecessary removal of the aircraft from revenue service until the inspection results prove the aircraft is safe for re-entry. The analysis of historical cases in which pilots announced a HHL revealed that many of these cases did not show damage at critical inspection points. Airlines are trending toward an automated system that provides a more accurate indication of HHL and can also guide the inspection to more focused critical inspection points based on the characteristics of the event. This capability reduces maintenance costs and improves the availability of aircraft.

The Sensory and Prognostics Management System (SPMS) HHL application focuses on a novel method that uses advanced algorithms to process available aircraft data and compute load response information at critical areas throughout the aircraft and compare it to respective design limits. A case study was presented in which an aircraft landed with a sink rate of approximately 8 ft/sec. The pilot announced a suspected hard landing by judging the shock he felt from his seat. By looking at historical landing cases, the current landing assessment methodology based on comparing measured data on landing to linear thresholds results in unnecessary inspections approximately 35% of the time. Advanced HHL loads algorithms result in a 5% false call rate when applied to these identical landing cases. To further reduce the false call rate, additional structural sensors can be used as additional inputs to the loads algorithms. Directly measured physical response information increases the fidelity of the landing severity assessment; however, additional hardware increases system configuration complexity; certification effort and cost; and maintenance cost. In addition, systems using sensors to measure strain and acceleration have not been shown to be reliable because of the limited life of the gages, especially on the landing gear, which is more prone to exposure to harsh ambient conditions. This greatly degrades the system assessment reliability, which is a key requirement for any system designed to waive structural inspections.

The key to successful implementation of these algorithms is the accuracy of the loads models, which are based on the fidelity of analytical landing model data by which the algorithms are developed, and the relevance by which this landing model data spans the operational data space. The SPMS HHL case study landing data is validated using empirically measured data collected from landing gear drop testing, ground vibration testing, and limited flight testing.

The focus on certification under SPMS is based on a typical in-service usage scenario, in which the pilot reports a suspected hard landing and documents it in the log book, followed by a landing severity assessment executed via the onboard system. The results of this assessment are then displayed on the landing condition maintenance page for maintenance technicians to view for determining the need for inspection and taking appropriate action. In this particular concept of operation studied under SPMS, the HHL loads algorithms process flight parameter input data to compute peak load response information for each inspection point and then normalize by each respective design limit. If the normalized load is less than 1, the inspection can be waived. The inspection is only performed when the normalized load is greater than 1.

The requirement of HHL assessment reliability is dictated by the flight criticality of the system shown by the fault hazard assessment. The acceptance of the HHL assessment is determined by the reliability of the data collection system, its host, and the methodology and accuracy of algorithms. If the HHL algorithms reside on the aircraft, the certification methods follow the same certification plan that addresses the updates to AIMS software. The second aspect is ensuring that the structural landing analysis methods comply with safety standards (Title 14 Code of Federal Regulations Part 25). These certification results are discussed in detail in this report.

4.1.2 Remote Non-Destructive Testing

With the increased use of composite materials for airframes, the ability to inspect airframe damage and repair from a remote site eliminates the need for continuous availability of local expert inspectors or costly, time-consuming travel to bring experts on-site. SPMS studied the use of network-enabled non-destructive testing (NDT) devices and Internet communication infrastructure for improving efficiency in composite structure inspection and repair. Remote NDT presents another opportunity for taking advantage of collected NDT data for efficient maintenance. The approach outlined using any one of three viable scenarios in this report will allow for rapid, high-quality, lower-cost inspections and better repair decision-making for composite damage events.

The expanding use of remote NDT requires addressing remote-in/out aspects related to NDT instruments; infrastructure for transmission and management of data; and the procedures and training for use of the equipment. Validation of remote NDT instruments and reference-based test calibration would be performed essentially as it is currently, in which a 3-to-1 signal-to-noise ratio is ensured for all flaws that must be found. Some commercial airlines appear ready to begin using remote-expert NDT, especially as their fleets become more composite-oriented. NDT equipment manufacturers are offering simplified, networkable NDT tools that will enable airlines to perform remote-expert NDT inspections. Airlines, NDT equipment manufacturers, and original equipment manufacturers (OEMs) are all looking for indications that the FAA will support remote NDT as a valid means of aircraft inspection. Confidence in this process will result in further planning and resources aimed at remote NDT implementation in the commercial (and eventually military) aviation industry.

4.1.3 Remote Tire Inspection

The tire inspections that are performed regularly at the gate require the presence of on-site inspectors. Because of the technical advances of cameras and Internet connectivity, SPMS studied the use of network-enabled cameras for capturing tire surface images and transferring them to a remote site where an expert inspector could view and assess the condition of the tire. Through this connectivity, the remote expert could guide the local operator (LO) in taking images and capturing the needed features related to the tire's status.

Currently, remote tire inspection technology—which is relatively immature—and the process for its use do not provide reliable remote tire inspections. The primary technology constraints and challenges identified in this trial effort were visualization of scale, illumination for defects characterization, and provision of tactile feedback alternatives for flat/soft spots. Other lesser technology constraints and operational uncertainties have also been identified that further weaken the case for immediate acceptance of remote tire inspection. These lesser items tend to lower the feasibility from a productivity standpoint rather than a fundamental capability standpoint. They include noise cancellation, autonomous smart software, and the skill set requirements that become an issue once a LO must be trained in the technology.

It is anticipated that, in the future, the technology will be improved such that remote tire inspection becomes a viable option. It is also likely that the tires and wheels themselves will eventually include technology that enhances the ability of external devices to assess the remaining life of tires and wheels, component by component.

4.1.4 Corrosion CBM

Corrosion CBM presented another SPMS opportunity to take advantage of data collected from the non-destructive evaluation (NDE) equipment and reduce the cost of periodic inspection and unscheduled maintenance. Ultrasonic methods, eddy current, and backscatter x-ray techniques are currently used for corrosion detection. The key technical capabilities that must be developed for implementing corrosion CBM are: 1) models that fully characterize the effect of corrosion damage on structural durability, and 2) infrastructure to collect and store historical NDE data for trending and analysis. Currently, there are no requirements for a commercial carrier to archive this data and report it back to airframe OEM. A cooperative relationship would need to be established with the carriers to encourage data collection, management, and sharing with the goal of reducing maintenance costs and improving the certification process.

5. OPERATING WITH DEGRADED STRUCTURE

Operating with degraded structure was considered a high priority for SPMS because it allows for the determination of inspection intervals and the prediction of repair events, which reduces maintenance costs. The major requirement for developing this capability is the establishment of a methodology to estimate crack growth and the associated confidence level. The SPMS program intended to examine Boeing-developed algorithms for military application and then restructure them for commercial use. Because of the lack of a parallel Boeing program, this case was not pursued under SPMS II.

5.1 RECOMMENDATIONS

Advances in onboard data collection and the communication system capabilities of newer aircraft provide an opportunity for SPMS applications. In parallel, the availability of high-speed data communication and high-capacity data storage allows for analysis of data wherever experts are available.

Moving forward, given the complexity of the data in terms of diversity in source and ownership, the transition of SPMS technologies to the field will require close collaboration between OEMs, operators, and regulatory agencies to address the technical, implementation, and certification aspects of these technologies. Policies will need to be put in place in regard to the storage and usage of data that historically were not collected or saved. The extent of this data, the period that it needs to be maintained, and access rights are all issues that will need to be discussed among stakeholders.

Certification of SPMS for maintenance credit will need to address the adequacy and integrity of collected data and the validity of algorithms and models. When the data is collected from an onboard system, the SPMS algorithms can reside on the airplane or in a ground system, such as the AHM system. In the first case, software changes should follow the guidance related to updates to modifiable aircraft software. In the latter case, assurances need to be in place regarding data integrity and the quality of the data transferred to the ground. The software assurance level depends on the criticality of the monitored system and the impact of maintenance credit on safety.

The second aspect of SPMS validation is in regard to the accuracy of algorithms in the prediction of failure and changing maintenance practices. Ensuring accuracy will require the validation of algorithms through modeling, simulation, and the use of hardware- and flight-test data. This can only be achieved through extensive, coordinated efforts among various organizations including airframe OEMs, subsystem suppliers, equipment suppliers, and operators. Only with this cooperation will SPMS become a reality and provide return on its significant potential. With limited flight-test validation, these technologies can be inserted as part of the overall routine for in-service maintenance operations as an aid alongside the current methods. With time, confidence in the technologies, such as landing loads assessment, will be gained and loads-based algorithms for HHL, like the one described in this report, will lead the industry for the future evolution of maintenance and operations capability.

The time appears right for a broader industry discussion on remote NDT, perhaps at an FAA-led session at the Airlines for America NDT Forum or at a similar venue such as the Airworthiness Assurance Conference. The FAA has a window of opportunity to promote and guide the emergence of remote-expert NDT as a significant advancement in commercial aviation maintenance practices.

6. REFERENCES

1. The Boeing Company, “777 Airplane Information Management System (AIMS-2) Update Certification Summary,” D243W018-14, August 2, 2014.

2. The Boeing Company, "Certification Plan 14199 777 Avionics – Airplane Information Management System (AIMS-2) – BP V17A Software Upgrade Program," PS13-1016, June 20, 2014.

3. The Boeing Company, "Hard Landing Limits for Revisions to Hard and Overweight Landing Inspection Procedures," LOADS-DL-ALL-M13-001, August 30, 2013.

4. The Boeing Company, "Boeing 787 Airplane Condition Monitoring System/Data Gathering Application (ACMS/DGA)," D617Z009-01, April 18, 2014.

5. Whaley, P.W., "Corrosion Damage Tolerance Methodology for C/KC-135 Fuselage Structure," *Third Joint FAA/DoD/NASA Conference on Aging Aircraft*, Albuquerque, New Mexico, September 20–23, 1999.

6. Chang, J.C.I., "Aging Aircraft Science and Technology Issues and Challenges and USAF Aging Aircraft Program," *Proceedings of ASME Winter Annual Meeting*, San Francisco, California, 1995.

7. Achenbach, J.D. and Thompson, D.O., "Towards Quantitative Non-Destructive Evaluation of Aging Aircraft," *Proceedings of Structural Integrity of Aging Airplanes*, Atlanta, Georgia, March 20–22, 1990, pp. 263–273.

8. Goranson, U.G., "Damage Tolerance – Facts and Fiction," *Proceedings of the 17th Symposium of the International Committee on Aeronautical Fatigue*, Stockholm, Sweden, June 1993, pp. 3–105.

9. Harlow, D.G., Domanowski, L.D., Dolley, E.J., and Wei, R.P., "Probability Modeling and Analysis of J-STARS Tear-Down Data From Two B707 Aircraft," *Third Joint FAA/DoD/NASA Conference on Aging Aircraft*, Albuquerque, New Mexico, September 20–23, 1999.

10. McAdam, D.J., "Corrosion of Metals as Affected by Time and by Cyclic Stress," *Transactions of the American Institute of Mining and Metallurgical Engineering*, Vol. 69, 1928, pp. 571–607.

11. Pao, P.S., Gill, S.J., and Feng, J.C.R., "Fatigue Crack Initiation from Corrosion Pits in Aluminum Alloys," *Third Joint FAA/DoD/NASA Conference on Aging Aircraft*, Albuquerque, New Mexico, September 20–23, 1999.

12. Rowe, L.C., "Measurement and Evaluation of Pitting Corrosion," *Galvanic and Pitting Corrosion–Field and Laboratory Studies*, ASTM STP 576, American Society for Testing and Materials, 1976, pp. 203–216.

13. Bellinger, N.C. and Komorowski, J.P., "Implications of Corrosion Pillowing on the Structural Integrity of Fuselage Lap Joints," *Proceedings of the FAA-NASA Symposium on the Continued Airworthiness of Aircraft Structures*, FAA Report DOT/FAA/AR-97/2, II, Atlanta, Georgia, August 28–30, 1996.

14. Koch, G.H., "On the Mechanisms of Interaction Between Corrosion and Fatigue Cracking in Aircraft Aluminum Alloys," *Proceedings of ASME Winter Annual Meeting*, San Francisco California,, 1995.

15. Brooks, C.L.D., Peeler, K., Honeycutt, T., and Prost-Domasky, S., "Predictive Modeling for Corrosion Management: Modeling Fundamentals," *Proceedings of the Third Joint FAA/DoD/NASA Conference on Aging Aircraft*, Albuquerque, New Mexico, September 20–23, 1999.

16. Dolley, E.J. and Wei, R.P., "The Effect of Frequency on Chemically Short-Crack Behavior and its Impact on Fatigue Life," *Third Joint FAA/DoD/NASA Conference on Aging Aircraft*, Albuquerque, New Mexico, September 20–23 1999.

17. Swift, T., "Widespread Fatigue Damage Monitoring Issues and Concerns," *Proceedings of the 5th International Conference on Structural Airworthiness of New and Aging Aircraft*, Hamburg, Germany, June 1993.

18. Chen, C.-S., Wawrzynek, P.A., and Ingraffea, A. R., "Residual Strength Prediction in KC-135 Fuselages and Curvilinear Crack Growth Analysis in Narrow Body Fuselages," *Third Joint FAA/DoD/NASA Conference on Aging Aircraft*, Albuquerque, New Mexico, September 20–23, 1999.

19. Schmidt, H.-J., Schmidt-Brandecker, B., and Trey, H., "Airbus A300 Fuselage Program for Life Extension and Widespread Fatigue Damage Evaluation," *Third Joint FAA/DoD/NASA Conference on Aging Aircraft*, Albuquerque, New Mexico, September 20–23, 1999.

20. Goranson, U.G., "Structural Airworthiness Initiatives," *1st Joint DoD/FAA/NASA Conference on Aging Aircraft*, Ogden, Utah, July 8–10, 1997.

21. Schmidt, H.-J. and Brandecker, B., "Results of the AAWG Industry Committee on Widespread Fatigue Damage," *Proceedings of the International Workshop on Structural Integrity of Aging Airplanes*, Atlanta Georgia, 1992, pp. 279–295.

22. Piascik, R.S. and Willard, S.A., "The Characteristics of Multi-Site Fatigue Damage in the Fuselage Riveted Lap Splice Joint," *Proceedings of the First Joint DoD/FAA/NASA Conference on Aging Aircraft*, Ogden, Utah, July 8–10, 1997.

23. Lincoln, J.W., "Risk Assessment of Aging Aircraft," *Proceedings of the First Joint DoD/FAA/NASA Conference on Aging Aircraft*, Ogden, Utah,July 8–10, 1997.

24. Hagemaier, D., Jappe, B., Wilson, D., and Wood, N., "Improved NDI Techniques for Aircraft Inspection," Proceedings of the *First Joint DoD/FAA/NASA Conference on Aging Aircraft*, Ogden, Utah, July 8–10, 1997.

25. Hagemaier, D. and Kark, G., "Eddy Current Detection of Short Cracks Under Installed Fasteners," *Materials Evaluation*, January 1997.

26. Federal Aviation Administration, "Establishing and Implementing Limit of Validity to Prevent Widespread Fatigue Damage," AC 120-104, January 10, 2011.

27. The Boeing Company, "Boeing 727/737/747/757/767/777/787 Compliance Plan for 14 CFR 26.21," Document D6-84678 May 10, 2011.

28. Communication with J. Kollgaard and J. Thompson, Boeing Commercial Airplane NDE Specialists, July 26, 2013.

29. ASM International, "Metals Handbook (Desk Edition)," 1997.

APPENDIX A. BPI-2040 DEVELOPMENT OF IN-SERVICE NONDESTRUCTIVE TEST (ISSUE DATE FEBRUARY 18, 2013)

Purpose/Summary

To establish the process for in-service nondestructive test (NDT) inspection techniques to be published in the referenced in service NDT manuals.

This business process instructions (BPI) defines the process of applicable organizations and establishes methods for developing NDT techniques for all Heritage Boeing commercial airplanes.

Supersedes

February 19, 2010

Applies To

Boeing Commercial Airplanes Engineering
737 Program Puget Sound
747 Program Puget Sound
767 Program Puget Sound
777 Program Puget Sound
787 Program Puget Sound
Commercial Aviation Services Puget Sound
Manufacturing
737 Program Puget Sound
747 Program Puget Sound
767 Program Puget Sound
777 Program Puget Sound
787 Program Puget Sound
Commercial Aviation Services Puget Sound

Roles Affected

Service engineering focal, Maintenance Program Engineering (MPE) focal, Maintenance and Ground Operations Systems (MGOS) focal, Service Bulletin Engineering personnel, Boeing Research and Technology technology development personnel, Stress engineer, customer

Maintained By

Engineering – Nondestructive Testing – Boeing Research & Technology

Authority Reference

Procedure PRO-6560, "Commercial Aviation Services Product and Support Requirements"

Approved By

Mahender Reddy, process owner

Summary of Changes (including the Title Page)

The Issue Date and Supersedes sections were updated. The Applies To, Roles Affected, Maintained By and Authority Reference sections were revised. This revision supports compliance to the three year review requirement. A. Scope

This BPI describes the process for establishing Nondestructive Test (NDT) techniques from initiation of NDT inspection requests to publication of the techniques in the appropriate format (NDT manual, service bulletin, etc.).

Input (Product/Service): NDT inspection requests
Output (Product/Service): Published NDT manual procedure and related Boeing user group documentation
From (Supplier): Customer requests, Service Bulletin Engineering requests, Service Engineering, MGOS, MPE, Structures Engineering,
To (Customer): Service Engineering, MGOS, Airplane Maintenance and Repair Engineering, Service Bulletin Engineering

B. Process Flow

1. Initiate NDT Support Requests (Stress Engineer, Service Bulletin, Engineering Personnel, Customer)
2. Oversee Evaluation (Service Engineering Focal)
3. Complete Evaluation (BR&T Technology Development Personnel)
4. Incorporate Maintenance Information (MPE Focal)
5. Incorporate NDT Data (Service Bulletin Engineering Personnel)
6. Investigate Procedures (BR&T Technology Development Personnel)
7. Approve Procedures (Service Engineering Focal)
8. Release NDT Procedures (Service Engineering Focal)
9. Publish and Maintain NDT Manuals (MGOS Focal)
10. Publish Maintenance Planning Data (MPD) and SSID (MPE Focal)
11. Publish Service Bulletins (Service Bulletin Engineering Personnel)
12. Maintain Process (BR&T Technology Development Personnel)

C. General

1. In conjunction and close coordination with the applicable Structures Engineering organizations, NDT requirements are submitted to Commercial Aviation Services (CAS) Service Engineering for evaluation and action as required.

2. NDT requirements are generated from sources such as aircraft inspection, structural assessments and testing programs, service reports, customer requests, Service Bulletin Engineering requests, etc.

3. CAS Service Engineering provides direct technical support to the customer and evaluates NDT requirements.

D. Process Steps

This process begins with the initiation of an NDT inspection request.

1. Initiate NDT Support Requests

Role(s): Stress engineer, Service Bulletin Engineering personnel, customer

Submit all NDT support requests to CAS Service Engineering focal for coordination, evaluation, and prioritization.

2. Oversee Evaluation

Role(s): Service Engineering focal

a. Receive NDT support requests from Structures Engineering organizations.
b. Forward NDT requirements to BR&T for development of NDT procedures or appropriate action.
c. Coordinate schedules and priorities of NDT work sent to BR&T Nondestructive Evaluation Group with other organizations such as MGOS (for Supplemental Structural Inspection Document [SSID]), Structures Engineering, etc.

3. Complete Evaluation

Role(s): BR&T Technology Development personnel (Nondestructive Evaluation group)

a. Accept NDT procedure development requirements from Service Engineering.

b. Refer all groups to Service Engineering for NDT activity coordination, prioritization, and scheduling, before accepting assignments.

c. Perform NDT activities as requested.

4. Incorporate Maintenance Information

Role(s): MPE focal

a. Identify structural items/areas for which NDT procedures are required as a result of the scheduled maintenance program development process (MSG-3).

b. Include specific NDT information in the affected Maintenance Planning Data document and SSID.

c. Advise Service Engineering focal to changes in MPD structural inspection thresholds or changes to the Damage Tolerance Rating (DTR) forms or the addition/s of DTR form/s that require NDT procedure development.

5. Incorporate NDT Data

Role(s): Service Bulletin Engineering personnel

Include specific NDT data in service bulletins covering special inspection requirements, see BPI-548 for further information.

6. Investigate Procedures

Role(s): BR&T Technology Development personnel (Nondestructive Evaluation group)

a. Perform necessary investigation and develop NDT procedures to satisfy inspection requirements.

b. Submit developed procedures to Service Engineering for approval, before releasing them to other organizations.

7. Approve Procedures

Role(s): Service Engineering focal

Approve NDT procedures and route to appropriate Structures Engineering organizations for coordination.

8. Release NDT Procedures

Role(s): Service Engineering focal

a. Release procedures to Service Bulletin Engineering, MPE, and MGOS for action as required.

b. Inform Structures Engineering organizations as applicable.

c. Consider customer requests for Boeing in-house NDT training (based on the specific model support being provided).

9. Publish and Maintain NDT Manuals

Role(s): MGOS focal

a. Publish and maintain the non-destructive testing manuals. Review NDT procedures and revisions submitted for publishing to ensure that specific NDT procedures and illustrations are described in sufficient detail to satisfy customer requirements and that data complies with the requirements of Air Transport Association specification 100.

b. Submit an NDT manual for inclusion in the instructions for continued airworthiness, prior to new aircraft type certification in accordance with 14CFR Part 25, H25.3(d) and ODA-300064-NM "BCA Organization Designation Authorization Procedures Manual" paragraph 15.1.18.5 Instructions for Continued Airworthiness."

10. Publish MPD and SSID

Role(s): MGOS focal

Publish NDT procedure information in model-specific MPD and SSID.

11. Publish Service Bulletins

Role(s): Service Bulletin Engineering personnel

Publish NDT procedure information in Service Bulletins.

12. Maintain Process

Role(s): BR&T Technology Development personnel (Nondestructive Evaluation group)

a. Maintain a level of NDT capability compatible with in-service airplane inspection needs.

1) Equipment and facilities shall be compatible with the development of NDT procedures for in-service airplane inspection.

2) Technical adequacy of developed NDT procedures shall be ensured through technical review by qualified American Society for Nondestructive Testing Level III engineer or equivalent in the applicable NDT method.

b. Annually account for previous year's fund expenditures, and forecast the upcoming year's funding.

c. Provide Service Engineering with feedback, as applicable.

d. Approve NDT procedures as applicable.

APPENDIX B. 737-600/700/800/900 AIRCRAFT MAINTENANCE MANUAL TIRES AND WHEELS–INSPECTION/CHECK

GENERAL

A. This procedure contains scheduled maintenance task data.
B. This procedure has these tasks:
(1) A fast check of the wheels
(2) An inspection of the wheels
(3) An inspection of the tires.

WARNINGS AND CAUTIONS

Warnings and Cautions are inserted in YELLOW and are branches in the procedure to be taken when necessary.
WARNING: HUBCAPS AND WHEEL COMPONENTS MAY BE HOT FROM VARIOUS OPERATING CONDITIONS OR PROBLEMS, USE EXTREME CAUTION IN TOUCHING OR INSPECTING WHEEL AND TIRE COMPONENTS.

PROCEDURE OPERATIONS

This procedure has three alternatives for performance of inspections:
1. Traditional Manual Process
2. Mobile Device Aided Local Inspection
3. Remotely Managed Mobile Device Aided Inspection

The different approaches follow the same process, however the tools and communications steps are different to achieve the same goals, assurance of tire health.

[NOTE: Boeing has included/created the example concept for a generic remote tire inspection process. We term the Mobile Remote- Tire Inspection Device MR-**TID**. Boeing has technologies and patent applications in process for mobile device enabled tire inspection aids.]

TRADITIONAL MANUAL PROCESS

A qualified inspector reviews the health of the tire(s) per this procedure, logging issues and making a final recommendation to leave a tire in service or pull it for further action.

EXPERT MOBILE DEVICE AIDED LOCAL INSPECTION

A qualified inspector reviews the health of the tire(s) per this procedure, following any BLUE steps, logging issues and making a final recommendation to leave a tire in service or pull it for further action.

REMOTELY MANAGED WITH MOBILE REMOTE TIRE INSPECTION DEVICE (*MR-TID*)

A remote unqualified assistant remotely gathers data on the health of the tire(s) per this procedure, overseen by a qualified expert remote inspector and ***MR-TID***, following the GREEN

steps. The team and ***MR-TID*** log issues and make a final recommendation to leave a tire in service or pull it for further action.

TASK 32-45-00-700-801----------

2. WHEELS FAST CHECK (WHEEL INSTALLED ON THE AIRPLANE)

A. General

(1) This procedure is a scheduled maintenance task.

B. References

Reference Title	
32-00-01-480-801	Landing Gear Downlock Pins Installation (P/B 201)
32-45-11 P/B 401	MAIN LANDING GEAR WHEEL AND TIRE ASSEMBLY –REMOVAL/INSTALLATION
32-45-21 P/B 401	NOSE LANDING GEAR WHEEL AND TIRE ASSEMBLY –REMOVAL/INSTALLATION

C. Location Zones

Zone Area	
713	Nose Landing Gear
734	Left Main Landing Gear
744	Right Main Landing Gear

D. Procedure

SUBTASK 32-45-00-480-003

WARNING: MAKE SURE THE DOWNLOCK PINS ARE INSTALLED ON ALL THE LANDING GEAR. WITHOUT THE DOWNLOCK PINS, THE LANDING GEAR COULD RETRACT AND CAUSE INJURIES TO PERSONS AND DAMAGE TO EQUIPMENT.

MR-TID PROVIDES THE REMOTE INSPECTOR THE DATA TO VALIDATE THAT THE DOWNLOCK PIN INSTALLATIONS ARE PROPERLY IN PLACE. IF THE PINS ARE PROPERLY INSTALLED PROCEED TO SUBTASK 32-45-00-210-001.

(1) If the downlock pins are not installed in the nose and main landing gear, do this task: Landing Gear Downlock Pins Installation, TASK 32-00-01-480-801.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

SUBTASK 32-45-00-210-001

MR-TID PROVIDES THE REMOTE INSPECTOR THE DATA TO INSPECT THE TIRE FOR ALL OF THE REQUIRED CONDITIONS THROUGH IMAGES AND REMOTE SENSING OF THE NECESSARY INFORMATION TO ASSURE SATISFACTORY CONDITION OF THE TIRE AND WHEEL ASSEMBLY.

(2) Examine the wheels for these forms of damage:

a. corrosion
b. cracks
c. flaked or blistered paint
d. heat shield damage
e. loose, damaged, or missing tiebolts and tiebolt nuts that you can see

1) If you find a loose or damaged tiebolt or if there is a missing tiebolt, remove the wheel
(MAIN LANDING GEAR WHEEL AND TIRE ASSEMBLY - REMOVAL/INSTALLATION, PAGEBLOCK 32-45-11/401; NOSE LANDING GEAR WHEEL AND TIRE ASSEMBLY - REMOVAL/INSTALLATION, PAGEBLOCK 32-45-21/401).

f. overheat damage
g. scratches along the rim of a wheel that show that the wheel rolled without a tire.

WARNING: It is not necessary to remove the hubcap to examine the wheels for damage
unless the examination reveals a condition that makes a more detailed check of the area hidden by the hubcap necessary.

1) If there is evidence that the wheel has turned on the runway without the tire, remove
and discard the wheel.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

SUBTASK 32-45-00-210-002

3. Make sure the hubcaps are not loose.

WARNING: HUBCAPS AND WHEEL COMPONENTS MAY BE HOT FROM VARIOUS OPERATING CONDITIONS OR PROBLEMS, USE EXTREME CAUTION IN TOUCHING OR INSPECTING WHEEL AND TIRE COMPONENTS.

Tighten or replace hubcaps if it is necessary.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG BOTH THE SUBTASK AND THE TASK COMPLETE.*

---------- END OF TASK 32-45-00-700-801----------

TASK 32-45-00-700-802----------

3. WHEELS INSPECTION (WHEEL REMOVED FROM THE AIRPLANE)

A. REFERENCES

Reference Title	
05-51-07-210-801	High Energy Stop (P/B 201)

6.1.1.1 B. Zone Area

Zone Area	
713	Nose Landing Gear
734	Left Main Landing Gear

744	Right Main Landing Gear

6.1.1.2 C. Procedure

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE DATA TO INSPECT THE TIRE FOR ALL OF THE REQUIRED CONDITIONS THROUGH IMAGES AND REMOTE SENSING OF THE NECESSARY INFORMATION TO ASSURE SATISFACTORY CONDITION OF THE TIRE AND WHEEL ASSEMBLY.*

SUBTASK 32-45-00-210-003

Examine the wheel for:

a. breaks
b. corrosion
c. cracks
d. distortion
e. flaked or blistered paint
f. heat shield damage
g. loose, damaged, or missing tiebolts and tiebolt nuts
h. nicks or gouges
i. overheat damage
j. scratches along the rim of a wheel that show the wheel rolled without a tire
k. worn plating
l. other damage.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

SUBTASK 32-45-00-210-004

Examine the grease seals for:

a. nicks
b. gouges
c. overheat damage.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

SUBTASK 32-45-00-210-005

Examine the bearing and bearing surfaces for:

a. distortion
b. flat spots
c. sufficient lubrication
d. wear.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

SUBTASK 32-45-00-210-006

Examine the brake keyway inserts for wear.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

SUBTASK 32-45-00-210-007

Examine the wheel heat shield for:

a. cracks
b. wear
c. other damage.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

SUBTASK 32-45-00-210-008

Make sure the wheel balance weights are tightly installed.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

SUBTASK 32-45-00-220-001

If a wheel has a blown thermal fuse, do this task: High Energy Stop, TASK 05-51-07-210-801.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG BOTH THE SUBTASK AND THE TASK COMPLETE.*

---------- END OF TASK 32-45-00-700-802 ----------

TASK 32-45-00-700-803

4. TIRES INSPECTION

A. GENERAL

(1) This procedure is a scheduled maintenance task.
(2) Bias ply tires should not be used on the same axle as radial ply tires.

B. REFERENCES

Reference Title	
12-15-51-780-801	Landing Gear Tire Pressure Check and Tire Servicing (P/B 301)
32-00-01-480-801	Landing Gear Downlock Pins Installation (P/B 201)

C. LOCATION ZONES

Zone Area	
713	Nose Landing Gear
734	Left Main Landing Gear
744	Right Main Landing Gear

D. PROCEDURE

MR-TID PROVIDES THE REMOTE INSPECTOR THE DATA TO INSPECT THE TIRE FOR ALL OF THE REQUIRED CONDITIONS THROUGH IMAGES AND REMOTE SENSING OF THE NECESSARY INFORMATION TO ASSURE SATISFACTORY CONDITION OF THE TIRE AND WHEEL ASSEMBLY.

SUBTASK 32-45-00-480-004

WARNING: MAKE SURE THE DOWNLOCK PINS ARE INSTALLED ON ALL THE LANDING GEAR. WITHOUT THE DOWNLOCK PINS, THE LANDING GEAR COULD RETRACT AND CAUSE INJURIES TO PERSONS AND DAMAGE TO EQUIPMENT.

(1) If the downlock pins are not installed in the nose and main landing gear, do this task: Landing Gear Downlock Pins Installation, TASK 32-00-01-480-801.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

SUBTASK 32-45-00-220-002

(2) Do this task: Landing Gear Tire Pressure Check and Tire Servicing, TASK 12-15-51-780-801.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

SUBTASK 32-45-00-210-009

(3) Do the steps that follow and examine the tires (Figure 601, Figure 602):
   a. Examine the tires for air leaks, abrasions, unusual worn areas, cuts, and flat spots.
   b. Examine the tires for the presence of contaminants.
      1) Keep the tires clean of contaminants such as oils, fuels, hydraulic fluids, aircraft cleaning agents, and greases. Cover the tire if these or other potentially harmful chemicals might spill on the tire during aircraft servicing operations.
      2) Wipe off the tire with a soapy solution if the tire becomes contaminated.
      3) The tire should be removed from service as soon as practical if the surface of the tire appears soft, spongy, or there are bulges present.
   c. Remove the tires that have the conditions that follow:
      1) Cuts or weather cracks in the grooves, the tread, shoulders or sidewalls that exceed the limits in (Figure 602).
      2) Blisters, bulges, or other signs of ply separation in the tread, shoulder or sidewall area.
      3) Tires with a flat spot which shows the tread reinforcement ply (bias) or cut protector (radial).

         NOTE: If the tread reinforcement ply (bias) or the cut protector (radial) shows, the tire should be replaced as soon as possible. If necessary, the tire may be used for a small number of landings until it is replaced. However, you may not be able to retread the tire if you leave the tire in service too long with this condition.
      4) Other types of damage which can cause tire problems.
   d. Examine the tires for worn areas:
      1) Measure the depth of the tire tread groove at three points that are equally apart.
      2) If the average depth of any groove is 1/32 inch (0.79 mm) or less, the tire must be replaced at the next convenient maintenance opportunity.
      3) If the tread belt ply (radial) or carcass ply (bias) shows at any location, the tire is not serviceable and must be replaced.
      4) If the tread is worn so that the cut protector (radial) or tread reinforcement ply (bias) shows at any location, the tire must be replaced at the next convenient maintenance opportunity

         NOTE: If the cut protector (radial) or tread reinforcement ply (bias) shows, the tire should be replaced as soon as possible. If necessary, the tire may be

used for a small number of landings until it is replaced. However, you may not be able to retread the tire if you leave the tire in service too long with this condition.

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG THE SUBTASK COMPLETE.*

E. Tire Tread Conditions and Service

SUBTASK 32-45-00-220-003

WARNING: DO NOT PUSH ON THE TIRE WITH TOOLS OR OTHER OBJECTS. A DAMAGED TIRE CAN EXPLODE AND CAUSE INJURIES TO PERSONS AND DAMAGE TO EQUIPMENT.

(1) See (Figure 602) for the tire tread conditions:

***MR-TID** PROVIDES THE REMOTE INSPECTOR THE ABILITY TO LOG BOTH THE SUBTASK AND THE TASK COMPLETE.*