Reliability Modeling of Telecommunication Networks for Air Traffic Control

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TEM640/263-PTZ-A - PST Professional - Spring 2026 - Session 3

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January 19, 2026

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The Federal Aviation Administration is faced with a challenge of modernizing oceanic air traffic control communications that must serve the increasing demands for airspace traffic while meeting the exceptionally high reliability requirements for this safety-critical application. The case study will discuss how reliability principles were used, with mathematical modeling approaches, for the assessment of proposed solutions for an Automatic Dependent Surveillance Function system intended for the modernization of outdated High Frequency radio communications systems with new satellite communication links. Case studies offer valuable insights into how reliability modeling helps decision makers effectively determine key system elements, decide upon design requirements for manufacturers, before proceeding with full system implementations for complex telecommunications systems.

Case Summary

Aircraft flying in oceanic airspaces, which are beyond the range of land-based radar surveillance systems, rely on High Frequency radio communication capabilities for the transmission of position data concerning their latitude, longitude, and height in response to queries from air traffic control authorities. However, the HF radio communication system in place has several reliability constraints because of atmospheric conditions of congestion, electrostatic disturbances, and solar activity causing “communication blackouts.” These communication blackouts have led air traffic control authorities to maintain a conservative “safety buffer,” mandating that aircraft maintain a 60-mile “longitudinal separation distance in order for a certain degree of collision avoidance to be achieved.”

Regarding the shortcomings and to meet the expected rise in oceanic air traffic, the International Civil Aviation Organization introduced the Automatic Dependent Surveillance Function. According to this, Automatic Dependent Surveillance Function refers to a 'modernized system wherein the aircraft automatically transmits its position information obtained from its onboard navigation systems via satellite data links at an interval determined by ground air traffic control systems'. The new scheme solution includes several interlinked systems functioning in unison to constitute an integrated telecommunication system. The avionics in the Aeronautical Earth Station develop the position information gleaned from the aircraft navigation systems, which are later communicated via satellite data units to the Communication Satellites in the INMARSAT System. The satellites receive the information, which is then relayed to ground Earth Stations. These ground Earth Stations disseminate the information via a ground telecommunication subnet to finally reach the Air Route Traffic Control Center for decisions by the control authorities to direct the aircraft movement and separate them by standards.

Problem Statement

The major problem that the FAA had in this situation was to identify the system configurations able to ensure the high reliability required in the system. The typical availability requirement level of aviation systems is 0.99999. This simply means that the system cannot have even the slightest downtime and communication breakage. However, since the system involved was the Automatic Dependent Surveillance Function system, it was quite complex in nature. This system had to involve aircraft systems right from the point of plane avionics to orbiting satellites in space and then ground systems to traffic control centers.

Without performing reliability analysis in a proactive manner, the FAA faced the possibilities of over-designing the system through costly redundancy or under-designing it through inadequate reliability margins in the system. The FAA required more quantitative techniques to assess various hardware configurations in terms of system reliability, ascertain critical hardware elements impacting system reliability most directly, and derive system reliability specifications for hardware elements. These hardware elements had subsystem interactions like navigation systems, automatic surveillance units, communications management units, satellite data units, satellite constellation system, ground earth stations, terrestrial communications network system, and the air traffic control system. These complex subsystem interactions made it difficult to carry out this analysis in a simplistic or intuitive manner.

Solution Description

The Federal Aviation Administration established a mathematical approach to this reliability issue. The approach is based on a theory for reliability and specifically models how important a system is. The mathematics involved uses the importance measure proposed by Birnbaum. The importance measure is a commonly accepted theory in the study of system reliability. The approach models the entire telecommunication system by breaking it down into various interconnected subsystems. Each subsystem fails in a unique manner. The approach determines how a failure in an individual component influences the probability that the position data for an aircraft successfully reaches air traffic controllers.

The modeling technique broke the system into five major subsystems, and each subsystem was again divided into various hardware systems. The Aeronautical Earth Station, present in every air vehicle, had navigation systems to provide the fix to the aircraft, an automatic dependent surveillance element that realized the ADSF service, communication management, and the satellite data manager to manage modulation and signal processing. The satellite communication subsystem had the major satellites, consisting of seven spares in the

INMARSAT constellation, and the ground earth stations, totaling thirteen, to receive the signal coming from the satellites. The terrestrial subnetwork had redundancy, consisting of two identical communications channels, each having modems, air to ground interface systems, and data network service. The fifth, the Air Route Traffic Control Center, had the National Airspace Data Interchange Network, routers, and modems to connect to the overall traffic management system.

From the projected rates of failure for each component, the engineering team was able to determine reliability values for a given time horizon of 1000 operating hours. In calculations done using the Birnbaum importance, the importance values at this point in time were determined to be 0.992816 for the AES, 0.966502 for the satellite system, 0.966510 for the terrestrial subnetwork, 0.973387 for the ARTCC, and 0.966502 for the ground earth stations. These values enabled the engineering team to determine the relative importance of the various subsystems to the probability of system failure, such that the components that needed the highest reliability could be given priority. The modeling also took into account the terrestrial subnetwork, which was assumed to have two parallel redundant links, and its reliability was determined using the formula in the context of the two failing before the subnetwork, while the ARTCC components were in series such that the failure of anyone would cause the ARTCC to be inoperative.

Critical Analysis

The solution for the problem of reliability modeling in this case is that the approach taken in the above problem is pragmatic and scientifically correct in that it identifies and assesses complex reliability-related problems in relation to the system prior to major resource expenditure on its actual implementation. The approach involving Birnbaum’s importance measure in the problem above helped identify system components that affected the system's overall reliability, thereby allowing the FAA to make informed decisions on major system resource allocation based on strict manufacturing requirements and standards based on quantitative importance value measures that ranged from 0.966 and 0.992, thereby showing that there was a balanced system without major vulnerability points that could easily fail the system.

However, if I were addressing this issue from another perspective, then certainly I would consider considering time-dependent reliabilities to analyze the whole life cycle of system operation instead of considering only one cycle of 1000 hours. Since aircraft systems are used for many thousands of hours, system component failure rates could variably differ with time following bathtub curve characteristics. To consider this aspect, importance measures could be calculated for various time points to derive system component importance variations throughout the system life cycle. As an example, electronic system components, such as the satellite data unit, could be of great importance in the early stages of system life due to manufacturing defects, while mechanical components of the system could be of importance in the latter stages of system life.

In addition, although a case study is carried out, it is mainly based on hardware reliability and lacks equal emphasis on the reliability of the communication components, which is a major drawback since communication software processes and procedures have been known to significantly influence failures in practical telecommunication networks. Modern satellite telecommunication networks encounter problems such as electromagnetic interference, degradation, errors in telecommunication protocols, and software defects, which may be hard to analyze using only hardware reliability. I would propose using Markov modeling or a fault tree analysis method able to analyze state transformations and interrelated failures such as common-cause failures where solar storms may cause several independent components to fail at once.

Furthermore, the analysis might benefit from sensitivity analysis, showing how uncertainties in the projected failure rates flow through to the reliability calculations. The specific failure rate values used in the case, such as 3×10^{-6} failures per hour for the terrestrial subnetwork and 7.2×10^{-6} failures per hour for the ARTCC, are subject to uncertainty, particularly for newly developed components for which operational experience is only just accumulating. Monte Carlo simulation techniques would provide quantification of how variation in input parameters operates on the reliability predictions and importance measures, giving confidence intervals around the point estimates and helping decision-makers understand the range of possible outcomes. The basic approach of using formal reliability modeling to inform system design decisions is appropriate and sound engineering practice that balances analytical rigor against with practical decision-making needs for aviation safety systems.

References

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