SURVEILLANCE/POSITIONING BACKUP STRATEGY ALTERNATIVES ANALYSIS

FINAL REPORT

JANUARY 8, 2007

NOTE

This Surveillance/Positioning Backup Strategy Alternatives Analysis has been developed based on a fully functioning primary ADS-B capability as described in the *Final Program Requirements for Surveillance and Broadcast Services*, *Version 1.0, ATO-E, May 9, 2006*. The backup strategy alternatives described in this report were developed to support the ATC surveillance application during a loss of GPS L1 service to at least the same extent as current backup surveillance capabilities are provided today during a loss of service from a single radar facility.

This report recognizes the Surveillance and Broadcast Services program baseline, and responds only to the stated requirement for an assessment of backup strategies to support a loss of GPS L1 as a positioning source.

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Executive Summary

Introduction

The purpose of this analysis is to recommend a backup strategy for mitigating the impact of a loss of GPS on ADS-B surveillance. It has been developed based on a fully functioning primary ADS-B capability as described in the Final Program Requirements for Surveillance and Broadcast Services. The backup strategy alternatives described in this report were developed to support the ATC surveillance application during a loss of GPS L1 service to at least the same extent as current backup surveillance capabilities are provided today during a loss of service from a single radar facility.

This report recognizes the Surveillance and Broadcast Services program baseline, and responds only to the stated requirement for an assessment of backup strategies to support a loss of GPS L1 as a positioning source. This analysis provides sufficient rationale to justify an approach for subsequent acquisition and potential rulemaking. This effort has had broad participation from the FAA, industry, users and stakeholders, to ensure a collaborative effort and result.

ADS-B will be the primary means of surveillance in the future, using GPS L1 as the positioning source. As with any service, there are inherent vulnerabilities that require mitigation methods. This report focuses on developing strategies to mitigate the loss of GPS L1 for ADS-B positioning to support ATC surveillance, but also considers mitigation of other GPS vulnerabilities. At a minimum, the backup strategy must support ATC surveillance services in terminal and en route airspace. Capacity must be maintained to at least the same level that would be experienced from a radar outage in today’s system. Safety of operations must be maintained. Finally, this strategy must be implementable and made operational on or before ADS-B rule compliance date.

This analysis recommends that the FAA retain approximately one-half of the Secondary Radar network as the backup strategy for ADS-B. Implementation of this recommendation would further reduce the backup infrastructure required from that presented in the June 2006 Final Investment Decision (JRC 2B).

Background

With the FAA decision to move forward with the ADS-B program, several actions took place. Initial work identified the need for a backup strategy for ADS-B in September 2005. Further work was conducted by a focus team for an initial quick-look, completed in March 2006. Initial findings suggested that broader participation in the development of a strategy was necessary. To address this, a technical team was formed in May 2006, with direction from an aviation community Steering Committee, organized in June 2006 under the RTCA ATMAC. An investment decision for the Surveillance Broadcast Services program (including ADS-B) is scheduled for February 2007 that will require the results from this report for appropriate consideration.

Methodology

The methodology used in this analysis is based on the Trade Study process described in the FAA System Engineering Manual. An essential aspect of trade study analyses is that consistent, configuration-controlled parameters are used in the computations to ensure comparison of likely solutions. With Steering Committee direction and guidance, the technical team defined evaluation criteria and developed alternative backup strategies for assessment. The strategies were developed using one or more likely technologies to satisfy minimum backup requirements. The team evaluated performance, cost, and safety risk for each strategy, and coordinated these activities iteratively with the Steering Committee.

Performance Evaluation Criteria

The evaluation criteria consist of guiding assumptions and a set of metrics.

Several key assumptions were made to bound the problem for determination of a mitigation strategy. A number of GPS vulnerabilities were identified with varying likelihood and operational impact. Based on historical evidence, the team assumed a nominal GPS L1 outage of 40-60 nautical mile radius and three to four days duration, anywhere in the NAS. An ADS-B rule compliance date of 2020 was assumed. In addition, other assumptions were made to address equipage timelines, future surveillance and navigation capabilities, and external programmatic dependencies.

Metrics were developed to provide the basis for comparing performance between strategies. These metrics addressed operational capability and coverage, technical maturity, independence, flexibility/agility, global interoperability, and operational duration.

Strategies

The team identified potential technologies and methods that could be used as components of a backup strategy. After an initial assessment of their capabilities, a narrowed set of potential technologies was identified that met all or most of the minimum requirements. From this narrowed set, the team developed candidate strategies, all of which use primary radar to mitigate single-aircraft avionics failures:

- Secondary Radar: Retain a reduced secondary radar network to cover required airspace
- Passive Multilateration: Use passive multilateration to cover required airspace
- Active Multilateration: Use active multilateration to cover required airspace
- SSR and DME/DME/IRU for AT, SSR and eLoran for GA: Retain secondary radar network to cover high-density terminal airspace; use DME/DME/IRU (for AT) and eLoran (for GA IFR fleet and regional aircraft) to cover medium-density airspace
- SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA: Retain secondary radar network to cover high-density terminal airspace; use DME/DME/IRU and enhanced SATNAV (GPS L5 and Galileo) (for AT) and enhanced SATNAV only (for GA IFR fleet and regional aircraft) to cover medium-density airspace

- SATNAV only: Use GPS L5 and Galileo to provide the backup positioning source for ADS-B
- SATNAV with Terminal SSR: Same as above, except using secondary radar in high-density terminal airspace to mitigate multi-frequency interference in these areas

Evaluation

The strategies were evaluated and scored against the metrics using weighting factors provided by the Steering Committee. Sensitivity analyses showed that the results were not influenced by reasonable changes to any one metric's weighting factor.

Cost estimates were developed for each strategy and combined with their relative performance scores to assess overall cost effectiveness. A comparative safety assessment was also conducted to ensure that there were no significant safety risks, and to identify any additional discrimination among strategies. None of the safety risks evaluated were significant.

The Secondary Radar strategy was assessed as having the highest performance ranking and lowest life cycle cost among the strategies evaluated. The strategy with the next highest performance ranking had $700M additional cost; the strategy with the next lowest cost had $210M additional cost and had the lowest performance ranking.

Recommendation

The technical team recommends that the FAA adopt the Secondary Radar backup strategy. The team further recommends that the ADS-B backup strategy be reassessed to reflect further ADS-B operational experience and emerging requirements prior to the FAA's commitment to radar investments beyond 2020.

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Surveillance/Positioning Backup Strategy Alternatives Analysis
Final Report

1. Introduction

The purpose of this analysis is to recommend a backup strategy for mitigating the impact of a loss of Global Positioning System (GPS) positioning on Automatic Dependent Surveillance - Broadcast (ADS-B) surveillance. This analysis has been developed based on a fully functioning primary ADS-B capability as described in the Final Program Requirements for Surveillance and Broadcast Services. The backup strategy alternatives described in this report were developed to support the ATC surveillance application during a loss of GPS L1 service to at least the same extent as current backup surveillance capabilities are provided today during a loss of service from a single radar facility.

This report recognizes the Surveillance and Broadcast Services program baseline, and responds only to the stated requirement for an assessment of backup strategies to support a loss of GPS L1 as a positioning source. This analysis provides sufficient rationale to justify an approach for subsequent acquisition and potential rulemaking. This effort has had broad participation from the Federal Aviation Administration (FAA), industry, users and stakeholders, to ensure a collaborative effort and result.

ADS-B will be the primary means of surveillance in the future, using GPS L1 as the positioning source. As with any service, there are inherent vulnerabilities that require mitigation methods. This report focuses on developing strategies to mitigate the loss of GPS L1 for ADS-B positioning to support Air Traffic Control (ATC) surveillance in terminal and en route airspace, but also considers mitigation of other GPS vulnerabilities.

1.1 ADS-B Description

ADS-B is a surveillance technology that allows avionics to broadcast an aircraft’s identification, position, altitude, velocity, and other information. The aircraft’s position is normally derived from the GPS L1 frequency, and is more accurate than most current radar-based position information. The greater positional accuracy and ability to provide certain aircraft-derived flight parameters, in addition to position data, defines ADS-B as enhanced surveillance. The accuracy and broadcast characteristics of ADS-B supports numerous cockpit-based and ATC applications. ADS-B broadcasts can be received by ground-based transceivers to provide air-to-ground and airport surface surveillance information for air traffic services and other functions. ADS-B-equipped aircraft with cockpit displays can receive ADS-B messages from other suitably-equipped aircraft within the reception range, resulting in an air-to-air surveillance capability.

In the United States, two different data links have been adopted for ADS-B: 1090 MHz Extended Squitter (1090 ES) and the Universal Access Transceiver (UAT) on 978 MHz. The 1090 ES link is generally intended for air transport aircraft, and likewise the UAT link for general aviation aircraft. In addition to ADS-B, these data links also support Traffic Information Service-Broadcast (TIS-B) uplink services on both data links, and Flight Information Service-Broadcast (FIS-B) uplink services on the UAT data link only. TIS-B derives traffic information from one or more ground-based surveillance sources and uplinks this information to ADS-B-equipped aircraft. TIS-B enables ADS-B-equipped aircraft to receive position reports on non-ADS-B-equipped aircraft within the coverage volume of ground-based surveillance systems. Similar to TIS-B is the Automatic Dependent Surveillance-Rebroadcast (ADS-R), which translates ADS-B messages received on one link and uplinks these messages on the other link, making it possible for each aircraft to receive the information being transmitted by the other. FIS-B provides aeronautical and flight information, such as textual and graphical weather reports, Notices to Airmen (NOTAMs), etc., and uplinks this information on the UAT link only.

1.2 Recent Activities

Development of ADS-B capabilities for potential applications in the National Airspace System (NAS) began in earnest with the FAA’s Safe Flight 21 program in the late 1990s. Based on the results of this program, the FAA’s Joint Resources Council (JRC) made an initial investment decision in September 2005, where the Surveillance and Broadcast Services (SBS) Program was formed and directed to validate benefits, identify program risks, and formalize program requirements for subsequent acquisition approvals.

One of the program risks identified was the potential need for a surveillance backup strategy to mitigate the loss of GPS L1 positioning on ADS-B, to support ATC surveillance in terminal and en route airspace. A focus team was formed to assess potential strategies, and developed an initial quick-look report in March 2006. Among other findings, the report suggested that broader stakeholder participation was necessary in the development of a backup strategy. As a result, the Surveillance/Positioning Backup Strategy Technical Team was formed in May 2006 to revisit the assessment of candidate strategies, with participation from members representing key stakeholders such as Air Transport, General Aviation, avionics manufacturers, FAA Aircraft Certification, and FAA Air Traffic organizations. In order to ensure that user needs were being properly addressed, the Surveillance/Positioning Backup Strategy Steering Committee was formed in June 2006, organized under the RTCA ADS-B Working Group and the RTCA Air Traffic Management Advisory Committee (ATMAC), to provide guidance and direction to the Technical Team (see Appendix E).

In June 2006, the JRC made a final investment decision on initial funding for Segment 1 of the SBS Program. Segment 1 is designed to reduce program risk by validating ADS-B, TIS-B, and FIS-B services at targeted locations, establishing test beds for the evaluation of future air-to-air applications, and providing planning for Segment 2 (NAS-wide implementation). ADS-B-enabled applications identified for initial implementation include (see Appendix D):

- ATC Surveillance
- Airport Surface Situational Awareness (ASSA)
- Final Approach Runway Occupancy Awareness (FAROA)
- Enhanced Visual Acquisition (EVAcq)
- Enhanced Visual Approach (EVApp)
- Conflict Detection (CD)

The JRC also reinforced the importance of identifying a recommended backup surveillance strategy that would have broader stakeholder support.

An Interim Report was generated by the Technical Team in September 2006, which identified at least one candidate strategy that had a high confidence of meeting the requirements of a potential ADS-B rule. A subsequent investment decision for the SBS Program is scheduled for February 2007, where the final results from the Technical Team (this report) will be included for appropriate consideration.

2. Methodology

The methodology used in this analysis is based on the Trade Study process described in the FAA System Engineering Manual. Trade studies are conducted to discover the best value solution, best value to the government, and best value to a set of requirements from technical, cost, or schedule points of view. They provide an objective determination of comparative metrics for various system options. An essential aspect of the analyses performed for these studies is that consistent, configuration-controlled parameters be used in the computations to ensure comparison of likely solutions. Figure 2-1 depicts the process used in this analysis.
The scope of this analysis was determined based on the outcome of a functional analysis and risk assessment conducted by the SBS program. The problem being addressed (i.e., loss of GPS positioning) was clearly defined and bounded to provide the basis for further assessment. A series of ground rules and assumptions were also defined to provide a viable framework for the assessment. The scope, ground rules and assumptions of this analysis were coordinated with key stakeholders via the Steering Committee to ensure that user needs and expectations would be satisfied.

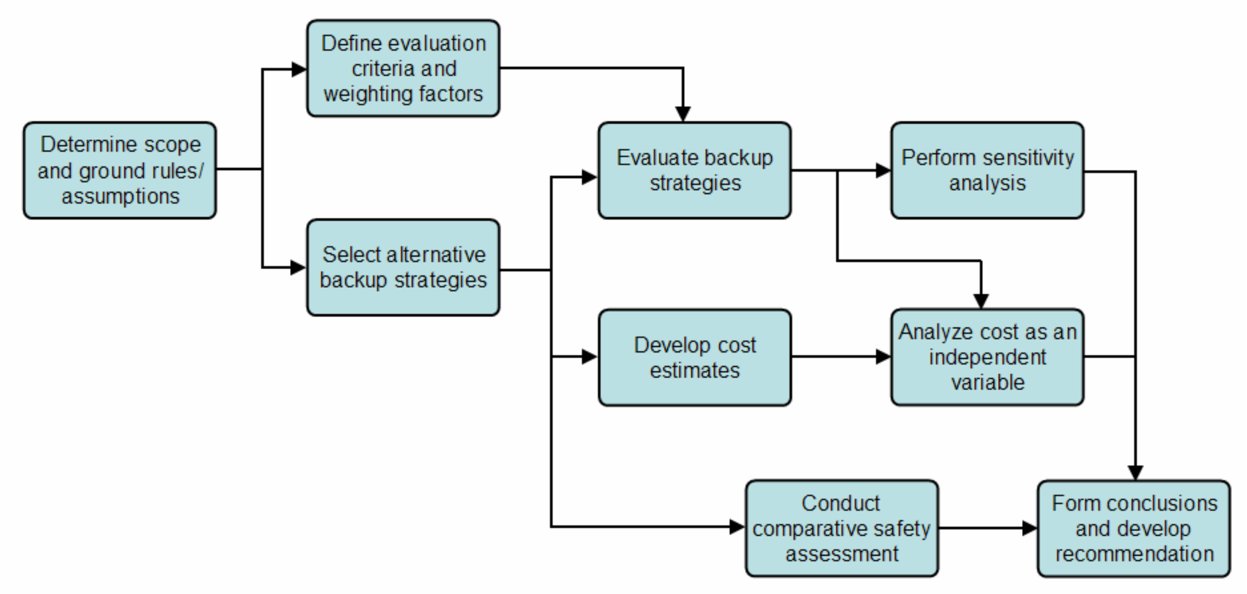

Figure 2-1: Backup Strategy Alternatives Analysis Process

The composition of the team conducting the assessment consisted of subject matter experts, representatives from key user groups, and team facilitators and support analysts (see Appendix E). The subject matter experts were responsible for developing detailed technical descriptions for each strategy to be assessed. The user representatives ensured that user needs were being addressed, and provided final approval within the team of the evaluation and scoring process. Team facilitators and support analysts assisted the team throughout the assessment and in the formulation of conclusions and a final recommendation.

A set of evaluation criteria were developed by the team and coordinated with the Steering Committee. The evaluation criteria consisted of a set of metrics, sub-metrics, and measures. Metrics were identified to describe the major requirements areas that were relevant to a backup strategy. Sub-metrics were defined, where necessary, to ensure that each metric could be measurable or quantified in some manner. A set of measures were defined for each measurable metric/sub-metric that described the range of values, or trade space, to be used for the assessment of each strategy.

Each metric was given a weight from 0 to 1 by the Steering Committee. The total of the weights for all metrics was set to 1; i.e., the importance of each metric was proportioned. The weight reflects the collective judgment of the Steering Committee regarding the relative importance of each metric relative to the others.

A set of alternative backup strategies were identified based on the projected performance and availability of key technologies, current plans for NAS evolution (roadmaps), and inputs from the Steering Committee. Each strategy was developed such that the needs of each major user group in the NAS were addressed. These strategies were further refined and down-selected based on an initial assessment of projected viability by the team. A final set of alternative backup strategies were selected in coordination with the Steering Committee for further assessment.

Each strategy (of the final set of strategies) was evaluated and scored on a scale of 0 to 10 against each metric/sub-metric range of measures, with 10 representing the highest score and 0 representing the lowest score. The bases for the scores for each metric, as well as the scores themselves, were agreed to by team consensus, with final approval of the team's user representatives, and based primarily on expert judgment. The weighted sum of the scores for each strategy was calculated as the basis for determining their relative performance.

A sensitivity analysis was conducted on each metric by varying their respective weights. The weighted score for each strategy was examined as a function of the weight of a specific metric. The sensitivity analysis allowed observation of how the weighted importance of each metric affected the overall result of the evaluation.

Cost was considered to be an independent variable from the evaluation criteria. The total cost of each strategy was estimated, and included both infrastructure and user costs. The estimated costs include only the incremental costs beyond those that will be incurred in order to comply with planned ADS-B equipage. The relationship between performance (score) and incremental cost of each strategy were compared to identify the most cost-effective backup strategy.

A comparative safety assessment was conducted to identify and characterize the safety risks associated with each backup strategy. The results of this assessment were used to ensure that there were no significant safety risks associated with any of the strategies, and to provide additional discrimination between individual strategies, if possible, to aid the team in the development of a recommended backup strategy.

Based on the results of this analysis, a series of conclusions were generated, along with a recommended backup strategy to be included in the SBS program acquisition baseline. Considerations for follow-on assessments were also identified.

3. Ground Rules and Assumptions

3.1 Overview of GPS Risks

In order to determine the degree of impact a potential loss of GPS L1 would have on ATC surveillance in the NAS using ADS-B, and thus the required scope of a backup strategy, it is necessary to identify potential types of GPS vulnerabilities and their associated impacts and risks. Past assessments have categorized types of GPS vulnerabilities as follows:

- Unintentional interference
- Planned testing interference
- Interference from emerging technologies (RFI)
- Intentional interference
- Sustainment issues
- Ionospheric effects
- System attack (ground, space)

Based on past assessments, and both historical and anecdotal evidence, the team identified the potential impact and perceived likelihood of each of these vulnerabilities on a qualitative basis. The results of this activity are presented in Figure 3-1. Also shown are the team's assessment of how certain factors, such as the introduction of GPS L5, and improved detection and location capabilities, could reduce the likelihood or the impact of these vulnerabilities. Likewise, factors such as increased dependency are also shown as drivers of potentially increased likelihoods or impacts.

Several conclusions were made based on the results of this exercise. First, GPS losses due to ground or space attack were assumed to fall outside the scope of any proposed FAA mitigation strategy, and should not be included in this evaluation as a requirement. Losses due to sustainment issues were considered by the team to be a policy issue, and should be addressed from that perspective (this issue was raised to the ATMAC for consideration).

Losses due to unintentional or planned testing interference were considered by the team to present the greatest risk (combination of likelihood and impact) to the NAS. Losses of GPS due to these types of vulnerabilities have been documented in the past, and will continue to occur in the future. Also, most mitigation strategies that could be implemented in the projected timeframe that would mitigate these types of losses would also mitigate many other types, including ionospheric, RFI, and most types of likely intentional interference vulnerabilities. Therefore, the team determined that GPS losses based on unintentional interference or planned testing interference should be the basis for the development of a backup strategy (shown in bold in Figure 3-1).

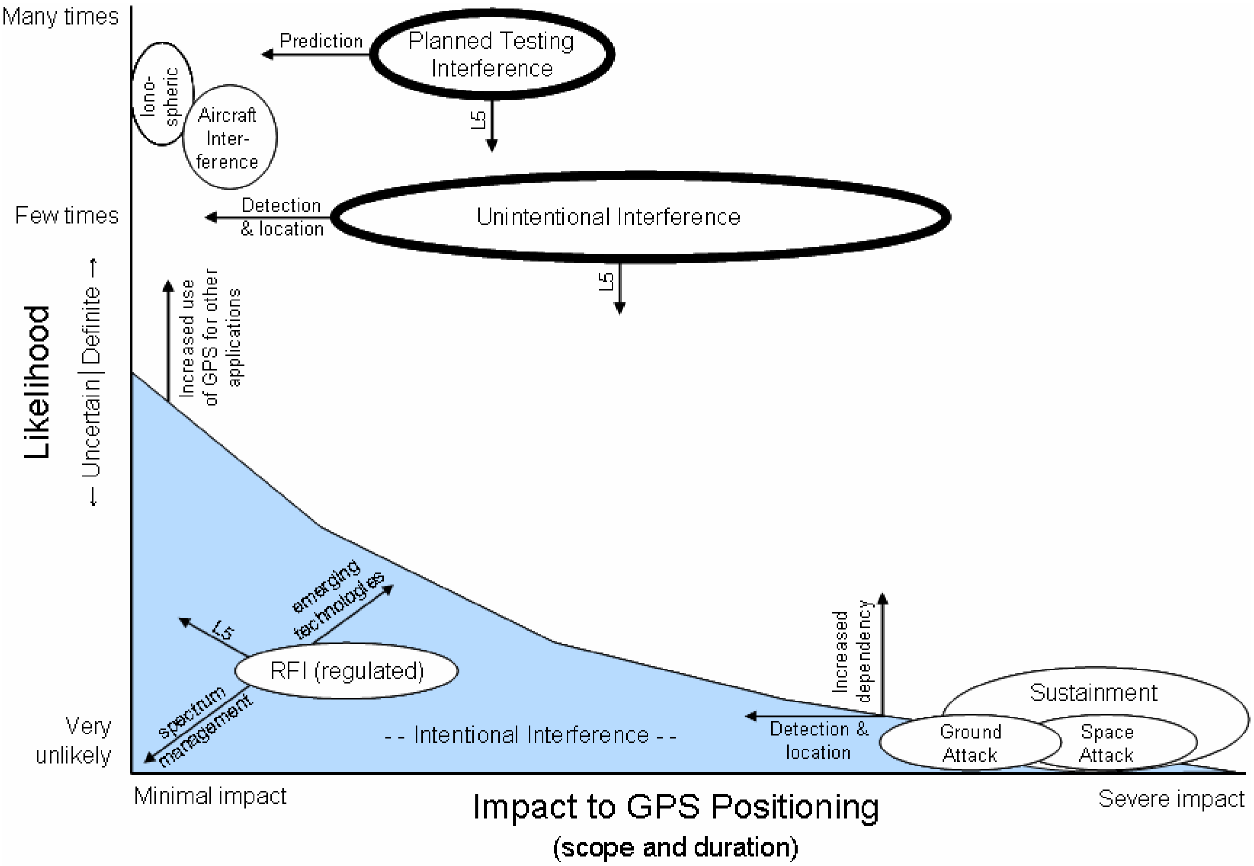

Figure 3-1: GPS Vulnerabilities and Their Potential Risks

In order to develop an effective backup strategy, the impact of a loss of GPS due to unintentional or planned testing interference needed to be quantified in some way. Past assessments and historical evidence suggested that either type of interference could affect areas ranging anywhere from less than one to hundreds of nautical miles (nmi) radius from the interference source, depending on many factors including source transmitting power and altitude of impacted aircraft. These interference events would not be limited to just certain locations in the U.S., and could therefore occur anywhere in the NAS. Given the wide range of possible impacts, the team decided to select a specific level of impact that would be viewed as being both realistic and representative of a challenging condition, and upon which a quantitative assessment of candidate strategies could be based. A loss of GPS covering an affected area of 40 - 60 NM in radius, the typical area covered by a terminal radar today, was selected as meeting these criteria, and was approved by the Steering Committee.

A realistic and representative duration of GPS loss also needed to be identified to support a quantitative assessment of candidate strategies. Based on historical and anecdotal evidence, losses due to planned testing interference occurred over relatively short periods (several hours) at a time, but repetitively over many days or weeks. Losses due to unintentional interference tended to be more continuous in nature, have lasted anywhere from a few hours to several weeks. Given the wide range in durations of past events, tempered with an assumption of improving detection and location capabilities over time, the team selected 3 - 4 days as a realistic and representative duration of a loss of GPS L1, which was also approved by the Steering Committee.

3.2 Backup Strategy Minimum Requirements

Based on guidance from the Steering Committee, the backup strategy must meet certain minimum requirements in order to satisfy the needs of airspace users in the future. Given the anticipated scope and duration of potential losses of GPS described above, the backup strategy must be able to support the ATC surveillance application to at least the same extent as current backup surveillance capabilities are provided today. In other words, at least the same level of capacity must be maintained during a loss of GPS that would be experienced during a comparative loss of radar services today. Generally, a loss of radar services for a given area is mitigated in one of several ways: by providing terminal capabilities (e.g., 3 nmi separations) with reduced coverage using a nearby terminal radar; by providing en route capabilities (e.g., 5 nmi separations) with reduced coverage using the nearest en route radar; or by reversion to procedural separation if neither of the first two options are feasible.

There are approximately 40 terminal areas that are served by more than one terminal radar, in which terminal capabilities continue to be provided should one of the terminal radars become inoperative, albeit with reduced (but acceptable) coverage. These areas are also among the highest capacity terminal areas in the NAS, in terms of IFR operations. For the purposes of this evaluation, these terminal areas are referred to as high density terminal airspace. During a loss of GPS in one of these areas in the future, terminal operations must continue to be maintained in at least some usable portion of the affected airspace, so that NAS capacity is not excessively impacted.

Many terminal areas served by radar today are provided with en route capabilities using the nearest en route radar, should the local terminal radar become inoperative. Under these circumstances, en route capabilities are provided only down to a certain altitude, which varies depending on the distance to the nearest en route radar; this is often referred to as Center Radar ARTS Presentation (CENRAP) coverage. For the purposes of this evaluation, the terminal airspace covered by en route radar during a backup condition is referred to as medium density terminal airspace. During a loss of GPS in one of these areas (CENRAP coverage areas) in the future, en route capabilities must be maintained so that NAS capacity is not excessively impacted.

Due to a significant amount of overlapping coverage, much of the en route airspace served by radar today (18,000 ft MSL and above in most areas, 24,000 ft MSL and above in Rocky Mountain areas) continues to be provided with en route capabilities in the event of a single radar outage, albeit with reduced (but acceptable) coverage; areas outside of the backup area revert to procedural separation. For the purposes of this evaluation, all of these areas are referred to as (medium density) en route airspace. During a loss of GPS in one of these areas in the future, en route operations must continue to be maintained in all affected airspace, so that NAS capacity is not excessively impacted.

For all of these areas, continuity of services must be maintained during the transition to the backup. For the purposes of this evaluation, all other airspace not described above is referred to as “other” airspace, where coverage during a loss of GPS would be desirable, but not considered a requirement for this evaluation. Other capabilities, such as surface surveillance and support for cockpit-based surveillance applications, would also be desirable during a loss of GPS, but are not considered a requirement.

As with any critical NAS infrastructure, safety of operations must always be maintained. Lastly, the backup strategy must be able to be implemented and made operational on or before the ADS-B rule compliance date, which for this evaluation is assumed to be 2020.

3.3 Guiding Assumptions

This section provides some context for the evaluation of the backup strategies. First, it details assumptions on future navigation and positioning capabilities, both satellite and ground based. Assumptions are then provided on future (ground-based) surveillance capabilities. General assumptions are also described. All assumptions were coordinated and approved by the Steering Committee.

Navigation/Positioning

- Per current U.S. policy, 21/24 nominal plane/slot GPS positions will be operational and transmitting a usable navigation signal with 0.98 probability
- The GPS constellation will be upgraded to provide a usable L5 signal by 2020
- Dual frequency Wide Area Augmentation System (WAAS) will also be available in the same timeframe
- 27 Galileo satellites (with 3 spares) will be in orbit and operational by 2015, with three frequencies for aviation
- Avionics will be available to take advantage of both GPS and Galileo frequencies within the required timeframe
- The air transport fleet will have upgraded their Global Navigation Satellite System (GNSS) receivers to take advantage of both GPS L5 and Galileo by 2020
- The General Aviation (GA) fleet will have GPS L1 (as a basic part of ADS-B equipage)
- There will be no simultaneous open air testing of more than one GNSS frequency by the Department of Defense (DoD) during peacetime in the NAS

- The Distance Measuring Equipment (DME) ground infrastructure will support Required Navigation Performance (RNP) 2 operations in en route airspace by 2018 as part of the planned navigation services backup strategy
- Future DME avionics requirements will be consistent with current performance standards

Surveillance

- The backup performance required to support terminal and en route capabilities must be consistent with the SBS program final Program Requirements (fPR) document
- Mode A/C/S transponder carriage rules will not change in the projected timeframe (through 2035) due to Traffic Collision and Avoidance (TCAS) interoperability requirements (at least within Mode C Veil terminal airspace)
- Primary radar can be used to validate ADS-B reports
- Primary radar can be used to provide radar vectors, and mitigate single aircraft outages (in the same way it can be used today)
- Use of primary radar will be acceptable as a safety backup in all required airspace
- Terminal area primary radar coverage will not be reduced from current levels

General

- From the time new avionics are available for installation and certification aboard aircraft, full fleet equipage can be achieved in 7 years for Air Transport aircraft, and 10 years for General Aviation and DoD aircraft
- From the time avionics upgrades are available for installation and certification aboard aircraft, full fleet equipage can be achieved in 5 years for Air Transport (AT) aircraft, 8 years for General Aviation aircraft, and 10 years for DoD aircraft

For the purposes of this study, new avionics are defined as those avionics that would require significant changes in the aircraft for installation and certification, such as new holes in the aircraft (for new antennas), new wiring runs, etc.; avionics upgrades are defined as changes to avionics that do not involve significant changes in the aircraft, such as software upgrades, hardware card swaps, etc.

4. Evaluation criteria

A set of evaluation criteria were developed by the team and coordinated with the Steering Committee. The evaluation criteria consists of both a set of metrics and a series of sub-metrics and measures that serves as the framework for the assessment of backup strategies.

4.1 Metrics

A set of evaluation metrics were developed by the team to serve as the basic framework for the assessment of alternative backup strategies. These criteria were refined and coordinated with the

Steering Committee as the team progressed with its assessment of backup strategies. The final definitions for the metrics used in the evaluation are as follows:

- <u>Operational capability & coverage</u> – the extent to which a strategy supports ATC and initial air-air applications, including impacts on transition workload
- <u>Technical maturity</u> – the estimated time and risk involved in implementing a strategy
- <u>Independence</u> – the extent to which a strategy does not have common vulnerability with the primary means (of surveillance)
- <u>Flexibility/agility</u> – the degree to which a strategy can accommodate evolving user requirements and changes in dependent plans
- <u>Global interoperability</u> – the degree to which a strategy will be compatible with international standards and adopted by other states
- <u>Operational duration</u> – the length of time a strategy meets operational requirements after a loss of GPS (L1)

4.2 Measures

In order to accurately assess each strategy, each metric must be specified to a sufficient level of detail such that quantitative measures can be identified. In some cases, this resulted in the formation of sub-metrics within a metric so that different aspects of the metric could be adequately assessed. The expanded set of metrics and sub-metrics became as follows:

- <u>Operational capability & coverage</u>:
    - En route airspace - the separation supported by a strategy in en route airspace (Class A, i.e. above 18,000 ft mean sea level, or MSL), combined with the extent that strategy covers the same airspace.
    - High density airspace - the separation supported by a strategy in high density terminal airspace (the Class B/Class C airspace over the top 40 airports in terms of capacity), combined with the extent that strategy covers the same airspace.
    - Medium density airspace - the separation supported by a strategy in medium density terminal airspace (Class C and Class D airspace above the CENRAP floor), combined with the extent that strategy covers the same airspace.
    - Other airspace - the separation supported by a strategy in all other airspace not included in the other sub-metrics (Class C/Class D airspace below the CENRAP floor, Class E, etc.), combined with the extent that strategy covers the same airspace.
    - Support for initial air-to-air applications – the extent to which a strategy supports EVAcq, EVApp, CD, FAROA, and ASSA applications based on requirements described in the SBS program’s fPR document.
    - Support for ADS-B position validation – while operating in normal mode (not during backup), the extent to which a strategy can provide enhanced validation of ADS-B position reports (beyond what is possible using primary radar alone) to support position integrity validation and/or spoofing protection.

  - Impact on controller workload during transition – the level of impact on controller workload during the transition from the primary means of surveillance to the backup mode of operation, as defined by the particular strategy.
- <u>Technical maturity</u>:
  - Estimated availability - the estimated timeframe in which a strategy could be fully developed, tested, standardized, and fielded to acceptable levels in the NAS (both ground infrastructure and fleet equipage).
  - Schedule uncertainty – the level of confidence/risk in the estimated availability date of a particular strategy.
- <u>Flexibility/agility</u>:
  - Short-term user requirements - the level of difficulty involved for a given strategy in temporarily expanding the areas that can support terminal area separations in backup mode.
  - Long-term user requirements - the degree to which a strategy can support additional capabilities (extendibility) in backup mode as user requirements change over time.
  - Dependence on non-GPS programs - the degree to which a strategy is dependent on non-GPS programs for successful implementation.
  - Does not preclude eventual path for GA Mode A/C/S transponder retirement - the degree to which a strategy does not preclude the eventual retirement of transponders for GA aircraft, assuming that TCAS is modified to accept and process ADS-B messages.
  - Potential applicability to navigation services/operations - the extent to which a strategy can support navigation services and/or operations.
- <u>Global interoperability</u>:
  - Equipage imposition on incoming aircraft - the degree to which additional equipage will be required on foreign carriers entering the NAS for a given strategy.
  - Usability outside of U.S. for outgoing aircraft – the degree to which additional equipage required by a particular strategy could be used (leveraged) for approved operations outside of the U.S.
  - Status of International Civil Aviation Organization (ICAO) standards – the level of maturity of international standards for avionics required by a given strategy.
- <u>Independence</u> (no sub-metrics required or defined)
- <u>Operational duration</u> (no sub-metrics required or defined)

A range of measures were then identified for each metric/sub-metric and correlated to relative scores that were based on a sliding scale from 0 to 10. In most cases, the minimum score was set to the related minimum operational requirement, if one existed. In some cases, the minimum score was set below this requirement in order to make sure a particular strategy would be included in the trade space, per Steering Committee direction. Maximum scores were set to the perceived ideal condition related to each metric/sub-metric, as determined by the technical team and approved by the Steering Committee. Intermediate scores were defined in many cases to aid in the assessment and scoring of each strategy.

Finally, as a result of initial scoring exercises, several of the metrics/sub-metrics were shown to be non-discriminating, or were shown to be redundant with others. These metrics were not included as part of the final scoring exercise. These included:

- Operational capability & coverage - En route airspace: Justifications for all scores were identical to those for the medium density airspace sub-metric; redundant sub-metric.
- Operational capability & coverage - High density airspace: All strategies support the same capability in high density terminal areas, and so all strategies achieved the same score; non-discriminating sub-metric.
- Operational capability & coverage - Impact on controller workload during transition: The level of impact for each strategy is directly proportional to the separations supported in medium density airspace for that strategy; redundant sub-metric.
- Global interoperability - Usability outside of U.S. for outgoing aircraft: Usability is achieved through the use of Mode A/C/S transponders on outgoing aircraft, and so all strategies achieved the same score; non-discriminating sub-metric.
- Global interoperability - Status of ICAO standards: Interoperability is achieved through the use of Mode A/C/S transponders for aircraft flying internationally, and so all strategies achieved the same score; non-discriminating sub-metric.
- Operational duration (no sub-metrics defined): None of the strategies exhibit time-dependent performance relative to the GPS outage scenario, and so all strategies achieved the same score; non-discriminating sub-metric.

4.3 Scoring Criteria

The final set of metrics, sub-metrics, and measures used in the calculation of scores for each strategy are shown in Table 4-1.

Table 4-1: Scoring Metrics, Sub-Metrics, and Measures

Metric	**Sub-Metric**	**Range of Measures**		
		Minimum (0)	**Intermediate (5)**	**Maximum (10)**
Operational Capability & Coverage	**Medium density airspace**	5.2-7nmi separation in most en route airspace	5 nmi separation (0.3nmi 95% accuracy)	3 nmi separation (0.1nmi 95% accuracy)
	Other airspace	20 nmi separation (procedural)	5 nmi separation (0.3nmi 95% accuracy)	3 nmi separation (0.1nmi 95% accuracy)
	Support for initial air-to-air applications	supports none		supports all
	Support for ADS-B position validation	no	partially	yes
Technical Maturity	**Estimated availability**	2022	2020	2018
	Schedule uncertainty	2 years	1 year	none
Global Inter-operability	**Equipage imposition on incoming aircraft**	New equipage imposed on incoming aircraft	Upgraded equipage imposed	No additional equipage imposed
Flexibility/ Agility	**Short-term user requirements**	inflexible, unable to adapt to short term changes		dynamic reconfigurability to support short term changes
	Long-term user requirements	inflexible, unable to adapt to long term changes (not extendable)		supports additional applications in more areas in backup mode (extendable)
	Dependence on non-GPS programs	Dependent on multiple non-GPS programs with programmatic uncertainties	Dependent on one non-GPS program with programmatic uncertainty	No dependencies
	Does not preclude eventual path for GA transponder retirement	no	partially	yes
	Potential applicability to navigation services/operations	none	en route area navigation	non-precision approach or better
Independence		significant dependence (e.g., single-freq GPS intf mitigated, but not multi-freq)	moderate or partial dependence (e.g., GPS timing dependency, limited area impacted)	no dependence

5. Initial Assessment of Backup Technologies and Methods

With the establishment of the evaluation criteria as described in Section 4 above, potential ADS-B surveillance/positioning backup technologies and methods, both airborne and ground-based, were filtered into one of three "tiers" or categories:

Tier 1: Technology/method meets all minimum backup criteria for at least one airspace type (e.g., standard terminal operations in high density terminal airspace, standard en route operations in medium density terminal and all en route airspace);

Tier 2: Technology/method meets most minimum backup criteria for at least one airspace type, with uncertainty regarding certain metrics;

Tier 3: Technology/method does not or will not meet minimum criteria.

Tier 1 and Tier 2 technologies/methods would subsequently be candidates for components of backup strategies, which would use one or more technologies to satisfy all minimum backup criteria for all airspace types and users. The resulting strategies, which were developed by the team and confirmed as being appropriate for analysis by the Steering Committee, are discussed in Section 6 of this Report. Tier 3 technologies would be recorded as having been considered, but would not be the subject of further assessment.

5.1 Potential Backup Technologies and Methods

The potential backup technologies considered by the team were as follows:

<u>Ground-Based Surveillance Technologies</u>

Secondary Radar
Primary Radar
Passive Multilateration
Active Multilateration

<u>Aircraft-Computed Positioning Technologies</u>

DME/DME/Inertial Reference Unit (IRU)
DME/DME
Enhanced Loran (eLoran)
IRU only
Satellite Navigation Only (Satellite-Based Augmentation System (SBAS), L5, Galileo)
VHF Omnidirectional Range (VOR)/DME
Localizer/DME
Microwave Landing System/Area Navigation (MLS/RNAV)

<u>Procedural Separation (Method)</u>

Because of its limitations in being able to support sufficient levels of capacity, procedural separation was categorized as being in Tier 3, with the exception of its ability to provide backup services in low density airspace.

The categorization of ground-based surveillance and aircraft-computed positioning technologies listed above is now discussed.

5.2 Categorization of Ground-Based Surveillance Technologies

All candidate ground-based surveillance technologies were classified as being in Tier 1. Indeed, secondary and primary surveillance radars form the backbone, along with procedural separation, of today's backup surveillance. Passive and active multilateration, although not yet implemented as "critical" ground infrastructure, have been demonstrated to meet stringent surveillance accuracy, availability, and integrity requirements. A potential concern with active multilateration technology is spectrum occupancy in high density areas on the 1090 MHz frequency, also used by the secondary surveillance radar system and TCAS.

5.3 Categorization of Aircraft-Computed Positioning Technologies

The operational capability provided by aircraft-computed positioning technologies hinges upon the ability of those technologies to provide, with appropriate coverage and integrity, 95% positioning accuracy of 0.3 nmi or better to support standard en route operations/separations, and 0.1 nmi to support standard terminal area operations/separations. This level of performance needs to be sustainable throughout a multi-day outage of GPS (L1).

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<u>DME/DME/IRU</u>

After considerable discussion and fact-finding, the team categorized DME/DME/IRU as a Tier 2 candidate technology. As can be seen in Appendix A, this positioning technology does not support a 95% positioning accuracy of 0.3 nmi on a NAS-wide basis. Given, however, the widespread use of DME/DME/IRU in the air transport community, FAA plans to increase the number of DME ground stations in the time frame pertinent to the effective date of ADS-B rulemaking, and the planned use of DME/DME/IRU within an RNP/RNAV route structure for the NAS, the team received approval from the Steering Committee to assess what types of separations DME/DME/IRU might support as part of a backup strategy. Uncertainty regarding the definition of standardized avionics interface requirements for the use of DME/DME/IRU was seen to be a further potential issue.

<u>DME/DME</u>

Without the mitigations of poor DME-DME station geometries that are provided by an IRU, the team categorized DME/DME as a Tier 3 technology.

<u>eLoran</u>

eLoran technology (see Appendix A) has been under evaluation for a number of years by the FAA. The team made a preliminary finding that the performance of this technology would likely be suitable for the support of standard en route operations/separations in medium density terminal and all en route airspace. Questions remained, however, on whether localized correction factors would need to be applied to eLoran positions in order to meet the 0.3 nmi 95%

accuracy, with appropriate integrity, on a NAS-wide basis. Furthermore, the team recognized an element of uncertainty about the ability to have mature avionics standards completed within the required time frame to have fleet equipage with eLoran by 2018 to 2020. Therefore, eLoran was categorized as a Tier 2 technology.

IRU Only

IRU technology was assessed as not being able to provide reliable and predictable positioning accuracy during a GPS outage. IRU performance would have to be adequate for the duration of any aircraft's operation within the affected area; due to the uncertainty of the amount of time in the area and the level of performance of current GPS/IRU-equipped aircraft, adequate performance can not be guaranteed (typical accuracy performance degrades at up to 8 nmi per hour for the first 15 minutes after loss of GPS). This technology was therefore categorized as being in Tier 3.

Satellite Navigation Only (SBAS, L5, Galileo)

The use of the L5 frequency as well as the use of a second, independently-controlled Galileo constellation was seen by the team as providing mitigation of GPS L1 vulnerabilities. While there was no doubt that the positioning accuracy and integrity performance of this technology would meet pertinent backup surveillance requirements, the uncertainty of the independence of this technology from GPS L1 (i.e., owing to the possibility of unintentional multiple frequency interference) and the ability, from a Government policy perspective, to rely upon the (non U.S.) Galileo constellation as part of the backup strategy, led the team to categorize this technology as being in Tier 2. The Steering Committee asked the team to assume, in evaluating this technology further, that the Government policy question involving the use of the Galileo constellation would be resolved in a manner favorable to use of that constellation. The Steering Committee further asked the team to assume, for the purposes of evaluation, that the probability of substantial unintentional interference occurring simultaneously on both the L1 and L5 frequencies would be acceptably low for NAS-wide use of the technology in a backup strategy. Based on this feedback, the technical team evaluated the operational capability of all alternatives against a scenario of interference to L1. Schedule uncertainty regarding satellite launching schedules for GPS L5 and Galileo was seen as a further factor in the categorization of this technology as Tier 2.

VOR/DME, Localizer/DME, and MLS/RNAV

VOR/DME and Localizer/DME technologies were classified as being in Tier 3 because of accuracy and coverage considerations. MLS/RNAV technology, while implemented by an important portion of the aviation user community, was seen as lacking appropriate coverage characteristics, and was therefore classified as being in Tier 3.

5.4 Summary of Initial Assessment

The team accordingly presented the following classification of candidate backup technologies and methods in an Interim Report in August 2006:

Tier 1: meets all minimum criteria for at least one airspace type

Secondary Radar, Primary Radar, Passive and Active Multilateration

Tier 2: meets most criteria, with uncertainty regarding certain metrics

DME/DME/IRU, eLoran, Satellite Navigation Only

Tier 3: Does not or will not meet minimum criteria

DME/DME, IRU Only, VOR/DME, Localizer/DME, MLS/RNAV, Procedural Separation (except for low density airspace)

Tier 1 and Tier 2 technologies and methods were subsequently used, consistent with Steering Committee guidance, as components of seven surveillance/positioning backup strategies, as described in the following section.

6. Backup Strategy Descriptions

Based on the team's assessment of available technologies, seven strategies were developed for evaluation and scoring. Summary descriptions for each backup strategy are provided in the following sections. Detailed technical descriptions for these strategies are provided in Appendix A of this report.

6.1 Strategy 1: Secondary Radar

This strategy consists of maintaining a reduced network of secondary surveillance radars (SSRs) to serve as a backup to ADS-B surveillance capabilities. In this strategy, secondary radar services will be provided in high density terminal airspace (surrounding approximately the top 40 airports in terms of capacity), all en route airspace above 18,000 feet above MSL, and medium density terminal airspace above certain altitudes, as determined by proximate en route SSR coverage (identical to today's CENRAP coverage). Primary surveillance radar (PSR) services will be retained in all terminal areas covered by primary radar today (approximately 200 locations), to serve as the means of mitigating single-aircraft avionics failures. No new avionics will be required to support this strategy; legacy transponders (Mode A/C/S) will continue to be required to support secondary radar surveillance.

6.2 Strategy 2: Passive Multilateration

This strategy consists of clusters of multilateration ground stations that will provide airspace coverage equivalent to the coverage provided by current en route and terminal radar systems. In this strategy, approximately 7 ground stations will be fielded to emulate each terminal radar and approximately 10 ground stations will be fielded to emulate each en route radar. These clusters will provide coverage in high density terminal airspace, all en route airspace, and medium density terminal airspace above certain altitudes, as determined by proximate en route SSR coverage (equivalent to today's CENRAP coverage). This strategy does not interrogate the aircraft's avionics, so no transmission license is required for the installation and use of the system and there is no increase in the number of interrogations or replies caused by the system.

Passive multilateration will utilize signals periodically broadcast from aircraft equipped with ADS-B avionics (1090-ES and UAT). The geographically distributed ground stations will receive the broadcast signals and measure the time-of-arrival (TOA) of the same broadcast message and forward the information to a central processing station.

The aircraft's position is determined by joint processing of the time difference of arrival (TDOA) measurements computed between a reference and the ground stations' measured TOA by a centralized target processor. Receipt of a message at three synchronized ground stations within an update interval is sufficient to determine the horizontal position of an aircraft. Aircraft identity and barometric altitude will be determined by decoding the information contained within the ADS-B messages. The central target processor generates target reports based on the received information and forwards the target report to terminal and en-route automation systems for further processing and display.

6.3 Strategy 3: Active Multilateration

This strategy is similar to Strategy 2, and consists of clusters of multilateration ground stations that will provide airspace coverage equivalent to the coverage provided by current en route and terminal radar systems. In this strategy, approximately 5 ground stations will be fielded to emulate each terminal radar and approximately 6 ground stations will be fielded to emulate each en route radar. These clusters will provide coverage in high density terminal airspace, all en route airspace, and medium density terminal airspace above certain altitudes, as determined by proximate en route SSR coverage (equivalent to today's CENRAP coverage). This strategy will utilize signals transmitted from Modes A, Mode C and Mode S transponders to calculate an aircraft's position. Active multilateration requires no changes in current aircraft equipage.

Active multilateration transmits interrogations to transponders and utilizes its interrogations for range enhancement processing, where the target range from the interrogator is measured for each interrogation/reply transaction. This data supplements the TDOA calculations, and improves the accuracy outside the boundary of the multilateration constellation. This also increases siting flexibility, and reduces the number of ground stations required as compared to passive multilateration.

6.4 Strategy 4: SSR and DME/DME/IRU for AT, SSR and eLoran for GA

This strategy combines the capabilities of secondary radar, DME/DME/IRU, and eLoran to provide backup surveillance capabilities for all aircraft in the required airspace. In high density terminal areas, a reduced secondary radar network is retained to maintain terminal area capacity and accuracy requirements for all aircraft. In en route airspace and a small number of medium density terminal areas, Air Transport category aircraft will take advantage of DME/DME/IRU avionics and the DME ground infrastructure that will be retained for navigation purposes; General Aviation category aircraft will use eLoran to support backup surveillance in this same airspace. This strategy will not provide "tagged" surveillance (i.e., surveillance with aircraft identification (ID) and aircraft-derived position information) for Air Transport aircraft at all medium density terminal areas; in these instances, primary radar will be used where it is available to provide some level of surveillance services for these aircraft. As with Strategy 1, primary radar will also be used to mitigate single-aircraft avionics failures in terminal areas.

6.5 Strategy 5: SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA

This strategy combines the capabilities of secondary radar, DME/DME/IRU, and enhanced (multiple-frequency, expanded satellite constellation) satellite navigation (SATNAV) to provide backup surveillance capabilities for all aircraft in the required airspace. In high density terminal areas, a reduced secondary radar network is retained to maintain terminal area capacity and accuracy requirements for all aircraft. In medium density airspace (both en route and terminal), Air Transport category aircraft will take advantage of enhanced SATNAV capabilities to support backup surveillance; in those instances when enhanced SATNAV is not available (e.g., due to multi-frequency interference), Air Transport aircraft will use DME/DME/IRU avionics and the DME ground infrastructure that will be retained for navigation purposes to provide a reduced backup surveillance level of performance. General Aviation category aircraft will use enhanced SATNAV alone in medium density airspace to support backup surveillance, and will accept the risk of reduced access to certain airspace when enhanced SATNAV is not available. As with Strategy 1, primary radar will be used to mitigate single-aircraft avionics failures in terminal areas.

6.6 Strategy 6: SATNAV Only

This strategy uses the GPS L5 and the Galileo E5a signals as a backup to the loss of the GPS L1 signal (the ADS-B primary positioning source) for all aircraft. The coverage and performance of this strategy satisfies en route and terminal requirements for backup surveillance. Its primary limitation is that it is nearly as vulnerable to radio-frequency interference (RFI) as is the primary positioning source. As with Strategy 1, primary radar will be used to mitigate single-aircraft avionics failures in terminal areas.

6.7 Strategy 7: SATNAV with Terminal SSR

This strategy is the same as Strategy 6, except that secondary radar is used to provide backup surveillance in high density terminal areas for all Air Transport category aircraft. This is included as part of this strategy in order to provide greater assurance that surveillance for these aircraft will not be lost due to a loss of enhanced SATNAV under any anticipated scenario (i.e., conditions leading to a loss of either single-frequency or multiple-frequency GPS signals).

7. Backup Strategy Evaluations

The evaluation of the strategies provides assessments as numerical results. The assessment of each strategy is the summed weighted scores of five metrics. A sensitivity analysis of the weighting factors was performed to ensure that the ranking of the strategies was insensitive to small variations in these factors.

7.1 Backup Strategy Scoring

Each of the seven backup strategies was scored against the set of metrics. The five metrics forming the basis of the evaluation are Operational Capability and Coverage, Technical Maturity, Global Interoperability, Flexibility/Agility, and Independence. Each metric consists of up to five sub-metrics, define in Section 4. Each metric's or sub-metric's scores range from a minimum of 0 to a maximum of 10, with intermediate values specified to aid in the evaluation.

7.1.1 Strategy 1: Secondary Radar

Operational Capability & Coverage

This strategy achieved an overall (raw) score of 4.25 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

Medium Density Airspace: Score = 5; En route SSR accuracy and automation processing techniques are not adequate to support better than 5 nmi separations.

Other Airspace: Score = 0; The SSR network will not provide coverage below the current (CENRAP) radar floor.

Support for Initial Air-to-Air Applications: Score = 2; Only the enhanced visual acquisition (EVAcq) application would be supported (out of 5 possible applications), using TIS-B, supported by SSR data, to provide situational awareness in the cockpit.

Support for ADS-B Position Validation: Score = 10; SSR-derived positions are independent of ADS-B, and therefore can support validation of ADS-B position reports in the required airspace.

Technical Maturity

This strategy achieved an overall (raw) score of 10 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

Estimated Availability: Score = 10; SSR capabilities (both ground systems and legacy Mode A/C/S transponder avionics) are in use now and well understood, and will be available to support this strategy in 2018.

Schedule Uncertainty: Score = 10; SSRs are included in the FAA's current transition plans, and presents no uncertainty in the estimated availability.

Global Interoperability

This strategy achieved a (raw) score of 10 for this metric; Legacy transponders (Mode A/C/S) have been in use worldwide for many years, and will continue to be used to support ATC surveillance, and therefore no additional equipage requirements would be imposed on incoming aircraft.

Flexibility / Agility

This strategy achieved an overall (raw) score of 3.4 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

Short-Term User Requirements: Score = 3; Although SSR capabilities are not completely inflexible, they are generally more difficult to adapt to changing requirements on short notice (such as providing temporary terminal coverage) than some of the other strategies being evaluated, due in large part to siting and logistic requirements.

Long-Term User Requirements: Score = 3; Although SSR capabilities are not completely inflexible, as currently defined they generally will not support additional, more demanding applications; however, they can be (re)distributed over time to cover additional airspace, if needed (although at potentially greater cost than some of the other strategies).

Dependence on Non-GPS Programs: Score = 10; The implementation of this strategy is not dependent on any programs other than for the SSRs themselves.

Does Not Preclude Eventual Path for GA Transponder Retirement: Score = 0; This strategy perpetuates the requirement for Mode A/C/S transponders for all users in the required airspace.

Potential Applicability to Navigation Services/Operations: Score = 1; TIS-B may have some limited potential for supporting navigation using SSR as the data source, but the SSR update rate may be too slow.

Independence

This strategy achieved a (raw) score of 10 for this metric; This strategy does not depend on GPS in any way to achieve its expected performance.

7.1.2 Strategy 2: Passive Multilateration

Operational Capability & Coverage

This strategy achieved an overall (raw) score of 5.75 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

Medium Density Airspace: Score = 10; Multilateration performance specifications support accuracy required for 3 nmi separations.

Other Airspace: Score = 1; While coverage provided by multilateration was designed to mimic en route SSR coverage, there is a softer coverage cutoff compared to radar, and so in some instances, some airspace outside the required area will be covered by multilateration.

Support for Initial Air-to-Air Applications: Score = 2; Only the enhanced visual acquisition (EVAcq) application would be supported, using TIS-B, supported by multilateration data.

Support for ADS-B Position Validation: Score = 10; Multilateration-derived positions are independent of ADS-B, and therefore can support validation of ADS-B position reports.

Technical Maturity

This strategy achieved an overall (raw) score of 5 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

Estimated Availability: Score = 5; Implementation of ground stations cannot be completed until 2020, due to the large number of stations required by this strategy in the NAS.

Schedule Uncertainty: Score = 5; There is a moderate level of risk in the implementation schedule, due to the large number of new (greenfield) sites required for this strategy.

Global Interoperability

This strategy achieved a (raw) score of 10 for this metric; This strategy requires ADS-B "out" avionics only to achieve the required performance, and therefore no additional equipage would be imposed on incoming aircraft (above and beyond what would be imposed for ADS-B alone).

Flexibility/Agility

This strategy achieved an overall (raw) score of 5 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

Short-Term User Requirements: Score = 5; Multilateration is more flexible than SSR due to the distributed nature of its ground systems and less restrictive siting requirements, but is still significantly less flexible than some of the other strategies.

Long-Term User Requirements: Score = 3; The multilateration strategy is significantly less flexible than those incorporating SATNAV capabilities in supporting applications beyond the initial applications.

Dependence on Non-GPS Programs: Score = 5; Multilateration is dependent on Loran-C for timing.

Does Not Preclude Eventual Path for GA Transponder Retirement: Score = 10; Mode A/C/S transponders are not required for passive multilateration, and therefore would not preclude their eventual retirement should changes be made to TCAS in the future.

Potential Applicability to Navigation Services/Operations: Score = 2; TIS-B may have some limited potential for supporting navigation, using multilateration as the data source.

Independence

This strategy achieved a (raw) score of 10 for this metric; This strategy does not depend on GPS in any way to achieve its expected performance.

7.1.3 Strategy 3: Active Multilateration

Operational Capability & Coverage

This strategy achieved an overall (raw) score of 5.75 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

Medium Density Airspace: Score = 10; Multilateration performance specifications support accuracy required for 3 nmi separations.

Other Airspace: Score = 1; While coverage provided by multilateration was designed to mimic en route SSR coverage, there is a softer coverage cutoff compared to radar, and so in some instances, some airspace outside the required area will be covered by multilateration.

Support for Initial Air-to-Air Applications: Score = 2; Only the enhanced visual acquisition (EVAcq) application would be supported, using TIS-B, supported by multilateration data.

<u>Support for ADS-B Position Validation</u>: Score = 10; Multilateration-derived positions are independent of ADS-B, and therefore can support validation of ADS-B position reports.

<u>Technical Maturity</u>

This strategy achieved an overall (raw) score of 4.5 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

<u>Estimated Availability</u>: Score = 5; Implementation of ground stations cannot be completed until 2020, due to the large number of stations required by this strategy in the NAS.

<u>Schedule Uncertainty</u>: Score = 4; There is a moderate level of risk in the implementation schedule, due to the large number of new (greenfield) sites required for this strategy, which may be impacted as well by spectrum issues in high density areas.

<u>Global Interoperability</u>

This strategy achieved a (raw) score of 10 for this metric; This strategy requires only legacy transponders (Mode A/C/S) achieve the required performance, and therefore no additional equipage would be imposed on incoming aircraft.

<u>Flexibility / Agility</u>

This strategy achieved an overall (raw) score of 5 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

<u>Short-Term User Requirements</u>: Score = 4; Multilateration is more flexible than SSR due to the distributed nature of its ground systems and less restrictive siting requirements, but is still significantly less flexible than some of the other strategies, and may suffer additional limitations due to potential spectrum issues in high density airspace.

<u>Long-Term User Requirements</u>: Score = 3; The multilateration strategy is significantly less flexible than those incorporating SATNAV capabilities in supporting applications beyond the initial applications.

<u>Dependence on Non-GPS Programs</u>: Score = 5; Multilateration is dependent on Loran-C for timing.

<u>Does Not Preclude Eventual Path for GA Transponder Retirement</u>: Score = 0; This strategy perpetuates the requirement for Mode A/C/S transponders for all users in the required airspace.

<u>Potential Applicability to Navigation Services/Operations</u>: Score = 2; TIS-B may have some limited potential for supporting navigation, using multilateration as the data source.

<u>Independence</u>

This strategy achieved a (raw) score of 10 for this metric; This strategy does not depend on GPS in any way to achieve its expected performance.

7.1.4 Strategy 4: SSR and DME/DME/IRU for AT, SSR and eLoran for GA

This strategy is scored in two parts for each metric/sub-metric. The first part of the score (a) applies to those aircraft (AT) that would be supported by SSR and DME/DME/IRU. The second part of the score (b) applies to those aircraft (GA) that would be supported by SSR and eLoran. The total score for each metric/sub-metric is determined from a combination of the two parts, which is computed as a simple average unless otherwise specified.

<u>Operational Capability & Coverage</u>

This strategy achieved an overall (raw) score of 3.75 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

> <u>Medium Density Airspace</u>: Score (a) = 0, Score (b) = 7, Total Score = 3.5; DME/DME/IRU will support only 5.2 nmi - 7 nmi separations, depending on the aircraft geometries involved, and with coverage that is not as extensive as the other strategies (a); eLoran may support better than 5 nmi separations in medium density airspace (but not 3 nmi separations) if correction factors based just on modeling are used (b).
>
> <u>Other Airspace</u>: Score (a) = 0, Score (b) = 7, Total Score = 3.5; Coverage provided by DME/DME/IRU is less extensive than the other strategies (a); eLoran is available in all airspace, and will support better than 5 nmi separations as in medium density airspace (within coverage of ADS-B ground stations) (b).
>
> <u>Support for Initial Air-to-Air Applications</u>: Score (a) = 2, Score (b) = 4, Total Score = 3; EVAcq would be supported in high density terminal areas using TIS-B supported by SSR, and in medium density areas that are covered by DME/DME/IRU (a); EVAcq and CD would be supported by eLoran in all airspace (b).
>
> <u>Support for ADS-B Position Validation</u>: Score (a) = 5, Score (b) = 5, Total Score = 5; SSR supports independent validation of ADS-B positions, but only in high density terminal airspace for this strategy, for all aircraft (a and b).

<u>Technical Maturity</u>

This strategy achieved an overall (raw) score of 10 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

> <u>Estimated Availability</u>: Score (a) = 10, Score (b) = 0, Total Score = 5; SSR capabilities are available today and will be able to meet an implementation date of 2018; DME/DME/IRU integration issues relating to its use as an on-board position source for ADS-B will be resolved such that an implementation date of 2018 can also be met (a); eLoran avionics, however, will not be available for installation on aircraft until at least 2012, based on the time required to generate standards and develop acceptable and certifiable avionics, and will only support an implementation date of 2022 (b).
>
> <u>Schedule Uncertainty</u>: Score (a) = 7, Score (b) = 3, Total Score = 5; There are outstanding issues with the integration of DME/DME/IRU and FMS capabilities to support positioning for ADS-B, which presents greater schedule risk than SSR (for example), but has less schedule risk than multilateration with respect to ground implementation, and so the score reflects this balance (a); eLoran presents less schedule risk than SATNAV (for example),

since once avionics are available the capability can be used, however, the risk is still moderately high due to uncertainties in the standards development process (b).

Global Interoperability

This strategy achieved a total (raw) score of 8, with Score (a) = 10, Score (b) = 0 (80% weighting for a); Most aircraft flying internationally will be equipped with DME/DME/IRU, and so these aircraft will have no additional equipage requirements imposed (a); For remaining incoming aircraft (those without an IRU), the assumption is that they would opt to equip with eLoran (lower cost) to meet performance requirements (b); The total score was weighted to account for the greater numbers of DME/DME/IRU-equipped incoming aircraft.

Flexibility / Agility

This strategy achieved an overall (raw) score of 6.1 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

Short-Term User Requirements: Score (a) = 3, Score (b) = 3, Total Score = 3; The ability to expand the number of locations where terminal capabilities can be implemented is dependent solely on SSR for this strategy, since neither DME/DME/IRU nor eLoran can be used for this purpose (a and b).

Long-Term User Requirements: Score (a) = 3, Score (b) = 5, Total Score = 4; For aircraft equipped with DME/DME/IRU, long-term flexibility is driven by SSR capabilities, due to limitations in DME performance (a); Although eLoran cannot support additional applications beyond those described under Operational Capability above, it will provide greater coverage than SSR (for example) (b).

Dependence on Non-GPS Programs: Score (a) = 10, Score (b) = 10, Total Score = 10; This strategy is not dependent on any programs other than for the DMEs and eLoran (a and b).

Does Not Preclude Eventual Path for GA Transponder Retirement: Score (a) = n/a, Score (b) = 5, Total Score = 5 (100% weighting for b); GA aircraft are not expected to equip with DME/DME/IRU, and so this portion of the fleet does not affect this sub-metric (a); For aircraft equipped with eLoran, users can choose not to equip with Mode A/C/S transponders (assuming TCAS is changed) and lose access to high density airspace, or retain their transponders, and so the score reflects this balance (b); The total score was weighted to account for the portion of the fleet that affects this sub-metric.

Potential Applicability to Navigation Services/Operations: Score (a) = 7, Score (b) = 10, Total Score = 8.5; DME/DME/IRU will support en route area navigation and some terminal approach capabilities, but not as extensively as eLoran (for example) (a); eLoran will be able to support non-precision approaches with airport-specific ASFs (not costed in this strategy) (b).

Independence

This strategy achieved a total (raw) score of 10 for this metric, with Score (a) = 10, Score (b) = 10; This strategy does not depend on GPS in any way to achieve its expected performance (a and b).

7.1.5 Strategy 5: SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA

This strategy is scored in two parts for each metric/sub-metric. The first part of the score (a) applies to those aircraft (AT) that would be supported by SSR, DME/DME/IRU and SATNAV. The second part of the score (b) applies to those aircraft (GA) that would be supported by SSR and SATNAV alone. The total score for each metric/sub-metric is determined from a combination of the two parts, which is computed as a simple average unless otherwise specified.

Operational Capability & Coverage

This strategy achieved an overall (raw) score of 8.25 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

> Medium Density Airspace: Score (a) = 10, Score (b) = 10, Total Score = 10; Capability driven by SATNAV capabilities for all users; SATNAV supports 3 nmi separations in all airspace (within coverage of ADS-B ground stations) (a and b).
>
> Other Airspace: Score (a) = 10, Score (b) = 10, Total Score = 10; Capability driven by SATNAV capabilities for all users; SATNAV supports 3 nmi separations in all airspace (within coverage of ADS-B ground stations) (a and b)
>
> Support for Initial Air-to-Air Applications: Score (a) = 8, Score (b) = 8, Total Score = 8; Capability driven by SATNAV capabilities for all users; EVAcq, EVApp, and CD applications are supported by this strategy for all aircraft; for those with augmentation, FAROA and ASSA would also be supported, so half credit is given for these two applications, since not all aircraft are expected to have augmentation (a and b).
>
> Support for ADS-B Position Validation: Score (a) = 5, Score (b) = 5, Total Score = 5; Capability driven by SSR capabilities for all users; SSR supports independent validation of ADS-B positions, but only in high density terminal airspace for this strategy (a and b).

Technical Maturity

This strategy achieved an overall (raw) score of 3.5 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

> Estimated Availability: Score (a) = 7, Score (b) = 7, Total Score = 7; Capability driven by SATNAV capabilities for all users; current assumptions on satellite launching schedules for L5 and Galileo limit the availability of signal-in-space, limited by the Galileo launch schedule, which drives the availability of signal-in-space until at least 2012; this in turn will delay the anticipated equipage schedule for most aircraft (a and b).
>
> Schedule Uncertainty: Score (a) = 0, Score (b) = 0, Total Score = 0; Capability driven by SATNAV capabilities for all users; there is relatively low confidence in both the L5 and Galileo launch schedules, and uncertainty regarding airframe manufacturers' commitment to earlier equipage cycles.

Global Interoperability

This strategy achieved a total (raw) score of 7.4, with Score (a) = 8, Score (b) = 5 (80% weighting for a); Most aircraft flying internationally will be equipped with DME/DME/IRU, and so these aircraft could operate at reduced capability with no immediate additional equipage requirements imposed, but they would need to equip with SATNAV to achieve full capabilities, and so the score reflects this tradeoff (a); remaining aircraft may not already have L5 and Galileo and will need to equip with upgraded avionics to meet minimum performance requirements (b).

Flexibility / Agility

This strategy achieved an overall (raw) score of 7.4 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

> Short-Term User Requirements: Score (a) = 10, Score (b) = 10, Total Score = 10; Since SATNAV is an area solution, no additional implementation is required to extend the area of ATC surveillance capability (within coverage of ADS-B ground stations) (a and b).
>
> Long-Term User Requirements: Score (a) = 10, Score (b) = 10, Total Score = 10; SATNAV can support applications beyond the initial applications described above, and can support these applications outside the minimum required airspace (a and b).
>
> Dependence on Non-GPS Programs: Score (a) = 7, Score (b) = 5, Total Score = 6; For DME/DME/IRU equipped aircraft there is some dependence on Galileo to meet the anticipated schedule and minimum performance, but this is offset somewhat by the DME/DME/IRU capabilities overlay in certain airspace (a); for other aircraft, there is greater dependency on Galileo (b).
>
> Does Not Preclude Eventual Path for GA Transponder Retirement: Score (a) = n/a, Score (b) = 5, Total Score = 5 (100% weighting for b); GA aircraft are not expected to equip with DME/DME/IRU, and so this portion of the fleet does not affect this sub-metric (a); For aircraft equipped with eLoran, users can choose not to equip with Mode A/C/S transponders (assuming TCAS is changed) and lose access to high density airspace, or retain their transponders, and so the score reflects this balance (b); The total score was weighted to account for the portion of the fleet that affects this sub-metric.
>
> Potential Applicability to Navigation Services/Operations: Score (a) = 7, Score (b) = 5, Total Score = 6; DME/DME/IRU will support en route area navigation and some terminal approach capabilities, but not as extensively as SATNAV (for example) (a); for aircraft that have SATNAV only, there is significant uncertainty regarding applicability to navigation services when surveillance is no longer independent; the score reflects this uncertainty, and the comparison to other strategies where independence is achieved.

Independence

This strategy achieved a total (raw) score of 4 for this metric, with Score (a) = 5, Score (b) = 3; Independence is achieved in high density airspace for all aircraft; for aircraft with DME/DME/IRU, independence is achieved elsewhere, but with lower performance (a); for aircraft with SATNAV only, independence is achieved only in high density terminal areas with SSR (b).

7.1.6 Strategy 6: SATNAV Only

Operational Capability & Coverage

This strategy achieved an overall (raw) score of 7 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

> Medium Density Airspace: Score = 10; SATNAV supports 3 nmi separations in all airspace (within coverage of ADS-B ground stations).
>
> Other Airspace: Score = 10; SATNAV supports 3 nmi separations in all airspace (within coverage of ADS-B ground stations).
>
> Support for Initial Air-to-Air Applications: Score = 8; EVAcq, EVApp, and CD applications are supported by this strategy for all aircraft; for those with augmentation, FAROA and ASSA would also be supported, so half credit is given for these two applications, since not all aircraft are expected to have augmentation.
>
> Support for ADS-B Position Validation: Score = 0; This strategy provides no independent means of ADS-B position validation.

Technical Maturity

This strategy achieved an overall (raw) score of 3.5 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

> Estimated Availability: Score = 7; Current assumptions on satellite launching schedules for L5 and Galileo limit the availability of signal-in-space, limited by the Galileo launch schedule, which drives the availability of signal-in-space until at least 2012; this in turn will delay the anticipated equipage schedule for most aircraft.
>
> Schedule Uncertainty: Score = 0; There is relatively low confidence in both the L5 and Galileo launch schedules, and uncertainty regarding airframe manufacturers’ commitment to earlier equipage cycles.

Global Interoperability

This strategy achieved a (raw) score of 5 for this metric; Incoming aircraft may not already have L5 and Galileo and will need to equip with upgraded avionics to meet minimum performance requirements.

Flexibility / Agility

This strategy achieved an overall (raw) score of 8 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

> Short-Term User Requirements: Score = 10; Since SATNAV is an area solution, no additional implementation is required to extend the area of ATC surveillance capability (within coverage of ADS-B ground stations).
>
> Long-Term User Requirements: Score = 10; SATNAV can support applications beyond the initial applications described above, and can support these applications outside the minimum required airspace.

Dependence on Non-GPS Programs: Score = 5; This strategy is dependent on Galileo to meet the anticipated schedule and minimum performance requirements.

Does Not Preclude Eventual Path for GA Transponder Retirement: Score = 10; Mode A/C/S transponders are not required for this strategy, and therefore would not preclude their eventual retirement should changes be made to TCAS in the future.

Potential Applicability to Navigation Services/Operations: Score = 5; There is significant uncertainty regarding this strategy's applicability to navigation services when surveillance is no longer independent; the score reflects this uncertainty, and the comparison to other strategies where independence is achieved.

Independence

This strategy achieved a (raw) score of 0 for this metric; This strategy is significantly dependent on GPS, and does not mitigate multi-frequency interference.

7.1.7 Strategy 7: SATNAV with Terminal SSR

Operational Capability & Coverage

This strategy achieved an overall (raw) score of 8.25 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

Medium Density Airspace: Score = 10; SATNAV supports 3 nmi separations in all airspace (within coverage of ADS-B ground stations).

Other Airspace: Score = 10; SATNAV supports 3 nmi separations in all airspace (within coverage of ADS-B ground stations).

Support for Initial Air-to-Air Applications: Score = 8; EVAcq, EVApp, and CD applications are supported by this strategy for all aircraft; for those with augmentation, FAROA and ASSA would also be supported, so half credit is given for these two applications, since not all aircraft are expected to have augmentation.

Support for ADS-B Position Validation: Score = 5; SSR supports independent validation of ADS-B positions, but only in high density terminal airspace for this strategy.

Technical Maturity

This strategy achieved an overall (raw) score of 3.5 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

Estimated Availability: Score = 7; Current assumptions on satellite launching schedules for L5 and Galileo limit the availability of signal-in-space, limited by the Galileo launch schedule, which drives the availability of signal-in-space until at least 2012; this in turn will delay the anticipated equipage schedule for most aircraft.

Schedule Uncertainty: Score = 0; There is relatively low confidence in both the L5 and Galileo launch schedules, and uncertainty regarding airframe manufacturers' commitment to earlier equipage cycles.

<u>Global Interoperability</u>

This strategy achieved a (raw) score of 5 for this metric; Incoming aircraft may not already have L5 and Galileo and will need to equip with upgraded avionics to meet minimum performance requirements.

<u>Flexibility / Agility</u>

This strategy achieved an overall (raw) score of 7.8 for this metric, based on the averaged scores for the individual sub-metrics, which were determined as follows:

> <u>Short-Term User Requirements</u>: Score = 10; Since SATNAV is an area solution, no additional implementation is required to extend the area of ATC surveillance capability (within coverage of ADS-B ground stations).
>
> <u>Long-Term User Requirements</u>: Score = 10; SATNAV can support applications beyond the initial applications described above, and can support these applications outside the minimum required airspace.
>
> <u>Dependence on Non-GPS Programs</u>: Score = 5; This strategy is dependent on Galileo to meet the anticipated schedule and minimum performance requirements.
>
> <u>Does Not Preclude Eventual Path for GA Transponder Retirement</u>: Score = 9; This strategy would not preclude an eventual path for Mode A/C/S transponder retirement for most GA aircraft; however, a small percentage of GA aircraft (those that intend to fly in high density terminal airspace) would still require transponders to meet performance availability requirements, regardless of any future TCAS changes.
>
> <u>Potential Applicability to Navigation Services/Operations</u>: Score = 5; There is significant uncertainty regarding this strategy's applicability to navigation services when surveillance is no longer independent; the score reflects this uncertainty, and the comparison to other strategies where independence is achieved.

<u>Independence</u>

This strategy achieved a (raw) score of 3 for this metric; This strategy achieves independence in high density terminal airspace, but not elsewhere, where it is significantly dependent on GPS, and does not mitigate multi-frequency interference.

7.1.8 Summary of Results

The scoring of each strategy against each metric/sub-metric was reviewed by comparing the scores for each metric/sub-metric at a time across all strategies to ensure that the results were reasonable, and that the scoring methods were applied consistently for each strategy.

Final strategy scoring is performed by taking the raw score achieved for each metric for the strategy, multiplying by the baseline weighting factor, and summing the results across all metrics. The final weighted score is scaled to a range from 0 to 1, where 1 is equivalent to a maximum score (10) for each metric. Baseline weighting factors, representing the relative importance of each metric from the users' point of view, were determined and provided by the Steering Committee.

Table 7-1 provides a summary of the scoring activity. The left column lists each of the five metrics. The second column shows the baseline weighting factors, and each of the successive columns provides the averaged scored of each strategy for the corresponding metric. The final weighted scores for each strategy are shown in the bottom row.

Table 7-1: Backup Strategy Scoring Results

Metric	Baseline Weighting	Raw Scores						
		Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5	Strategy 6	Strategy 7
Operational Capability & Coverage	0.3	4.25	5.75	5.75	3.75	8.25	7	8.25
Technical Maturity	0.25	10	5	4.5	5	3.5	3.5	3.5
Global Interoperability	0.18	10	10	10	8	7.4	5	5
Flexibility/Agility	0.16	3.4	5	2.8	6.1	7.4	8	7.8
Independence	0.11	10	10	10	10	4	0	3
Weighted Scores		**0.72**	**0.67**	**0.62**	**0.59**	**0.63**	**0.52**	**0.58**

7.2 Sensitivity Analysis

The scoring results were analyzed to determine the sensitivity of the results to variations in metric weighting. This analysis was conducted to ensure that the final recommendation was not excessively influenced by small changes to any one metric's weight.

For each metric, the weighting at which a particular metric causes the score of the highest-ranked strategy to break-even with the score of another is determined (crossover point). The subject metric's weight (control weight) is varied from 0 to 1, with the ratios between the remaining weights being fixed, and scaled based on the difference from the control weight; all weights continue to sum to 1. Individual raw scores for each strategy are unchanged; only the weighted scores for each strategy change as the control weight is changed.

The percentage change required of the control weight to meet the nearest crossover point is calculated for each metric. Weights for each metric are calculated as follows:

With the weight for the (control) metric = x

The weight for each of the other metrics will be:

(original metric weight/total weight of the other metrics) * (1-x)

The resulting score for each strategy is calculated based on these revised weights, and the nearest crossover point determined from the resulting data. The analysis for each of the five metrics is discussed below.

7.2.1 Operational Capability and Coverage

The baseline weight given to this metric is 0.3, and the total weight of the other four metrics is 0.7. Each of the applications was re-scored using a new set of weights for each value of control weight. The results are plotted as lines in Figure 7-1. The nearest crossover point is at a control weight of 0.43, a change of +43%, at which point Strategy 5 (SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA) becomes the highest-ranked strategy.

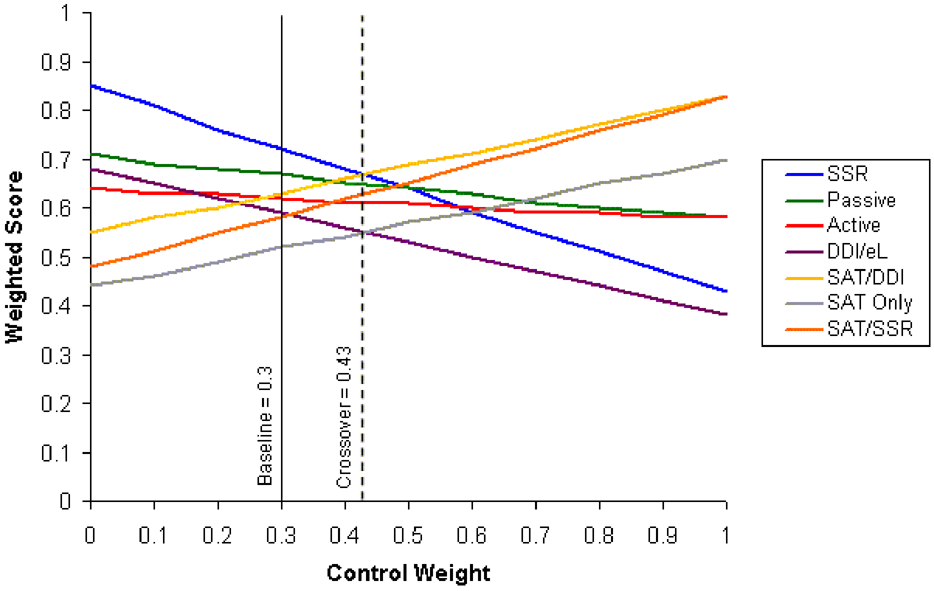


Figure 7-1: Operational Capability & Coverage Sensitivity Analysis

These results show that as the importance of Operational Capability and Coverage grows, the ability of the SSR strategy to meet user expectations declines, eventually losing its dominance as the preferred alternative. If the set of weighting factors changes over time, based on changing user needs and expectations, the preferred alternative could change; however, a significant change in weighting factors would be required to elicit such a change. Since these results are based on large part on the assumptions and guidance outlined in this report, any changes in these criteria could also alter the results of this analysis.

7.2.2 Technical Maturity

The baseline weight given to this metric is 0.25, and the total weight of the other four metrics is 0.75. Each of the applications was re-scored using a new set of weights for each value of control weight. The results are plotted as lines in Figure 7-2. The nearest crossover point is at a control weight of 0.16, a change of -37%, at which point Strategy 2 (Passive Multilateration) becomes the highest-ranked strategy.

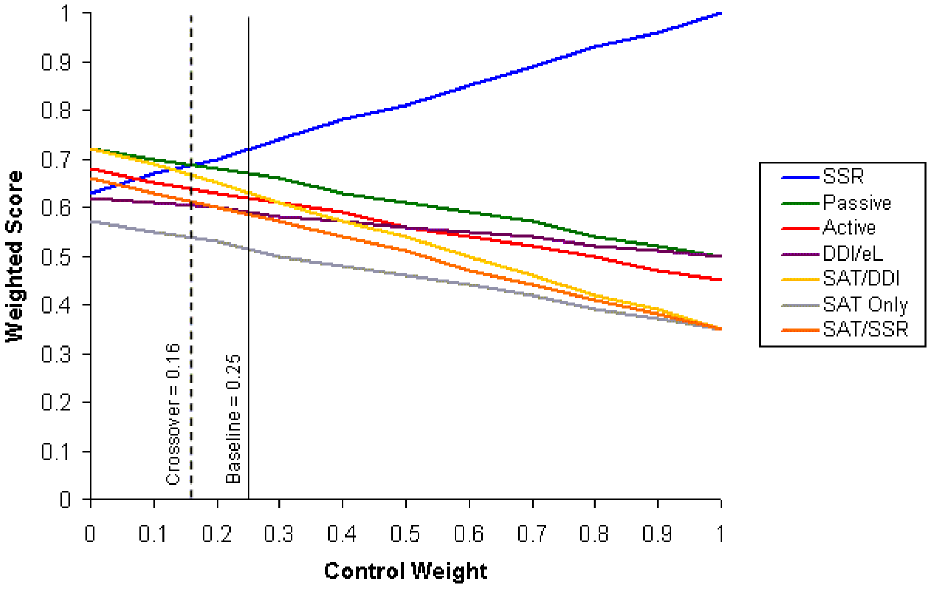


Figure 7-2: Technical Maturity Sensitivity Analysis

These results show that as the importance of Technical Maturity decreases, the ability of the SSR strategy to meet user expectations declines, eventually losing its dominance as the preferred alternative. However, since the importance of Technical Maturity is very unlikely to decrease over time, based on Steering Committee feedback, the likelihood of the results of this analysis changing based on changes in this metric's weighting factor is very low. In fact, based on Steering Committee feedback, the most likely scenario would be an increase in the importance of Technical Maturity over time, actually increasing the dominance of the SSR strategy.

7.2.3 Global Interoperability

The baseline weight given to this metric is 0.18, and the total weight of the other four metrics is 0.82. Each of the applications was re-scored using a new set of weights for each value of control weight. The results are plotted as lines in Figure 7-3. There was no crossover point for any control weight value, which shows that changes in the importance of Global Interoperability had no effect on the dominance of the SSR strategy.

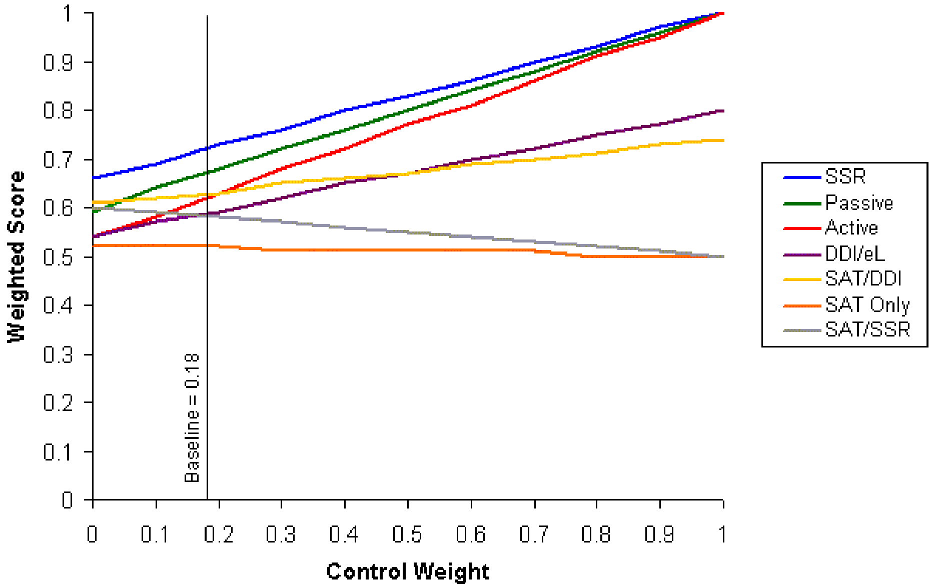


Figure 7-3: Global Interoperability Sensitivity Analysis

7.2.4 Flexibility/Agility

The baseline weight given to this metric is 0.16, and the total weight of the other four metrics is 0.84. Each of the applications was re-scored using a new set of weights for each value of control weight. The results are plotted as lines in Figure 7-4. The nearest crossover point is at a control weight of 0.32, a change of +97%, at which point Strategy 5 (SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA) becomes the highest-ranked strategy.

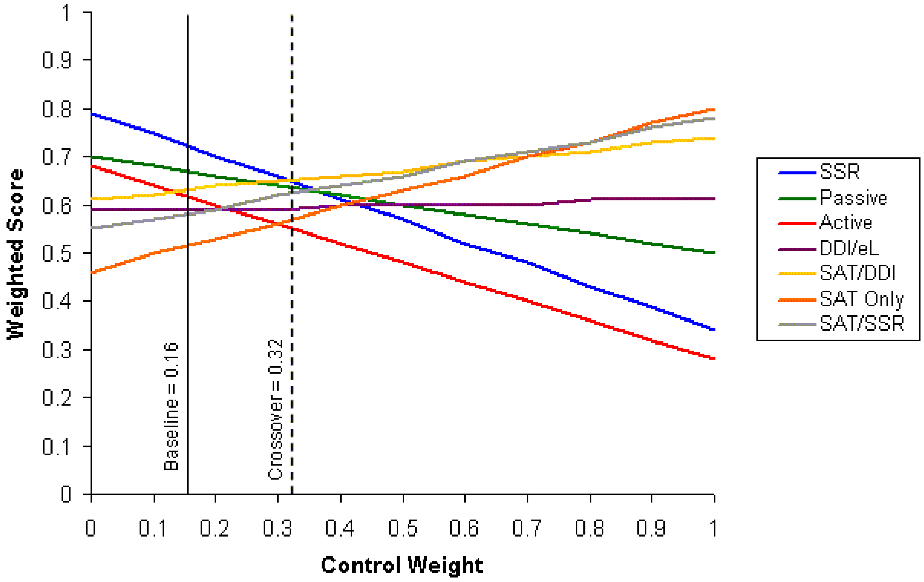


Figure 7-4: Flexibility/Agility Sensitivity Analysis

These results show that as the importance of Flexibility/Agility grows, the ability of the SSR strategy to meet user expectations declines, eventually losing its dominance as the preferred alternative. If the set of weighting factors changes over time, based on changing user needs and expectations, the preferred alternative could change; however, a significant change in weighting factors would be required to elicit such a change. Since these results are based on large part on the assumptions and guidance outlined in this report, any changes in these criteria could also alter the results of this analysis.

7.2.5 Independence

The baseline weight given to this metric is 0.11, and the total weight of the other four metrics is 0.89. Each of the applications was re-scored using a new set of weights for each value of control weight. The results are plotted as lines in Figure 7-5. There was no crossover point for any control weight value, which shows that changes in the importance of Independence had no effect on the dominance of the SSR strategy.

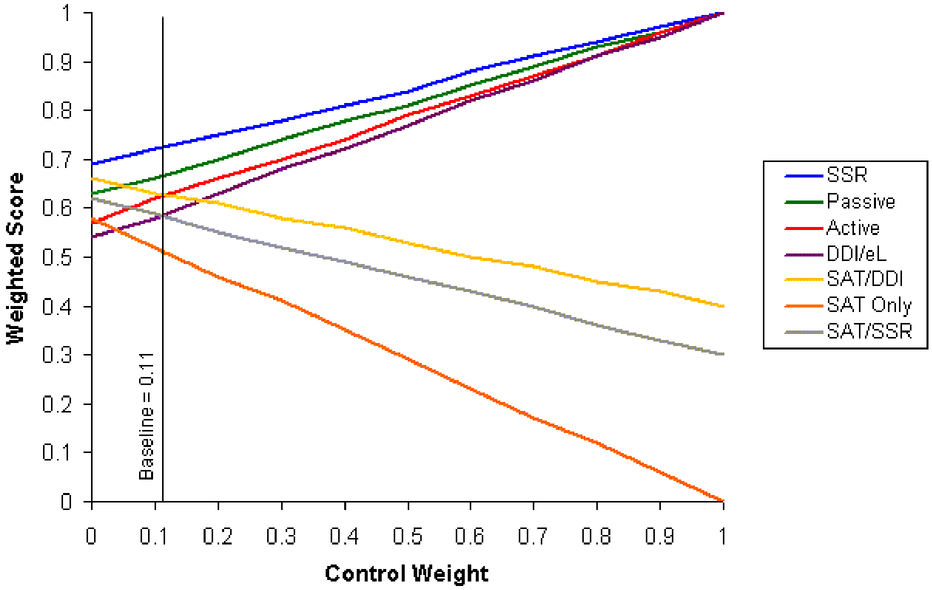


Figure 7-5: Independence Sensitivity Analysis

7.2.6 Summary

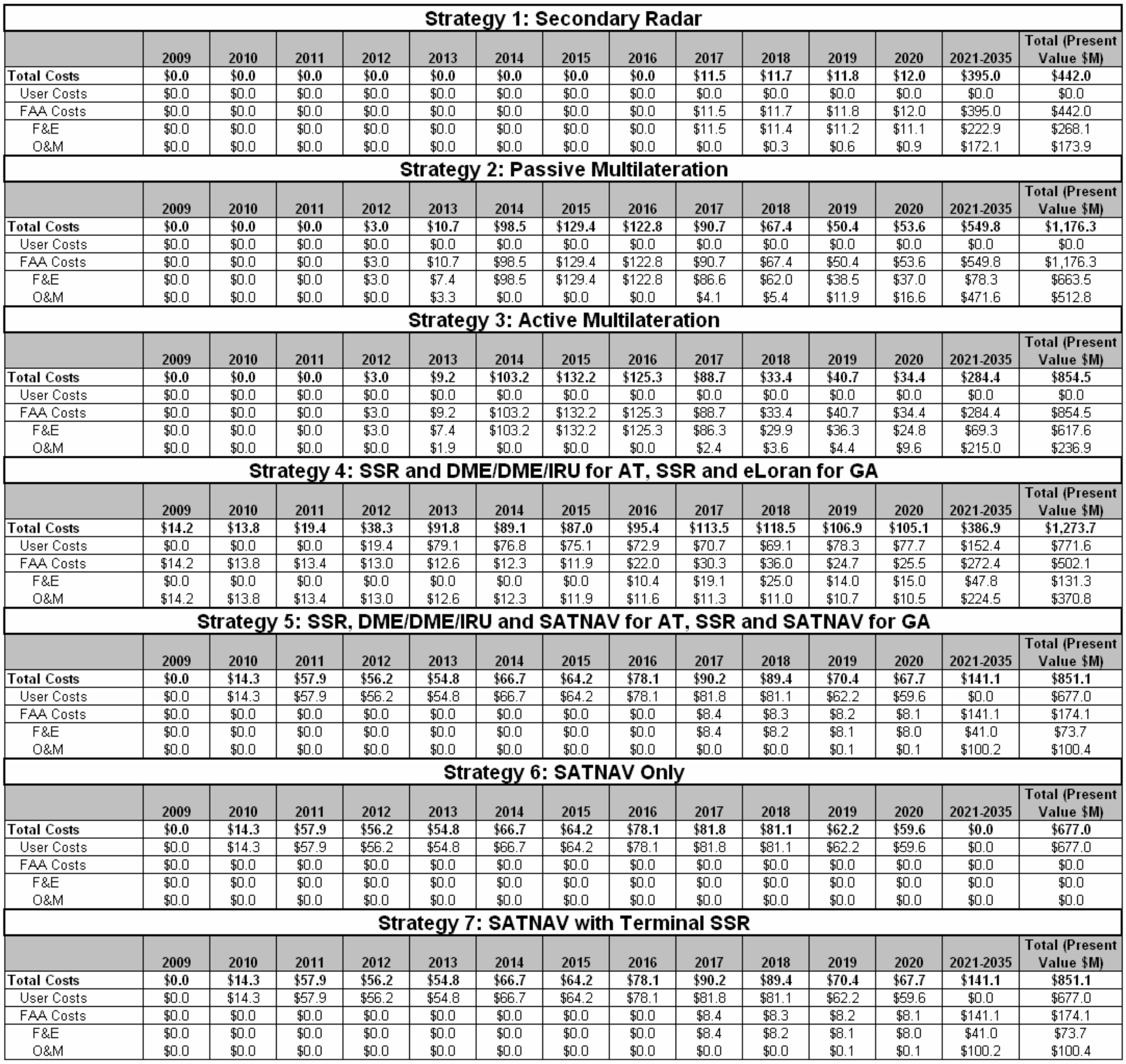
As can be seen from these results, it may be possible for the ranking of the highest-scoring strategy to change, but a significant change in weighting factors would be required to elicit such a change. The most likely scenario in which this may occur would be if the importance of Operational Capability and Coverage grew such that it's weighting factor increased by at least 43%. Increased importance of Flexibility/Agility could also elicit a change, but only with a much greater percentage increase (97%). This shows that the scoring results are not excessively influenced by small changes to any one metric's weight. However, should some of the basic assumptions change over time, these results could be affected, and would need to be revisited.

8. Cost Assessment

8.1 Life Cycle Costs

Life cycle cost estimates were developed for each backup strategy. The costs imposed by each strategy (above and beyond what would be required to support ADS-B surveillance alone) were estimated starting in FY2009 and ending in FY2035. The costs associated with each strategy are shown in Table 8-1, presented in Present Value by applying OMB circular No a94, using a discount rate of 2.9%. All costs shown are point estimates, and have not been risk adjusted. The basis for these cost estimates are presented in Appendix B.

Table 8-1: Life Cycle Cost Summary



Strategy 1: Secondary Radar

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**$11.5**	**$11.7**	**$11.8**	**$12.0**	**$395.0**	**$442.0**
User Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
FAA Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$11.5	$11.7	$11.8	$12.0	$395.0	$442.0
F&E	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$11.5	$11.4	$11.2	$11.1	$222.9	$268.1
O&M	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.3	$0.6	$0.9	$172.1	$173.9

Strategy 2: Passive Multilateration

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$0.0**	**$0.0**	**$3.0**	**$10.7**	**$98.5**	**$129.4**	**$122.8**	**$90.7**	**$67.4**	**$50.4**	**$53.6**	**$549.8**	**$1,176.3**
User Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
FAA Costs	$0.0	$0.0	$0.0	$3.0	$10.7	$98.5	$129.4	$122.8	$90.7	$67.4	$50.4	$53.6	$549.8	$1,176.3
F&E	$0.0	$0.0	$0.0	$3.0	$7.4	$98.5	$129.4	$122.8	$86.6	$62.0	$38.5	$37.0	$78.3	$663.5
O&M	$0.0	$0.0	$0.0	$0.0	$3.3	$0.0	$0.0	$0.0	$4.1	$5.4	$11.9	$16.6	$471.6	$512.8

Strategy 3: Active Multilateration

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$0.0**	**$0.0**	**$3.0**	**$9.2**	**$103.2**	**$132.2**	**$125.3**	**$88.7**	**$33.4**	**$40.7**	**$34.4**	**$284.4**	**$854.5**
User Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
FAA Costs	$0.0	$0.0	$0.0	$3.0	$9.2	$103.2	$132.2	$125.3	$88.7	$33.4	$40.7	$34.4	$284.4	$854.5
F&E	$0.0	$0.0	$0.0	$3.0	$7.4	$103.2	$132.2	$125.3	$86.3	$29.9	$36.3	$24.8	$69.3	$617.6
O&M	$0.0	$0.0	$0.0	$0.0	$1.9	$0.0	$0.0	$0.0	$2.4	$3.6	$4.4	$9.6	$215.0	$236.9

Strategy 4: SSR and DME/DME/IRU for AT, SSR and eLoran for GA

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$14.2**	**$13.8**	**$19.4**	**$38.3**	**$91.8**	**$89.1**	**$87.0**	**$95.4**	**$113.5**	**$118.5**	**$106.9**	**$105.1**	**$386.9**	**$1,273.7**
User Costs	$0.0	$0.0	$0.0	$19.4	$79.1	$76.8	$75.1	$72.9	$70.7	$69.1	$78.3	$77.7	$152.4	$771.6
FAA Costs	$14.2	$13.8	$13.4	$13.0	$12.6	$12.3	$11.9	$22.0	$30.3	$36.0	$24.7	$25.5	$272.4	$502.1
F&E	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$10.4	$19.1	$25.0	$14.0	$15.0	$47.8	$131.3
O&M	$14.2	$13.8	$13.4	$13.0	$12.6	$12.3	$11.9	$11.6	$11.3	$11.0	$10.7	$10.5	$224.5	$370.8

Strategy 5: SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$14.3**	**$57.9**	**$56.2**	**$54.8**	**$66.7**	**$64.2**	**$78.1**	**$90.2**	**$89.4**	**$70.4**	**$67.7**	**$141.1**	**$851.1**
User Costs	$0.0	$14.3	$57.9	$56.2	$54.8	$66.7	$64.2	$78.1	$81.8	$81.1	$62.2	$59.6	$0.0	$677.0
FAA Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$8.4	$8.3	$8.2	$8.1	$141.1	$174.1
F&E	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$8.4	$8.2	$8.1	$8.0	$41.0	$73.7
O&M	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.1	$0.1	$100.2	$100.4

Strategy 6: SATNAV Only

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$14.3**	**$57.9**	**$56.2**	**$54.8**	**$66.7**	**$64.2**	**$78.1**	**$81.8**	**$81.1**	**$62.2**	**$59.6**	**$0.0**	**$677.0**
User Costs	$0.0	$14.3	$57.9	$56.2	$54.8	$66.7	$64.2	$78.1	$81.8	$81.1	$62.2	$59.6	$0.0	$677.0
FAA Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
F&E	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
O&M	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0

Strategy 7: SATNAV with Terminal SSR

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$14.3**	**$57.9**	**$56.2**	**$54.8**	**$66.7**	**$64.2**	**$78.1**	**$90.2**	**$89.4**	**$70.4**	**$67.7**	**$141.1**	**$851.1**
User Costs	$0.0	$14.3	$57.9	$56.2	$54.8	$66.7	$64.2	$78.1	$81.8	$81.1	$62.2	$59.6	$0.0	$677.0
FAA Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$8.4	$8.3	$8.2	$8.1	$141.1	$174.1
F&E	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$8.4	$8.2	$8.1	$8.0	$41.0	$73.7
O&M	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.1	$0.1	$100.2	$100.4

8.2 Cost as an Independent Variable (CAIV) Analysis

The cost estimates presented above were combined with the associated performance scores for each strategy to assess overall cost effectiveness. The results of this Cost as an Independent Variable (CAIV) analysis are shown in Figure 8-1. Based on these results, Strategy 1: Secondary Radar stands out as having the greatest cost effectiveness (performance vs. cost) compared to the other strategies.

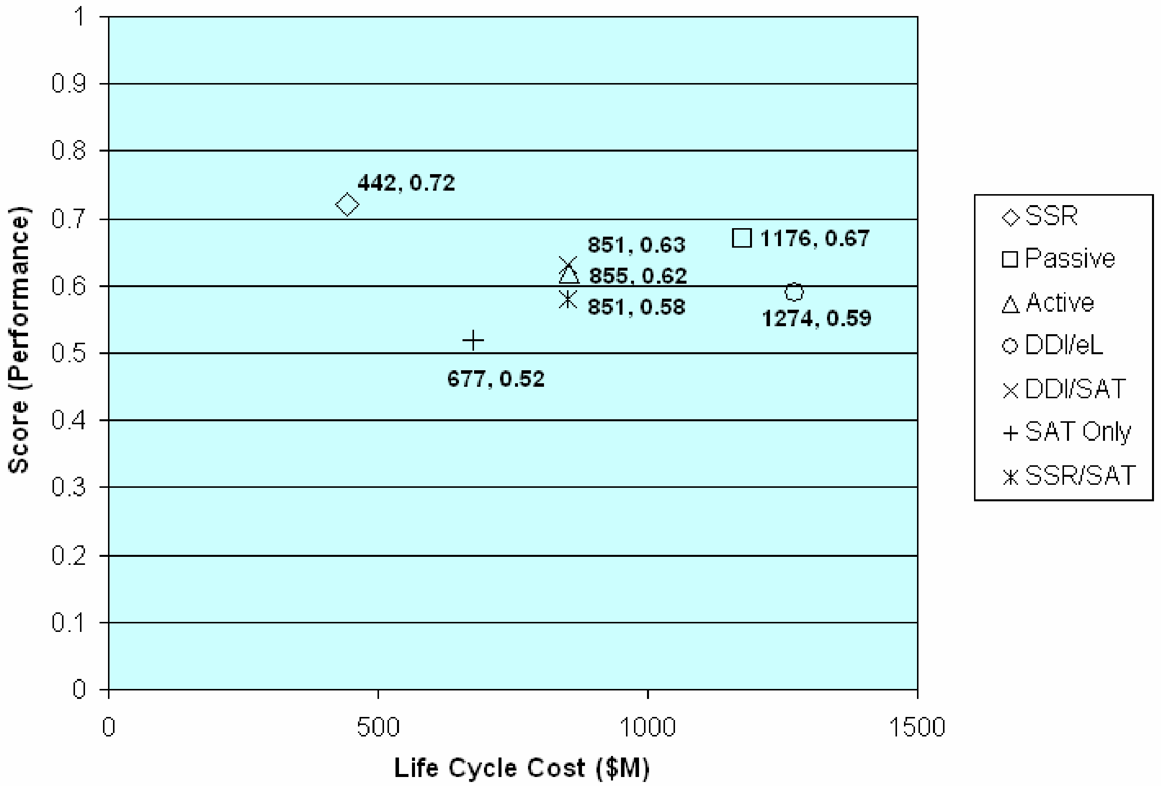


Figure 8-1: Cost as an Independent Variable (CAIV) Analysis Results

9. Comparative Safety Assessment

A Comparative Safety Assessment (CSA) was prepared to identify and characterize the safety risks associated with each backup strategy alternative. Only ATC Surveillance application hazards were evaluated in the CSA, since the purpose of the backup strategy is to maintain ATC Surveillance in the event of a GNSS failure. No new hazards were evaluated for any strategy, though a hazard for loss of aircraft navigation should be considered in a future analysis. The following ATC Surveillance hazards were evaluated:

- H1: Loss of ATC Surveillance (All Aircraft)
- H2: Loss of Surveillance (Single Aircraft)
- H17: Loss of Surveillance (Multiple Aircraft)

The SBS Preliminary Hazard Analysis (PHA) also addressed hazards associated with inaccurate position, altitude, and identification. The backup strategies were configured with appropriate technology to ensure that the required accuracy was met; therefore, hazards that dealt with inaccurate position would not function as a discriminator in comparing the alternatives and was not evaluated. The source for altitude and identification data was not affected by any of the backup strategies, so the SBS PHA already aptly addressed hazards associated with inaccurate altitude or identification. While the hazards evaluated in this CSA are similar to those addressed in the SBS PHA, the system states varied slightly. Therefore, the assessed risk levels from the CSA should not be compared to those assessed in the SBS PHA, as it would not be an equivalent comparison. To determine if the backup strategy provides any mitigating controls for the SBS system hazards, a more detailed analysis will be done on the SBS system, including the selected backup strategy.

A multi-step process was employed to determine the risk associated with each strategy-hazard combination. First, functional flow block diagrams were developed for each backup strategy alternative based on the draft technical descriptions. These block diagrams were used to identify potential faults or failure modes for each backup strategy that could cause a hazard. Fault trees were prepared using the functional flow block diagrams and technical descriptions of each strategy. Each fault tree represents the SBS system and backup strategy faults that, if present in a certain combination, result in a hazard. Individual faults were assigned a likelihood of occurrence derived from requirements documentation, technical description information, engineering judgment, or a combination thereof. Fault tree analysis software was used to calculate the probability of the top-level fault occurring (i.e., the hazard). Next, event trees were developed for each hazard to represent the possible system state variables, actions subsequent to the hazard, and resultant range of hazard effects. Probabilities associated with certain system state variables were also modified from the original event trees. Effects and severities were assigned to each path (i.e., set of branches) in the event trees, and likelihoods for each path were calculated. For each event tree path, the combined likelihood of the hazard occurring and that particular path was calculated. Worst case risk was determined by comparing the total likelihood and severity pairs, and selecting the maximum resultant risk.

The worst, credible outcome for each of the hazards was a significant increase in ATC workload, which is classified as a “Minor” (4) severity. While higher severity outcomes were addressed, the likelihood of occurrence for those scenarios was often several orders of magnitude below “Extremely Improbable,” and thereby deemed not credible. The likelihood for the loss of surveillance for all aircraft (H1) did not vary with the differing strategies, as the failures of automation and power were the primary drivers for the hazard. The likelihood for the loss of surveillance for a single aircraft (H2) is primarily driven by avionics failures. For the analysis, it was assumed that the probability of failures of ADS-B avionics, DME/DME/IRU avionics, and Mode A/C/S transponders were equivalent. The likelihoods varied from “Remote” (C) to “Frequent” (A) for the risks of losing surveillance for multiple aircraft (H17). The likelihood for hazard H17 was driven by the probability of detection for SSR and Multilateration and ground station faults for the navigation driven alternatives. The systems that were employed for each alternative depended on the type of airspace. The hazards were evaluated separately for terminal and en route airspace. Then the maximum resultant risk was assigned to that hazard. For hazards H2 and H17, the en route airspace resulted in the maximum risk, primarily due to en route Primary Surveillance Radar not being used for ATC surveillance.

Additional hazards were identified by the team, but were determined to be outside the scope of this study. These included the effects of a large number of aircraft losing all navigation capability at the same time as the loss of ATC surveillance. Given the recommended backup alternative of SSR, ATC surveillance retains significant independence from the ADS-B positioning source so this hazard is not considered to be significant. The loss of navigation and surveillance in the low-density airspace outside the coverage of the SSR backup systems will be addressed within the SBS program safety analysis, and does not impact selection of the backup alternative. If the selected alternative had been Strategy 6 (SATNAV Only) or Strategy 7 (SATNAV with Terminal SSR), closer examination of this issue would have been required.

The chart and table below provide a summary of the risk assessed for each backup strategy per hazard. Each alternative had acceptable levels of risk (zero high-level risks). Further safety analyses will be performed on the SBS system once the backup strategy is selected. Details of this comparative safety assessment can be found in Appendix C.

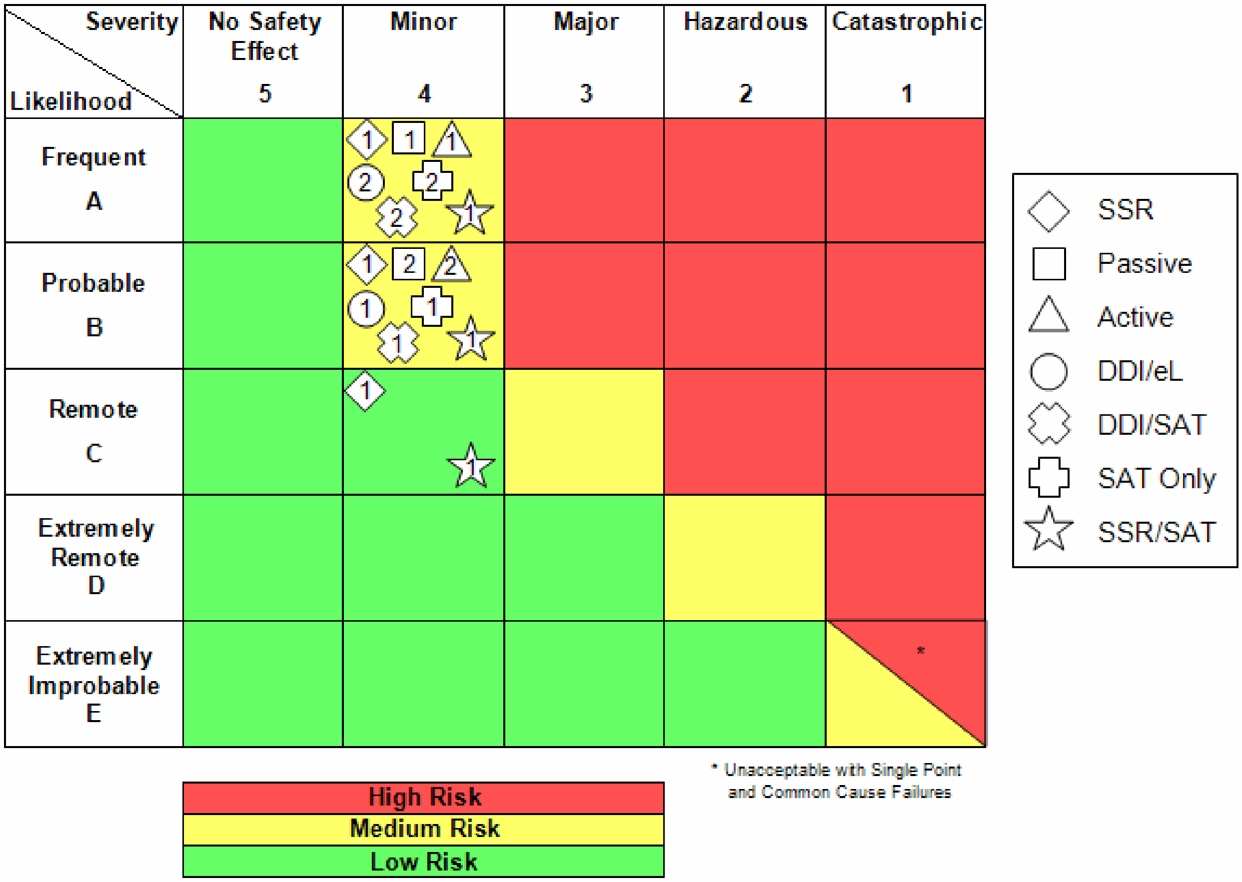


Figure 9-1: Risk Assessment Matrix for Backup Strategies

Table 9-1: Risk by Hazard and Strategy

No.	**Hazard**	**1: SSR**	**2: Passive ML**	**3: Active ML**	**4: SSR, DDI & eLoran**	**5: SSR, DDI & SATNAV**	**6: SATNAV Only**	**7: SATNAV & SSR**
H1	Loss of ATC Surveillance (All Aircraft)	4B (Med)	4B (Med)	4B (Med)	4B (Med)	4B (Med)	4B (Med)	4B (Med)
H2	Loss of Surveillance (Single Aircraft)	4A (Med)	4A (Med)	4A (Med)	4A (Med)	4A (Med)	4A (Med)	4A (Med)
H17	Loss of Surveillance (Multiple Aircraft)	4C (Low)	4B (Med)	4B (Med)	4A (Med)	4A (Med)	4A (Med)	4C (Low)

10. Recommendations

The technical team recommends that the FAA adopt the Secondary Radar backup strategy:

- The FAA should retain a reduced secondary radar network to cover the required airspace in the event of a GPS outage, and use primary radar to mitigate single-aircraft avionics failures
- This strategy will require retaining approximately 40 terminal SSRs and 150 en route SSRs beyond 2020, approximately one-half the quantity in use today
- No additional equipage will be required for any aircraft as a result of implementing this strategy
- This strategy is assessed as having the highest performance ranking and lowest life cycle cost among those evaluated

Changes in the evaluation assumptions used in this report over time could significantly affect the results. Therefore, the team further recommends that the ADS-B backup strategy be reassessed to reflect further ADS-B operational experience and emerging requirements prior to the FAA's commitment to radar investments beyond 2020.

Appendix A - Detailed Technical Descriptions

A1. Strategy 1: Secondary Radar

A1.1 Overview

Strategy 1: Secondary Radar consists of maintaining a reduced network of SSRs to serve as a backup to ADS-B surveillance capabilities. In this strategy, secondary radar services will be provided in high density terminal airspace (surrounding approximately the top 40 airports in terms of capacity), all en route airspace above 18,000 feet above MSL, and medium density terminal airspace above certain altitudes, as determined by proximate en route SSR coverage (identical to today's CENRAP coverage). Primary radar services will be retained in all terminal areas covered by primary radar today (approximately 200 locations), to serve as the means of mitigating single-aircraft avionics failures. No new avionics will be required to support this strategy; legacy transponders (Mode A/C/S) will continue to be required to support secondary radar surveillance.

A1.2 Architecture

The proposed architecture shown in Figure A1-1 below consists of SSRs, PSRs, Legacy Transponders (Mode A/C/S), and interfaces with existing automation systems.

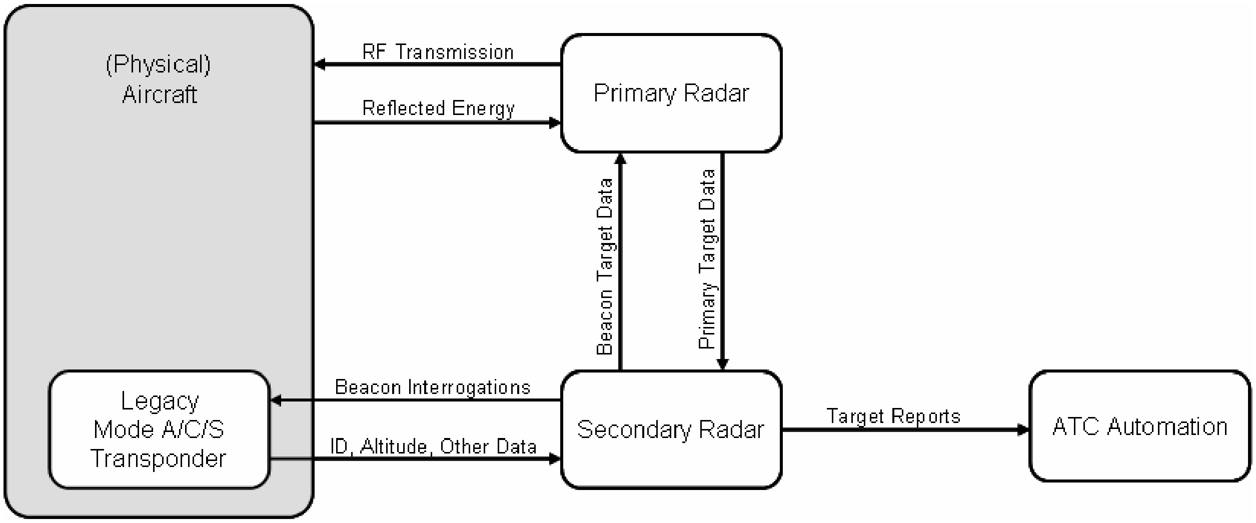


Figure A1-1: Secondary Radar Strategy High-Level Block Diagram

A1.2.1 Components

Secondary Surveillance Radar

An SSR is a cooperative surveillance system, where the determination of aircraft position is based on the SSR's interrogation of transponders on the aircraft; in other words, surveillance requires the "cooperation" of both aircraft and ground systems. Aircraft equipped with legacy transponders (Mode A, Mode C, or Mode S) are interrogated by the SSR to elicit beacon code and altitude information for each aircraft. The SSR processes the replies from the aircraft transponder to determine slant range, based on time of reply receipt, and azimuth based on antenna position at the time the reply is received. The SSR also correlates the identification and altitude information embedded in the replies with the position estimate to generate a target report for the aircraft. Target reports are sent via ground communication lines to the ATC automation system for tracking, correlation to flight plans (when available), and display to controllers.

The proposed backup architecture for this strategy will require the continuation of SSR services at all current en route and at high density terminal locations beyond 2020. Specifically, the architecture will require the retention of the approximately 150 SSRs that provide secondary surveillance from en route SSR locations, which currently consist of a mix of Air Traffic Control Beacon Interrogator Model 6 (ATCBI-6) and Mode Select (Mode S) systems, and the retention of approximately 40 terminal SSRs that provide secondary surveillance in high density terminal airspace, which currently consist of Mode S systems only.

Primary Surveillance Radar

A PSR is an independent surveillance system, where the determination of aircraft position is based on the reflected radio-frequency (RF) energy from aircraft, "independent" of any system on the aircraft. The PSR sends out a pulsed RF signal that reflects off of an aircraft within the coverage volume of the radar. A portion of this reflected energy returns to the PSR antenna, where it is detected and processed to determine the aircraft's slant range and azimuth. As with the SSR, the information is used to generate a target report, which is sent via ground communication lines to the ATC automation system for tracking and display. When the PSR is co-located with an SSR, target correlation may be performed at the radar site prior to target report generation to enhance the reliability or confidence of the report before it is sent to the automation system.

The proposed backup architecture for this strategy (and for all backup strategies in this report) will require the continuation of PSR services beyond 2020 for all terminal areas covered by primary radar today. Specifically, the architecture will require the retention of the approximately 200 terminal PSRs that provide primary surveillance in terminal airspace today, which currently consist of a mix of Airport Surveillance Radar Model 9 (ASR-9), ASR-7/8, and ASR-11 systems.

Legacy Transponders

A transponder is an avionics system that responds to interrogations from ground-based SSRs with replies containing aircraft identification, altitude, and other selected data. Transponders in use today (i.e., "legacy") consist of Mode A, Mode C, and Mode S varieties. Mode A transponders provide a 12-bit code (not necessarily unique) that identifies the aircraft; Mode C transponders also provide this information, along with the aircraft's barometric altitude. Mode S transponders offer improvements over Mode A and Mode C transponders in that they use 24-bit unique aircraft identity codes, and can be selectively interrogated to prevent overlapping or garbled replies from proximate aircraft, improving detection and flight data correlation performance.

The proposed backup architecture for this strategy requires the continued use of existing Mode A, Mode C, or Mode S transponders on board aircraft within the coverage volume of the ground-based SSR network. No new or modified avionics will be required, and no changes to existing transponder carriage requirements will be implemented.

A1.2.2 System Performance

The performance of key components of the proposed backup architecture for this strategy is shown in Table A1-1. These values are based on the Mode S (SSR) and ASR-9 (PSR) performance as specified in NAS-SS-1000.

Table A1-1: Strategy 1 System Performance (Components)

System / Parameter	En Route SSR	Terminal SSR	Terminal PSR
Coverage	Range: 0 - 250 nmi Azimuth:0 - 360°	Range: 0 - 60 nmi Azimuth:0 - 360°	Range: 0.5 - 60 nmi Azimuth:0 - 360°
Positional Accuracy (RMS)	± 4370 ft @ 250 nmi (0.72 nmi)	± 1050 ft @ 60 nmi (0.17 nmi)	± 1020 ft @ 60 nmi (0.17 nmi)
Update Rate	~ 12 sec	~ 4.8 sec	~ 4.8 sec
Availability	≥ 0.9999578	≥ 0.9999578	≥ 0.99984

The SSR coverage volume for this strategy is depicted at representative altitudes by Figures A1-2 through A1-4.

A1.3 Operational Environment

The performance of secondary radar allows it to support current operations within terminal and en route airspace today. There would be a moderate impact on current operations if surveillance transitioned from ADS-B to secondary radar, due to the reduced separations that would be supported in many terminal areas in backup mode. There may also be some additional workload

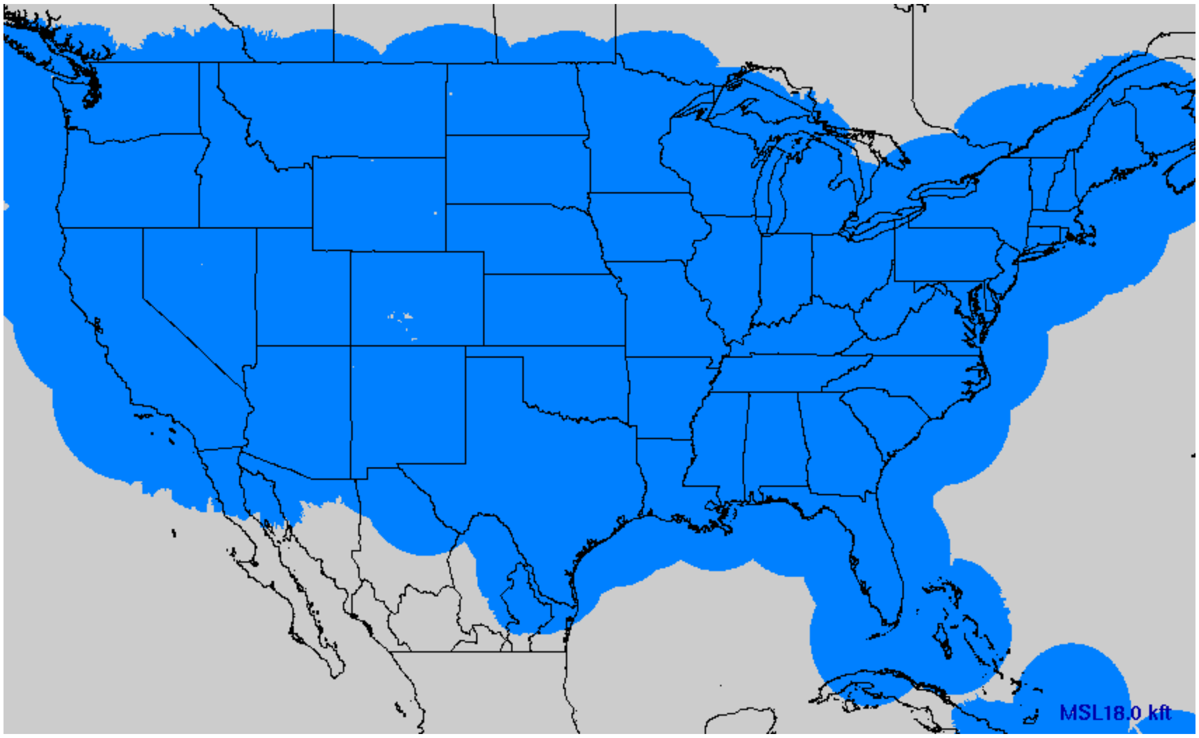


Figure A1-2: SSR backup surveillance coverage at 18,000 feet MSL

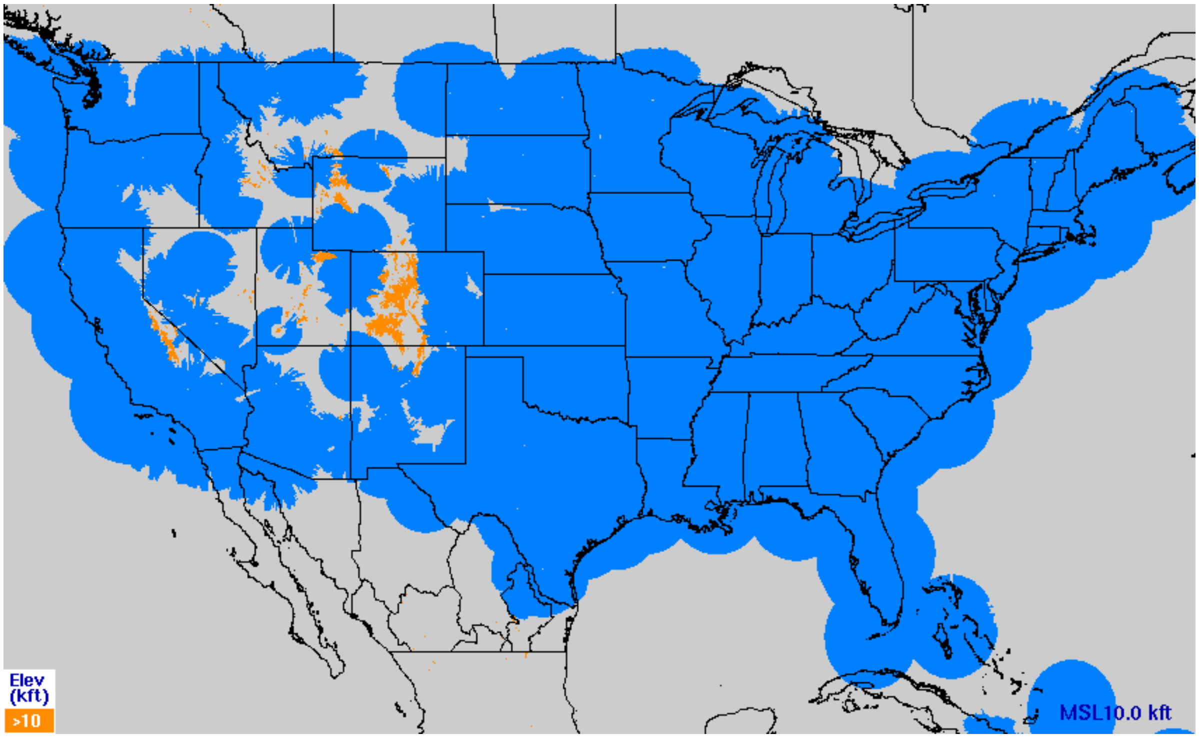


Figure A1-3: SSR backup surveillance coverage at 10,000 feet MSL

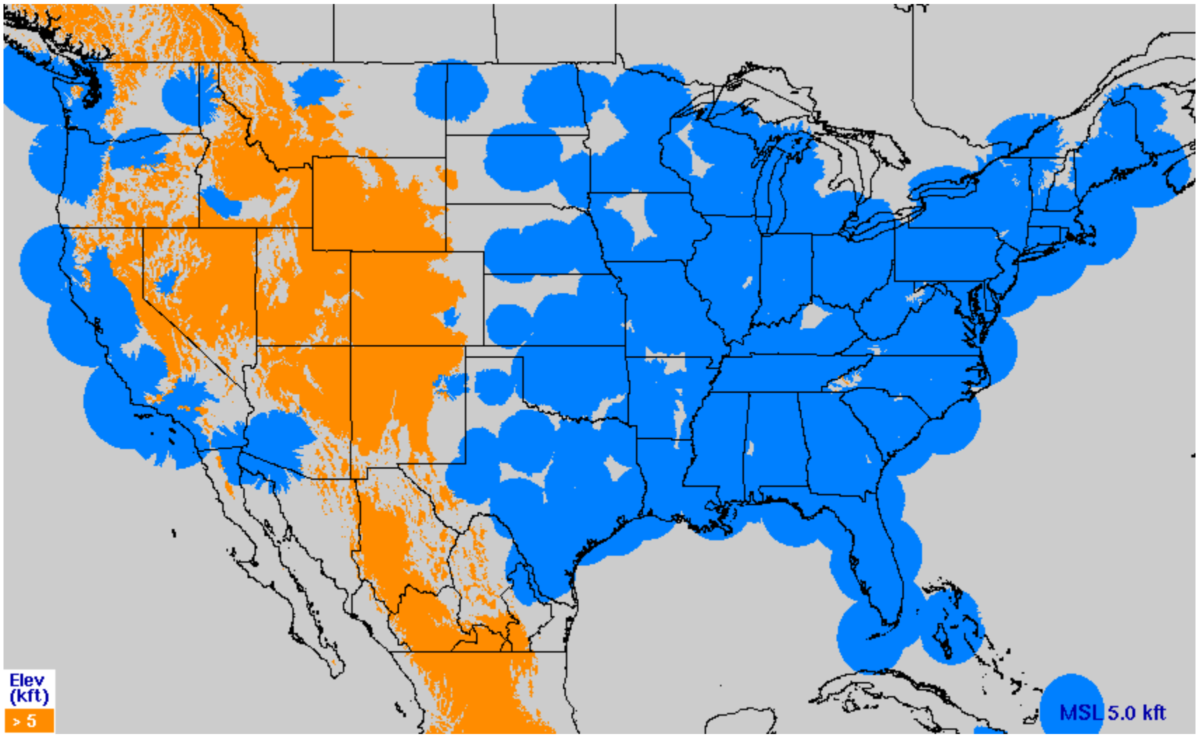


Figure A1-4: SSR backup surveillance coverage at 5,000 feet MSL

required to transition aircraft using certain ADS-B air-to-air applications, as these may not be supportable using secondary radar and TIS-B alone.

In addition to the ATC Surveillance application, secondary radar can also support the Enhanced Visual Acquisition application. The surveillance architecture may uplink, through TIS-B, the aircraft positions of all aircraft in view. Depending on the required performance, the TIS-B uplink data determined using secondary radar could also support a minimal navigation capability in the aircraft.

Secondary radar can also provide an independent means of validation of ADS-B position reports. ADS-B report accuracy and integrity can be validated through comparison to secondary radar positions for an aircraft.

Terminal secondary radars could be used to support short-term extensions of terminal services. However, providing additional coverage would require a siting analysis to determine optimum radar position and the installation of required equipment and shelters.

A1.4 Implementation Status

Secondary radar relies on legacy transponder avionics, and therefore requires no changes in current aircraft equipage. No additional rulemaking is required to implement this strategy.

This strategy will leverage existing secondary radar installations in en route and high density terminal areas as the basis for providing future secondary radar backup services. Currently fielded SSRs that would be carried forward as part of this strategy include the ATCBI-6 and Mode S beacon systems. Replacement of these systems will occur at the end of their respective life cycles, if required, to meet service life requirements through 2035.

Currently fielded PSRs in terminal areas would also be carried forward as part of this and all other strategies. As with the secondary radars, replacement of these systems will also occur at the end of their respective life cycles, if required, to meet service life requirements through 2035.

Secondary radar is the international standard for basic surveillance services, and has been certified for use by international air traffic service providers. No additional equipage will be imposed on incoming aircraft as long as they are equipped a Mode A, Mode C, or Mode S transponder. Currently there are no outstanding technical issues or programmatic dependencies related to the use of secondary radar for backup surveillance.

A2. Strategy 2: Passive Multilateration

A2.1 Overview

Passive Multilateration consists of clusters of multilateration ground stations that will provide airspace coverage equivalent to the coverage provided by current en route and terminal radar systems. The passive multilateration strategy does not interrogate the aircraft avionics so no transmission license is required for the installation and use of the system and there is no increase in the number of interrogations or replies caused by the system.

This strategy will utilize signals periodically broadcast from aircraft equipped with ADS-B avionics (1090-ES and UAT). The geographically distributed ground stations will receive the broadcast signals and measure the time-of-arrival (TOA) of the same broadcast message and forward the information to a central processing station.

The aircraft position is determined by joint processing of the time difference of arrival (TDOA) measurements computed between a reference and the ground stations' measured TOA by a centralized target processor. Receipt of a message at three synchronized ground stations within an update interval is sufficient to determine the horizontal position of an aircraft.

Aircraft identity and barometric altitude are determined by decoding the information contained within the ADS-B messages. The central target processor generates target reports based on the received information and forwards the target report to terminal and en-route automation systems for further processing and display.

A2.2 System Architecture

Multilateration is a distributed surveillance technology that utilizes a constellation of ground stations to provide surveillance coverage within a defined region. This technology makes use of signals transmitted by an aircraft to calculate the aircraft's position. A depiction of the passive multilateration architecture is shown in Figure A2-1. The system consists of the following components; ground stations, a target processor, a Remote Monitoring Subsystem (RMS), and a communication infrastructure.

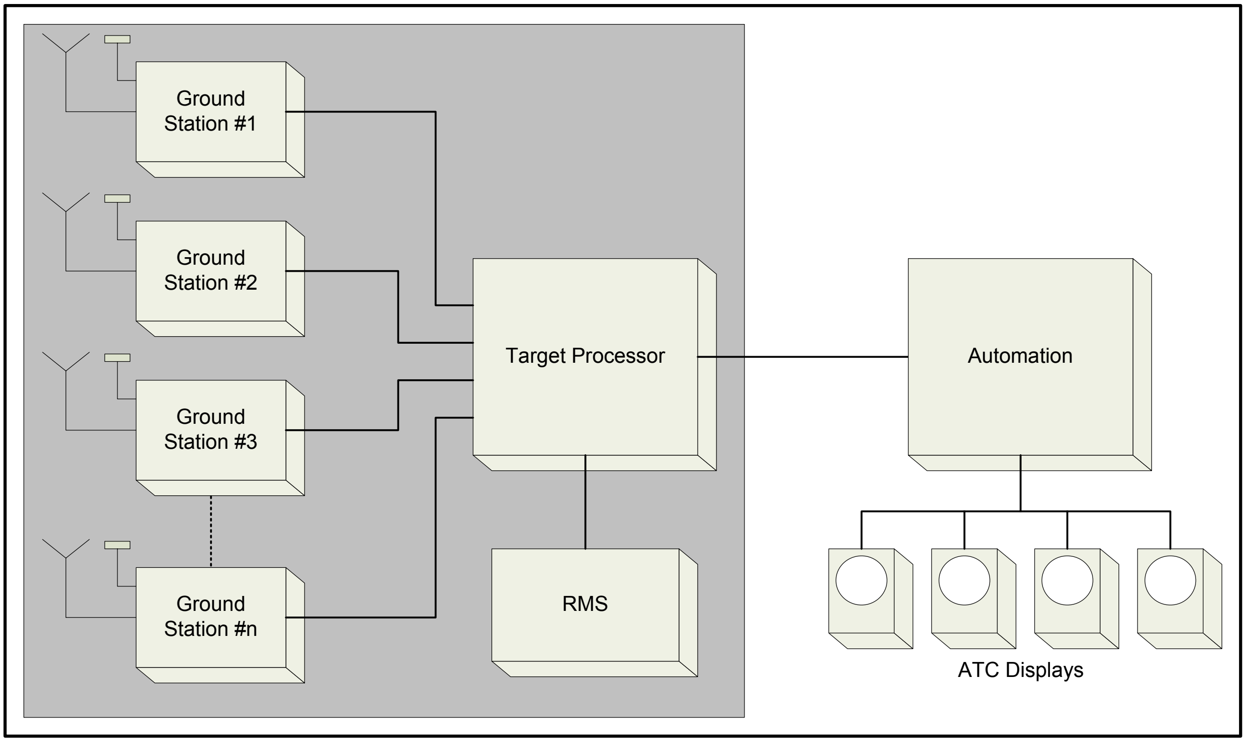


Figure A2-1: Passive Multilateration System Block Diagram

A2.2.1 Components

<u>Ground Stations</u>

Receive-only ground stations receive the 1090 ES and UAT signals periodically broadcast from aircraft equipped with ADS-B avionics. The ground station decodes the signals, timestamps them and sends the target signals to the target processor via the communications infrastructure for further processing.

Each ground station utilizes two antennas. The first antenna is connected to the receiver contained within the ground station and is used for reception of the 1090ES and UAT squitters. This antenna can be either omni-directional or sectorized depending on the location of the ground station with reference to the defined coverage volume. The second antenna is connected to a LORAN-C timing receiver contained within the ground station. The LORAN-C signal is used as the timing source to synchronize the clock at each ground station. A GPS time source may be used as the primary timing source, but is not assumed in this backup due to the potential of interference to GPS or degradation of the constellation.

The ground stations feature ruggedized, weatherproof enclosures designed for harsh environments. The enclosures are relatively small units that can easily be mounted within existing facilities or externally placed on a pad at an undeveloped site.

Target Processor

The target processor is the central computer that collects transponder information from all ground stations. The target processor uses the received information and calculates a target positions. The target processor develops target tracks based on position and identification information and outputs the track data to automation systems. The target processor also monitors the status and health of all multilateration components.

Remote Monitoring Subsystem

The RMS provides all of the necessary software tools and programs to allow the user to optimize, control, and monitor the entire system. The RMS provides the human machine interface to the system.

Communications Infrastructure

The communications infrastructure is used to communicate target signals from the ground stations to the target processor. The system is designed with flexible data communication interfaces. Data may be transmitted from the ground stations to the target processor over wired or wireless serial data modems, an Ethernet Local Area Network (LAN), or a combination of these data links.

A2.2.2 System Performance

Multilateration systems are currently being fielded as part of the Airport Surface Detection Equipment Model X (ASDE-X) program to provide surface coverage of airport movement areas. Multilateration has not been formally certified in the U.S. to conduct air surveillance in terminal or En Route airspace, however formal demonstrations by the FAA and other Government agencies have proven that this technology is feasible for air surveillance and that its performance can surpass that of current terminal and en route radar systems.

Coverage

The distributed architecture of multilateration permits optimized coverage design through careful selection of ground station locations in the desired coverage region. Ground station constellations would be centered on designated airports for terminal area coverage and on current long range radar locations for en route coverage. The position of the ground stations would be selected so that the coverage provided by the constellation would be equal to or better than the existing operational en route and terminal SSR coverage. Approximately 7 ground stations will be fielded to emulate each terminal radar and approximately 10 ground stations will be fielded to emulate each en route radar. These clusters will provide coverage in high density terminal airspace (surrounding approximately 40 airports in terms of capacity), all en route airspace above

18,000 feet above MSL, and medium density terminal airspace above certain altitudes, as determined by proximate en route SSR coverage (identical to today's CENRAP coverage).

<u>Positional Accuracy</u>

Operational wide area multilateration systems and demonstration systems have shown that horizontal position accuracy of 180ft (95th percentile) or better can be achieved with multilateration. The positional accuracy of multilateration supports current standard operations in terminal and en route airspace and exceeds the performance of current terminal and en route radars.

<u>Update Rate</u>

Operational wide area multilateration systems and demonstration systems have shown that a 99-percent update interval of 2 seconds is achievable with multilateration.

<u>Availability</u>

Currently fielded multilateration systems utilized for airport surface detection are required to provide a minimum system availability of at least 0.9997. ASDE-X operational data indicates that the fielded equipment has exceeded this requirement.

A2.3 Operational Environment

The performance of multilateration allows it to support current operations within terminal and en-route airspace today. There would be moderate impact on operations if surveillance were transitioned from ADS-B to multilateration, due to the reduced separations that would be supported in many terminal areas with ADS-B. There may also be some additional workload required to transition aircraft using certain ADS-B air-to-air applications, as these may not be supportable using multilateration and TIS-B alone. Depending on the required performance, the TIS-B uplink data determined using passive multilateration could also support a minimal navigation capability in the aircraft.

In addition to the ATC Surveillance application, multilateration can also support the Enhanced Visual Acquisition application. The multilateration surveillance backup may uplink, through TIS-B, the aircraft positions of all aircraft in view. Depending on the required performance, the TIS-B uplink data determined using passive multilateration could also support a minimal navigation capability in the aircraft.

Multilateration can provide an independent means of validation of ADS-B position reports. ADS-B report accuracy and integrity can be validated through comparison to multilateration derived positions for an aircraft. Multilateration could also be used for spoofing detection. The system could be used to identify real aircraft position reports and the source of spoof transmissions.

Multilateration could be used to support short-term extensions of terminal services. The distributed architecture of multilateration provides for a somewhat more flexible siting solution than for a terminal radar sensor. However, providing additional coverage would require a siting analysis to determine optimum ground station position and the installation of the additional ground stations.

A2.4 Implementation Status

The passive multilateration strategy is dependent on compliance with the upcoming ADS-B equipage rules. No additional rulemaking is required to implement this strategy.

Multilateration ground stations will need to be fielded at multiple locations across the United States. The ground station enclosures are relatively small units that can easily be mounted within existing facilities. The intent will be to utilize existing FAA equipment sites for ground station placement. For undeveloped ground station locations a small plot of land (roughly 400 square feet) will be required for the ground station and associated antenna mast. Power and communications will need to be brought to these locations. The equipment being fielded for ADS-B surveillance functions can also be utilized for the backup multilateration system. The same message generated by the ground station for ADS-B can be utilized by multilateration.

Air surveillance with multilateration has been certified for use by international air traffic service providers. Multilateration systems are currently being implemented in other parts of the world including Europe, Australia, and the Far East. It is envisioned that no additional equipage will be imposed on incoming aircraft as long as they are equipped with ADS-B avionics.

Technical Issues

Multilateration is currently used in the NAS for surface surveillance of aircraft equipped with 1090 transponders that also incorporate 1090-ES transmit capability. However, multilateration of aircraft of equipped with UAT ADS-B avionics has not been validated. Multilateration has not been formally approved in the United States to conduct air surveillance in terminal or en route airspace. Formal demonstrations by the FAA and other Government agencies have proven that this technology is feasible for air surveillance. In addition, air surveillance with multilateration is certified for use by international air traffic service providers. The absence of the certification in the United States is primarily due to the lack of a defined need for distributed surveillance. With a need identified, multilateration can be readily certified for air surveillance.

Multilateration requires at least three sensors to see an aircraft in order to unambiguously determine the aircraft's position. The need for multiple ground stations to see the aircraft will increase the required number of ground stations in relation to other ground based surveillance strategies.

The current multilateration system (ASDE-X) used in the NAS does not provide a validated interface to current automation systems. However, a demonstration was successfully conducted that employed an All-Purpose Structured Eurocontrol Radar Information Exchange (ASTERIX) to CD-2 format converter to provide the capability to interface with the Host Computer System.

The ASDE-X program is currently implementing an ASTERIX interface to the Standard Terminal Automation Replacement System (STARS).

<u>Programmatic Dependencies</u>

Multilateration surveillance requires a method to synchronize the timing of each ground station to make accurate position measurements. The LORAN-C ground infrastructure is relied upon as the timing source to synchronize the clock at each ground station. GPS timing may be used as the primary source of timing; however it is not relevant for this backup analysis. Other sources of synchronization are available including reference transponders or highly stable clocks, however these alternatives would be more costly to implement.

The implementation schedule duration for installing the required number of ground stations to support the entire NAS is estimated to be 12 years. Implementation could be complete in 2020 if installation started in 2008. There is an estimated schedule uncertainty of about 1 year due to possible site procurement issues including power and communication availability, environmental impacts, and real estate acquisition.

A3. Strategy 3: Active Multilateration

A3.1 Overview

Active Multilateration is a distributed surveillance technology that consists of clusters of multilateration ground stations that will provide airspace coverage equivalent to the coverage provided by current en route and terminal radar systems. This strategy utilizes signals transmitted from legacy transponders (Mode A/C/S) to calculate an aircraft's position. Active multilateration requires no changes in current aircraft equipage. Active multilateration requires the continued carriage of transponders.

Active multilateration transmits interrogations to transponders and utilizes its interrogations for range enhancement processing. With range enhancement processing, target range from the interrogator is measured for each interrogation/reply transaction. This data supplements the TDOA calculations and improves the accuracy outside the boundary of the multilateration constellation. This also increases siting flexibility and reduces the number of ground stations required as compared to passive multilateration.

Active multilateration provides position and identification information on transponder equipped aircraft by multilaterating on signals transmitted by transponders. Multilateration is the process of determining a transponder's location in two (or three) dimensions by solving for the mathematical intersection of multiple hyperbolas (or hyperboloids) based on the TDOA between the transponder's signal receipts at multiple sensors. Receipt of a message at two ground stations and the determination of the round trip propagation time to the interrogating ground station are sufficient to determine the horizontal position of an aircraft.

A3.2 System Architecture

A depiction of the active multilateration architecture is shown in Figure A3-1. The system consists of the following components; ground stations, a target processor, an RMS, and a communication infrastructure.

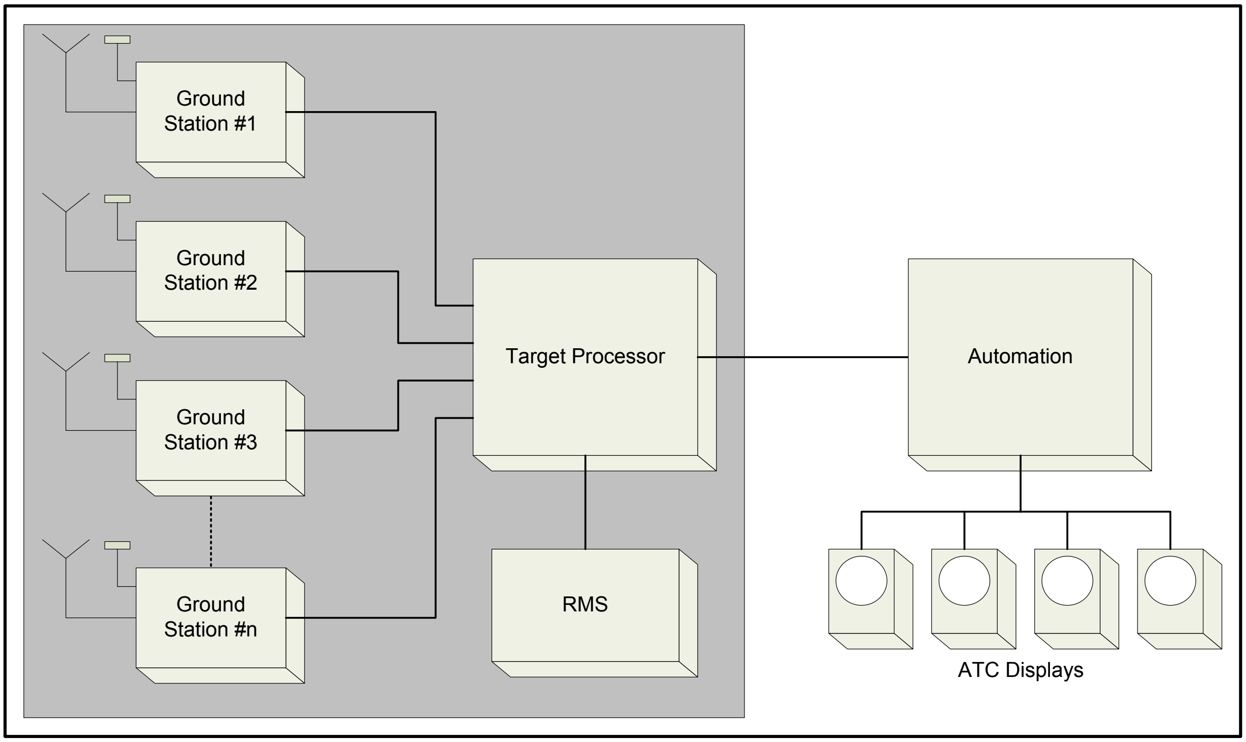


Figure A3-1: Active Multilateration System Block Diagram

A3.2.1 Components

Ground Stations

Active multilateration uses two types of ground stations, Receive/Transmit stations and Receive Only stations. Both types of ground stations receive, timestamp, and decode transponder reply signals. The ground station communicates the target signals to the target processor via the communications infrastructure for further processing. The Receive/Transmit stations also can request information from transponders using scheduled interrogations commanded by the target processor. A variation of the whisper shout technique developed for TCAS is used to interrogate these transponders to limit transponder utilization and to avoid synchronous garble.

Each ground station utilizes two antennas. The first antenna is used for reception of transponder reply signals and for transmission of transponder interrogations. This antenna can be either omni-directional or sectorized depending on the location of the ground station with reference to the defined coverage volume. The second antenna is connected to a LORAN-C timing receiver contained within the ground station. The LORAN-C signal is used as the timing source to synchronize the clock at each ground station. A GPS time source may be used as a primary timing source, but is not assumed in this backup due to the potential of interference to GPS or degradation in the constellation.

Target Processor

The target processor is the central computer that collects transponder information from all ground stations. The target processor uses the received information and calculates a target positions. The target processor develops target tracks based on position and identification information and outputs the track data to automation systems. The target processor also schedules transponder interrogations as required and monitors the status and health of all multilateration components.

Remote Monitoring Subsystem

The RMS provides all of the necessary software tools and programs to allow the user to optimize, control, and monitor the entire system. The RMS provides the human machine interface to the system.

Communications Infrastructure

The communications infrastructure is used to communicate target signals from the ground stations to the target processor. The system is designed with flexible data communication interfaces. Data may be transmitted from the ground stations to the target processor over wired or wireless serial data modems, an Ethernet LAN, or a combination of these data links.

A3.2.2 System Performance

Multilateration systems are currently being fielded as part of the ASDE-X program to provide surface coverage of airport movement areas. Multilateration has not been formally certified in the United States to conduct air surveillance in terminal or En Route airspace, however formal demonstrations by the FAA and other Government agencies have proven that this technology is feasible for air surveillance and that its performance can surpass that of current terminal and En Route radar systems.

Coverage

The distributed architecture of multilateration permits optimized coverage design through careful selection of ground station locations in the desired coverage region. Ground station constellations would be centered on designated airports for terminal area coverage and on current long range radar locations for en route coverage. The position of the ground stations would be selected so that the coverage provided by the constellation would be equal to or better than the existing operational en route and terminal SSR coverage. Approximately 5 ground stations will be fielded to emulate each terminal radar and approximately 6 ground stations will be fielded to emulate each en route radar. These clusters will provide coverage in high density terminal airspace (surrounding approximately 40 airports in terms of capacity), all en route airspace above

18,000 feet above MSL, and medium density terminal airspace above certain altitudes as determined by proximate en route SSR coverage (identical to today's Center Radar ARTS Presentation (CENRAP) coverage).

Positional Accuracy

Operational wide area multilateration systems and demonstration systems have shown that horizontal position accuracy of 180ft (95th percentile) or better can be achieved with multilateration. The positional accuracy of multilateration supports current standard operations in terminal and en route airspace and exceeds the performance of current terminal and en route radars.

Update Rate

Current multilateration systems utilized for surface surveillance and precision runway monitoring applications provide update rates of one second. Operational wide area multilateration systems have shown that a 99-percent update interval of 2 seconds is achievable.

Availability

Currently fielded multilateration systems utilized for airport surface detection are required to provide a minimum system availability of at least 0.9997. ASDE-X operational data indicates that the fielded equipment has exceeded this requirement.

A3.3 Operational Environment

The performance of multilateration allows it to support current operations within terminal and en-route airspace today. There would be moderate impact on operations if surveillance were transitioned from ADS-B to multilateration, due to the reduced separations that would be supported in many terminal areas with ADS-B. There may also be some additional workload required to transition aircraft using certain ADS-B air-to-air applications, as these may not be supportable using multilateration and TIS-B alone. Depending on the required performance, the TIS-B uplink data determined using active multilateration could also support a minimal navigation capability in the aircraft.

In addition to the ATC Surveillance application, multilateration can also support the Enhanced Visual Acquisition application. The multilateration surveillance backup may uplink, through TIS-B, the aircraft positions of all aircraft in view.

Multilateration can provide an independent means of validation of ADS-B position reports. ADS-B report accuracy and integrity can be validated through comparison to multilateration derived positions for an aircraft. Multilateration could also be used for spoofing detection. The system could be used to identify real aircraft position reports and the source of spoof transmissions.

Multilateration could be used to support short-term extensions of terminal services. The distributed architecture of multilateration provides for a somewhat more flexible siting solution than for a terminal radar sensor. However, providing additional coverage would require a siting analysis to determine optimum ground station position and the installation of the additional ground stations. Frequency transmission authorizations would be required if additional transmitting units were installed.

A3.4 Implementation Status

Active multilateration relies on legacy avionics so it requires no changes in current aircraft equipage. No additional rulemaking is required to implement this strategy.

Multilateration ground stations will need to be fielded at multiple locations across the United States. The ground station enclosures are relatively small units that can easily be mounted within existing facilities. The intent will be to utilize existing FAA equipment sites for ground station placement. For undeveloped ground station locations a small plot of land (roughly 400 square feet) will be required for the ground station and associated antenna mast. Power and communications will need to be brought to these locations. The equipment being fielded for ADS-B surveillance functions can also be utilized for the backup multilateration system. The same message generated by the ground station for ADS-B can be utilized by multilateration.

No additional equipage will be imposed on incoming aircraft as long as they are equipped a Mode A/C or Mode S transponder.

<u>Technical Issues</u>

Currently, TCAS and ground-based interrogators compete for transponder time in the NAS. Each system operates within the same frequency band. The ADS-B 1090-ES link also uses this frequency. Introduction of active multilateration may impact the operation of these systems as it also operates within this frequency band. Further analysis is needed to determine if implementing active multilateration in high density terminal areas may negatively impact the 1030/1090 spectrum.

Multilateration is currently used in the NAS for surface surveillance of aircraft equipped with 1090 transponders. Multilateration has not been formally certified in the United States to conduct air surveillance in terminal or en route airspace. Formal demonstrations by the FAA and other Government agencies have proven that this technology is feasible for air surveillance. In addition, air surveillance with multilateration is certified for use by international air traffic service providers. The absence of the certification in the United States is primarily due to the lack of a defined need for distributed surveillance. With a need identified, multilateration can be readily certified for air surveillance.

Multilateration requires at least two sensors to see an aircraft in order to unambiguously determine the targets position. The need for multiple ground stations to see the aircraft will increase the required number of ground stations in relation to other ground based surveillance strategies.

The current multilateration system (ASDE-X) used in the NAS do not provide a validated interface to current automation systems. However, a demonstration was successfully conducted that employed an ASTERIX to CD-2 format converter to provide the capability to interface with the Host Computer System. The ASDE-X program is currently implementing an ASTERIX interface to STARS.

Programmatic Dependencies

Multilateration surveillance requires a method to synchronize the timing of each ground station to make accurate position measurements. The LORAN-C ground infrastructure is relied upon as the timing source to synchronize the clock at each ground station. GPS timing may be used as the primary source of timing; however it is not relevant for this backup analysis. Other sources of synchronization are available including reference transponders or highly stable on board clocks, however these alternatives would be more costly to implement.

The implementation schedule duration for installing the required number of ground stations to support the entire NAS is estimated to be 12 years. Implementation could be complete in 2020 if installation started in 2008. There is an estimated schedule uncertainty of about 1 year due to possible site procurement issues including power and communication availability, environmental impacts, and real estate acquisition.

A4. Strategy 4: SSR and DME/DME/IRU for AT, SSR and eLoran for GA

This strategy combines the capabilities of secondary radar, DME/DME/IRU, and eLoran to provide backup surveillance capabilities for all aircraft in the required airspace. In high density terminal areas, a reduced secondary radar network is retained to maintain terminal area capacity and accuracy requirements for all aircraft. In medium density airspace (both en route and terminal), Air Transport category aircraft will take advantage of DME/DME/IRU avionics and the DME ground infrastructure that will be retained for navigation purposes; General Aviation category aircraft will use eLoran to support backup surveillance in this same airspace. Coverage in medium density terminal areas will be limited for Air Transport aircraft, however, based on DME performance and ground infrastructure limitations. As with Strategy 1, primary radar will be used to mitigate single-aircraft avionics failures in terminal areas.

SSR capabilities for high-density terminal areas are discussed under Strategy 1. DME/DME/IRU and eLoran capabilities are discussed separately in the following sections.

A4.1 DME/DME/IRU

For those aircraft that would equip with DME/DME/IRU capability, this architecture takes advantage of the DME infrastructure and avionics that will be retained for navigation purposes to provide a redundant positioning source for ADS-B in certain regions. The coverage and performance of this independent positioning is limited, and coverage is not provided throughout the current backup surveillance region, as depicted in Strategy 1.

A4.1.1 Architecture

DME/DME area navigation has been in use for several decades, with good experience where DME coverage is provided. In DME/DME positioning, the aircraft uses distance information to multiple ground stations to determine a position solution.

Distance to each DME station is measured through normal DME sensors. The aircraft interrogates the ground station, the ground station replies, and the aircraft sensor measures the round-trip propagation time to determine distance. In order to determine position in WGS-84 coordinates, the aircraft must also have a current database of the locations of all the ground facilities.

The accuracy of the resulting position solution is driven by the accuracy of each of the measured ranges and the relative geometry of the stations. Accuracy of the ground component of DME is specified in FAA and ICAO specifications as 0.1 nmi (95%), and is monitored to tight tolerances around the nominal delay (1 microsecond, or 500 ft). The accuracy of the airborne system is specified in FAA Technical Standard Order (TSO) c66. The current standard (TSO-c66c) requires a 95% accuracy of 0.1 nmi or 0.25% of the distance, whichever is greater. The majority of in-service DME avionics were designed and approved to an earlier standard, but compliance to this accuracy performance has been determined in support of RNAV route implementation (see AC 90-100). Within the U.S., the additional error in the published locations of the DME facilities is negligible provided current data is used. The resulting minimum standard for total range accuracy is:

$$RangeAccuracy95\% = \sqrt{0.1^2 + \left(MAX\left\{0.17, 0.0025D\right\}\right)^2}$$

Some airborne equipment may support a tighter airborne accuracy, of 0.1 nmi (95%) regardless of the distance. During the development of policy for RNAV routes and procedures, this issue was reviewed with the DME avionics manufacturers to assess if they could satisfy this requirement. The manufacturers indicated that the original compliance testing and analysis was not adequate to determine compliance to this tighter requirement, and that not all equipment can be expected to satisfy this higher level of accuracy. As a result, the Performance-Based Aviation Rulemaking Committee (PARC) recommended that navigation implementation of DME/DME be based on the TSO-C66c accuracy. Since the basis for the use of DME/DME within this strategy is to build off of the navigation solutions (and avoid the need for new testing, certification and potentially equipment), the TSO-c66c accuracy has been used when assessing the performance of DME/DME in an ADS-B context.

The positioning accuracy is also dependent on the geometry of the stations: when ground stations are too close together, the error ellipse becomes elongated and the overall accuracy degraded. Within the aircraft, the individual range measurements are converted to a position solution within a multi-sensor navigation system (typically referred to as a flight management system, or FMS). To ensure reasonable geometry, most systems restrict the DME/DME geometry to between 30 and 150 degrees (the inclusion angle at the aircraft). Some systems will use only two DME measurements at a time, while others track many stations and integrate that information in a least-squares or Kalman filter. During the development of RNAV routes and procedures, these different implementations were assessed, and in order to ensure current equipment can be used the minimum solution was defined as that based on only two stations. This is also consistent with the long-term navigation services objective to eliminate redundant facilities, so that if only two facilities are adequate some cost avoidance may result by divesting the stations that are not needed for DME/DME positioning.

For navigation, DME/DME accuracy is typically assessed in terms of the radial 95% accuracy. This is consistent with the ADS-B definition of the Navigation Accuracy Category (NAC), so it is assumed in this analysis that the ellipticity is not a constraint and only the radial accuracy needs to be addressed. Given the ranging accuracy to two stations (R1 and R2), the resulting radial accuracy is:

$$PositionAccuracy95\% = \frac{\sqrt{R_1^2 + R_2^2}}{\sin \alpha}$$

The resulting accuracy is shown in Figure A4.1-1. Within the terminal area (where stations must be nearby in order to provide line-of-sight coverage), the accuracy is within 0.6 nmi (95%). For en route applications where the facility can be further away, the accuracy degrades to up to 1.2 nmi (for two stations at 160 nmi and marginal geometry). This accuracy does not comply with the fPR requirements for 3 nmi and 5 nmi ATC surveillance applications, of 0.1 nmi and 0.3 nmi, respectively. The accuracy of DME/DME positioning can be improved through denser DME siting to improve both the geometry and the distance. However, to achieve the en route 0.3 nmi accuracy would require two facilities within 68 nmi and with an inclusion angle between 70 and 110 degrees, a significant change to the ground infrastructure. The best-case accuracy for a minimum DME/DME position solution is 0.28 nmi, so terminal accuracy is not feasible under any circumstance. Some systems use multiple DME stations to improve accuracy, with typical achieved accuracy within 0.2 nmi to 0.7 nmi, depending on DME station geometry and density. This type of performance is adequate for navigation applications, where the position accuracy requirement to support RNP-1 and RNP-2 is 0.8 nmi and 1.75 nmi, respectively, which is well within the capability of DME/DME and is the basis for its selection as a navigation backup. DME/DME does not provide any appreciable value as a navigation backup for RNP-0.3 procedures, as the accuracy is not adequate to support RNP-0.3 operations.

A significant issue when considered DME/DME positioning is the coverage of the DME ground infrastructure. Multi-sensor systems have developed different facility-selection logic through experience and based on interpretations of published service volumes. Differences in logic between systems make it difficult to generalize a coverage analysis that is appropriate to all the target multi-sensor systems. This issue was discussed in support of the implementation of RNAV routes, and some common selection conditions identified to allow coverage to be evaluated (for details on how coverage is assessed for navigation, see FAA Order 7470.1).

Figure A4.1-2 illustrates the coverage of DME/DME in the terminal area, using existing DME facilities. DME signals are limited to line-of-sight propagation, and coverage is limited due to field strength requirements and the multi-sensor system selection logic. The figure shows the coverage within 200 nmi of Denver at 10000 ft height above the airport (HAA): even 5000 ft above the airport, there are significant gaps in coverage.

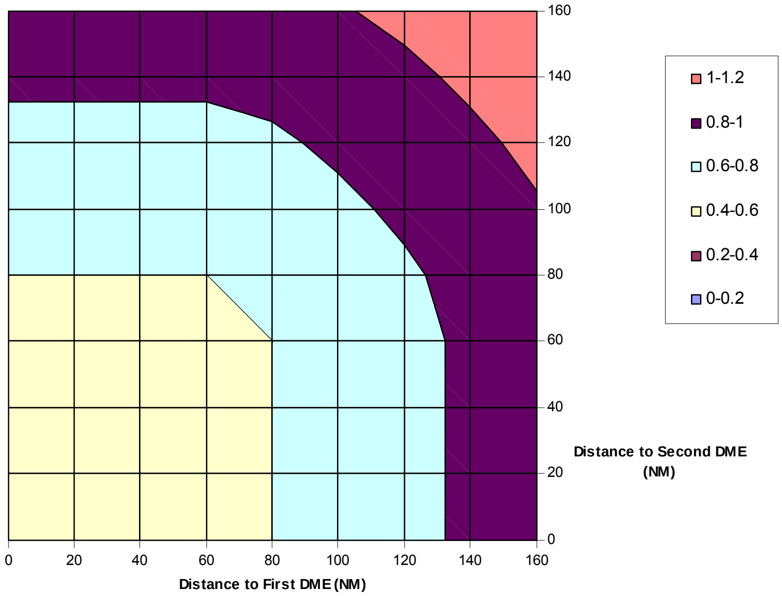


Figure A4.1-1: DME/DME Accuracy under Marginal Geometry (30/150 degrees)

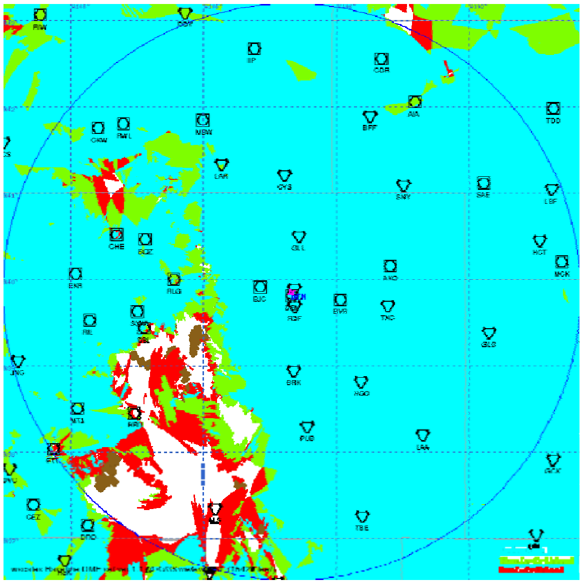


Figure A4.1-2: Coverage of DME/DME within 200 nmi of Denver at 10000 ft HAA

Another illustration of the coverage limitations of DME/DME is shown in the Figure A4.1-3. This figure shows the DME/DME coverage at 2000 ft above ground level (AGL), using all the current DMEs in the NAS. Some DMEs are expected to be added in the western US to fill in coverage gaps above flight level (FL) 240, but many stations in the eastern U.S. will be divested under the navigation plan when they are no longer needed. As illustrated, DME/DME will not provide the same coverage as the backup radar coverage shown in Strategy 1.

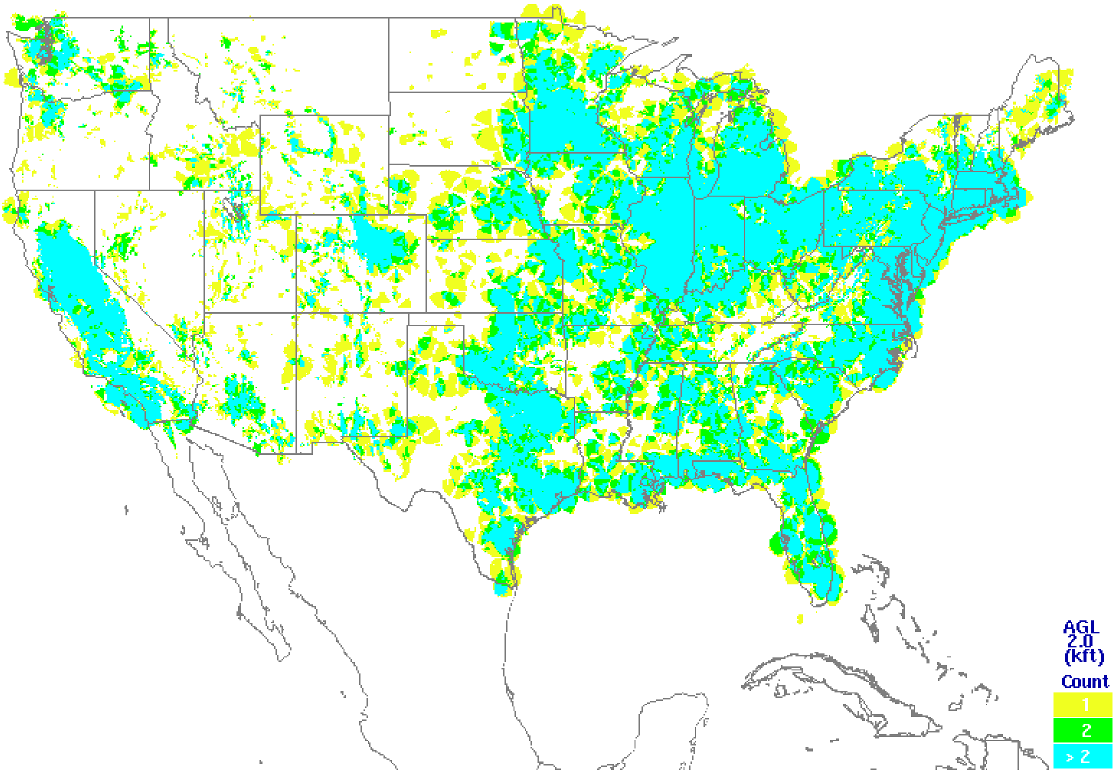


Figure A4.1-3: Coverage of DME/DME at 2000 ft AGL

The primary mitigation for these gaps is to take advantage of aircraft IRUs. For those aircraft that have an IRU, the multi-sensor system can use the most-recent valid DME/DME position as a starting point and the IRU measurements to update position. The IRU is measuring aircraft acceleration, which is integrated to determine change in position, and some error accumulates over time so that the resulting accuracy degrades. The rate of performance degradation depends on the aircraft implementation and the error states of the IRU at the time of loss of updating (this is affected by the type of position solution, number of error states modeled, the flight trajectory prior to loss). To accommodate existing implementations, navigation implementation is based on the documented performance for B747, B757, B767 and B777 aircraft (see the RNP Capabilities documents published by Boeing for these aircraft). As an upper bound, the resulting 95% radial positioning accuracy can degrade at 8 nmi/hr for the first 15 minutes, which is the only period of interest to maintain a reasonable level of positioning accuracy for the ATC surveillance application.

The accuracy of the resulting position solution is based on the accuracy of the most recent valid position update (from DME/DME) and the time since that update. This is shown in Figure A4.1-4, assuming marginal DME/DME geometry at the time positioning is lost. The resulting accuracy is shown for both a terminal area case where the stations are assumed to be near-by and an en route case where they may be up to 160 nmi away.

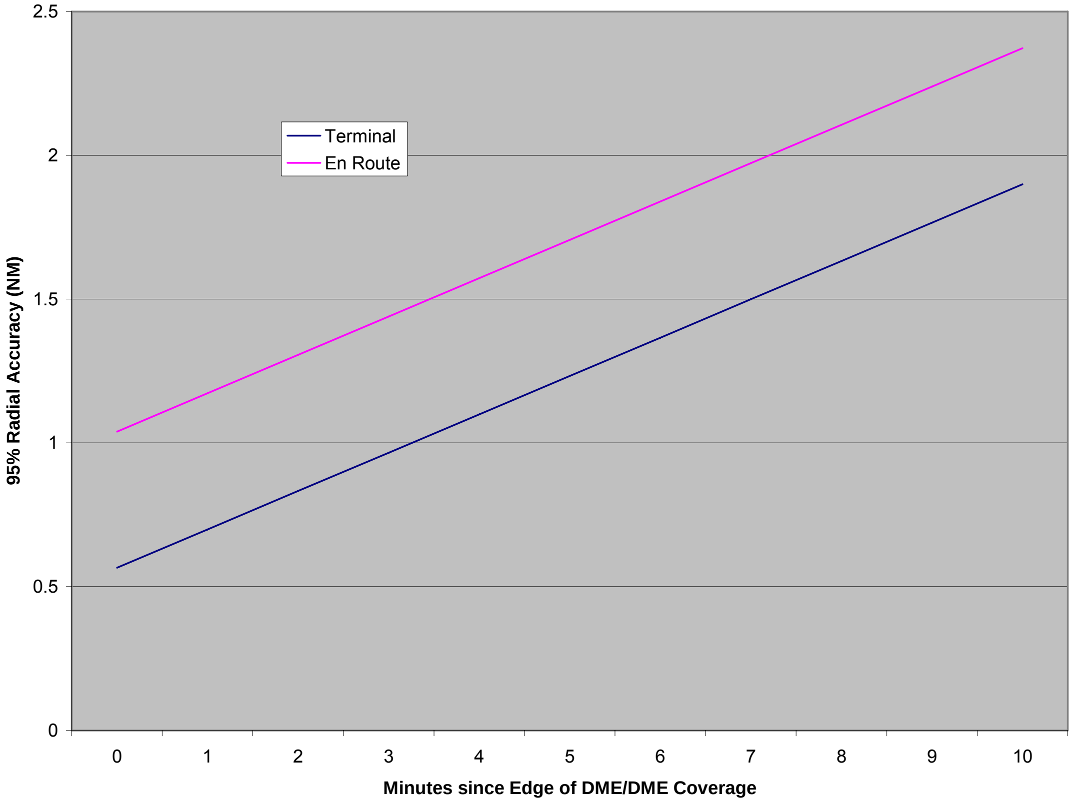


Figure A4.1-4: Degradation in Radial Positioning Accuracy using Inertial for DME/DME Coverage Gaps

For navigation, the FAA plans to provide DME/DME/IRU positioning service above FL240 throughout the conterminous US with 95% accuracy of 1.7 nmi. DME/DME/IRU positioning service is also planned for major airports above 2000 ft (height above airport) with a 95% accuracy of 0.86 nmi. The extent of airports that should have this coverage is still under consideration, and varies between the Operational Evolution Partnership (OEP) airports and the top 100 airports.

This strategy is based on leveraging the investment in DME/DME that is planned for navigation purposes. As such, the resulting positioning accuracy that should be assumed when evaluating operational capability is the navigation-based requirements:

1.75 nmi (95%) for en route
0.86 nmi (95%) for terminal areas

It is possible to improve this positioning performance, through an increased network of ground stations, requalification of some airborne equipment and replacement of other equipment. The costs for the increased DME ground infrastructure are expected to become prohibitive, and the resulting performance even with improvements does not satisfy the 3 nmi separation requirements.

DME/DME/IRU positioning has no direct dependency on GNSS. Some DME stations do operate at the same frequency as the new GPS L5 and Galileo E5a/E5b signals, so that interference to the L5 signals may deteriorate DME performance as well. However, the FAA may re-channel the DME facilities in the center of the GNSS band to improve GNSS performance, which would also mitigate the risks that interference to L5/E5a/E5b also impacts DME/DME. The majority of DME facilities are assigned frequencies in other portions of the band and would not be affected.

A4.1.2 Operational Environment

DME/DME/IRU positioning provides a continuous ADS-B-based position report during any type of GNSS disruption. Each aircraft would automatically switch from a GNSS-based position to the DME/DME/IRU-based position. No flight crew interaction is expected, so there would be no impact on the flight crew for ADS-B out. The NAC would increase to the value based on the particular DME infrastructure available to the aircraft, ranging between 0.6 nmi and 1.2 nmi as discussed under the technical assessment. The resulting accuracy does not satisfy any of the ADS-B Segment 1 applications. New separation standards based on the available DME/DME/IRU positioning accuracy would have to be determined, and ATC automation would have to indicate the degraded operation to the controller to change the separation standard. An increased workload is expected during the initial transition from the normal separation standard to the DME/DME standard, after which time the workload would be normal but capacity would be reduced.

Since the DME/DME/IRU position would only be transmitted when GNSS position is not available, this component of the backup strategy does not provide any additional capability during normal operations.

The DME/DME/IRU accuracy is not expected to be adequate for future ADS-B applications.

A4.1.3 Implementation Status

For the DME/DME/IRU component of this strategy, the technology is mature with several decades of operational experience in navigation applications. Criteria for the facilities are already promulgated through ICAO, and standards for the aircraft are defined in TSOs (TSO-C66c) and Advisory Circulars (ACs) (AC 20-130A, AC 90-100). However, the integration of this position with ADS-B out would require a change in the existing aircraft implementations and includes some implementation challenges that would affect costs. For navigation applications, the flight crew has indications of what type of positioning solution is being used and also has the ability to manually select or inhibit certain modes or facilities. For example, some aircraft implementations rely on the flight crew to manually inhibit the use of a particular ground facility that is undergoing maintenance and broadcasting a test signal (which is indicated via a NOTAM). An example of where the flight crew may want to inhibit the use of DME/DME updating is for RNP approaches with tight performance requirements: on those particular procedures, it is better to revert from GNSS to IRU directly to provide better initial performance, as the DME/DME accuracy is not sufficient to support the initial stage of a missed approach. If the position solution for ADS-B out and navigation are the same, then the crew procedure to inhibit test facilities would support both applications but the backup would not always be available as the crew may inhibit it. Alternatively, if a unique position solution is determined then issues such as a test facility have to be resolved a different way. None of these integration issues are insurmountable, but the aircraft modifications to support a DME/DME/IRU ADS-B out position backup would be significant, even for an aircraft that already has a DME/DME/IRU navigation capability. These issues can readily be resolved within the program timeframe, but would ultimately impact costs.

A significant ground infrastructure to support DME/DME/IRU positioning is already in place. Work is ongoing to detail the requirements to right-size that infrastructure based on the RNAV navigation requirements, and several dozen new facilities will be required while many existing stations may be divested.

The aircraft and facility standards used in implementing a DME/DME/IRU backup are internationally adopted and the technology is mature. Within Europe, a similar strategy may be feasible as the DME coverage is similar to the U.S. and their navigation plan makes use of that infrastructure as the RNAV backup to GNSS. In other regions of the world, the coverage of DME/DME is generally not adequate to allow a similar strategy to be adopted, but international air carriers are expected to carry DME/DME equipment regardless.

A4.2 eLoran

Loran (LOng RAnge Navigation) is a low-frequency (90-110 kHz band) radio navigation system developed by the military beginning in the 1950s. In the U.S., the Coast Guard operates the Loran-C ground infrastructure, which includes eighteen stations in the Continental U.S. (CONUS) and six in Alaska. Loran-C coverage is shown in Figure A4.2-1. Signals from Canadian and Russian stations are also available in the NAS, improving accuracy and availability.

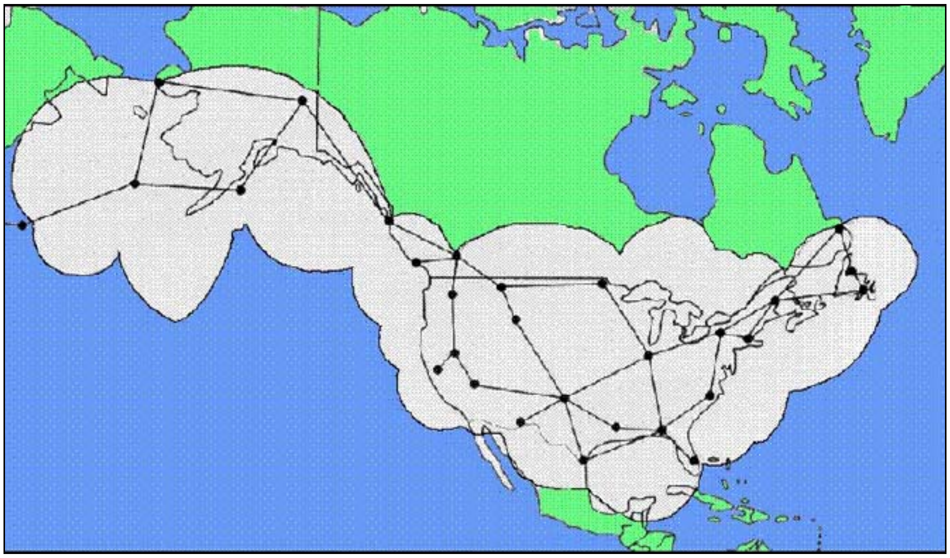


Figure A4.2-1: Loran-C Coverage as Shown in the Federal Radionavigation Plan

A4.2.1 Architecture

Loran provides a two-dimensional horizontal fix. Aviation use of Loran thus requires a separate source for determining altitude (e.g., barometric altimeter). In actuality, there are three Loran architectures in simultaneous operation at this time: Loran-C, modernized Loran, and enhanced Loran (eLoran). Definitions aimed at distinguishing these architectures are presented below.

A4.2.1.1 Loran System Descriptions

Legacy Loran-C

The legacy system is based upon measurement of the difference in time of arrival of pulses of RF energy radiated by a chain of synchronized transmitters that are separated by hundreds of miles. The measurements of time difference (TD) are made by a receiver which achieves high accuracy by comparing a zero crossing of a specified RF cycle within the pulses transmitted by a master and two or more secondary stations within a chain. Making this signal comparison early in the ground wave pulse assures that the measurement is made before the arrival of the corresponding skywaves. Precise control over the pulse shape ensures that the proper comparison point can be identified by the receiver.

To aid in preventing skywaves from affecting TD measurements, the phase of the 100 kHz carrier of some of the pulses is changed in a predetermined pattern. Envelope matching of the signals is also possible but cannot provide the advantage of cycle comparison in obtaining the full system accuracy. The characteristics of legacy Loran-C are summarized in Table A4.2-1.

Table A4.2-1: Loran-C System Characteristics (Signal-in-Space)

ACCURACY (2 drms)		AVAILABILITY	COVERAGE	RELIABILITY	FIX RATE	FIX DIMENSIONS	SYSTEM CAPACITY	AMBIGUITY POTENTIAL
PREDICTABLE	REPEATABLE							
0.25nmi (460m)	60-300 ft. (18-90m)	99.7%	U.S. coastal areas, continental U.S., selected overseas areas	99.7%*	10-20 fix/sec.	2D + Time	Unlimited	Yes, easily resolved

* *Triad reliability*

Each Loran-C station includes: a frequency standard set (three cesium clocks), a timer set, a high-power transmitter (350 kW to 1.4 MW peak power), and an antenna (625 ft to 1,350 ft tall). Stations presently are grouped into chains of from three to six stations. Each chain consists of one master and multiple secondary stations that are synchronized to the master station. A station can be a member of one or two chains, as a master or secondary.

The legacy Loran-C broadcast signal (Figure A4.2-2) consists of a pulse group (9 for the master and 8 for the secondary stations) that propagates via ground wave mode. The effective range of the signal depends on the propagation path (over seawater or land) and the atmospheric noise level at the receiver.

Typical coverage range is on the order of 1,000 nmi, and coverage altitude is typically 60,000 ft. Unlike radio navigation systems using higher frequencies, line-of-sight blockage of the path between the transmitter and receiver antennas is generally not an issue. However, multipath reflections from large metallic surfaces near the receiver limit performance.

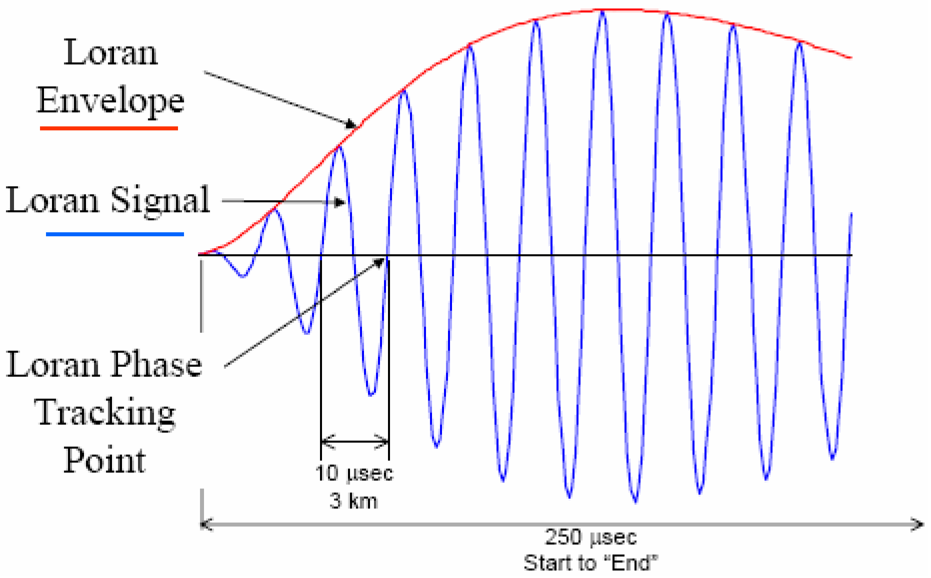


Figure A4.2-2: Loran Signal Structure

Relative to a pre-established navigation datum (e.g., WGS-84), legacy Loran-C provides a predictable accuracy of 0.25 nmi, 2 drms (distance root-mean-square) or better within the published coverage area. Repeatable accuracy of Loran-C is usually between 60 ft and 300 ft, 2drms. Individual station availability normally exceeds 99.9%, resulting in a triad availability exceeding 99.7% (Table A4.2-1).

<u>Modernized Loran</u>

In the mid-1990s, the U.S. Coast Guard initiated a project to recapitalize the Loran system. The project initially was aimed at replacing aging or damaged facilities and equipment, but in time the U.S. Congress directed additional funds to "modernize" Loran-C.

The modernized Loran system continues to be a low-frequency, terrestrial navigation system operating in the 90 kHz to 110 kHz frequency band. This modernized system has a recapitalized infrastructure, including transmitters that are synchronized to Coordinated Universal Time (UTC), and a new communication modulation method that enables operations that satisfy the accuracy, availability, integrity, and continuity performance requirements for non-precision approaches and harbor entrance and approaches, as well as the requirements of non-navigation time and frequency applications. Required changes to the legacy system include modern solid-state transmitters, a new time and frequency equipment suite, modified monitor and control equipment, and revised operational procedures that new receiver technology can exploit. The modernized Loran system improves upon the characteristics of the legacy Loran-C system.

Modernization of the Loran-C system was initiated in 1997 by budgetary legislation that directed the FAA "…to further develop the Loran-C system." Since that time, extensive work has been accomplished to overcome transmitter and user equipment limitations and to determine whether the modernized Loran system can meet performance requirements for aviation nonprecision approach (NPA), maritime Harbor Entrance and Approach (HEA), and time/frequency synchronization.

Modernized Loran includes a new communications modulation method, for example, but not renovation of the building that houses the transmitter electronics. Modernized Loran provides system performance enhancements beyond legacy Loran-C.

Enhanced Loran (eLoran)

The term “eLoran” has multiple meanings, which in part is why “modernized” Loran also is used. The difference springs from the many civil applications that would use eLoran for positioning, navigation, or timing, each application utilizing a subset of modernized Loran’s features. A definition favored by the FAA is the following:

> “eLoran includes the modernized infrastructure and user electronics that enable users to realize NPA, harbor entrance and approach, and time/frequency performance requirements.”

The eLoran system infrastructure block diagram is shown in Figure A4.2-3.

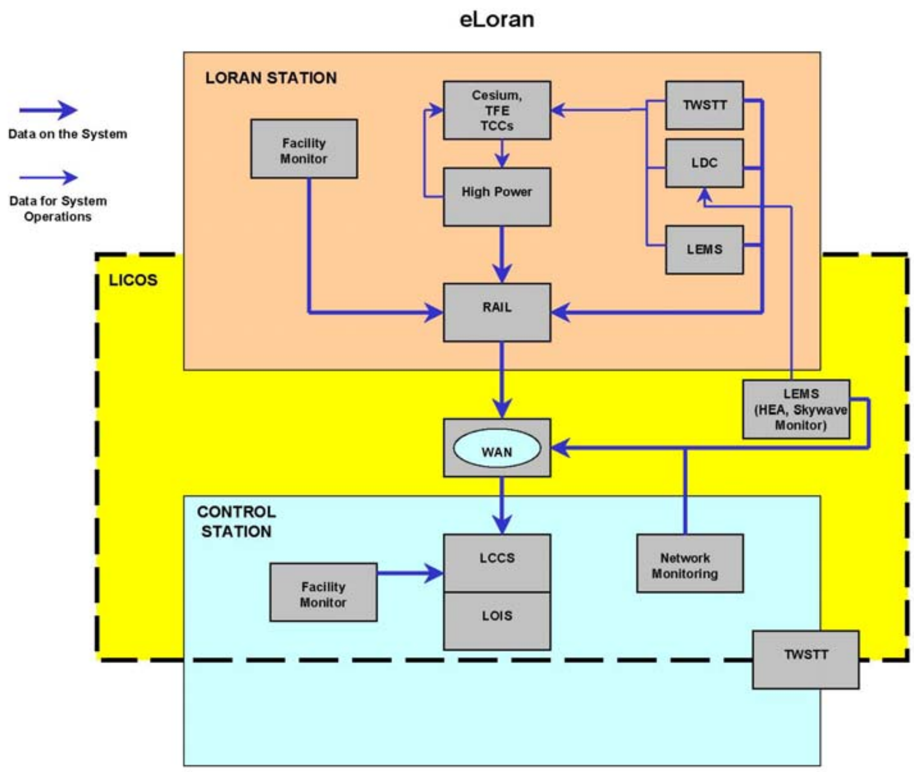


Figure A4.2-3: eLoran Infrastructure Block Diagram

An important aspect of this definition for aviation is the idea that the necessary infrastructure will be in place, but users must ensure that their eLoran equipment will provide adequate performance for their needs.

Information available at this time indicates that eLoran avionics that get certified for NPA operations will be able to support ADS-B backup requirements without further hardware modification.

Table A4.2-2 compares capabilities for key applications in the performance progression from legacy Loran-C to eLoran. Additional infrastructure, differential monitor sites, will be needed for comprehensive HEA and 50-nanosecond time performance. Also, several additional secondary factor (ASF) measurements may be needed around some airports, to support terminal area surveillance requirements.

Table A4.2-2: Capabilities of Legacy, Modernized and Enhanced Loran

Status Today	**Loran-C**	**Modernized Loran**	**eLoran**
Aviation			
En Route (RNP-2)	**Yes**	**Yes**	**Yes**
Terminal (RNP-1)	**No**	**No**	**Possible**
NPA	**No**	**No**	**Yes**
Maritime			
Ocean	**Yes**	**Yes**	**Yes**
Coastal Confluence Zone	**Yes**	**Yes**	**Yes**
HEA	**No**	**No**	**Yes**
Time/Freq			
Stratum 1 Frequency	**Yes**	**Yes**	**Yes**
Time of Day/Leap Second/UTC Ref.	**No**	**Yes**	**Yes**
Precise Time [< 50 ns UTC (USNO)]	**No**	**No**	**Yes**

The development of eLoran enables receiver designs that exploit new capabilities of the modernized transmitters. The goal is a combination of modernized infrastructure and user equipment that together satisfy the accuracy, availability, integrity, and continuity performance requirements for NPA, and the needs of non-navigation time and frequency applications.

The terms modernized Loran or eLoran refer to:

- Modern, more reliable solid-state transmitters at all stations
- New time and frequency equipment (TFE) at all stations
- Modified monitor and control equipment at all stations and other locations in the coverage region

- Revised operational procedures, including synchronizations of all transmitters to UTC
- On-site emergency power (Uninterruptible Power Supplies - UPS)
- The legacy aviation blink feature is now replaced by off-air requirement within 2 sec.
- New receiver designs that can utilize signals from all stations within range, independent of any chain affiliation, and can take advantage of information broadcast over the "ninth pulse" Loran Data Channel (LDC). The data include an integrity message (early skywave), real-time differential corrections, station identification, and time directly referenced to UTC.
- A Loran Enhanced Monitor System (LEMS) receiver that is compatible with LDC; and the Loran Information, Control, and Operations System (LICOS), to automate processes in the Loran infrastructure as part of the overall objective to automate station operations.
- User installation of H-field (magnetic field) antennas in lieu of E-field (electric field) antennas, to reduce sensitivity to noise disturbances—especially precipitation static.

New receiver designs that can utilize signals from all stations within range, independent of any chain affiliation, and can take advantage of information broadcast over the "ninth pulse" LDC. The data include an integrity message (early skywave), real-time differential corrections, station identification, and time directly referenced to UTC.

Legacy Loran-C users can use eLoran, although they cannot derive the full benefit of eLoran's capability. This report focuses on eLoran capabilities and performance relative to legacy Loran-C.

eLoran can meet the positioning requirements for general aviation aircraft operating in medium density conditions. Its ability to meet RNP 0.3 requirements for nonprecision approach has regularly been confirmed in flight tests conducted throughout the U.S. eLoran is also capable of precise time transfer and frequency recovery, because of its use of cesium clocks synchronized directly to UTC.

A4.2.1.2 Component Descriptions and System Performance

Specific enhancements to the eLoran system, and their present status, include the following:

- **Station/Transmitter Upgrades.** All of the tube transmitters have now been replaced and several of the early solid-state transmitters have been replaced with units having updated designs, thereby significantly improving signal stability and reliability.
- **Time and Frequency Equipment.** The TFE in all 18 CONUS plus the Kodiak, Alaska transmitter stations have been replaced and upgraded. Three state-of-the art cesium clocks, part of the TFE, also have been installed at all 24 U.S. stations. The new TFE will support local, instantaneous local and automatic phase adjustments.
- **Communications Equipment.** Communications equipment is being replaced at all stations to improve control procedures and enable tighter control tolerances. The installations are performed along with the TFE upgrades.

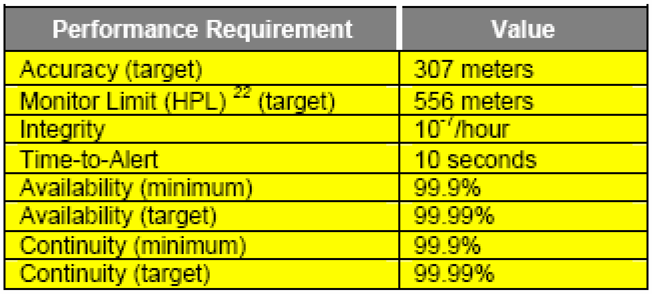
- **Time of Transmission Control.** The new TFE and communications equipment allows operation with Time-of-Transmission (TOT) control — i.e., maintenance of a constant time of transmission referenced to UTC at each transmitting station. This permits user receivers to operate with stations independent of the chains to which they have been associated, enhancing accuracy and availability. Under TOT control, the legacy hyperbolic intersections for position fixes are replaced by intersections of (at least two) circles, similar to GPS-based fixes.

- **Monitor and Control Equipment.** Control equipment is housed at the 24 transmitter stations, two control stations at the U.S. Coast Guard facilities in Petaluma, CA and Alexandria, VA, and at 24 system monitor sites in CONUS and Alaska. Equipment used includes a transmitter control set (TCS) for each station, and remote automatic integrated Loran (RAIL) equipment. The TCS and RAIL equipment allow for the monitoring and control of all station equipment at a central facility, to reduce the number of personnel assigned to specific locations. When abnormal performance in a transmitter station is detected by a monitor, rather than "blinking" the station's signal (integrity alert), the control equipment will shut the signal off within two seconds, enhancing system integrity.

- **System Dependencies.** eLoran operates completely independently of GPS, which is not needed to synchronize signal transmission. Some integrated positioning or navigation systems may operate with GPS "conditioning," and eLoran is regularly packaged with GPS components.

- **System Performance.** The eLoran system was designed – and has shown an ability – to meet the following key requirements:

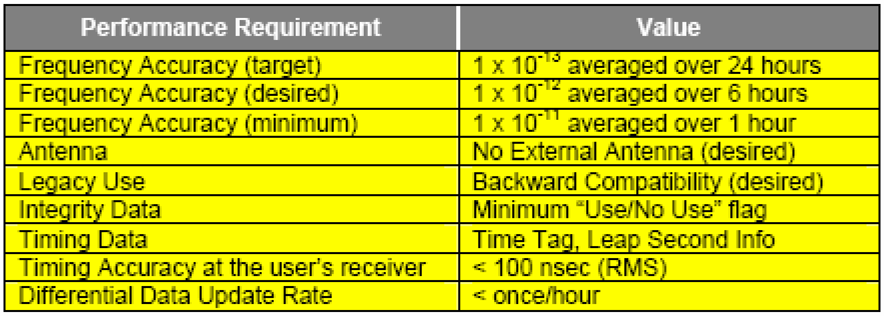
Table A4.2-3: Aviation RNP-0.3 Requirements



Performance Requirement	Value
Accuracy (target)	307 meters
Monitor Limit (HPL) [22] (target)	556 meters
Integrity	10^{-7}/hour
Time-to-Alert	10 seconds
Availability (minimum)	99.9%
Availability (target)	99.99%
Continuity (minimum)	99.9%
Continuity (target)	99.99%

- **Time and Frequency Requirements.** The timing and frequency users have no known published government requirements that equipment must meet. However, timing and frequency applications, including those used by government agencies, employ applications with specific timing and frequency requirements.

Table A4.2-4: Time and Frequency Requirements



Performance Requirement	Value
Frequency Accuracy (target)	1 x 10^{-13} averaged over 24 hours
Frequency Accuracy (desired)	1 x 10^{-12} averaged over 6 hours
Frequency Accuracy (minimum)	1 x 10^{-11} averaged over 1 hour
Antenna	No External Antenna (desired)
Legacy Use	Backward Compatibility (desired)
Integrity Data	Minimum "Use/No Use" flag
Timing Data	Time Tag, Leap Second Info
Timing Accuracy at the user's receiver	< 100 nsec (RMS)
Differential Data Update Rate	< once/hour

A4.2.1.3 Design and Operational Factors that Influence eLoran Performance

Ninth Pulse

When eLoran is fully implemented, all stations (rather than just the chain master stations) will broadcast a 9th pulse. It will be modulated to provide differential corrections - these consist of real-time ASF adjustments to propagation delays - as well as station identification, a time stamp, and integrity information (e.g., early skywave detection – Figure A4.2-4) for aviation.

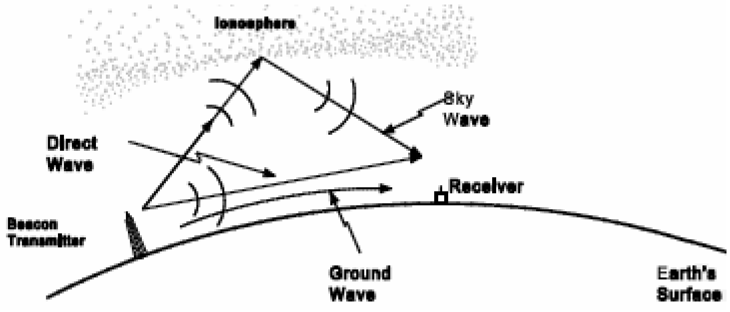


Figure A4.2-4: Loran Skywave

Additional Secondary Factors

The ASF accounts for the increased delay in the propagation of a Loran signal over a heterogeneous earth as compared to propagation over an all seawater path. ASFs contribute the largest source of error in Loran-C navigation. The pre-determined ASF value is used to adjust the receiver's TOA estimate of the Loran signal. Tests show that with good models of the temporal and spatial variations of ASF, a 0.3 nmi or less (95%) cross-track error can be achieved (Figure A4.2-5). Those same tests show, however, that ASF values will be required to meet the RNP-0.3 integrity requirement of 99.99999%. It is anticipated that an ASF database will be employed for this purpose, but additional data collection/analysis is required to confirm the effectiveness of this approach throughout the NAS.

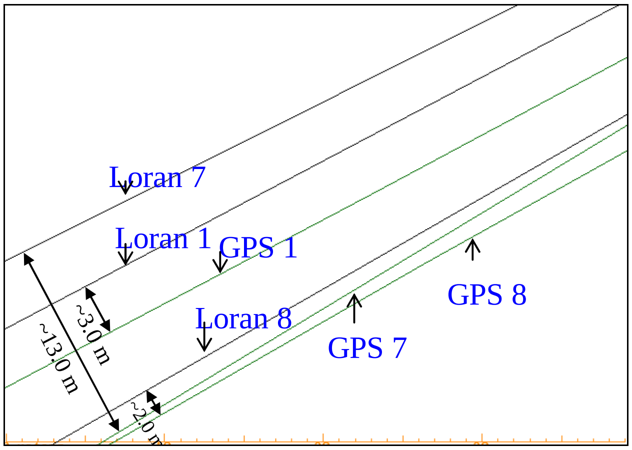


Figure A4.2-5: GPS and eLoran Track Repeatability During NPA Tests

Use of ASF corrections can significantly improve accuracy. Loran's high repeatable accuracy reflects the fact that a large percentage of the conductivity differences at a given location remain fairly static for long periods of time (up to a few weeks). Where there are high spatial ASF gradients, usually due to land-seawater interfaces, a grid of ASF values for each airport approach probably is needed; otherwise, one value per airport meets NPA requirements. A set of ASF values also is needed for each Loran transmitter "in view" of a particular locale. It still needs to be determined conclusively whether a ground-derived ASF can be used from the surface to about 5,000 feet AGL.

ASFs are generally calculated from formula-based models, for example, Millington's method, and validated/updated by field tests. Loran TDs are computed at a known location (using GPS/WAAS, for example), and compared to TDs that would result if the transmission path were all seawater. It takes about an hour at each airport of interest to collect the ASF data. For consistency, three approaches from each end of the runway are executed. TOAs from each station are measured using a Loran receiver clock locked to a composite frequency derived from all stations being tracked. The measured TOAs are differenced from those calculated using GPS-derived position and modeled primary (atmosphere relative to a vacuum) and secondary (over seawater) conductivity factors, to produce the ASF. The ASF has both UTC offset and receiver delays, and the latter can be accounted for using common (ground/air) receivers.

A spatial grid of such measurements can be used to interpolate an ASF correction for each location fix, as long as accuracy is maintained. An issue for aviation is grid size. A "coarse" grid of ASF values probably will be needed to support en route operations. The use of ASFs to enable eLoran terminal area operations requires more analysis. Since NPA performance has been proven at numerous NAS airports, eLoran can meet RNP-0.3 accuracy and integrity at airports where ASF values have been measured. Cross-track approach errors less than 100 meters have been regularly achieved, making RNP-0.3 accuracy "feasible and practical". Conservative model predictions support an RNP-0.3 capability using the current infrastructure (transmitters and monitor and control sites) in 95% of the CONUS (Figure A4.2-6). More work is needed to meet CONUS-wide RNP-0.3 availability.

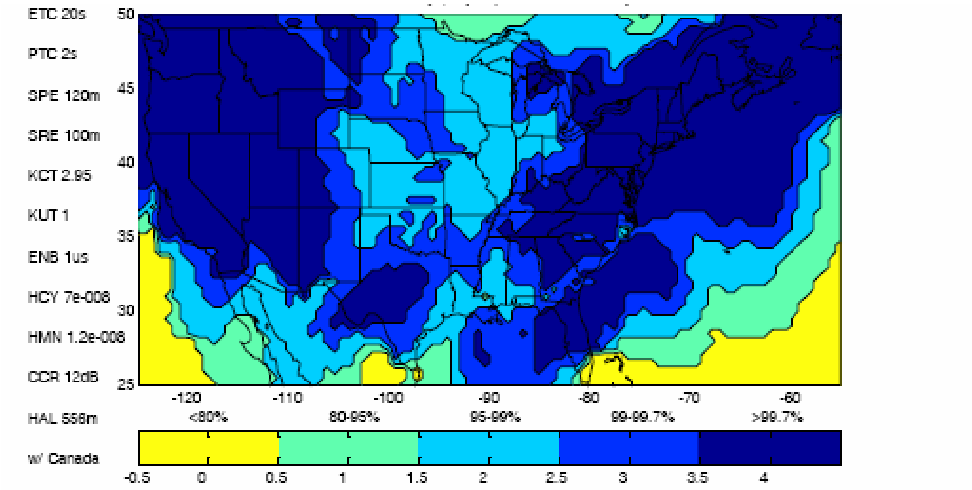


Figure A4.2-6: Predicted eLoran Availability of RNP-0.3

If RNP-1 accuracies do not suffice for ADS-B backup terminal area operations, either (1) a tighter ASF grid would be needed in the entire terminal area than in the roughly 10 nmi NPA area around the airport; or, (2) real-time ASF corrections (becoming known as differential Loran), possibly may be considered. Differential Loran was developed for maritime use, however, and probably would be prohibitively expensive for aviation.

User Receivers and H-Field Antennas

Aviation equipment will utilize (a) stored ASF data in deriving a fix, (b) knowledge of pulses' TOT to enable incorporating TOA information from all stations within range, and (c) H-field or equivalent antennas to reduce their susceptibility to impulsive atmospheric noise and precipitation static (p-static).

Envelope-to-Cycle Difference (ECD)

ECD is the time relationship between the phase of the RF carrier and the time origin of the envelope of the pulse waveform. Knowledge of the expected ECD, which varies temporally and spatially, is required for the cycle selection portion of the integrity calculation. The Loran Integrity Performance Panel confirmed in 2004 that, as with ASF, there are as yet no prediction models with sufficient fidelity to support RNP-0.3 operations. Accordingly, ECD measurements are planned as part of airport calibration efforts.

Time and Frequency Synchronization

In order to be a viable alternative to GPS for timing and frequency applications, Loran-C time synchronization required an order of magnitude improvement, as the drift of the clocks at legacy Loran-C stations and seasonal changes in propagation delay limit timing accuracy. These issues can be addressed by using differential corrections that provide for cancellation of common-mode errors (e.g., clock drift and correlated changes in propagation delay). Analysis of legacy data resulted in a predicted order of magnitude improvement for modernized Loran, with time recovery within 100 nsec of UTC. Recent tests using the initial three stations broadcasting precise time on the 9th data channel tend to confirm the viability of the eLoran timing/synchronization design.

Under TOT control, all stations are synchronized directly to UTC using GPS. When GPS is unavailable, a satellite link to the U.S. Naval Observatory (USNO), and later on, National Institute of Standards and Technology (NIST), can be used. GPS remains the primary timing conditioner in this process, but eLoran time can replace GPS if needed, using the two-way timing data link now being implemented for Loran operations. This greatly extends the already excellent precision holdover provided by the cesium clocks, and makes eLoran operation (synchronization of the stations' transmit times) fully independent of GPS. eLoran receivers also can track individual stations under TOT on an "all-in-view" basis. This provides generally better fix geometry, hence better accuracy and availability.

Cross Rate Interference

Cross rate interference (CRI) is interference from Loran transmitters operating on a different group repetition interval (GRI) than transmitters of interest. The interference is intermittent and periodic. CRI may shift phase and ECD if not accounted for. CRI's impact can be mitigated by cancellation or blanking. CRI blanking is used for modulated pulses, which explains the eLoran design for 9th pulse modulation vice the Eurofix design modulating six pulses. Receivers now are designed with CRI mitigation, which involves about a 0.5 dB signal-to-noise ratio (SNR) loss for blanking due to the 9th pulse, and 1.5 dB SNR loss for CRI canceling.

With the eLoran transmitter configuration changing from chain-based to all-in-view, it becomes possible to single rate (that is, designate only one GRI) each transmitter. This would reduce CRI; it also would reduce per station power utilization by about 30%, since dual rated stations need to synchronize properly and transmit simultaneously pulsed signals at two GRIs. It also would reduce receiver unit costs, since there would be fewer signals to track. Finally, it may be possible using this configuration to add a 10th or 11th pulse to the basic signal, greatly augmenting data channel capacity.

Flexibility/Agility

eLoran system capabilities include ubiquitous CONUS coverage, which will provide tactical and strategic flexibility within CONUS by 2009, when the 18 CONUS stations are fully eLoran-capable, and similarly by 2010 in Alaska (six stations). All five Canadian Loran stations operate close enough to the U.S. to enable their signals to be used in CONUS and Alaska. U.S. users therefore benefit from the added capability, but there are no plans to modernize the Canadian stations until continuation of the U.S. system is guaranteed. The eLoran designs and performance projections assume utilizing legacy Canadian station signals.

The modernized Loran infrastructure provides the required precise timing synchronization by means of improved cesium clocks located at each transmitter station. The system is mandated to maintain this capability fully independent of GPS. Recent tests have confirmed the viability of the signal design that enables this capability; it also provides GPS/GNSS timing/synchronization users with a near fully redundant Stratum 1 backup.

Aviation and non-aviation users of eLoran will have the same full access to its signal in space. No use of eLoran, certified or otherwise, will be able to negatively impact other uses.

A4.2.2 Operational Environment

The eLoran avionics suite will very likely be physically merged with GPS/GNSS. Prototype units already exist, and their performance has been validated. This physical integration is abetted by the display commonalities. Transition to backup mode does not require any action on the part of the pilot. If eLoran is operating while in standby mode, position outputs will be provided without disruption (prototype eLoran aviation receivers are being designed for one-second fix rates).

For this report, it has been assumed that eLoran cannot reliably support high density terminal area operations in the NAS. It is necessary to analyze and test how many ASF calibrations are needed in the terminal area (about 50 nmi radius, vice the 10 nmi radius for the ASF calibration that would support NPA), and if the number is cost effective.

Need for Conductivity Corrections (ASFs)

Airports typically require one ASF calibration to ensure acceptable NPA performance at both ends of all of an airport’s runways. The spatial ASF components have values that average about 3 to 4 µsec over the CONUS. Allowance has to be made for exceptions, and also for the seasonal (“temporal”) ASF variations. Temporal variations are caused by weather effects such as varying ground moisture, and the freeze-thaw cycle of lakes. ASF values, which generally vary seasonally and have a two month duration, will be contained in a database in the receiver. Long term monitoring of system performance will indicate a need and frequency for changing the values.

Altitude ASF variations at a given radial line also are a potential concern; flight testing to date has not yet established a definitive need for altitude-dependent ASFs at en route altitudes. Figure A4.2-7 shows 95% accuracy projections for eLoran in the CONUS, at en route altitudes, based on models appropriately adjusted by actual flight test results gathered along selected air routes. The green central area bounds the 3 nmi separation capability zone (0.1 nmi 95% accuracy); the 5 nmi separation zone is CONUS-wide.

Repeatable accuracy is a Loran performance feature that implicitly accounts for the spatial ASF component, which often is more than half of the conductivity difference.

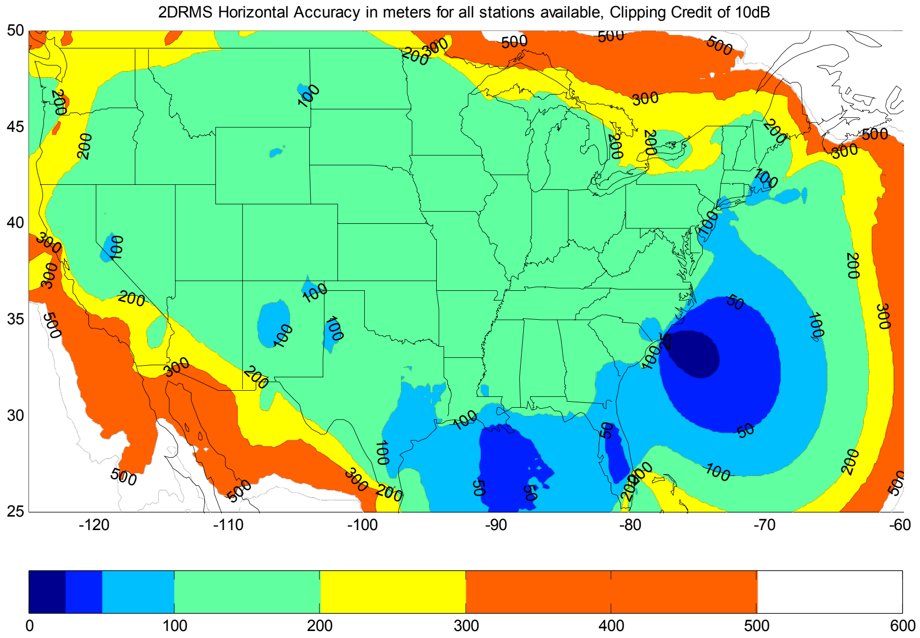


Figure A4.2-7: eLoran Horizontal Accuracy at En Route Altitudes

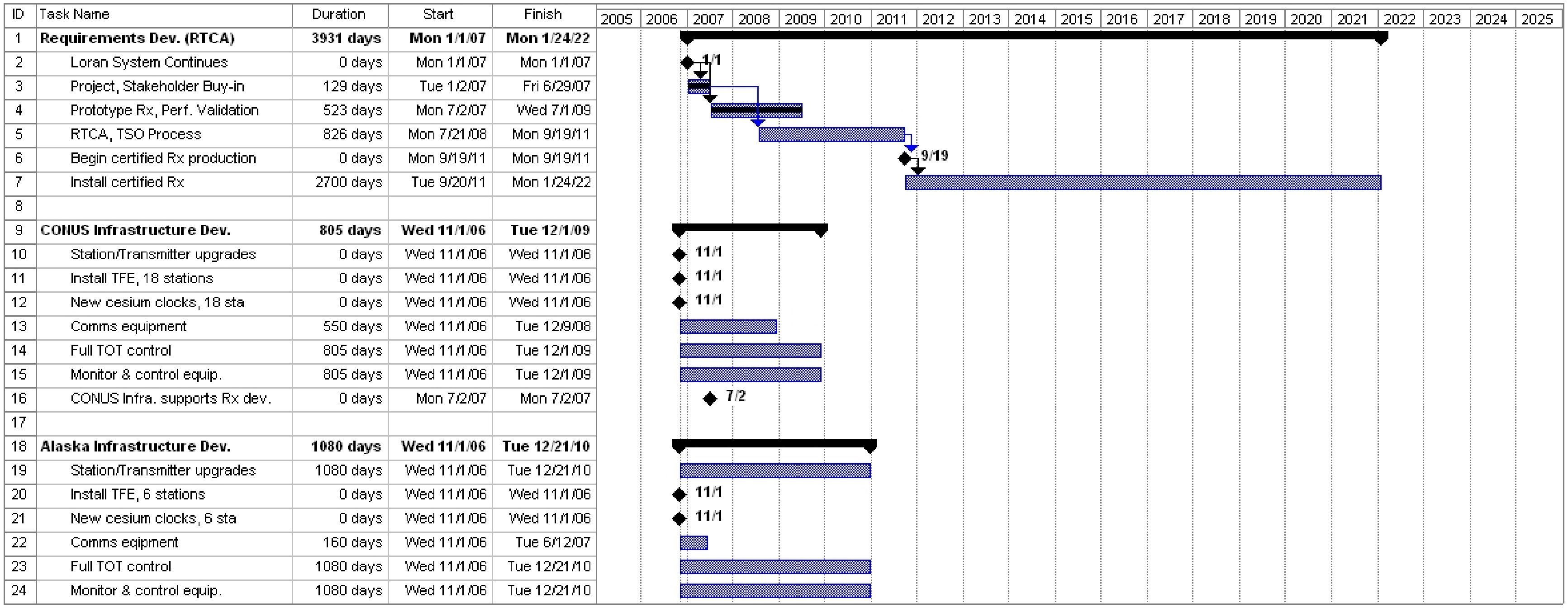
A4.2.3 eLoran Implementation Status

The eLoran Technical Evaluation report, released in June 2004, reached the preliminary conclusion that eLoran can, if fully implemented, satisfy the performance requirements of aviation NPA and maritime HEA operations, as well as serve as a time/frequency reference. Over two years of testing since, involving actual hardware and the operational Loran signal-in-space, have confirmed predicted performance in many key areas, and isolated specific problems in others. It is clear that several important steps must be completed before eLoran can be placed in operational service. Table A4.2-5 below summarizes the status of the elements that comprise eLoran, and Figure 8 on the next page shows the eLoran implementation timeline.

Table A4.2-5: Status of eLoran Elements

Element	Status
Solid-state transmitters	Implemented at all stations plus Kodiak, AK
New time and frequency equipment	Implemented at all CONUS stations plus Kodiak, AK
Ninth pulse	Implemented at five stations; full implementation by 2007
ASF corrections	Not validated, work underway and ongoing
Envelope-to-Cycle Difference	Required additional work underway
Cross Rate Interference	Required additional work underway
Two-Way Satellite Time/Freq Xfer	Required additional work underway
Automated Transmitter Operation	Required additional work underway
New-generation receivers	Prototypes available; MOPS or equivalent not established

The eLoran infrastructure, less certified and installed avionics, will be ready to support the performance standards and avionics development process, as shown in Figure A4.2-8. As the



ID	Task Name	Duration	Start	Finish
1	**Requirements Dev. (RTCA)**	**3931 days**	**Mon 1/1/07**	**Mon 1/24/22**
2	Loran System Continues	0 days	Mon 1/1/07	Mon 1/1/07
3	Project, Stakeholder Buy-in	129 days	Tue 1/2/07	Fri 6/29/07
4	Prototype Rx, Perf. Validation	523 days	Mon 7/2/07	Wed 7/1/09
5	RTCA, TSO Process	826 days	Mon 7/21/08	Mon 9/19/11
6	Begin certified Rx production	0 days	Mon 9/19/11	Mon 9/19/11
7	Install certified Rx	2700 days	Tue 9/20/11	Mon 1/24/22
8				
9	**CONUS Infrastructure Dev.**	**805 days**	**Wed 11/1/06**	**Tue 12/1/09**
10	Station/Transmitter upgrades	0 days	Wed 11/1/06	Wed 11/1/06
11	Install TFE, 18 stations	0 days	Wed 11/1/06	Wed 11/1/06
12	New cesium clocks, 18 sta	0 days	Wed 11/1/06	Wed 11/1/06
13	Comms equipment	550 days	Wed 11/1/06	Tue 12/9/08
14	Full TOT control	805 days	Wed 11/1/06	Tue 12/1/09
15	Monitor & control equip.	805 days	Wed 11/1/06	Tue 12/1/09
16	CONUS Infra. supports Rx dev.	0 days	Mon 7/2/07	Mon 7/2/07
17				
18	**Alaska Infrastructure Dev.**	**1080 days**	**Wed 11/1/06**	**Tue 12/21/10**
19	Station/Transmitter upgrades	1080 days	Wed 11/1/06	Tue 12/21/10
20	Install TFE, 6 stations	0 days	Wed 11/1/06	Wed 11/1/06
21	New cesium clocks, 6 sta	0 days	Wed 11/1/06	Wed 11/1/06
22	Comms eqipment	160 days	Wed 11/1/06	Tue 6/12/07
23	Full TOT control	1080 days	Wed 11/1/06	Tue 12/21/10
24	Monitor & control equip.	1080 days	Wed 11/1/06	Tue 12/21/10

Figure A4.2-8: eLoran Timeline for ADS-B Implementation standards development process is now understood, eLoran is very unlikely to improve much on the 2022 target date for full implementation of certified avionics in the planned GA fleet of 50,000 aircraft. In part, this is because the GA manufacturers contacted by the ADS-B backup strategy teams use a ten-year equipage cycle for GA aircraft.

Sufficient elements of the ground infrastructure have capability at this time to support realistic testing of prototype eLoran aviation receivers; detailed performance testing has been underway for several years and continues.

Loran as a generic system is not global, especially by SATNAV standards. Furthermore, the U.S. alone is actively upgrading its system to eLoran. However, Europe does have nine operating stations in five countries, and utilizes EuroFix, a precursor architecture to eLoran in some respects. The Europeans seem anxious for a positive U.S. decision on its Loran system before undertaking extensive system enhancements.

Saudi Arabia has three stations and just began constructing a fourth. East Asia has several operating stations, part of the Far East Radio-Navigation System: Russia and China have four stations apiece (two of China's are for timing use only), and Japan and Korea have two each. There are no short-term plans for the Asian stations to upgrade to eLoran. An eLoran receiver would be able to use the signals from all of these systems, with varying degrees of performance based on specific system capabilities.

All of the non-North American stations are located to support some of the important international routes in Europe and Asia. There are no southern hemispheric, Central American, or Caribbean area stations, however.

Because the planned use for eLoran is to back up GPS in GA aircraft, there is little anticipated penalty for eLoran's shortcomings in global interoperability, since GA aircraft operating in the U.S would seldom make international flights beyond North America. The same probably holds for foreign GA aircraft, whether or not they equip with Loran. International standards such as those promulgated by ICAO have not yet been developed. The Loran community has begun to plan for interacting with appropriate ICAO standards and harmonization working groups.

Outstanding Technical Issues and Risks

There are no known technical feasibility issues precluding eLoran from supporting GPS/GNSS users of ADS-B. There exist issues related generally to the possible extension of eLoran use beyond that already assumed by the backup strategies technical group, and the cost effectiveness of doing so.

Concerning spectrum protection for the Loran signal, there presently is an allocation for Radionavigation, which includes aeronautical radionavigation as a subset. The footnote US104 is relevant. It gives priority in the U.S. and its insular areas to Loran in the 90-110 kHz band. Operation by Federal and non-Federal licensees is subject to various conditions, including on-the-air testing, that may be required to ensure protection of Loran from harmful interference and to ensure compatibility among radiolocation operators. Also, Section K.3.2 of the National

Telecommunication and Information Administration (NTIA) Manual permits only spurious emissions in the frequency bands including Loran's. The band is specifically identified for Loran-C radionavigation. One exception is stated, allowing transmitters used to detect buried electronic markers at 101.4 kHz, used by telephone companies. Federal Communication Commission (FCC) rules, Part 87 (dealing with aviation), states the following: "Frequencies available for radionavigation land stations. Loran-C is a long range navigation system which operates in the 90-110 kHz band…" The FAA Spectrum Office feels there therefore may not be a need for an allocation change in order to provide aeronautical protection in the U.S. There may be more of an issue concerning international Radio Regulations.

If a change to the allocation table is needed, approval must be obtained from both FCC and NTIA for a proposal to change the international table, and this is not easy to do. It includes getting on the agenda of a future World Radiocommunication Conference (WRC). The 2007 and 2010 conferences apparently have full agendas already, making the earliest possible one in 2014. The Spectrum Office suggests this action be avoided unless absolutely necessary.

The signal-in-space NPA performance requirements include horizontal 95% accuracy at 220 meters (about 0.12 nmi), and an integrity risk of 1 – 0.9999999. From the RNP/RNAV Minimum Aviation System Performance Standard (MASPS), the RNP-0.3 Total System Error is 0.3 nmi, or about 556 meters, 95%. The cross-track RNP-0.3 integrity containment limit is 2*0.3, or 0.6 nmi, and the integrity risk is also 1 – 0.9999999. Testing eLoran equipment while executing controlled approaches in the NAS indicates that, as long as ASFs are used properly and managed well, eLoran can support RNP-0.3 accuracy and integrity requirements almost wherever it supports NPA accuracy and integrity requirements.

A5. Strategy 5: SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA

This strategy combines the capabilities of secondary radar, DME/DME/IRU, and enhanced (multiple-frequency, expanded satellite constellation) SATNAV to provide backup surveillance capabilities for all aircraft in the required airspace. In high density terminal areas, a reduced secondary radar network is retained to maintain terminal area capacity and accuracy requirements for all aircraft. In medium density airspace (both en route and terminal), Air Transport category aircraft will take advantage of enhanced SATNAV capabilities to support backup surveillance; in those instances when enhanced SATNAV is not available (e.g., due to multi-frequency interference), Air Transport aircraft will use DME/DME/IRU avionics and the DME ground infrastructure that will be retained for navigation purposes to provide a reduced backup surveillance level of performance. General Aviation category aircraft will use enhanced SATNAV alone in medium density airspace to support backup surveillance, and will accept the risk of reduced access to certain airspace when enhanced SATNAV is not available. As with Strategy 1, primary radar will be used to mitigate single-aircraft avionics failures in terminal areas.

Since this strategy incorporates different components used in some of the other strategies described in this report, the technologies used in this strategy are described elsewhere: SSR capabilities for high-density terminal areas are discussed under Strategy 1; DME/DME/IRU capabilities are discussed under Strategy 4; and Enhanced SATNAV capabilities are discussed under Strategy 6.

A6. Strategy 6: SATNAV Only

A6.1 Overview

This strategy uses the GPS L5 and the Galileo E1/E5a signals as a backup to the loss of the GPS L1 signal (the ADS-B primary positioning source) for all aircraft. Other potential GNSS signals are also considered within this strategy. The coverage and performance of this strategy satisfies en route and terminal requirements for backup surveillance. Its primary limitation is that it is nearly as vulnerable to RF interference (RFI) as is the primary positioning source. As with Strategy 1, primary radar will be used to mitigate single-aircraft avionics failures in terminal areas.

A6.2 Architecture

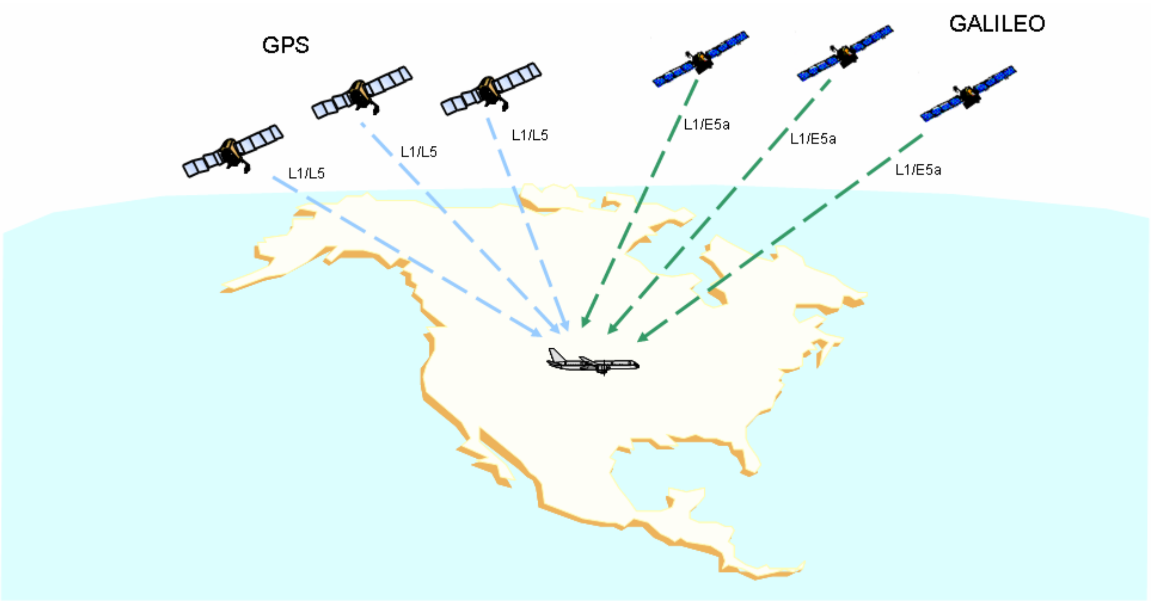


Figure A6-1: SATNAV Strategy

The SATNAV strategy relies upon future generations of GPS satellites, beginning with the GPS Block IIF, and continuing with the GPS Block III. These satellites will broadcast two navigation signals within the ITU Aeronautical Radio Navigation Service (ARNS) bands. These two signals are centered at 1575.42 MHz (L1) and 1176.45 MHz (L5). This strategy also uses the planned Galileo constellation of satellites, which will broadcast navigation signals at the same two frequencies (the Galileo signals are termed E1 and E5a). A dual-frequency SBAS is also assumed to be available (L1/L5), but its use is not explicitly assumed in the analysis as the ADS-B performance for 3 nmi and 5 nmi separation applications would be adequate without considering the SBAS signals. Those signals could affect more demanding ADS-B applications, but are beyond the scope of this study. The Galileo Safety of Life (SoL) service (using the Galileo E5b signal), or a comparable signal from GPS III, may also provide additional performance improvement similar to dual-frequency SBAS. However, its use will increase user costs (particularly for antennas that maintain radio frequency independence between E5a and E5b) and may carry other restrictions or fees as the safety-of-life service has not been designated as open for general use. Global Navigation Satellite System (GLONASS) signals may optionally be used for further enhancement or as risk mitigation in the event a full Galileo constellation does not materialize. Each of these additional signals bear additional program risks, add some schedule delay and costs to the avionics, and have no effect on the primary GPS vulnerability of interference. For these reasons, these alternatives are not discussed further in this report, but contribute to the expandability/flexibility of this solution.

Note that this strategy is not totally dependent upon Galileo in that adequate surveillance performance will typically be achieved with GPS alone; however, the combined GPS/Galileo constellation will be more robust to degradation in the GPS constellation. There are nominally 24 satellites in the GPS constellation and there are planned to be 27 satellites plus 3 spares in the Galileo constellation. The US is also studying the feasibility and advantages of expanding the GPS constellation to a larger constellation. The current U.S. policy is to provide 21 healthy and transmitting satellites in primary orbital slots 98% of the time.

The user avionics would receive both signals from each satellite in view. Normally, a minimum of four satellites would need to be tracked by the avionics to compute a position, and five satellites to provide integrity. When using satellites from both GPS and Galileo constellations in a combined solution, one additional satellite may be needed in order to compute the time offset between GPS-time and Galileo-time (if Galileo doesn’t provide this offset).

If there should be interference on L1 (the GPS signal used for the ADS-B primary position source), the avionics would be able to continue to compute a position solution using the navigation signals from the two constellations on L5 and E5a. However, if there should be interference on both L1 and L5/E5a, then the avionics would not be able to compute a position solution. An assumption used in the evaluation of the operational capability of this strategy is that there would no intentional (planned testing) interference on L1 and L5 simultaneously in peacetime in the NAS (outside of oceanic airspace). This assumption needs to be confirmed.

Horizontal position accuracy is typically reported as the Horizontal Figure of Merit (HFOM). The HFOM is a 95% bound on the horizontal position error. The HFOM is a function of the user-satellite geometry, as reflected in the horizontal dilution of precision (HDOP). Figure A6-2 shows the HFOM for a combined GPS/Galileo constellation, where HFOM was computed using:

$$HFOM \approx 2\sigma_r \cdot HDOP$$

where σ_r is the standard deviation of the range error for each measurement. For a single-frequency receiver (since this evaluation applies to ADS-B in backup mode), a typical value for σ_r is 6 m, resulting in 95% horizontal accuracy of between 9 and 11 m throughout CONUS.

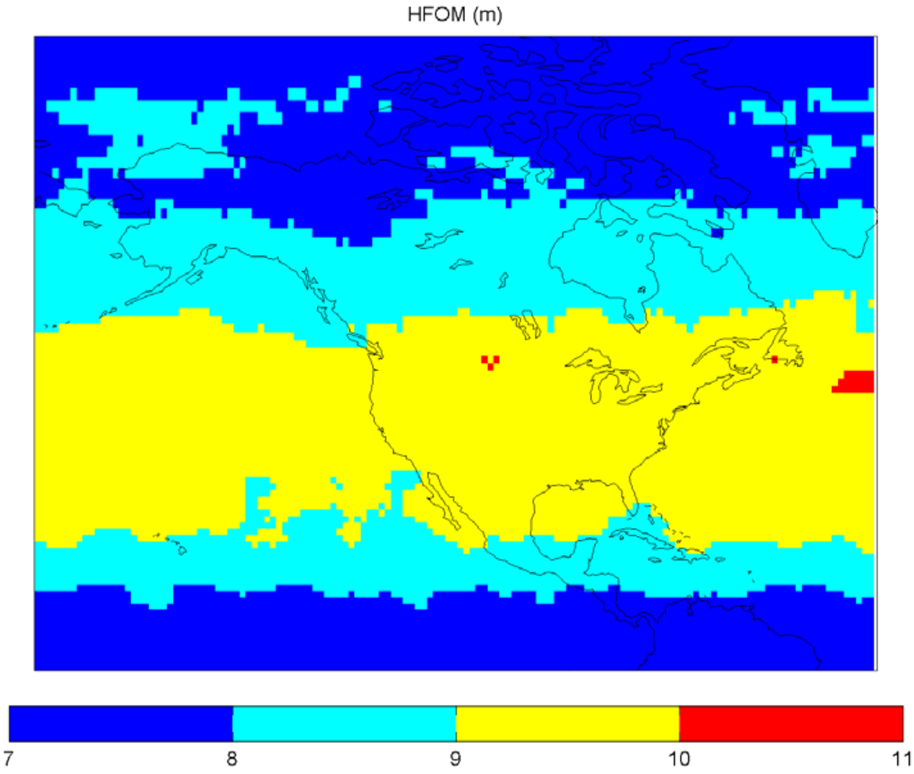


Figure A6-2: Horizontal Figure of Merit (HFOM) for a Combined GPS/Galileo Constellation

The availability of positioning with integrity for a combined GPS/Galileo constellation is shown in Figure A6-3. This result was obtained using a computer model that take into consideration user/satellite geometry and the performance of Receiver Autonomous Integrity Monitor (RAIM) algorithms with a Horizontal Alert Limit (HAL) of 0.6 nmi. The result shown is the 24 hour average availability of integrity, which is greater than 0.99999 throughout CONUS. This estimate assumes interference on either L1 or L5/E5a, but not both simultaneously. It also assumes individual, uncoupled, GPS and Galileo receivers. An integrated receiver would likely have better performance than indicated here.

Both GPS and Galileo constellations will provide global coverage, so the accuracy, integrity, and availability performance shown above are representative of the performance to be expected globally.

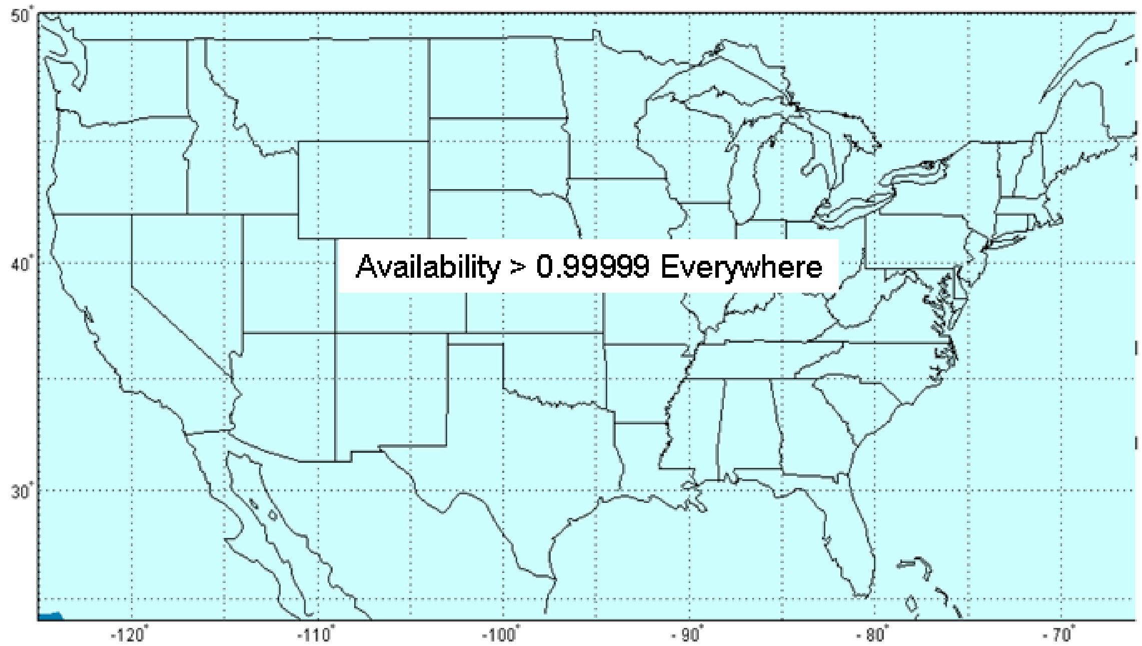


Figure A6-3: SATNAV Availability of Horizontal Containment of 0.6nmi

A6.3 Operational Environment

There are various ways in which avionics can use to advantage a combined constellation of GPS/Galileo satellites. One implementation might be to use the "best source," i.e., the avionics would select and use either GPS or Galileo satellites, depending upon which is providing an adequate level of service for the application. Another implementation might be to integrate and use all the available L1/L5/E1/E5a signals from both constellations. In either case, if there is disruption of the ADS-B GPS L1 signal, the avionics would continue to provide ADS-B positioning outputs using the L5 and/or E5a signals, without interruption. No flight crew interaction would be required, so there would be no impact on the flight crew for ADS-B out. The accuracy with L5/E5a will be similar to the accuracy with L1/E1, a degradation from dual-frequency operation, but still well within the fPR requirements for 3 nmi and 5 nmi separation applications.

In backup mode, this strategy supports Enhanced Visual Acquisition, Enhanced Visual Approach, and Conflict Detection for all aircraft. With augmentations such as SBAS or Ground-Based Augmentation Systems (GBAS) this strategy also supports Airport Surface Situational Awareness and Final Approach and Runway Occupancy Awareness. Ongoing research is investigating if these applications could be supported by GPS and Galileo without the need for an augmentation.

Assuming Galileo achieves full operational capability, dual-frequency GPS/Galileo avionics are likely to become the norm for aviation navigation. The dual-frequency capability mitigates unavailability of single-frequency GPS during precision approach caused by high ionospheric storm activity, and Galileo significantly improves the availability for all phases of flight.

A6.4 Implementation Status

The L5 signal will begin to appear on GPS satellites with the launch of the first Block IIF satellite. A full constellation of 24 L1/L5 GPS satellites is expected by approximately 2020. This estimate is based on the number and age of satellites currently in orbit, the number of satellites in inventory, and the expected mean lifetime of the satellites. The Galileo constellation is expected to be operational by 2014, with at least a two year uncertainty (the official European Union date is 2010).

Signal standards exist for the GPS L5 signal. Draft signal standards also exist for the Galileo signals. Initial work has begun on development of dual-frequency L1/L5 Minimum Operational Performance Standard (MOPS) for SBAS by RTCA SC-159. It would not be difficult to have MOPS ready for the projected equipage schedule. Avionics are expected to become available close to the time a full constellation is available; while standards may be complete before that, there is little market incentive to upgrade to the dual-frequency capability before it becomes available. Airframe manufacturers estimate first certified avionics installed and operational on their aircraft by 2015 (upgrade, full AT fleet equipage assumed by 2020). This date could be several years earlier if Galileo meets its schedule (or close to it) and the standards for GPS L5 are mature.

A7. Strategy 7: SATNAV with Terminal SSR

This strategy is the same as Strategy 6, except that secondary radar is used to provide backup surveillance in high density terminal areas for all Air Transport category aircraft. This is included as part of this strategy in order to provide greater assurance that surveillance for these aircraft will not be lost due to a loss of enhanced SATNAV under any anticipated scenario (i.e., conditions leading to a loss of either single-frequency or multiple-frequency GPS signals).

Since this strategy incorporates different components used in some of the other strategies described in this report, the technologies used in this strategy are described elsewhere: SSR capabilities for high-density terminal areas are discussed under Strategy 1; and Enhanced SATNAV capabilities are discussed under Strategy 6.

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Appendix B - Life Cycle Cost Analysis

B1. Introduction

Since ADS-B technology is heavily dependent on a Global Navigation Satellite System (GNSS), the Surveillance and Broadcast Services (SBS) program was required to identify a backup system or strategy in the event of a GNSS outage - local or global. This Life Cycle Cost Analysis was performed to identify and assess the costs associated with each alternative backup strategy. The results of this analysis, coupled with the technical evaluations, will support the selection of a recommended backup strategy.

Seven different strategies were examined that use ground-based and/or avionics-based methods for providing backup surveillance capabilities: 1) Secondary Radar; 2) Passive Multilateration; 3) Active Multilateration; 4) SSR and DME/DME/IRU for AT, SSR and eLoran for GA; 5) SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA; 6) SATNAV only; and 7) SATNAV with Terminal SSR.

For all strategies, costs were estimated starting in fiscal year 2009 (FY 2009) and ending in FY 2035. Costs are presented in Present Value by applying OMB circular No a94, using a discount rate of 2.9%. All costs shown are point estimates, and have not been risk adjusted. Qualitative assessments of confidence in these cost estimates are provided separately in the sections below.

B2. Ground Infrastructure Life Cycle Cost Analysis

A variety of estimating methodologies were used to derive ground infrastructure life cycle costs: vendor inputs, historical data, analogies to other FAA systems, and parametric modeling. The FAA Standard Work Breakdown Structure (WBS) was used to model the estimated costs. The FAA will bear the full cost burden of the ground infrastructure for any given backup strategy; no ground infrastructure costs are assigned to the user for any backup strategy.

B2.1 Strategy 1 - Secondary Radar

<u>Infrastructure Requirements</u>

The terminal secondary radars (SSRs) at the top 40 airports, in terms of capacity, will be retained in this strategy, which currently consist of Mode S SSRs exclusively; the remaining complement of terminal SSRs will be decommissioned, which currently include a mix of ATCBI-4, ATCBI-5, and (remaining) Mode S SSRs, and the SSR portion of ASR-11s. Additionally, 150 en route SSRs will be retained, which currently consist of a mix of Mode S and ATCBI-6 SSRs. As with all the backup strategies being considered, all current terminal primary radars (PSRs) will be retained, which consist of a mix of ASR-8 and ASR-9 PSRs, and the PSR portion of ASR-11s. There are no automation changes required by this strategy, and no new or updated avionics will be required. All systems will be located at existing FAA surveillance facilities. Replacements to the infrastructure being retained will be required as legacy radar systems reach the end of their respective life cycles. This strategy requires the continued use of Mode A/C/S transponders;

therefore there are no dependencies on rulemaking timelines, as existing transponder carriage rules will continue to apply. Table B2-1a shows baseline and future system quantities required for this strategy.

Table B2-1a: System Quantities, Strategy 1

System	Baseline Quantity		Future Quantity		Schedule
	Terminal	En Route	Terminal	En Route	
ASR-8	32	n/a	32	n/a	No Change
ASR-9	117		117		
ASR-11 (PSR Only)	66		66		
ASR-11 (SSR Only)	66	0	0	0	All systems to be decommissioned over a 7 year period from 2018-2024
ATCBI-4/5	32				
ATCBI-6	0	123	0	123	No Change
Mode S	117	27	40	27	77 terminal systems to be decommissioned over a 7 year period from 2018-2024

<u>Ground Rules and Assumptions</u>

As with all the strategies, this analysis excludes all costs associated with PSRs throughout the life cycle of the ADS-B program, since each of these systems will be required for all backup strategies being considered, and provide no discriminating factors between strategies upon which to base a comparison. This analysis also excludes all costs associated with SSRs that would have been incurred regardless of the backup strategy selected; i.e., only those costs that will be incurred to sustain or replace the SSRs that will be retained beyond 2020 were included. Beyond 2020, this strategy will retain approximately half of the SSRs for the remainder of the life cycle of the ADS-B program (through 2035). Projected costs associated with decommissioning SSRs fall well within the margin of error for this analysis, and are not accounted for separately.

The analysis life cycle extends from FY 2009 to FY 2035. The radar Economic Service Life (ESL) is assumed to be 20 years. When existing radars reach the end of their life cycle, those that will be retained in this strategy will be replaced with similar technology. The replacement will begin 3-5 years after the ESL to acknowledge that the FAA often sustains these systems beyond the 20 year ESL. Future replacement costs of systems being retained beyond 2020 (i.e., replacement of Mode S and ATCBI-6 systems) are included in the analysis, and are based on the ATCBI-6 Capital Investment Plan (CIP), scaled to appropriate system quantities.

A 15% factor on acquisition cost was used to account for technical refresh costs on systems being retained, and spread evenly over the ESL. Operations and Maintenance (O&M) costs are included, and will accrue throughout the life cycle. For ASR-11 radars, only the costs associated with decommissioning the secondary radar portions of these systems were included in this analysis. These costs were derived by analogy to ATCBI-6 costs, applying a 23% factor for F&E and a 38% factor for O&M to account for the secondary radar portions.

Table B2-1b shows the ground infrastructure life cycle cost estimate by year for this strategy.

Table B2-1b: Ground Infrastructure Cost Summary, Strategy 1 ($M, Present Value)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021+	Total
FAA Costs														
F&E	0	0	0	0	0	0	0	0	11.5	11.4	11.2	11.1	222.9	268.1
O&M	0	0	0	0	0	0	0	0	0	0.3	0.6	0.9	172.1	173.9
Total Costs	0	0	0	0	0	0	0	0	11.5	11.7	11.8	12.0	395.0	442.0

B2.2 Strategy 2 - Passive Multilateration

Infrastructure Requirements

This strategy will require the installation of 1,780 receive-only (RO) ground stations. Terminal coverage will require 280 ROs, broken down into clusters of 7 ROs that will cover each terminal area (equivalent coverage volume of an existing terminal SSR) at the top 40 airports, in terms of capacity. En route coverage will require 1,500 ROs, broken down into clusters of 10 ROs at 150 locations (each cluster providing coverage equivalent to the coverage volume of an existing en route SSR). It should be noted, however, that this strategy will leverage the planned ADS-B ground station infrastructure, such that ADS-B ground stations will be able to serve as ROs for passive multilateration by the nature of their performance requirements; this analysis assumes that the ADS-B infrastructure will account for one multilateration ground station per cluster, thereby reducing the requirement for the multilateration-specific infrastructure to 6 ROs for each terminal area cluster, and 9 ROs for each en route cluster, for a total of 1590 ROs. Two processors will be required per cluster for processing multilateration data, for a total of 380 processors. This analysis also assumes that 50% of the ground stations sites required for terminal coverage will be greenfield sites (no existing infrastructure currently in place), and 80% of the ground station sites required for en route coverage will also be greenfield sites.

This strategy will maintain the secondary radar infrastructure until the Passive Multilateration infrastructure is completed, at which time all secondary radars will be retired. As with Strategy 1, all terminal primary radars will be retained. No new or updated avionics will be required for this strategy. Table B2-2a shows baseline and future system quantities required for this strategy.

Ground Rules and Assumptions

The analysis includes all costs associated with Passive Multilateration for a life cycle beginning in FY 2009 and ending in FY 2035, with all systems being commissioned by FY 2020. Automation development costs were included in the analysis, and based on analogy to the ASDE-X program. Construction and installation costs were also based on analogy to the ASDE-X program. Greenfield site costs account for telecommunications and utility infrastructure, as well as more extensive construction and installation requirements. Technical refresh costs were included for all hardware and software, and is estimated at 20% of the acquisition cost for two refresh cycles. O&M costs accrue throughout the life cycle, and were based on analogy to ASDE-X. Projected costs associated with decommissioning SSRs fall well within the margin of

Table B2-2a: System Quantities, Strategy 2

System	Baseline Quantity		Future Quantity		Schedule
	Terminal	En Route	Terminal	En Route	
ASR-8	32	n/a	32	n/a	No Change
ASR-9	117		117		
ASR-11 (PSR Only)	66		66		
ASR-11 (SSR Only)	66	0	0	0	All systems to be decommissioned over a 7 year period from 2018-2024
ATCBI-4/5	32	0			
ATCBI-6	0	123			
Mode S	117	27			
ROs	40*	150*	280	1500	1590 additional systems to be deployed and commissioned over an 8 year period from 2012-2020

*Quantity of planned ADS-B ground stations to be deployed that will also serve as ROs for passive multilateration.

error for this analysis, and are not accounted for separately. As with all the strategies, this analysis excludes all costs associated with PSRs throughout the life cycle of the ADS-B program. Table B2-2b shows the ground infrastructure life cycle cost estimate by year for this strategy.

Table B2-2b: Ground Infrastructure Cost Summary, Strategy 2 ($M, Present Value)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021+	Total
FAA Costs														
F&E	0	0	0	3.0	7.4	98.5	129.4	122.8	86.6	62.0	38.5	37.0	78.3	663.5
O&M	0	0	0	0	3.3	0	0	0	4.1	5.4	11.9	16.6	471.5	512.8
Total Costs	0	0	0	3.0	10.7	98.5	129.4	122.8	90.7	67.4	50.4	53.6	549.8	1176.3

B2.3 Strategy 3 - Active Multilateration

Infrastructure Requirements

This strategy will require 1,100 ground stations, of which 550 will be receive-only (RO) and 550 will be receive/transmit (RT). Terminal coverage will require 200 ground stations, grouped in clusters of 5 (approximately 2-3 ROs and 2-3 RTs in each cluster, depending on geometry requirements) that will cover each terminal area (equivalent coverage volume of an existing terminal SSR) at the top 40 airports. En route coverage will require 900 ground stations, grouped in clusters of 6 (approximately 3 ROs and 3 RTs in each cluster, depending on geometry requirements) at 150 locations (each cluster providing coverage equivalent to the coverage volume of an existing en route SSR). Unlike Strategy 2, due to the nature of the active multilateration performance requirements, the planned ADS-B ground station infrastructure cannot be significantly leveraged to reduce the total number of multilateration-specific ground stations. Two processors will be required per cluster for processing multilateration data, for a total of 380 processors. This analysis also assumes that 40% of the ground sites required for terminal coverage and 80% of the ground station sites required for en route coverage will be greenfield sites.

This strategy will maintain the secondary radar infrastructure until the Active Multilateration infrastructure is completed, at which time all secondary radars will be retired. No new or updated avionics will be required. As with Strategy 1, all terminal primary radars will be retained. Table B2-3a shows baseline and future system quantities required for this strategy.

Table B2-3a: System Quantities, Strategy 3

System	Baseline Quantity		Future Quantity		Schedule
	Terminal	En Route	Terminal	En Route	
ASR-8	32	n/a	32	n/a	No Change
ASR-9	117		117		
ASR-11 (PSR Only)	66		66		
ASR-11 (SSR Only)	66	0	0	0	All systems to be decommissioned over a 7 year period from 2018-2024
ATCBI-4/5	32	0			
ATCBI-6	0	123			
Mode S	117	27			
ROs	0	0	100	450	All systems to be deployed and commissioned over an 8 year period from 2012-2020
RTs			100	450	

Ground Rules and Assumptions

The analysis includes all costs associated with Active Multilateration for a life cycle beginning in FY 2009 and ending in FY 2035, with all systems being commissioned by FY 2020. Automation development costs were included in the analysis, and based on analogy to the ASDE-X program. Construction and installation costs were also based on analogy to the ASDE-X program. Greenfield site costs account for telecommunications and utility infrastructure, as well as more extensive construction and installation requirements. Technical refresh costs were included for all hardware and software, and are estimated at 20% of the acquisition cost for two refresh cycles. O&M costs accrue throughout the life cycle, and were based on analogy to ASDE-X. Projected costs associated with decommissioning SSRs fall well within the margin of error for this analysis, and are not accounted for separately. As with all the strategies, this analysis excludes all costs associated with PSRs throughout the life cycle of the ADS-B program. Table B2-3b shows the ground infrastructure life cycle cost estimate by year for this strategy.

Table B2-3b: Ground Infrastructure Cost Summary, Strategy 3 ($M, Present Value)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021+	Total
FAA Costs														
F&E	0	0	0	3.0	7.3	103.2	132.2	125.3	86.3	29.8	36.3	24.8	69.4	617.6
O&M	0	0	0	0	1.9	0	0	0	2.4	3.6	4.4	9.6	215.0	236.9
Total Costs	0	0	0	3.0	9.2	103.2	132.2	125.3	88.7	33.4	40.7	34.4	284.4	854.5

B2.4 Strategy 4 - SSR and DME/DME/IRU for AT, SSR and eLoran for GA

Infrastructure Requirements

This strategy will require three basic infrastructure components. The first is a network of approximately 1100 DME ground stations, which will support DME/DME/IRU positioning capability for properly equipped (large) Air Transport aircraft in en route airspace. This network is the same as that currently planned as part of the NAS navigation backup capability, and so no additional DME infrastructure beyond this will be required for this strategy. The second component is a network of 19 eLoran ground stations, which will support eLoran positioning capability for properly equipped Regional Jet and General Aviation aircraft in en route airspace. This network will include one new tower and 5 tower Service Life Extension Programs (SLEPs) for Loran stations in Alaska, a SLEP and a new building for a Loran solid-state transmitter, and moving the Port Clarence, AK Loran station to Nome, AK. The last basic component for this strategy is a network of 40 terminal SSRs, which will provide backup surveillance capability in high density terminal airspace for all aircraft equipped with legacy Mode A/C/S transponders.

This strategy will maintain the secondary radar infrastructure until the required backup ground infrastructure is in place, and all aircraft in the required airspace are equipped with the proper avionics, at which time all secondary radars except the 40 terminal SSRs required by this strategy will be retired. As with Strategy 1, all terminal primary radars will be retained. Table B2-4a shows the baseline and future system quantities required for this strategy.

Table B2-4a: System Quantities, Strategy 4

System	Baseline Quantity		Future Quantity		Schedule
	Terminal	En Route	Terminal	En Route	
ASR-8	32	n/a	32	n/a	No Change
ASR-9	117		117		
ASR-11 (PSR Only)	66		66		
ASR-11 (SSR Only)	66	0	0	0	All systems to be decommissioned over a 7 year period from 2018-2024
ATCBI-4/5	32	0			
ATCBI-6	0	123			
Mode S	117	27	40	0	77 terminal systems and all en route systems to be decommissioned over a 7 year period from 2018-2024
DME	n/a	1025	n/a	~1100*	~75 additional systems to be deployed and commissioned over a 6 year period from 2008-2014
eLoran		19		19	No Change

*Part of NAS Navigation Evolution plan, no additional infrastructure required by this strategy.

Ground Rules and Assumptions

Costs for eLoran ground infrastructure are based on FAA/Volpe eLoran cost estimates, and include maintenance costs of the system starting in FY 2009. DME ground infrastructure costs were not captured as part of this analysis, since the FAA will fund the required DME infrastructure in order to support NAS backup navigation capabilities, regardless of the NAS ADS-B backup strategy selected. Costs associated with retaining the 40 terminal SSRs are accounted for; projected costs associated with decommissioning the remaining SSRs fall within the margin of error for this analysis, and are not accounted for separately. New or upgraded avionics required for this strategy are discussed in detail in Section B3. Table B2-4b shows the ground infrastructure life cycle cost estimate by year for this strategy.

Table B2-4b: Ground Infrastructure Cost Summary, Strategy 4 ($M, Present Value)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021+	Total
FAA Costs														
F&E	0	0	0	0	0	0	0	10.4	19.1	25.0	14.0	15.0	47.8	131.3
O&M	14.2	13.8	13.4	13.0	12.6	12.3	11.9	11.6	11.3	11.0	10.7	10.5	224.5	370.8
Total Costs	14.2	13.8	13.4	13.0	12.6	12.3	11.9	22.0	30.4	36.0	24.7	25.5	272.3	502.1

B2.5 Strategy 5 - SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA

Infrastructure Requirements

This strategy will require three basic infrastructure components. As with Strategy 4, the first component is a network of approximately 1100 DME ground stations, which will support DME/DME/IRU positioning capability for properly equipped (large) Air Transport aircraft in en route airspace. This network is the same as that currently planned as part of the NAS navigation backup capability, and so no additional DME infrastructure beyond this will be required for this strategy. Unlike Strategy 4, however, the second component required by this strategy is a constellation of 21 GPS satellites that incorporate L5 signal capability, and a constellation of 24 Galileo satellites. These constellations will provide enhanced SATNAV capability for properly equipped aircraft in all airspace. However, since the use of enhanced SATNAV will not fully mitigate multi-frequency interference, another component will be required to ensure that surveillance in high density terminal areas is maintained under these conditions. Therefore, as in Strategy 4, the last component required is a network of 40 terminal SSRs, which will ensure backup surveillance capability in high density terminal airspace for all aircraft equipped with legacy Mode A/C/S transponders.

This strategy will maintain the secondary radar infrastructure until the required backup ground infrastructure is in place, and all aircraft in the required airspace are equipped with the proper avionics, at which time all secondary radars except the 40 terminal SSRs required by this strategy will be retired. As with Strategy 1, all terminal primary radars will be retained. Table B2-5a shows baseline and future system quantities required for this strategy.

Table B2-5a: System Quantities, Strategy 5

System	Baseline Quantity		Future Quantity		Schedule
	Terminal	En Route	Terminal	En Route	
ASR-8	32	n/a	32	n/a	No Change
ASR-9	117		117		
ASR-11 (PSR Only)	66		66		
ASR-11 (SSR Only)	66	0	0	0	To be decommissioned completely over a 7 year period from 2018-2024
ATCBI-4/5	32	0			
ATCBI-6	0	123			
Mode S	117	27	40	0	77 terminal systems and all en route systems to be decommissioned over a 7 year period from 2018-2024
DME	1025		~1100*		~75 additional systems to be deployed and commissioned over a 6 year period from 2008-2014
GPS Satellite (L5)	0		21**		Systems to be deployed and commissioned over a 10 year period from 2008-2017
Galileo Satellite	0		27***		Systems to be deployed and commissioned over a 9 year period from 2007-2015

*Part of NAS Navigation Evolution plan, no additional infrastructure required by this strategy.
**Guaranteed quantity (at 98% availability), per current U.S. policy, no additional satellites required by this strategy.
***Part of European GNSS implementation, no additional satellites required by this strategy.

Ground Rules and Assumptions

SATNAV constellation costs were not captured as part of this analysis, since it is assumed that these will be implemented regardless of any projected surveillance backup positioning requirements. Also, as with Strategy 4, DME ground infrastructure costs were not captured as part of this analysis, since the FAA will fund the required DME infrastructure in order to support NAS backup navigation capabilities, regardless of the NAS ADS-B backup strategy selected. Costs associated with retaining the 40 terminal SSRs are accounted for; projected costs associated with decommissioning the remaining SSRs fall within the margin of error for this analysis, and are not accounted for separately. New or upgraded avionics required for this strategy are discussed in detail in Section B3. Table B2-5b shows the ground infrastructure life cycle cost estimate by year for this strategy.

Table B2-5b: Ground Infrastructure Cost Summary, Strategy 5 ($M, Present Value)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021+	Total
FAA Costs														
F&E	0	0	0	0	0	0	0	0	8.4	8.2	8.1	8.0	41.0	73.7
O&M	0	0	0	0	0	0	0	0	0	0	0.1	0.1	100.2	100.4
Total Costs	0	0	0	0	0	0	0	0	8.4	8.2	8.2	8.1	141.2	174.1

B2.6 Strategy 6 - SATNAV only

Infrastructure Requirements

This strategy will require a constellation of 21 GPS satellites that incorporate L5 signal capability, and a constellation of 24 Galileo satellites, which will provide enhanced SATNAV capability for properly equipped aircraft in all airspace. This strategy will rely solely on the positioning capabilities supported by enhanced SATNAV, without any other ground-based surveillance infrastructure.

This strategy will maintain the secondary radar infrastructure until all aircraft in the required airspace are equipped with the proper avionics, at which time all secondary radars will be retired. As with Strategy 1, all terminal primary radars will be retained. The avionics requirements for this solution are discussed in detail below in Section B3. Table B2-6 shows baseline and future system quantities required for this strategy.

Table B2-6: System Quantities, Strategy 6

System	Baseline Quantity		Future Quantity		Schedule
	Terminal	En Route	Terminal	En Route	
ASR-8	32	n/a	32	n/a	No Change
ASR-9	117		117		
ASR-11 (PSR Only)	66		66		
ASR-11 (SSR Only)	66	0	0	0	All systems to be decommissioned over a 7 year period from 2018-2024
ATCBI-4/5	32	0			
ATCBI-6	0	123			
Mode S	117	27			
GPS Satellite (L5)	0		21*		Systems to be deployed and commissioned over a 10 year period from 2008-2017
Galileo Satellite	0		27**		Systems to be deployed and commissioned over a 9 year period from 2007-2015

*Guaranteed quantity (at 98% availability), per current U.S. policy, no additional satellites required by this strategy.
**Part of European GNSS implementation, no additional satellites required by this strategy.

Ground Rules and Assumptions

As with Strategy 5, SATNAV constellation costs were not captured as part of this analysis, since it is assumed that these will be implemented regardless of any projected surveillance backup positioning requirements. Therefore, this strategy does not incur any additional costs for ground infrastructure beyond what is required for ADS-B. Projected costs associated with decommissioning SSRs fall within the margin of error for this analysis, and are not accounted for separately.

B2.7 Strategy 7 - SATNAV with Terminal SSR

Infrastructure Requirements

As in Strategy 6, this strategy will require a constellation of 21 GPS satellites that incorporate L5 signal capability, and a constellation of 24 Galileo satellites, which will provide enhanced SATNAV capability for properly equipped aircraft in all airspace. Unlike Strategy 6, however, this strategy will also require a network of 40 terminal SSRs, which will ensure backup surveillance capability in high density terminal airspace for all aircraft equipped with legacy Mode A/C/S transponders.

This strategy will maintain the secondary radar infrastructure until the required backup ground infrastructure is in place, and all aircraft in the required airspace are equipped with the proper avionics, at which time all secondary radars except the 40 terminal SSRs required by this strategy will be retired. As with Strategy 1, all terminal primary radars will be retained. Table B2-7a shows baseline and future system quantities required for this strategy.

Table B2-7a: System Quantities, Strategy 7

System	Baseline Quantity		Future Quantity		Schedule
	Terminal	En Route	Terminal	En Route	
ASR-8	32	n/a	32	n/a	No Change
ASR-9	117		117		
ASR-11 (PSR Only)	66		66		
ASR-11 (SSR Only)	66	0	0	0	To be decommissioned completely over a 7 year period from 2018-2024
ATCBI-4/5	32	0			
ATCBI-6	0	123			
Mode S	117	27	40	0	77 terminal systems and all en route systems to be decommissioned over a 7 year period from 2018-2024
GPS Satellite (L5)	0		21*		Systems to be deployed and commissioned over a 10 year period from 2008-2017
Galileo Satellite	0		27**		Systems to be deployed and commissioned over a 9 year period from 2007-2015

*Guaranteed quantity (at 98% availability), per current U.S. policy, no additional satellites required by this strategy.
**Part of European GNSS implementation, no additional satellites required by this strategy.

Ground Rules and Assumptions

As with Strategy 5, SATNAV constellation costs were not captured as part of this analysis, since it is assumed that these will be implemented regardless of any projected surveillance backup positioning requirements. Costs associated with retaining the 40 terminal SSRs are accounted for; projected costs associated with decommissioning the remaining SSRs fall within the margin of error for this analysis, and are not accounted for separately. New or upgraded avionics required for this strategy are discussed in detail in Section B3. Table B2-7b shows the ground infrastructure life cycle cost estimate by year for this strategy.

Table B2-7b: Ground Infrastructure Cost Summary, Strategy 7 ($M, Present Value)

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021+	Total
FAA Costs														
F&E	0	0	0	0	0	0	0	0	8.4	8.2	8.1	8.0	41.0	73.7
O&M	0	0	0	0	0	0	0	0	0	0	0.1	0.1	100.2	100.4
Total Costs	0	0	0	0	0	0	0	0	8.4	8.2	8.2	8.1	141.2	174.1

B3. Avionics Life Cycle Cost Analysis

This analysis documents the avionics assumptions, equipage rates, and costs for each of the backup strategies. Cost estimates were based on collective vendor inputs, and were identified only for those additional avionics components that would be required for the specific backup strategy, as compared to the ADS-B equipage baseline. The user will bear the full cost burden of any equipage required to support a given backup strategy; no equipage costs are assigned to the FAA for any backup strategy.

B3.1 General Ground Rules and Assumptions

Equipage

This analysis assumes that aircraft will equip with the backup capability, if required, at the same time they equip with the ADS-B capability, which minimizes the time an aircraft is out of service. Only retrofit equipage is considered in this analysis; those aircraft that are forward fitted with ADS-B are also assumed to be forward fitted with the backup capability, and so costs related to those specific aircraft are not assessed.

For Air Transport (AT) aircraft, equipage with the backup capability occurs on all aircraft considered for ADS-B retrofit (approximately 2,400 large AT aircraft out of 8,100 total by 2020, and approximately 2,700 regional jet aircraft out of 4,000 total by 2020). This includes those aircraft ranging from those not equipped with any avionics required for ADS-B capability, to those that have some latent equipage related to ADS-B (e.g., aircraft that have GPS installed but no ADS-B transmitters/receivers). All classes of AT aircraft, grouped into Large AT and Regional Jet categories, are included in the analysis.

For General Aviation (GA) aircraft, equipage with the backup capability occurs for 25% of those that will equip with ADS-B (approximately 48,000 out of 210,000 total by 2020), which this analysis assumes represents the GA Instrument Flight Rules (IFR) fleet. The remaining aircraft of those equipping with ADS-B will not require the backup capability, since this analysis assumes that these aircraft will be flying Visual Flight Rules (VFR) exclusively, or that they would be willing to accept significantly reduced services in airspace requiring the backup capability.

Costs

Only the costs required to obtain the backup capability are considered in this analysis. These are defined as the additional costs for the airborne backup capability that were not captured in the previous cost analysis for the ADS-B program (JRC-2B of June 2006). In most cases, installation costs are not included, since aircraft are assumed to equip with the backup capability at the time they equip with ADS-B, and the additional installation costs associated with the backup capability are assumed to fall within the margin of error of this analysis. The only exception to this is in Strategy 4, where the installation costs for an additional eLoran receive antenna on some aircraft were assumed to be of significance, and were therefore captured in this analysis.

B3.2 Strategies 1, 2 and 3 - Ground-Based Surveillance (SSR and Multilateration)

None of these strategies will require any new or upgraded avionics beyond what is required to support ADS-B capabilities. Strategy 1 (Secondary Radar) and Strategy 3 (Active Multilateration) will require all aircraft in the required airspace to retain their legacy Mode A/C/S transponders to support backup surveillance; Strategy 2 (Passive Multilateration) will require all aircraft in the required airspace to have baseline ADS-B “Out” equipage, using one of the two approved links (1090ES or UAT). Since there will be no additional retrofit equipage costs incurred to support these backup strategies (above what is required for ADS-B), no retrofit equipage cost analyses were performed.

B3.3 Strategy 4 - SSR and DME/DME/IRU for AT, SSR and eLoran for GA

Equipage Requirements

This strategy will require all aircraft in the required airspace to have either DME/DME/IRU or eLoran capability, serving as a backup surveillance positioning source with appropriate interfaces to ADS-B avionics, along with legacy Mode A/C/S transponders to support surveillance in high density terminal areas.

No changes to existing DME/DME/IRU capabilities will be required for this strategy; DME/DME/IRU capabilities as they are defined for AT aircraft today are assumed. For those aircraft that will equip with eLoran instead of DME/DME/IRU, this strategy will require the addition of eLoran avionics and an eLoran Receive Antenna. Depending on the particular aircraft, this analysis assumes that eLoran avionics could be implemented either as a stand-alone receiver with additional processing to handle switchovers from GPS, or as an integrated GPS/eLoran receiver with the same functionality.

Ground Rules and Assumptions

This analysis assumes that all large AT aircraft will have DME/DME/IRU capability implemented within the required time frame, regardless of any requirements for backup surveillance positioning in the aircraft. Therefore, retrofit costs for DME/DME/IRU avionics are not assessed in this analysis for these aircraft. It is assumed that Regional Jet aircraft (those without an IRU) will not have DME/DME/IRU capability in this time frame.

This analysis assumes that all Regional Jet aircraft not already equipped with an IRU will equip with eLoran using an eLoran module (approximately $60K per module) and an eLoran receive antenna. Each antenna will require an Antenna Installation Kit, which is an additional installation cost (approximately $10K per aircraft) that was not captured in the ADS-B Program's previous cost estimate (JRC-2B of June 2006). For those GA aircraft that equip with eLoran, this analysis assumes that half of these will be retrofitted with an integrated GPS/eLoran unit (approximately $20K per unit), while the remaining half will be retrofitted with a separate eLoran unit (approximately $18K per unit). All solutions will provide an automatic switchover from GPS in the event of an outage. Table B3-1a shows aircraft retrofit equipage quantities assumed for this strategy; Table B3-1b shows summary user costs for this same equipage profile.

Table B3-1a: Aircraft Retrofit Equipage Quantities, Strategy 4

	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**Total**
Large Air Transport	0	0	0	0	0	0	0	0	0	0	0	**0**
Regional Jet	0	111	111	111	111	111	122	386	426	475	471	**2435**
General Aviation	1196	4653	4647	4677	4668	4661	4651	4643	4634	4627	4619	**47676**

Table B3-1b: User Costs Summary, Strategy 4 ($M, Present Value)

	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**Total**
All Aircraft	19.4	79.1	76.8	75.1	72.9	70.7	69.1	78.3	77.7	76.4	76.1	**771.6**

B3.4 Strategy 5 - SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA

Equipage Requirements

This strategy will require all aircraft in the required airspace to have either enhanced SATNAV capability, or a combination of enhanced SATNAV and DME/DME/IRU capability, serving as a backup surveillance positioning source with appropriate interfaces to ADS-B avionics. Legacy Mode A/C/S transponders will also be required to support surveillance in high density terminal areas.

No changes to existing DME/DME/IRU capabilities will be required for this strategy; DME/DME/IRU capabilities as they are defined for AT aircraft today are assumed. Enhanced SATNAV equipage will require the implementation of L5 and Galileo receive capability, which could be achieved in several ways. For AT and Regional Jet aircraft, an enhanced SATNAV module upgrade would be implemented; older AT aircraft would also need to implement a Multi-Mode Receiver (MMR) upgrade in order to support the implementation of the enhanced SATNAV module. For those GA aircraft that would equip with enhanced SATNAV, a GPS replacement unit capable of supporting L5 and Galileo would be implemented, along with an antenna upgrade.

Ground Rules and Assumptions

This analysis assumes that all large AT aircraft will have DME/DME/IRU capability implemented within the required time frame, regardless of any requirements for backup surveillance positioning in the aircraft. Therefore, retrofit costs for DME/DME/IRU avionics are not assessed in this analysis for these aircraft. It is assumed that Regional Jet aircraft (those without an IRU) will not have DME/DME/IRU capability in this time frame.

Costs for all AT and Regional Jet retrofit equipage with an enhanced SATNAV module upgrade (approximately $40K per module) are included in the analysis. Older AT aircraft that cannot support the installation of the enhanced SATNAV module alone will incur additional MMR upgrade costs (approximately $100K per upgrade), which are also included.

For those GA aircraft that will equip with enhanced SATNAV, this analysis assumes that half of these will be retrofitted with the enhanced SATNAV capability (approximately $18K per aircraft), while the remaining half will have already equipped with enhanced SATNAV, regardless of ADS-B backup requirements; equipage costs associated with this latter category are therefore not assessed in this analysis. Table B3-2a shows aircraft retrofit equipage quantities assumed for this strategy; Table B3-2b shows summary user costs for this same equipage profile.

Table B3-2a: Aircraft Retrofit Equipage Quantities, Strategy 5

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Large Air Transport	87	151	150	150	289	283	423	390	396	209	201	**2728**
Regional Jet	0	111	111	111	111	111	122	386	426	475	471	**2435**
General Aviation	1196	4653	4647	4677	4668	4661	4651	4643	4634	4627	4619	**47676**

Table B3-2b: User Costs Summary, Strategy 5 ($M, Present Value)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
All Aircraft	14.3	57.9	56.2	54.8	66.7	64.2	78.1	81.8	81.1	62.2	59.6	**677.0**

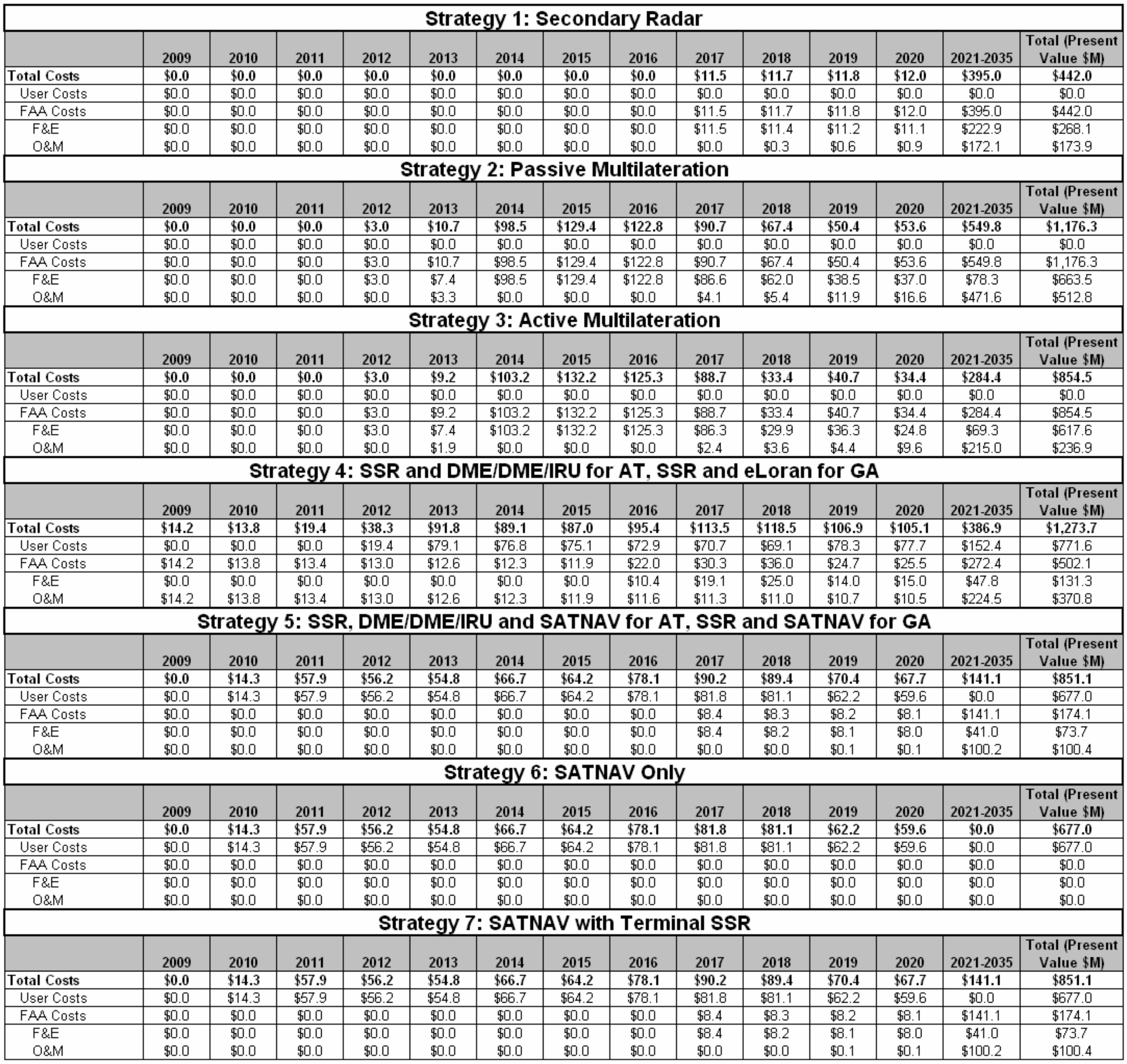
B3.5 Strategies 6 and 7 - SATNAV Only and SATNAV with Terminal SSR

Both Strategy 6 (SATNAV Only) and Strategy 7 (SATNAV with Terminal SSR) will require all aircraft in the required airspace to have enhanced SATNAV capability; Strategy 7 differs only in the addition of legacy Mode A/C/S transponder carriage for those aircraft in high density terminal airspace. From an equipage perspective, all equipage requirements and ground rules and assumptions that apply to SATNAV equipage in Strategy 5 apply to both of these strategies as well. Therefore, no separate retrofit equipage cost analyses were performed; the relevant retrofit equipage and cost estimates for Strategies 6 and 7 are identical to those of Strategy 5 above, as shown in Tables B3-2a and B3-2b.

B4. Life Cycle Cost Analysis Results

Table B4-1 summarizes the results of the life cycle cost analysis for each strategy.

Table B4-1: Life Cycle Cost Analysis Results



Strategy 1: Secondary Radar

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**$0.0**	**$11.5**	**$11.7**	**$11.8**	**$12.0**	**$395.0**	**$442.0**
User Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
FAA Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$11.5	$11.7	$11.8	$12.0	$395.0	$442.0
F&E	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$11.5	$11.4	$11.2	$11.1	$222.9	$268.1
O&M	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.3	$0.6	$0.9	$172.1	$173.9

Strategy 2: Passive Multilateration

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$0.0**	**$0.0**	**$3.0**	**$10.7**	**$98.5**	**$129.4**	**$122.8**	**$90.7**	**$67.4**	**$50.4**	**$53.6**	**$549.8**	**$1,176.3**
User Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
FAA Costs	$0.0	$0.0	$0.0	$3.0	$10.7	$98.5	$129.4	$122.8	$90.7	$67.4	$50.4	$53.6	$549.8	$1,176.3
F&E	$0.0	$0.0	$0.0	$3.0	$7.4	$98.5	$129.4	$122.8	$86.6	$62.0	$38.5	$37.0	$78.3	$663.5
O&M	$0.0	$0.0	$0.0	$0.0	$3.3	$0.0	$0.0	$0.0	$4.1	$5.4	$11.9	$16.6	$471.6	$512.8

Strategy 3: Active Multilateration

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$0.0**	**$0.0**	**$3.0**	**$9.2**	**$103.2**	**$132.2**	**$125.3**	**$88.7**	**$33.4**	**$40.7**	**$34.4**	**$284.4**	**$854.5**
User Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
FAA Costs	$0.0	$0.0	$0.0	$3.0	$9.2	$103.2	$132.2	$125.3	$88.7	$33.4	$40.7	$34.4	$284.4	$854.5
F&E	$0.0	$0.0	$0.0	$3.0	$7.4	$103.2	$132.2	$125.3	$86.3	$29.9	$36.3	$24.8	$69.3	$617.6
O&M	$0.0	$0.0	$0.0	$0.0	$1.9	$0.0	$0.0	$0.0	$2.4	$3.6	$4.4	$9.6	$215.0	$236.9

Strategy 4: SSR and DME/DME/IRU for AT, SSR and eLoran for GA

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$14.2**	**$13.8**	**$19.4**	**$38.3**	**$91.8**	**$89.1**	**$87.0**	**$95.4**	**$113.5**	**$118.5**	**$106.9**	**$105.1**	**$386.9**	**$1,273.7**
User Costs	$0.0	$0.0	$0.0	$19.4	$79.1	$76.8	$75.1	$72.9	$70.7	$69.1	$78.3	$77.7	$152.4	$771.6
FAA Costs	$14.2	$13.8	$13.4	$13.0	$12.6	$12.3	$11.9	$22.0	$30.3	$36.0	$24.7	$25.5	$272.4	$502.1
F&E	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$10.4	$19.1	$25.0	$14.0	$15.0	$47.8	$131.3
O&M	$14.2	$13.8	$13.4	$13.0	$12.6	$12.3	$11.9	$11.6	$11.3	$11.0	$10.7	$10.5	$224.5	$370.8

Strategy 5: SSR, DME/DME/IRU and SATNAV for AT, SSR and SATNAV for GA

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$14.3**	**$57.9**	**$56.2**	**$54.8**	**$66.7**	**$64.2**	**$78.1**	**$90.2**	**$89.4**	**$70.4**	**$67.7**	**$141.1**	**$851.1**
User Costs	$0.0	$14.3	$57.9	$56.2	$54.8	$66.7	$64.2	$78.1	$81.8	$81.1	$62.2	$59.6	$0.0	$677.0
FAA Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$8.4	$8.3	$8.2	$8.1	$141.1	$174.1
F&E	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$8.4	$8.2	$8.1	$8.0	$41.0	$73.7
O&M	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.1	$0.1	$100.2	$100.4

Strategy 6: SATNAV Only

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$14.3**	**$57.9**	**$56.2**	**$54.8**	**$66.7**	**$64.2**	**$78.1**	**$81.8**	**$81.1**	**$62.2**	**$59.6**	**$0.0**	**$677.0**
User Costs	$0.0	$14.3	$57.9	$56.2	$54.8	$66.7	$64.2	$78.1	$81.8	$81.1	$62.2	$59.6	$0.0	$677.0
FAA Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
F&E	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
O&M	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0

Strategy 7: SATNAV with Terminal SSR

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021-2035	Total (Present Value $M)
Total Costs	**$0.0**	**$14.3**	**$57.9**	**$56.2**	**$54.8**	**$66.7**	**$64.2**	**$78.1**	**$90.2**	**$89.4**	**$70.4**	**$67.7**	**$141.1**	**$851.1**
User Costs	$0.0	$14.3	$57.9	$56.2	$54.8	$66.7	$64.2	$78.1	$81.8	$81.1	$62.2	$59.6	$0.0	$677.0
FAA Costs	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$8.4	$8.3	$8.2	$8.1	$141.1	$174.1
F&E	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$8.4	$8.2	$8.1	$8.0	$41.0	$73.7
O&M	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0	$0.1	$0.1	$100.2	$100.4

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Appendix C - Comparative Safety Assessment

C1. Introduction

C1.1 Purpose and Scope

Since ADS-B technology is heavily dependent on a Global Navigation Satellite System, the Surveillance and Broadcast Services (SBS) program was required to identify a backup system or strategy in the event of a GNSS outage - local or global. This Comparative Safety Assessment (CSA) was performed to identify and assess the system safety hazards associated with the proposed alternatives for the backup strategy. The results of this assessment, coupled with the technical evaluations, will serve in selecting the appropriate backup strategy. The CSA provides a listing of system safety hazards associated with each backup strategy alternative, along with a risk assessment for each alternative-hazard combination. The CSA will aid in identifying the lowest risk alternative(s), from a system safety perspective.

As stated in section 3.1.6 of the Final Program Requirements (FPR) for SBS, the scope of the backup strategy is to maintain ATC Surveillance in the event of a GNSS failure:

a. ATC Surveillance application *shall* continue to operate in the event of GNSS failure.
b. A backup system or strategy *shall* be provided with the ADS-B system to ensure that the ATC surveillance application can be provided in the event the navigation source is operating in a degraded state.

The CSA does not address the in-cockpit applications, since the backup strategy is not intended to enable the continued operation of these applications in the event of GNSS failure or navigation source degradation.

The strategies under consideration utilize various technologies to obtain an aircraft's position. Strategy 1 (Secondary Radar) uses existing primary and secondary surveillance radar (SSR) sensors to determine the aircraft position. Strategy 2 (Passive Multilateration) is comprised of several ground stations that triangulate the location of the aircraft based on the time of arrival of the ADS-B message. Strategy 3 (Active Multilateration) uses ground stations to interrogate aircraft transponders to determine position. Strategy 4 (SSR, DME/DME/IRU for Air Transport (AT) and SSR, eLoran for General Aviation (GA)) uses Secondary Radar in high density airspace, and in medium density airspace, the position is obtained on the aircraft through Distance Measuring Equipment (DME) (Air Transport) or eLoran (General Aviation). Equipment on the aircraft communicates with ground-based facilities and uses the time of arrival to calculate position. Strategy 5 (SSR, DME/DME/IRU, SATNAV for AT and SSR, SATNAV for GA) uses the DME/DME/IRU technology as well as additional satellite positioning systems that are to be developed in the near future. Strategy 6 (SATNAV only) provides a more diverse and robust GNSS instead of an alternate technology system, backing up the current GPS L1 with GPS L5 and/or Galileo. Strategy 7 (Terminal SSR and SATNAV) uses SSR in terminal airspace and SATNAV in en route airspace.

C1.2 Background

Automatic Dependent Surveillance-Broadcast (ADS-B) is an advanced surveillance technology that enables equipped aircraft or surface vehicles to broadcast their identification, position, altitude, velocity, and other information. Since the position information is normally derived from the Global Positioning System (GPS) and broadcast approximately once per second, it provides improved accuracy and more timely information updates than conventional surveillance. The improved positional accuracy and the ability to provide additional aircraft-derived flight parameters (flight objects or flight data message elements) will result in enhanced surveillance in the NAS. ADS-B is automatic because no external stimulus is required; it is dependent because it relies on on-board navigation sources and onboard broadcast transmission systems to provide surveillance information to other users. The aircraft or vehicle originating the broadcast may or may not have knowledge of which users, aircraft or ground-based, are receiving its broadcast.

ADS-B technology also enables the implementation of Traffic Information Service-Broadcast (TIS-B), ADS-B Rebroadcast (ADS-R), and Flight Information Service-Broadcast (FIS-B) to support enhanced situational awareness and other applications intended for air crews. TIS-B service provides traffic information to receiver-equipped aircraft and surface vehicles based on the conventional radar returns received for non-ADS-B equipped aircraft. ADS-R provides traffic information to equipped aircraft based on ADS-B transmission from aircraft on independent data links. FIS-B provides weather and NAS Status information to equipped aircraft.

Per the FAA’s ADS-B Link Decision, two data link technologies, the 1090 MHz extended squitter (1090ES) and the 978 MHz Universal Access Transceiver (UAT) have been approved for use in the NAS. It is anticipated that air transport category aircraft will equip with the 1090ES link and general aviation will equip with the UAT link. Both the UAT and 1090ES links support TIS-B and ADS-R services. Only UAT supports FIS-B service.

The Surveillance and Broadcast Services Safety Risk Management Panel prepared and conducted the Preliminary Hazard Analysis (PHA) for seven applications selected for the near-term NAS implementation:

- ATC Surveillance
- Weather and NAS Status Situational Awareness
- Enhanced Visual Acquisition
- Enhanced Visual Approaches
- Final Approach and Runway Occupancy Awareness
- Airport Surface Situational Awareness
- Conflict Detection

Rulemaking is planned to require aircraft equipage with ADS-B transmit capability to support the ATC Surveillance application. On the other hand, equipping with avionics necessary to support the remaining applications is voluntary.

C1.3 SBS Description

C1.3.1 System Description

ADS-B is an advanced surveillance technology that enables equipped aircraft, or surface vehicles, to broadcast their identification, position, altitude, velocity, and other information. Since the position information is normally derived from the Global Positioning System (GPS) and broadcast approximately once per second, it provides improved accuracy and more timely information updates than conventional surveillance. The superior positional accuracy and the ability to provide additional aircraft-derived flight parameters (flight objects or flight data message elements) will result in enhanced surveillance in the NAS. ADS-B is automatic because no external stimulus is required; it is dependent because it relies on on-board navigation sources and onboard broadcast transmission systems to provide surveillance information to other users. The aircraft or vehicle originating the broadcast may or may not have knowledge of which users, aircraft or ground-based, are receiving its broadcast.

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The introduction of ADS-B services into the NAS will enable some well established applications, currently supported by radar and other existing surveillance sources, and facilitate the introduction of new applications, that promise to improve safety and increase capacity. See the FAA’s Surveillance and Broadcast Services Concept of Operations (CONOPS) for further details on ADS-B Services and Applications. Table C1-1 summarizes the relationship between ADS-B related applications, services, and SBS system operational system functions (described in Section 1.3.2).

Table C1-1: Applications, Services, and Functions

ADS-B Enabled Applications	**Services**	**Broadcast Services Function**	**Link-Specific Processing Function**	**ATC Automation Function**	**Aircraft / Vehicle Function**
ATC Surveillance	ADS-B		X	X	X (Transmit)
Airport Surface Situational Awareness (ASSA) Final Approach Runway Occupancy (FAROA) Enhanced Visual Acquisition (EVAcq) Enhanced Visual Approach (EVApp) Conflict Detection (CD)	ADS-B (only Aircraft/ Vehicle Functionality Required) ADS-R TIS-B*	X	X		X (Receive)
Weather and NAS Status Situational Awareness	FIS-B	X	X		X (Receive)

* TIS-B, as specified herein, supports the ASSA and EVAcq applications only

The Surveillance and Broadcast Services System's functions (Aircraft/Vehicle, Link Specific Processing, Broadcast Services, and ATC Automation) provide the ADS-B services that support ADS-B applications. Figure C1-1 shows the relationship between the principle and sub-system components:

- The Aircraft/Vehicle function is identified as the components located in the avionics section at the top of the illustration.
- The Link Specific function is identified as the air interfaces and 1090ES and UAT receive/transmit components located mid-illustration.
- The Broadcast Services function is identified as the ground interfaces and associated TIS-B and FIS-B processors.
- ATC Automation.

TIS-B and FIS-B services require all functions except ATC Automation. The ADS-B Rebroadcast (ADS-R) Service is a subset of the fundamental TIS-B Service.

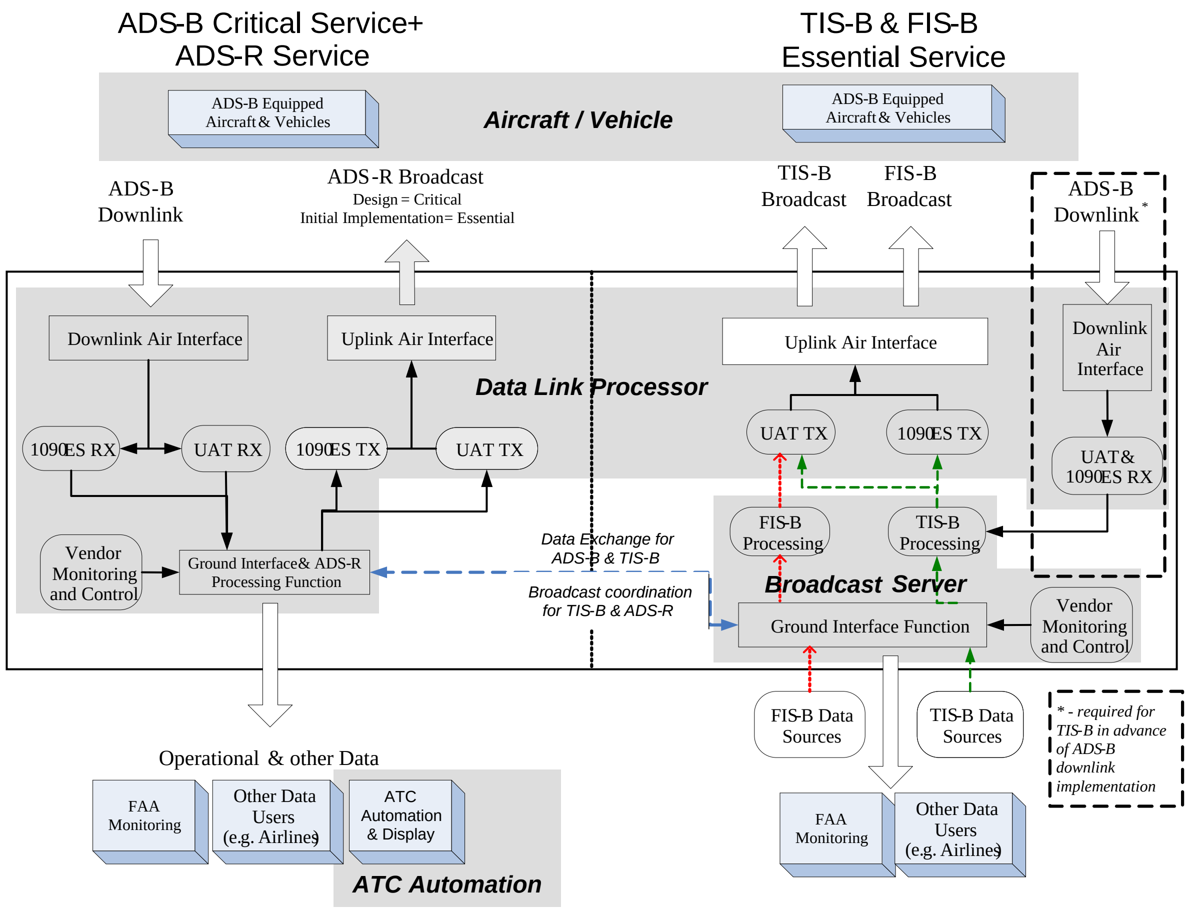


Figure C1-1: SBS Architecture

C1.3.2 Functional Description

The ADS-B System can be logically divided into five major functions (see Figure C1-2):

1. Aircraft/Vehicle Function
2. Link-Specific Processing (LSP) Function
3. Broadcast Services (BCS) Function
4. ATC Automation Function
5. Maintenance Function

The first four functions are operational, while the Maintenance Function provides for the control and monitoring of the operational functions. Note that only the operational functions are listed in Table C1-1, as the Maintenance Function supports the services and applications in an indirect manner. The Aircraft/Vehicle Function resides in participant aircraft and surface vehicles. The ATC Automation Function resides in participant automation systems. The Link-Specific Processing, Broadcast Services, and Maintenance Functions form the ADS-B ground infrastructure.

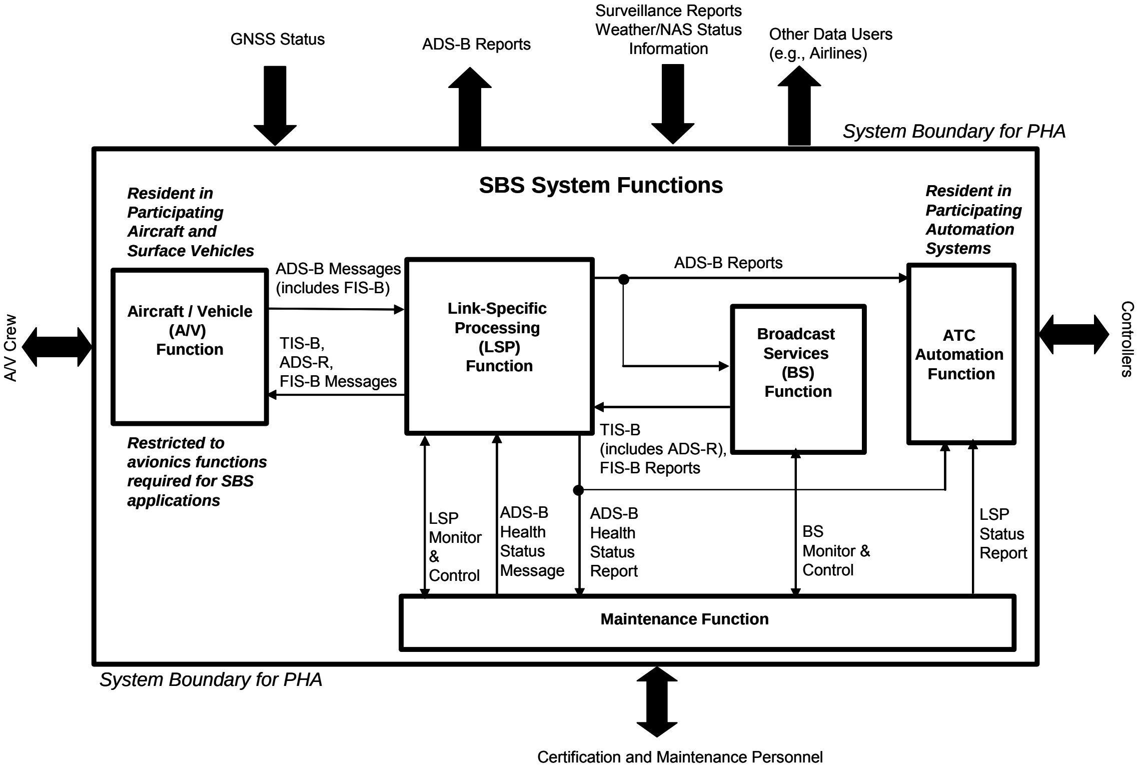


Figure C1-2: SBS System Functions

The ADS-B System receives surveillance reports, from various NAS systems, to support the TIS-B service and weather and NAS status information, from government and commercial sources, to support the FIS-B service. The ADS-B system distributes ADS-B Reports to authorized user systems. The status of the GNSS and other NAS systems is also an input to the ADS-B System to determine degraded operations or an outage of these systems.

Aircraft/Vehicle Function

The Aircraft/Vehicle includes a transmit capability that supports all applications and a receive capability for aircraft/vehicle based applications.

The Aircraft/Vehicle Function is the source of ADS-B information. The Function derives state vector information, using GNSS or another navigation source, and determines the associated integrity and accuracy indicators. The Aircraft/Vehicle function also ascertains altitude information from a qualified barometric altitude source. Vehicles for surface use only could use a pre-programmed source for altitude information. The Function collects other ownship data, potentially including weather related measurements, and provides a means for crew input of additional information, such as aircraft identification data. The Aircraft/Vehicle Function encodes and broadcasts ADS-B Messages, conveying the collected information.

The Aircraft/Vehicle Function receives and decodes ADS-B Messages transmitted by other Aircraft/Vehicles equipped with the same data link and TIS-B and ADS-R Messages transmitted by the ADS-B LSP Function. Aircraft/Vehicle Functions equipped with the UAT data link additionally receive and decode FIS-B Messages transmitted by the LSP Function. The Aircraft/Vehicle Function processes and displays the information conveyed in received messages.

Link-Specific Processing Function

The LSP Function provides the ADS-B System transmit/receive functionality on the ground. The Function receives ADS-B Messages from equipped aircraft and surface vehicles, formats the associated ADS-B Reports, and distributes them to ATC Automation, the BCS Function, and other authorized users. LSP transmits TIS-B, ADS-R, and FIS-B Messages as directed by the BCS Function. This Function supports all services and applications.

Broadcast Services Function

The BCS Function processes, including tracking, filtering, and applying quality indicators, surveillance reports from external sources and ADS-B Messages from the LSP Function. Broadcast Services generates TIS-B and ADS-R Reports for transmission as TIS-B and ADS-R Messages by LSP. The BCS Function additionally processes weather and NAS status data from external sources and generates applicable FIS-B Reports for transmission as FIS-B Messages by LSP. This Function supports TIS-B, ADS-R, and FIS-B Services, but is not required for ADS-B. It supports all applications except ATC Surveillance.

ATC Automation Function

The ATC Automation Function uses ADS-B surveillance data similar to its use of radar system surveillance information. The Function supports environments with only ADS-B Surveillance as well as those having both ADS-B and radar surveillance. ATC Automation validates the position information provided in ADS-B Reports by comparing it with reports from other surveillance sources, as available. The Function associates the ADS-B Report data with filed flight plans, creates and updates tracks, and displays target and emergency information to Air Traffic Specialists. ATC Automation performs safety function processing, including Minimum Safe Altitude Warning, Conflict Alert, and Restricted Airspace Monitoring, using ADS-B and radar data, as available, and displays any associated alerts.

Maintenance Function

The Maintenance Function provides for the control and monitoring of the ADS-B ground infrastructure operational functions, Link-Specific Processing and Broadcast Services. Control includes the setting of configuration items, the download of new software, the request for read back of monitored parameter values, and any other actions necessary to control the operation and support the maintenance of the system. Monitoring includes the generation of alerts and alarms as well as the injection of Health Status Messages (test targets) into the LSP Function, and any other monitoring activities necessary to support the operation and maintenance of the system. The Maintenance Function uses information gathered in monitoring the system to generate Status Reports, containing high-level alarm and alert information and system counts, such as number of

ADS-B Messages received, number of TIS-B Reports generated, etc. and distributing them to the ATC Automation Function.

The Maintenance Function additionally monitors ADS-B reception and the GNSS to analyze coverage and identify potential quality issues with Aircraft/Vehicle performance. The Function provides an interface to systems engineers and technicians for use in control and monitoring of the ADS-B System.

C2. Backup Strategy Alternatives

Addressing the requirement from the fPR, the backup strategy alternatives listed below provide a means for obtaining aircraft position in order to enable the ATC Surveillance application.

Each alternative uses primary radar to mitigate single-aircraft avionics failures in the terminal domain but not in the en route domain. Therefore, primary radar functions shown in each block diagram only apply to terminal surveillance. The primary radar transmits a radio frequency (RF) pulse. The radar system processes the reflected signal to determine azimuth and slant range. This information is supplied to automation and displayed to ATC.

C2.1 Alternative 1: Secondary Radar

The secondary radar alternative involves using existing secondary radar sensors to interrogate aircraft equipped with ATCRBS and/or Mode S transponders. The aircraft responds with aircraft information, such as beacon code and altitude. The radar receives the reply and processes the antenna position and time of reply to determine the azimuth and slant range for the aircraft. The target report is generated for the aircraft and sent to automation for tracking and alerting.

This alternative employs a reduced version of the current secondary radar network to cover the required airspace and primary radars in terminal areas.

C2.2 Alternative 2: Passive Multilateration

The passive multilateration alternative obtains the aircraft position by using three or more ground stations that receive the broadcast ADS-B message. The time-of-arrival (TOA) of the messages are measured for each of the ground stations. The ground stations are synchronized through a reference signal or clock, and this point of reference is used to calculate a time-difference-of-arrival (TDOA). A central processor uses this information to determine the aircraft position. Other target data, such as aircraft identity and barometric altitude, are obtained by decoding the ADS-B message.

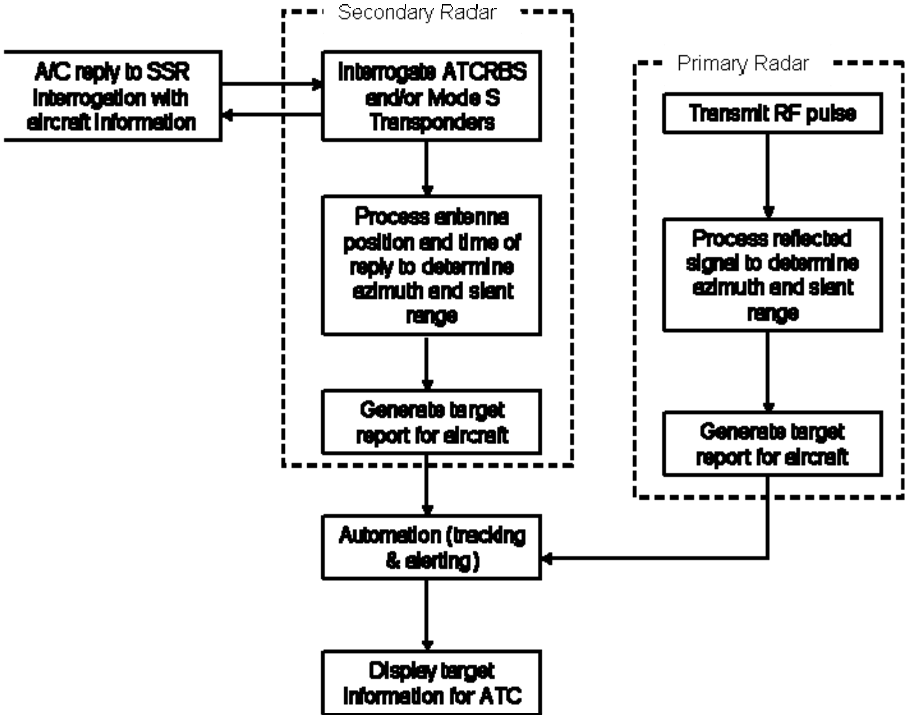


Figure C2-1: Functions of Secondary Radar Alternative

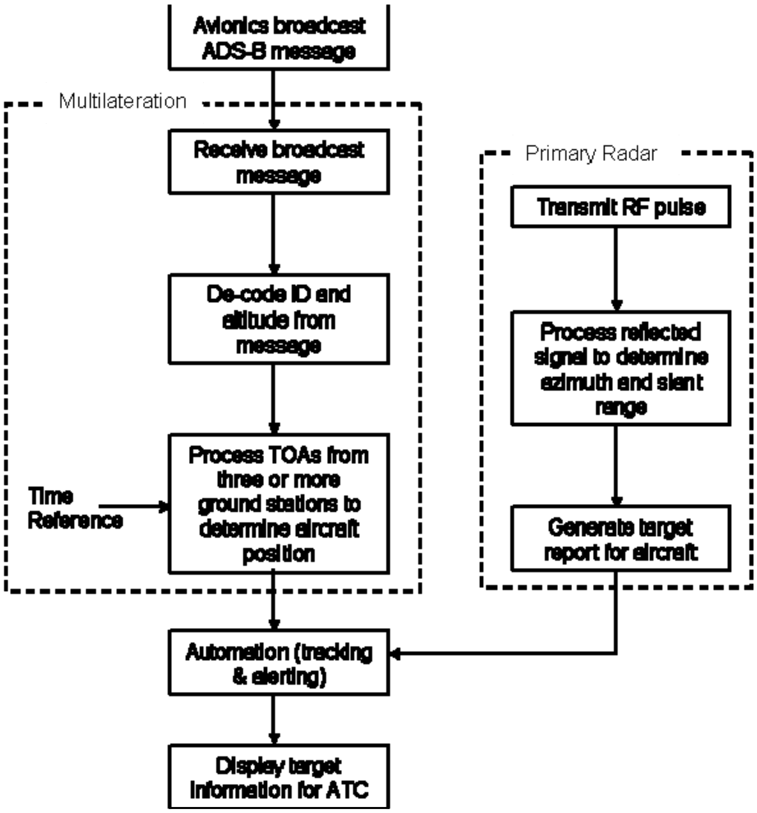


Figure C2-2: Functions of Passive Multilateration Alternative

C2.3 Alternative 3: Active Multilateration

Active multilateration relies on three or more geographically distributed ground stations successfully interrogating aircraft equipped with ATCRBS and/or Mode S transponders. The ground stations measure the TOA for the same transponder reply. As with passive multilateration, the aircraft position is determined by joint processing of the TDOA measurements, which are calculated with respect to the synchronized time source. Aircraft identity and barometric altitude are determined by decoding the information in the transponder replies.

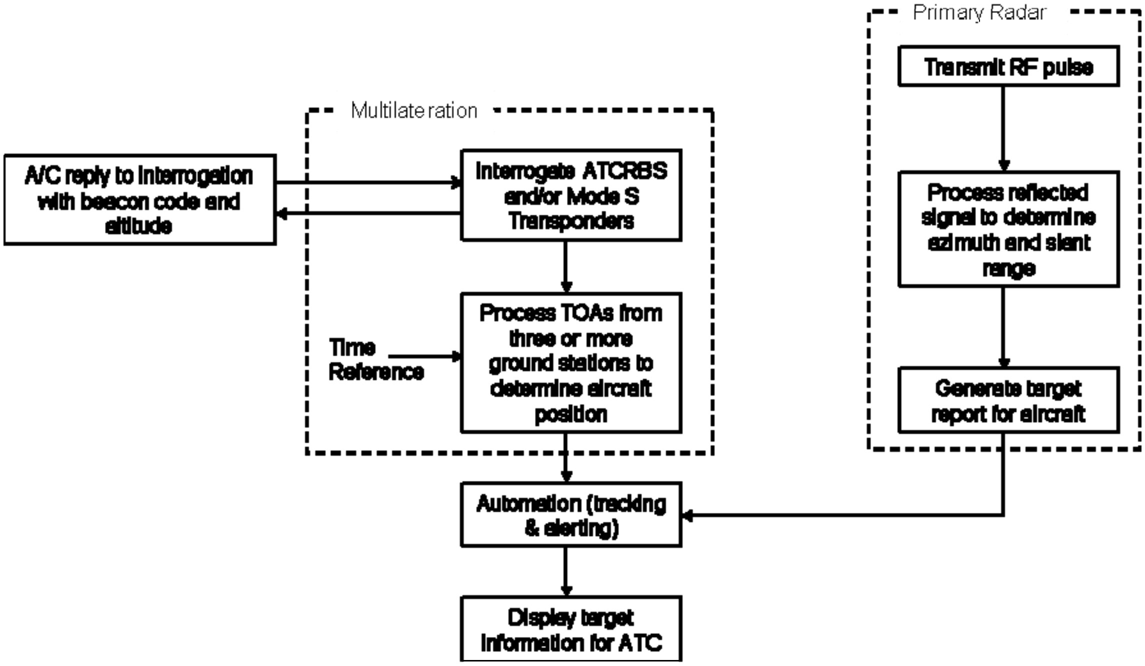


Figure C2-3: Functions of Active Multilateration Alternative

C2.4 Alternative 4: SSR, DME/DME/IRU for AT and SSR, eLoran for GA

Distance Measuring Equipment (DME) and Enhanced LOng RAnge Navigation (eLoran) are both navigation systems, with DME common to Air Transport (AT) and eLoran common to General Aviation (GA). The position is obtained on the aircraft and provided to ATC Surveillance via the ADS-B broadcast message.

The DME/DME/IRU approach consists of equipment on the aircraft that interrogates DME ground facilities. The ground facilities respond with a fixed delay. The aircraft uses the TOAs from the responses from two or more DME facilities and the known locations of the DME facilities (from a database on the aircraft) to determine the aircraft position. Inertial Reference Unit (IRU) is used to augment DME by mitigating the impact of gaps in coverage. IRU determines the aircraft position by using inertial metrics and last-known positions.

DME/DME/IRU is not able to support five nautical mile separation in medium density airspace.

The present Loran system, Loran-C, is comprised of a series of ground station groups (chains). The chains are made up of three to six ground stations, with one station serving as the master. The other stations are synchronized to the master through a radio frequency (RF) pulse that is transmitted by the master station. Most of the 24 U.S. Loran stations have been modernized to support eLoran performance. When that process is complete, the stations will operate in an “all-in-view” mode, which provides better system availability and integrity. All stations will be synchronized to Coordinated Universal Time (UTC).

The ground stations transmit a periodic series of nine RF pulses in the 90-110 kHz frequency band. The aircraft uses the TOAs of the pulses from three or more ground stations and the known locations of the ground stations (from a database on the aircraft) to determine the two-dimensional position of the aircraft. The ninth pulse in each broadcast is modulated to capture differential accuracy corrections (for maritime applications), station identification, and integrity information.

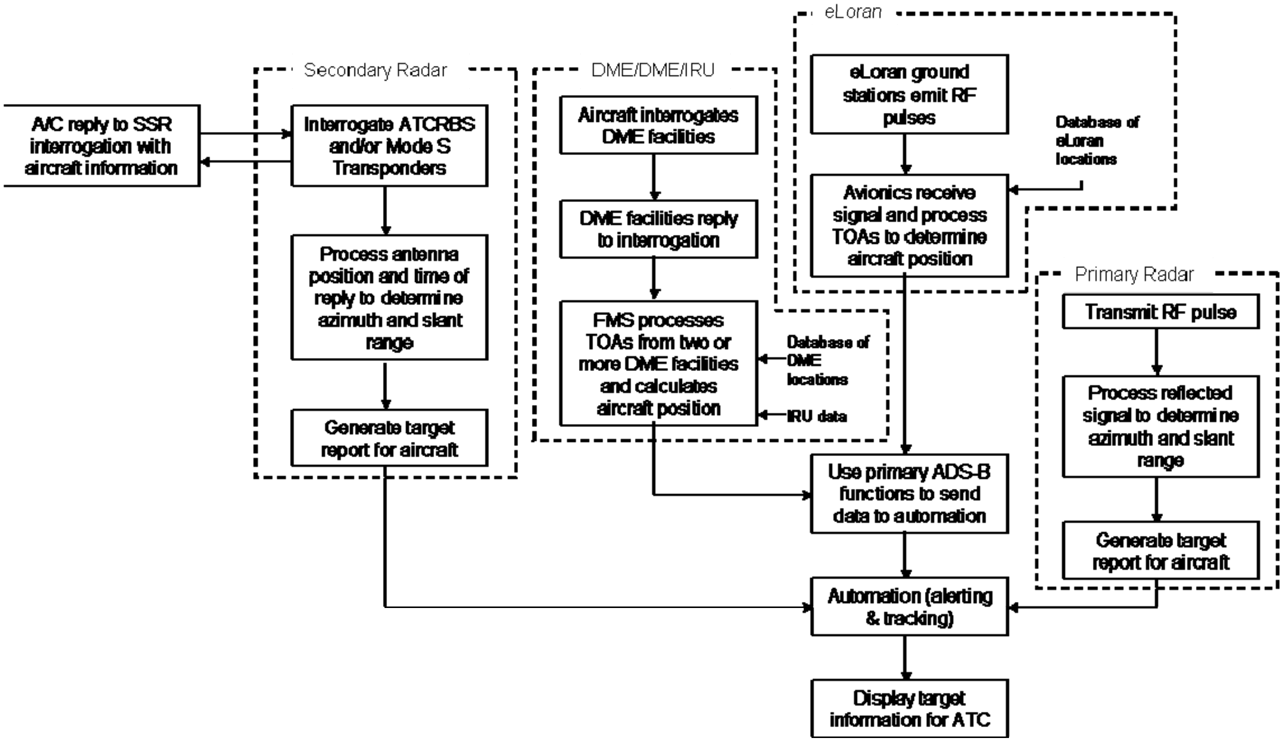


Figure C2-4: Functions of SSR, DME/DME/IRU for AT and SSR, eLoran for GA Alternative

C2.5 Alternative 5: SSR, DME/DME/IRU, SATNAV for AT and SSR, SATNAV for GA

This alternative uses SSR in high-density airspace. For AT in medium density airspace, DME/DME/IRU and Satellite Navigation (SATNAV, see Section C2.6) are used for backup. For GA in medium density airspace, SATNAV is used.

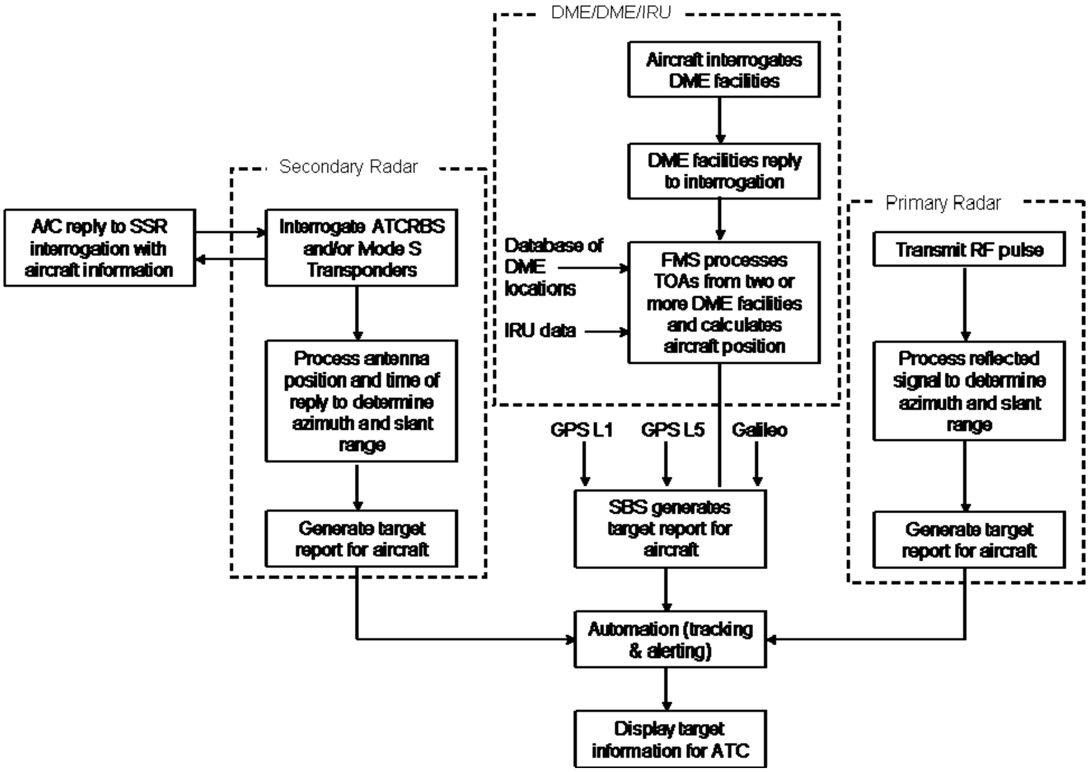


Figure C2-5: Functions of SSR, DME/DME/IRU, and SATNAV for AT, and SSR and SATNAV for GA

C2.6 Alternative 6: SATNAV Only

The SATNAV alternative continues to use a form of GNSS as its source for position, however, the probability of loss compared to GPS alone decreases significantly by providing more backup satellite sources. Currently, Global Positioning System (GPS) L1 is the only GNSS source used by ADS-B. The L5 GPS signal and the European Galileo system provide additional signals that are to be implemented within the next ten years. In the event of a GPS L1 loss of service, the ADS-B would default to one of the other GNSS signals to obtain the aircraft position.

Although this approach mitigates the likelihood of a GNSS outage, it does not mitigate multi-frequency interference.

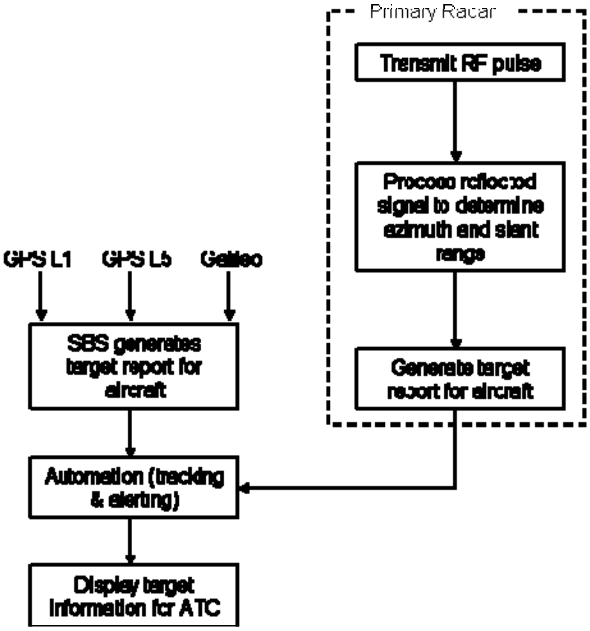


Figure C2-6: Functions of SATNAV Only Alternative

C2.7 Alternative 7: Terminal SSR and SATNAV

By using secondary radar in high-density terminal areas in addition to the SATNAV strategy, the multi-frequency interference is mitigated.

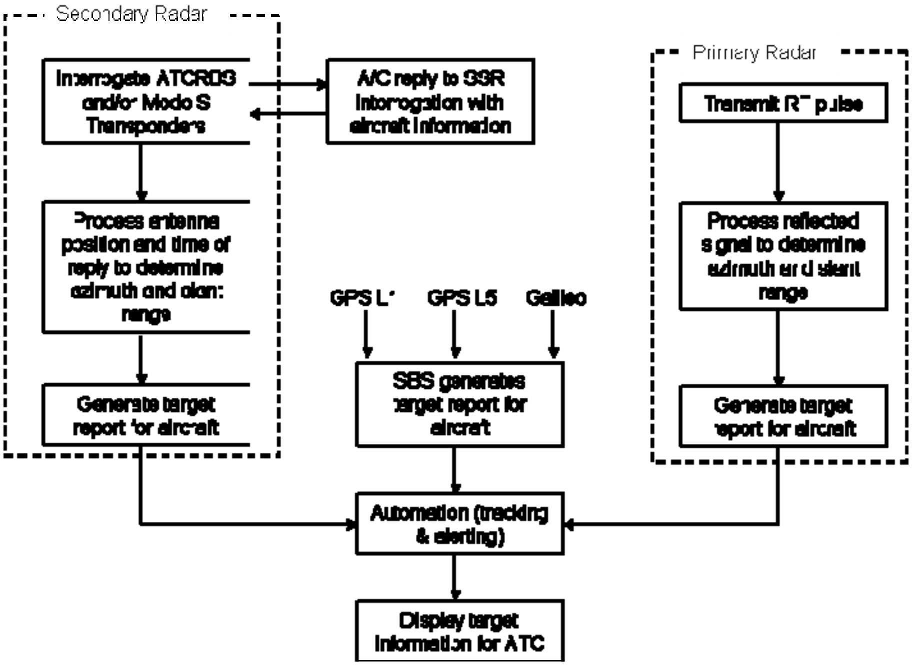


Figure C2-7: Functions of Terminal SSR and SATNAV Alternative

C3. Assessment Methodology

This CSA was developed by the SBS Program Office as a quick turn-around safety assessment using guidance contained in the NAS System Safety Handbook (SSH). This assessment, which has not yet been reviewed by the ATO-S System Safety Working Group (SSWG), will require an update to comply with the CSA content and format requirements outlined in the NAS Systems Safety Management Program (SSMP).

After determining and analyzing the pertinent system functions for providing ATC Surveillance, an initial set of hazards was identified. Only ATC Surveillance application hazards were evaluated in the CSA, since the purpose of the backup strategy is to maintain ATC Surveillance in the event of a GNSS failure. No new hazards were evaluated for any strategy, though a hazard for loss of aircraft navigation should be considered in a future analysis.

The following ATC Surveillance hazards were evaluated in the CSA:

- H1 Loss of ATC Surveillance (All Aircraft)
- H2 Loss of Surveillance (Single Aircraft)
- H17 Loss of Surveillance (Multiple Aircraft)

Hazards associated with inaccurate position, altitude, and identification are addressed in the SBS Preliminary Hazard Analysis (PHA). It was not necessary to address these hazards in the CSA for several reasons. First, the backup strategies were defined to ensure that accuracy requirements for terminal and en route ATC separation standards are met; therefore, hazards that dealt with inaccurate position would not function as a discriminator in comparing the alternatives. Also, the source for altitude and identification data was not affected by any of the backup strategies, and the risk already identified in the SBS PHA does not change as a function of alternative.

While the hazards evaluated in this CSA are similar to those addressed in the SBS PHA, system states that affected the risk assessment varied. For example, the hazards in the SBS PHA were analyzed for the terminal domain, whereas the CSA considered both en route and terminal domains. Therefore, the assessed risk levels from the CSA should not be compared to those assessed in the SBS PHA, as it would not be an equivalent comparison. The hazards identified in the SBS PHA will ultimately be re-evaluated based on the selected backup strategy.

A multi-step process was employed to determine the risk associated with each strategy – hazard combination. First, functional flow block diagrams, provided in Section 5, were developed for each backup strategy alternative based on the draft technical descriptions. These block diagrams were used to identify potential faults or failure modes for each backup strategy that could cause a hazard. Fault trees, provided in Section 8, were prepared using the functional flow block diagrams and technical descriptions of each strategy. Each fault tree represents the SBS system and backup strategy faults that, if present in a certain combination, result in a hazard. Individual faults were assigned a likelihood of occurrence derived from requirements documentation, technical description information, engineering judgment, or a combination thereof. Fault tree analysis software was used to calculate the probability of the top-level fault occurring (i.e., the hazard). Next, event trees, provided in Section 8, were developed for each hazard to represent the possible system state variables, actions subsequent to the hazard, and resultant range of hazard effects. Probabilities associated with certain system state variables were also modified from the original event trees presented in the SBS PHA. Effects and severities were assigned to each path (i.e., set of branches) in the event trees, and likelihoods for each path were calculated. For each event tree path, the combined likelihood of the hazard occurring and that particular path was calculated. Worst case risk was determined by comparing the total likelihood and severity pairs, and selecting the maximum resultant risk.

C3.1 Risk Definitions

Severity and likelihood definitions contained in the NAS SSMP are provided below. For more information regarding these definitions, refer to FAA Advisory Circular 25.1309-1A, "System Design Analysis".

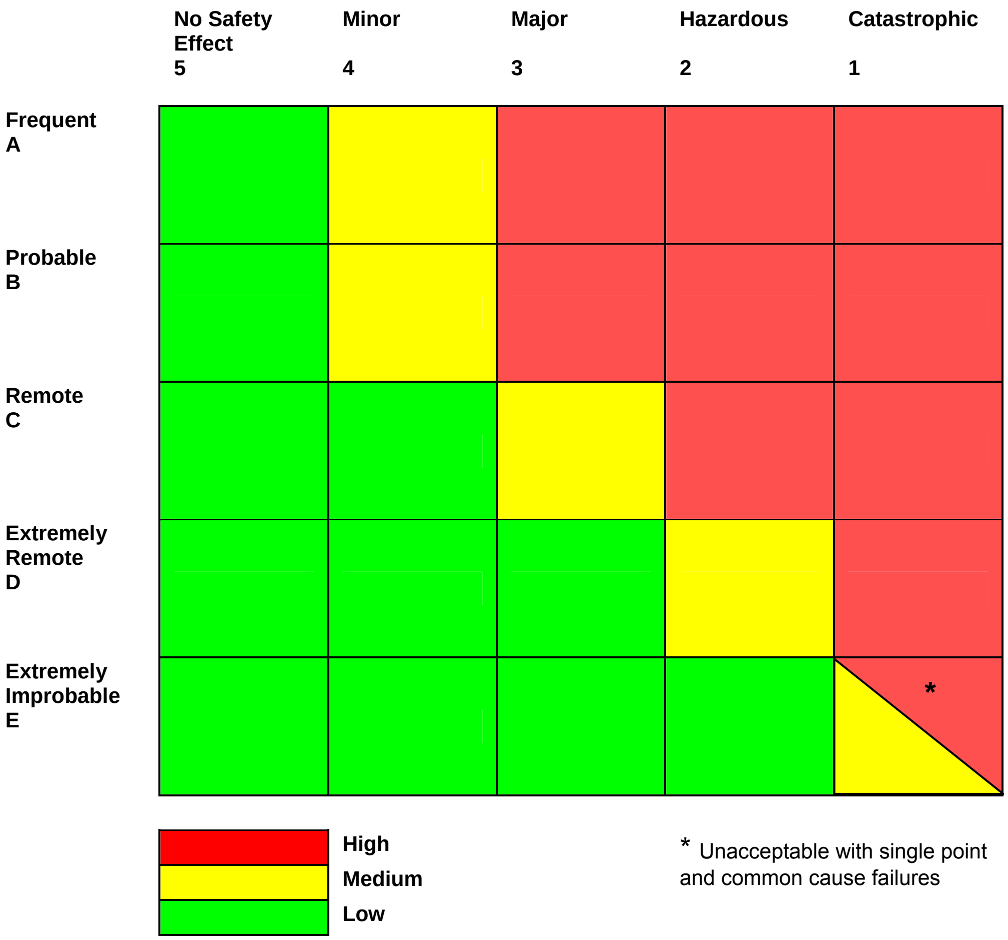
Table C3-1: Severity Definitions

Effect on ↓	**Hazard Severity Classification**				
	No Safety Effect (5)	**Minor (4)**	**Major (3)**	**Hazardous (2)**	**Catastrophic (1)**
General		Does not significantly reduce system safety. Required actions are within operator's capabilities. Includes (see below):	Reduces the capability of the system or operators to cope with adverse operating condition to the extent that there would be a (see below):	Reduces the capability of the system or the operator's ability to cope with adverse conditions to the extent that there would be a (see below):	Total loss of systems control such that (see below):
Air Traffic Control	Slight increase in ATC workload	Slight reduction in ATC capability, or significant increase in ATC workload	Reduction in separation as defined by a low/moderate severity operational error (as defined in FAA Order 7210.56), or significant reduction in ATC capability	Reduction in separation as defined by a high severity operational error (as defined in FAA Order 7210.56), or a total loss of ATC (ATC Zero)	Collision with other aircraft, obstacles, or terrain
Flying Public	- No effect on flight crew - Has no effect on safety -Inconvenience	- Slight increase in workload - Slight reduction in safety margin or functional capabilities - Minor illness or damage - Some physical discomfort	- Significant increase in flight crew workload - Significant reduction in safety margin or functional capability - Major illness, injury, or damage - Physical distress	- Large reduction in safety margin or functional capability - Serious or fatal injury to small number - Physical distress/ excessive workload	Outcome would result in: - Hull loss - Multiple fatalities

Table C3-2: Likelihood Definitions

	NAS Systems			**Flight Procedures**	**ATC Operational**	
	Quantitative	**Qualitative**			**Periodicity**	
		Individual Item/System	**ATC Service/ NAS Level System**		**Per Facility**	**NAS-wide**
Frequent **A**	Probability of occurrence per operation/ operational hour is equal to or greater than $1x10^{-3}$	Expected to occur about once every 3 months for an item	Experienced continuously in the system	$P \ge 1 \text{ x } 10^{-5}$	Expected to occur more than once per week	Expected to occur more than every 1-2 days
Probable **B**	Probability of occurrence per operation/ operational hour is less than $1x10^{-3}$, but equal to or greater than $1x10^{-5}$	Expected to occur about once per year for an item	Expected to occur frequently in the system		Expected to occur about once every month	Expected to occur about several times per month
Remote **C**	Probability of occurrence per operation/ operational hour is less than or equal to $1x10^{-5}$ but equal to or greater than $1x10^{-7}$	Expected to occur several times in life cycle of an item	Expected to occur numerous times in system life cycle	$10^{-5} > P \ge 10^{-7}$	Expected to occur about once every year	Expected to occur about once every few months
Extremely Remote **D**	Probability of occurrence per operation/ operational hour is less than or equal to $1x10^{-7}$ but equal to or greater than $1x10^{-9}$	Unlikely to occur, but possible in an item's life cycle	Expected to occur several times in the system's life cycle	$10^{-7} > P \ge 10^{-9}$	Expected to occur about once every 10-100 years	Expected to occur about once every 3 years
Extremely Improbable **E**	Probability of occurrence per operation/ operational hour is less than $1x10^{-9}$	So unlikely that it can be assumed that it will not occur in an item's life cycle	Unlikely to occur, but possible in system life cycle	$P < 10^{-9}$	Expected to occur less than once every 100 years	Expected to occur less than once every 30 years

Note: Table C3-2 includes corrections for errata contained in SSMP version 10 Table 4.2-2. Likelihood definitions for "Probable" and "Frequent" (which are reversed in the SSMP) and mathematical inequality expressions are corrected in the table above.



	No Safety Effect 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A	🟩	🟨	🟥	🟥	🟥
Probable B	🟩	🟨	🟥	🟥	🟥
Remote C	🟩	🟩	🟨	🟥	🟥
Extremely Remote D	🟩	🟩	🟩	🟨	🟥
Extremely Improbable E	🟩	🟩	🟩	🟩	🟨 🟥 *

🟥 High
🟨 Medium
🟩 Low

* Unacceptable with single point and common cause failures

Figure C3-3: Risk Assessment Matrix

C3.2 Assumptions

In identifying and assessing the hazards that apply to the SBS backup strategy, the following assumptions were made. The SBS FPR only explicitly called out the ATC Surveillance application to be supported by the backup strategy. Though some of the strategies presented may still have the capability to support the other applications, hazards specific to those applications were not addressed in this assessment, as they may not apply to all of the strategies. Accordingly, since these applications may not be available in the event of a switchover to backup, it is assumed the pilot and ATC would be notified.

C3.3 Data Sources

Quantitative data was used whenever it was available. If quantitative data was not available, qualitative numbers were provided by subject matter experts (SMEs). Probability of failure numbers for existing systems in the NAS were calculated from availability specifications for the most common systems currently in use (ASR-9, ATCBI-6, ASDE-X). The availability of DME/DME/IRU and eLoran were each 99.9%, as indicated in the technical descriptions provided by the SMEs. The SATNAV system was given a single-frequency availability of 99.9%, as a worst-case value. Probabilities of detection for SSR, PSR and Multilateration were taken from the system specifications and used for hazards H2 and H17. Transponder probability of failure was given as 10^{-5} for GA; the probability would only be lower for Air Transport (AT), so 10^{-5} was used for transponder failure in general. This number was also applied for other avionics, such as DME and eLoran.

C4. Results

C4.1 Risk Assessment Ratings

Based on the CSA, each alternative had acceptable levels of risk (i.e., there were no high risks). The assessed risk for each alternative – hazard combination is plotted in the risk matrix and listed in the table below. Different symbols are used to represent the alternative backup strategies. Each symbol is annotated with the number of hazards.

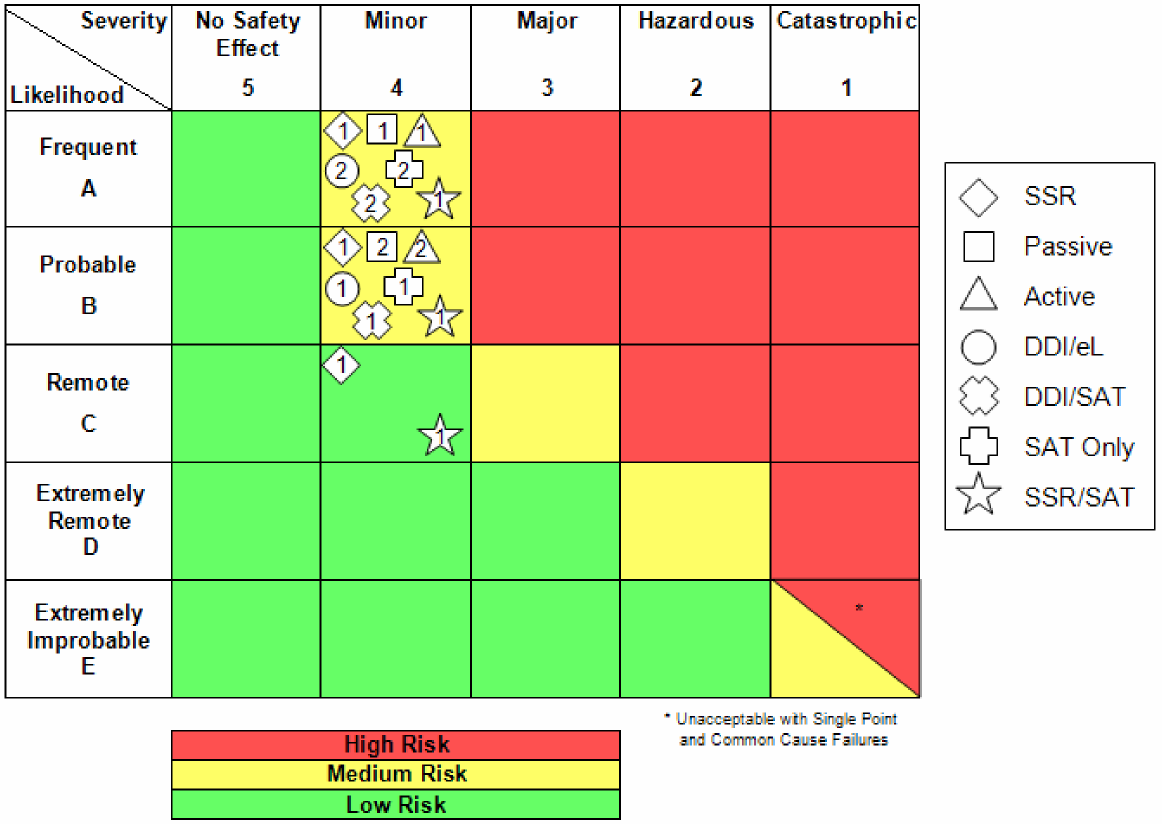


Figure C4-1: Risk Assessment Matrix for Backup Strategies

Table C4-1: Risk per Alternative-Hazard Combination

No.	Hazard	1: SSR	2: Passive ML	3: Active ML	4: SSR, DDI & eLoran	5: SSR, DDI & SATNAV	6: SATNAV Only	7: SATNAV & SSR
H1	Loss of ATC Surveillance (All Aircraft)	4B (Med)	4B (Med)	4B (Med)	4B (Med)	4B (Med)	4B (Med)	4B (Med)
H2	Loss of Surveillance (Single Aircraft)	4A (Med)	4A (Med)	4A (Med)	4A (Med)	4A (Med)	4A (Med)	4A (Med)
H17	Loss of Surveillance (Multiple Aircraft)	4C (Low)	4B (Med)	4B (Med)	4A (Med)	4A (Med)	4A (Med)	4C (Low)

The worst, credible outcome for each of the hazards was a significant increase in ATC workload, which is classified as a “Minor” (4) severity. While higher severity outcomes were evaluated, the likelihood of occurrence for those scenarios was often several orders of magnitude below “Extremely Improbable,” and therefore deemed not credible from an SMS perspective. The likelihood for the loss of surveillance for all aircraft (H1) did not vary with the different strategies, as automation and power system failures were the primary drivers for the hazard (the alternative backup strategies are not intended to mitigate the probability of automation or power system failure). The likelihood for the loss of surveillance for a single aircraft (H2) is primarily influenced by avionics failures. For the analysis, it was assumed that the probability of failures of ADS-B avionics, DME/DME/IRU avionics, and transponders were equivalent. The likelihoods varied from “Remote” (C) to “Frequent” (A) for the risk of losing surveillance for multiple aircraft (H17). The likelihood for hazard H17 was driven by the probability of detection for SSR (for alternative 1) and Multilateration (for alternatives 2 and 3). The probability of ground station faults influence the likelihood for hazard H17 in the case of navigation based alternatives. Because systems employed for each alternative depended on the type of airspace, hazards were evaluated separately for terminal and en route airspace. Then the maximum resultant risk was assigned to that hazard. For hazards H2 and H17, the en route airspace resulted in the maximum risk, primarily due to the lack of Primary Surveillance Radar.

The table below summarizes the results of the fault tree and event tree analyses used to determine the overall risk for each alternative-hazard combination.

Table C4-2: Likelihood Components per Alternative-Hazard Combination

Strategy	**Hazard / Cause ID**	**Description**	**Fault Tree Top-Level Event Likelihood (A)**		**Worst Case, Credible Event Tree Path**	**Likelihood for Event Tree Path N (B)**	**Hazard Likelihood (A) x (B)**	**Hazard Severity**	**Risk**
			Terminal	**En Route**					
Alt 1	H1	Loss of ATC surveillance (all aircraft)	10^{-5}	**10^{-5}**	vi	0.999999	**10^{-5}**	4	4B (Med)
Alt 1	H2	Loss of surveillance (single aircraft)	10^{-3}	**10^{-2}**	vii	0.999999	**10^{-2}**	4	4A (Med)
Alt 1	H17	Loss of surveillance (multiple aircraft)	10^{-10}	**10^{-6}**	vii	0.999999	**10^{-6}**	4	4C (Low)
Alt 2	H1	Loss of ATC surveillance (all aircraft)	10^{-5}	**10^{-5}**	vi	0.999999	**10^{-5}**	4	4B (Med)
Alt 2	H2	Loss of surveillance (single aircraft)	10^{-4}	**10^{-2}**	vii	0.999999	**10^{-2}**	4	4A (Med)
Alt 2	H17	Loss of surveillance (multiple aircraft)	10^{-9}	**10^{-5}**	vii	0.999999	**10^{-5}**	4	4B (Med)
Alt 3	H1	Loss of ATC surveillance (all aircraft)	10^{-5}	**10^{-5}**	vi	0.999999	**10^{-5}**	4	4B (Med)
Alt 3	H2	Loss of surveillance (single aircraft)	10^{-3}	**10^{-2}**	vii	0.999999	**10^{-2}**	4	4A (Med)
Alt 3	H17	Loss of surveillance (multiple aircraft)	10^{-9}	**10^{-5}**	vii	0.999999	**10^{-5}**	4	4B (Med)
Alt 4	H1	Loss of ATC surveillance (all aircraft)	10^{-5}	**10^{-5}**	vi	0.999999	**10^{-5}**	4	4B (Med)
Alt 4	H2	Loss of surveillance (single aircraft)	10^{-3}	**10^{-3}**	vii	0.999999	**10^{-3}**	4	4A (Med)
Alt 4	H17	Loss of surveillance (multiple aircraft)	10^{-10}	**10^{-2}**	vii	0.999999	**10^{-2}**	4	4A (Med)
Alt 5	H1	Loss of ATC surveillance (all aircraft)	10^{-5}	**10^{-5}**	vi	0.999999	**10^{-5}**	4	4B (Med)
Alt 5	H2	Loss of surveillance (single aircraft)	10^{-3}	**10^{-3}**	vii	0.999999	**10^{-3}**	4	4A (Med)
Alt 5	H17	Loss of surveillance (multiple aircraft)	10^{-10}	**10^{-2}**	vii	0.999999	**10^{-2}**	4	4A (Med)
Alt 6	H1	Loss of ATC surveillance (all aircraft)	10^{-5}	**10^{-5}**	vi	0.999999	**10^{-5}**	4	4B (Med)
Alt 6	H2	Loss of surveillance (single aircraft)	10^{-3}	**10^{-3}**	vii	0.999999	**10^{-3}**	4	4A (Med)
Alt 6	H17	Loss of surveillance (multiple aircraft)	10^{-2}	**10^{-2}**	vii	0.999999	**10^{-2}**	4	4A (Med)

Table C4-2 (ctd): Likelihood Components per Alternative-Hazard Combination

Strategy	Hazard / Cause ID	Description	Fault Tree Top-Level Event Likelihood (A)		Worst Case, Credible Event Tree Path	Likelihood for Event Tree Path N (B)	Hazard Likelihood (A) x (B)	Hazard Severity	Risk
			Terminal	En Route					
Alt 7	H1	Loss of ATC surveillance (all aircraft)	10^{-5}	**10^{-5}**	vi	0.999999	**10^{-5}**	4	4B (Med)
Alt 7	H2	Loss of surveillance (single aircraft)	10^{-3}	**10^{-2}**	vii	0.999999	**10^{-2}**	4	4A (Med)
Alt 7	H17	Loss of surveillance (multiple aircraft)	10^{-10}	**10^{-6}**	vii	0.999999	**10^{-6}**	4	4C (Low)

C5. Analysis Backup

C5.1 Fault Trees

Fault trees were used as to determine one component of the overall hazard likelihood. One fault tree is shown for each alternative-hazard combination. Some alternatives used a different system for terminal airspace and en route airspace. In the alternatives where a Primary Surveillance Radar (PSR) was not present, the faults associated with the PSR were mathematically removed (though still shown in the fault tree) by assigning a probability of 0% if it was under an “OR” gate or assigning a probability of 100% if it was under an “AND” gate. Shaded events in each tree denote backup strategy specific faults.

Table C5-1 indicates which fault trees were used to calculate the likelihood, based on the technical descriptions for the alternatives.

C5.2 Event Trees

Event trees are used in combination with fault trees to aid in identifying the worst, credible outcome. Since the severity of a hazard is greatly influenced by the circumstances under which it occurs, the event trees help identify the most severe outcome that can realistically happen. While it is possible that a collision could occur with any of the hazards examined in this assessment, certain conditions would have to be present in a particular combination and several existing controls would have to fail. Therefore, the likelihood of a collision occurring is not credible.

Table C5-1: Fault Trees by Airspace

Hazard	Airspace	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Alt 7
H1	Terminal	Fig. C5-1	Fig. C5-4	Fig. C5-7	Fig. C5-1	Fig. C5-1	Fig. C5-16	Fig. C5-19
	En Route	Fig. C5-1	Fig. C5-4	Fig. C5-7	Fig. C5-10	Fig. C5-13	Fig. C5-16	Fig. C5-16
H2	Terminal	Fig. C5-2	Fig. C5-5	Fig. C5-8	Fig. C5-2	Fig. C5-2	Fig. C5-17	Fig. C5-20
	En Route	Fig. C5-2	Fig. C5-5	Fig. C5-8	Fig. C5-11	Fig. C5-14	Fig. C5-17	Fig. C5-17
H17	Terminal	Fig. C5-3	Fig. C5-6	Fig. C5-9	Fig. C5-3	Fig. C5-3	Fig. C5-18	Fig. C5-21
	En Route	Fig. C5-3	Fig. C5-6	Fig. C5-9	Fig. C5-12	Fig. C5-15	Fig. C5-18	Fig. C5-18

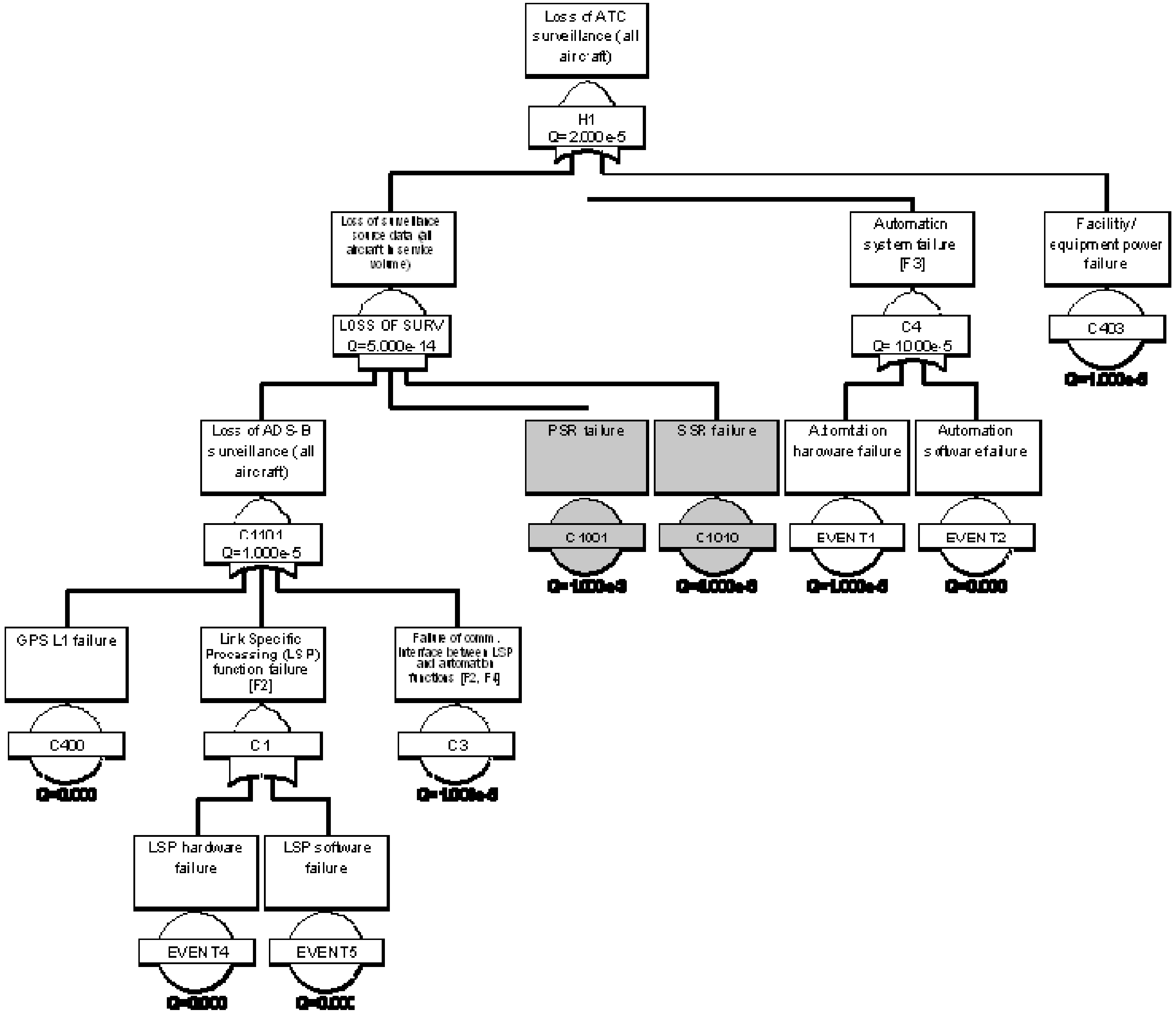


Figure C5-1: Strategy 1 - Hazard H1

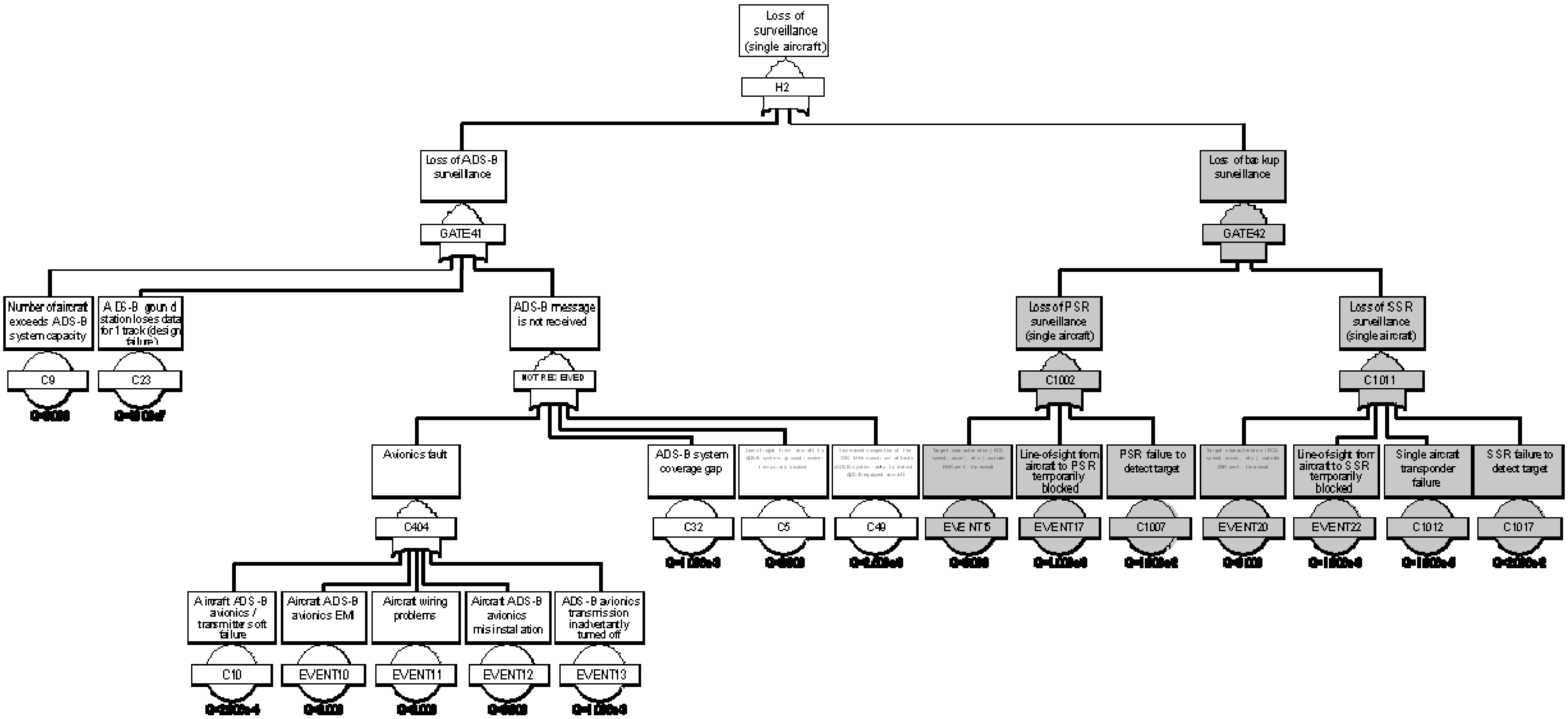


Figure C5-2: Strategy 1 - Hazard H2

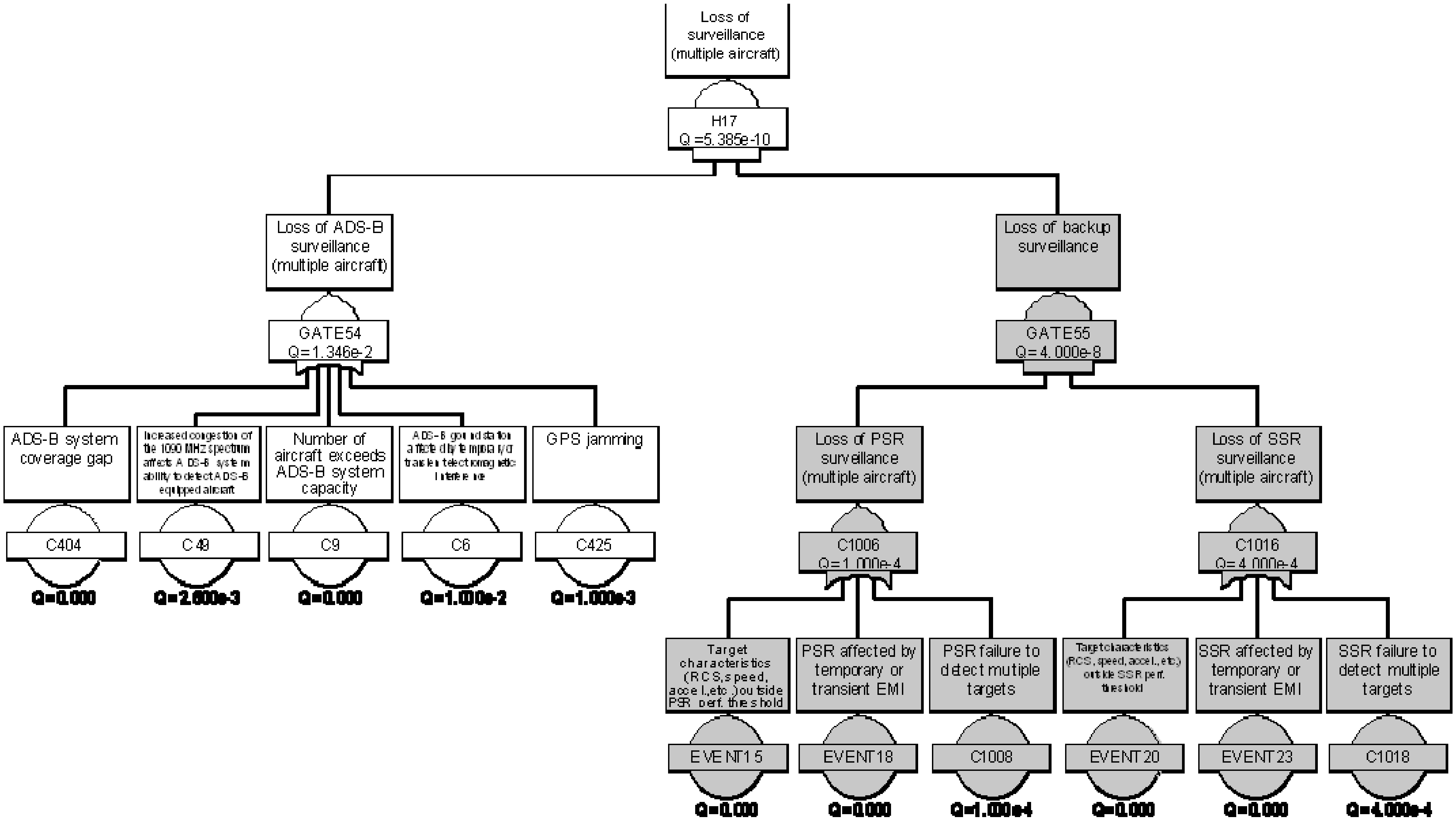


Figure C5-3: Strategy 1 - Hazard H17

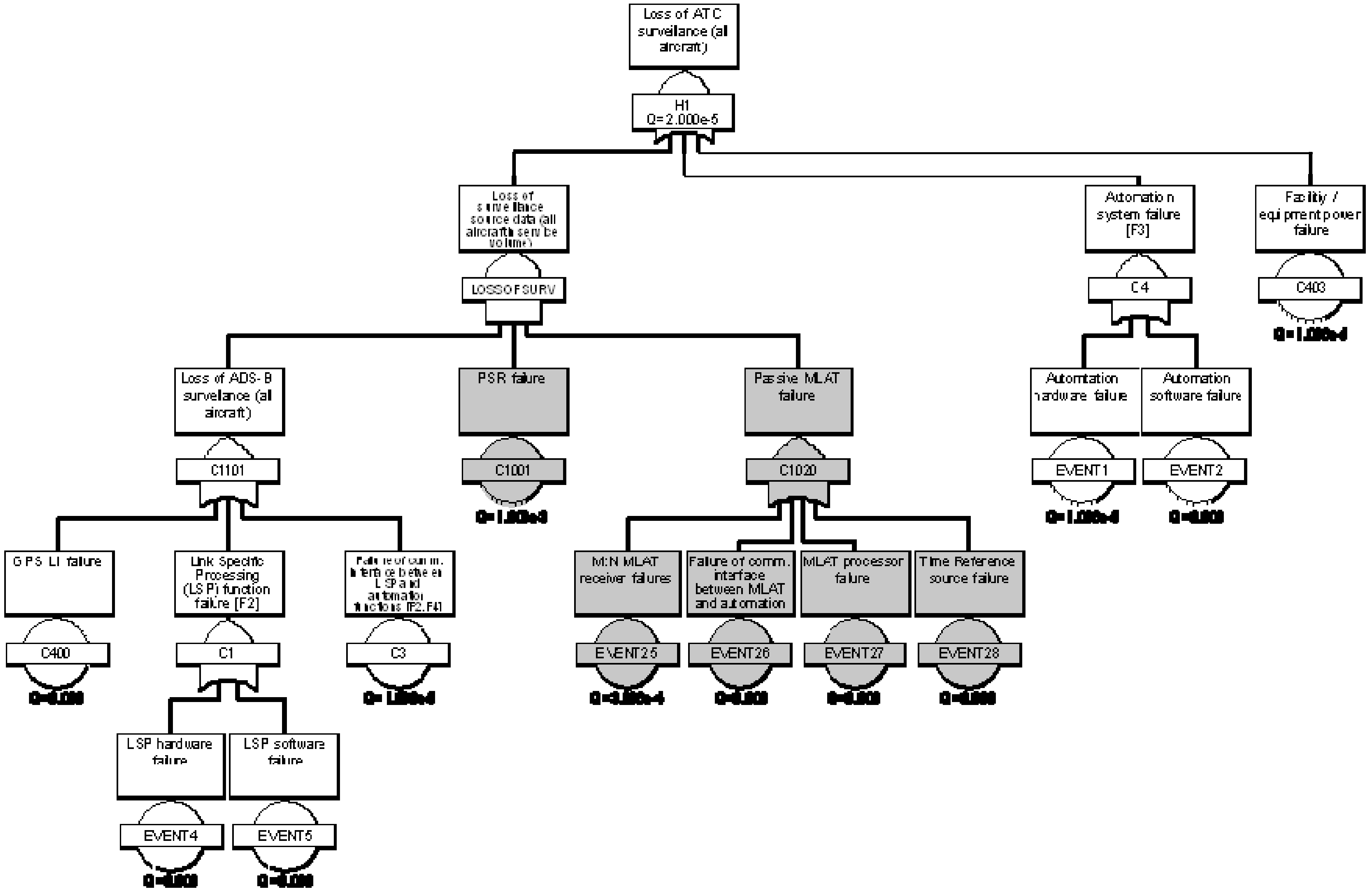


Figure C5-4: Strategy 2 - Hazard H1

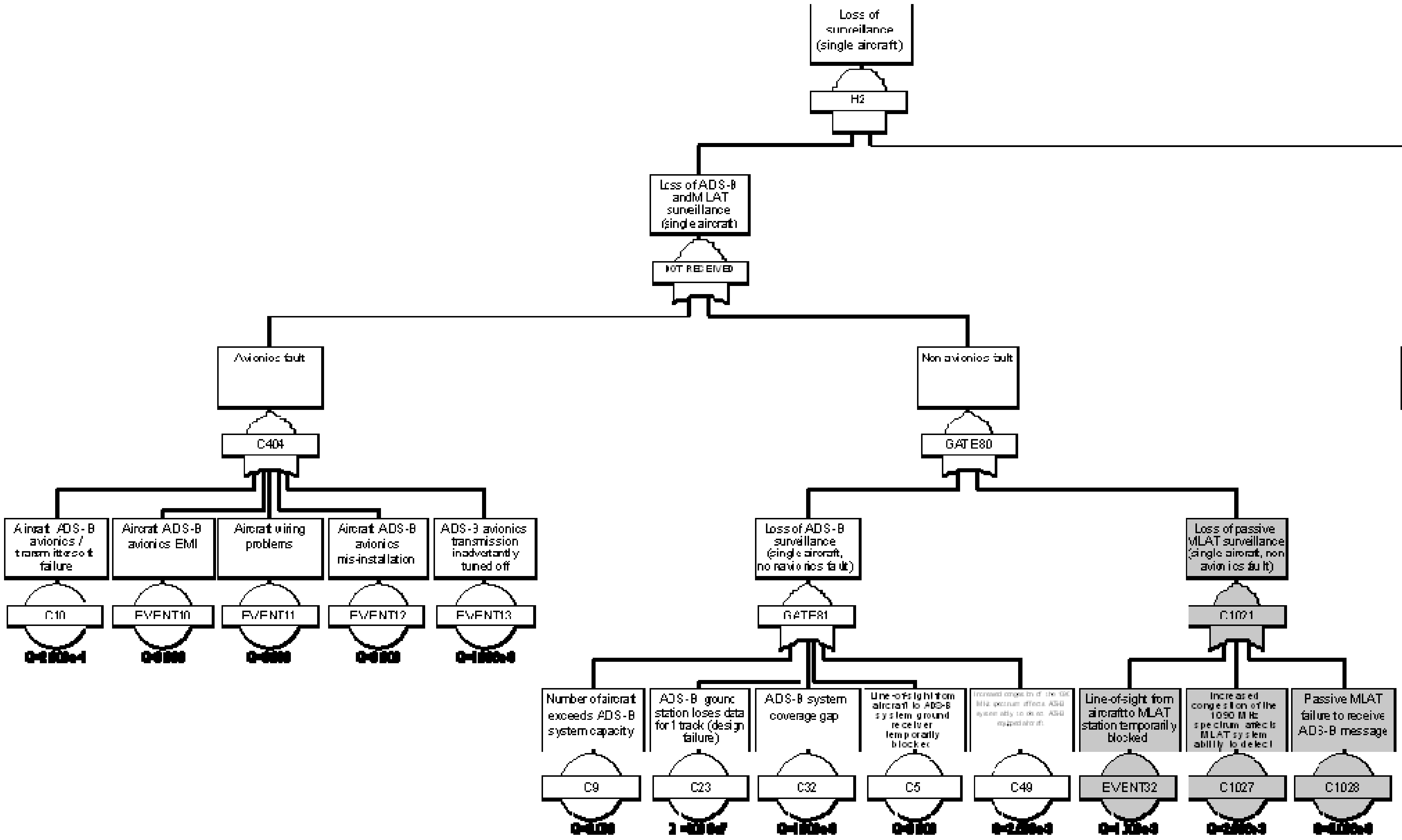


Figure C5-5: Strategy 2 - Hazard H2

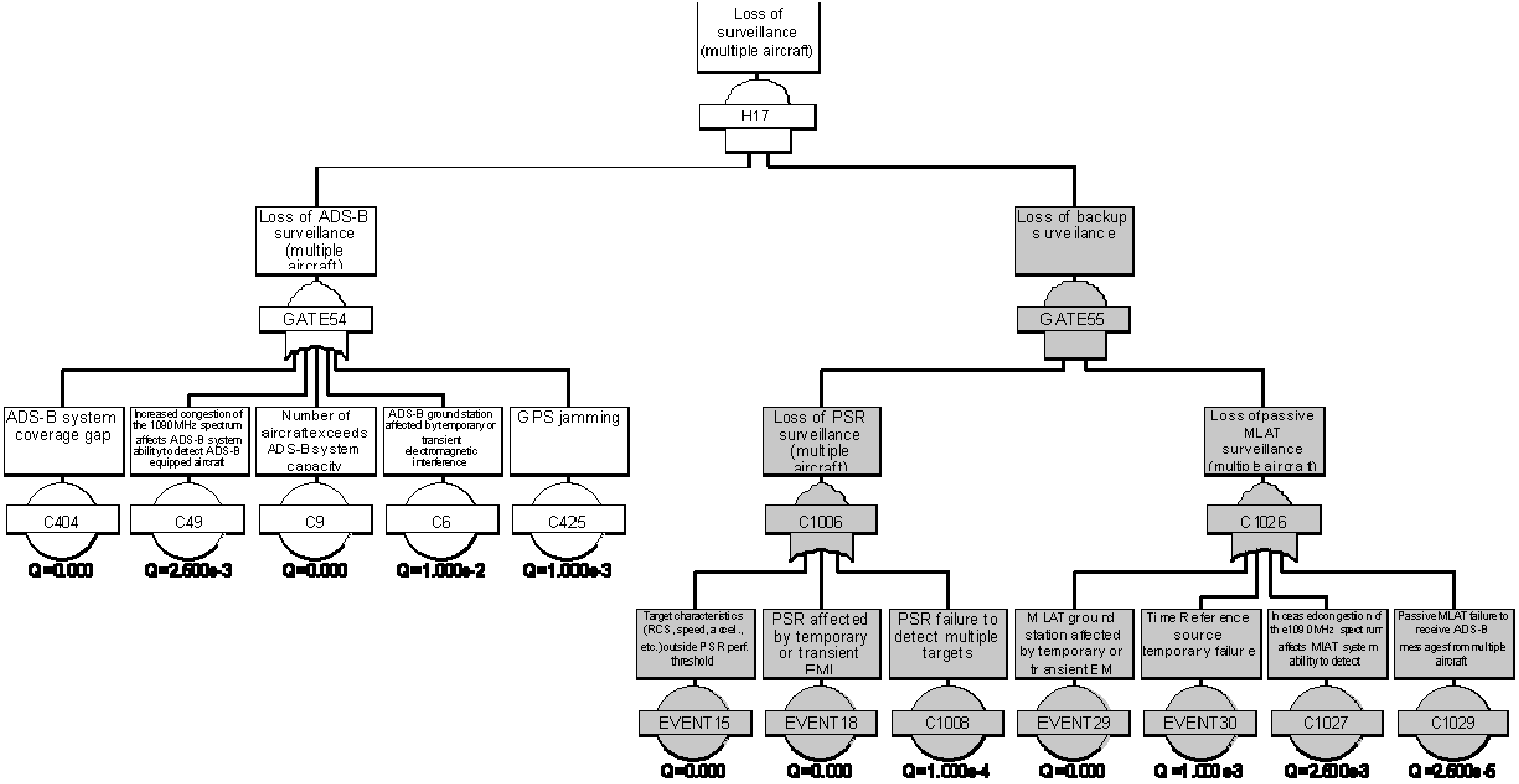


Figure C5-6: Strategy 2 - Hazard H17

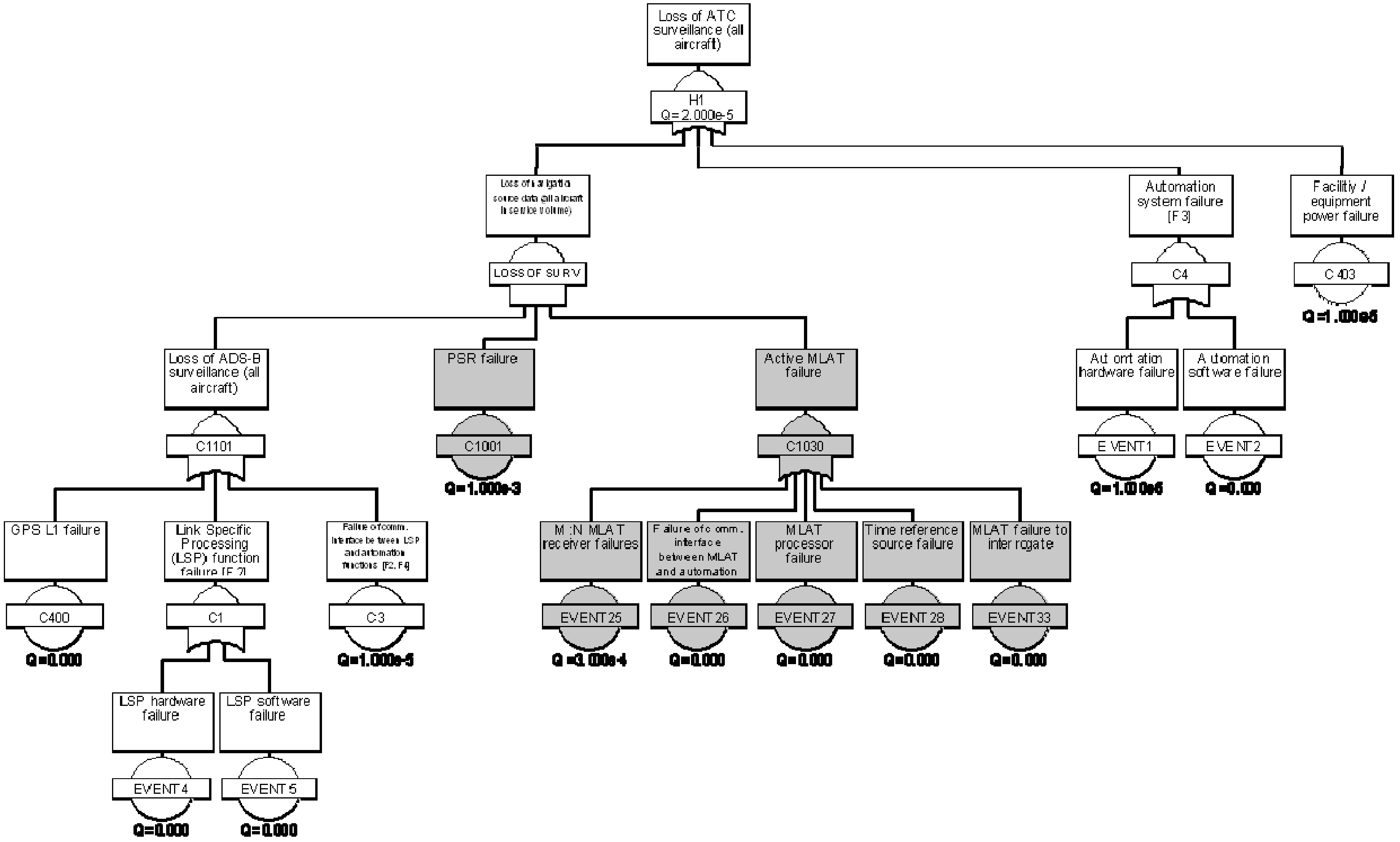


Figure C5-7: Strategy 3 - Hazard H1

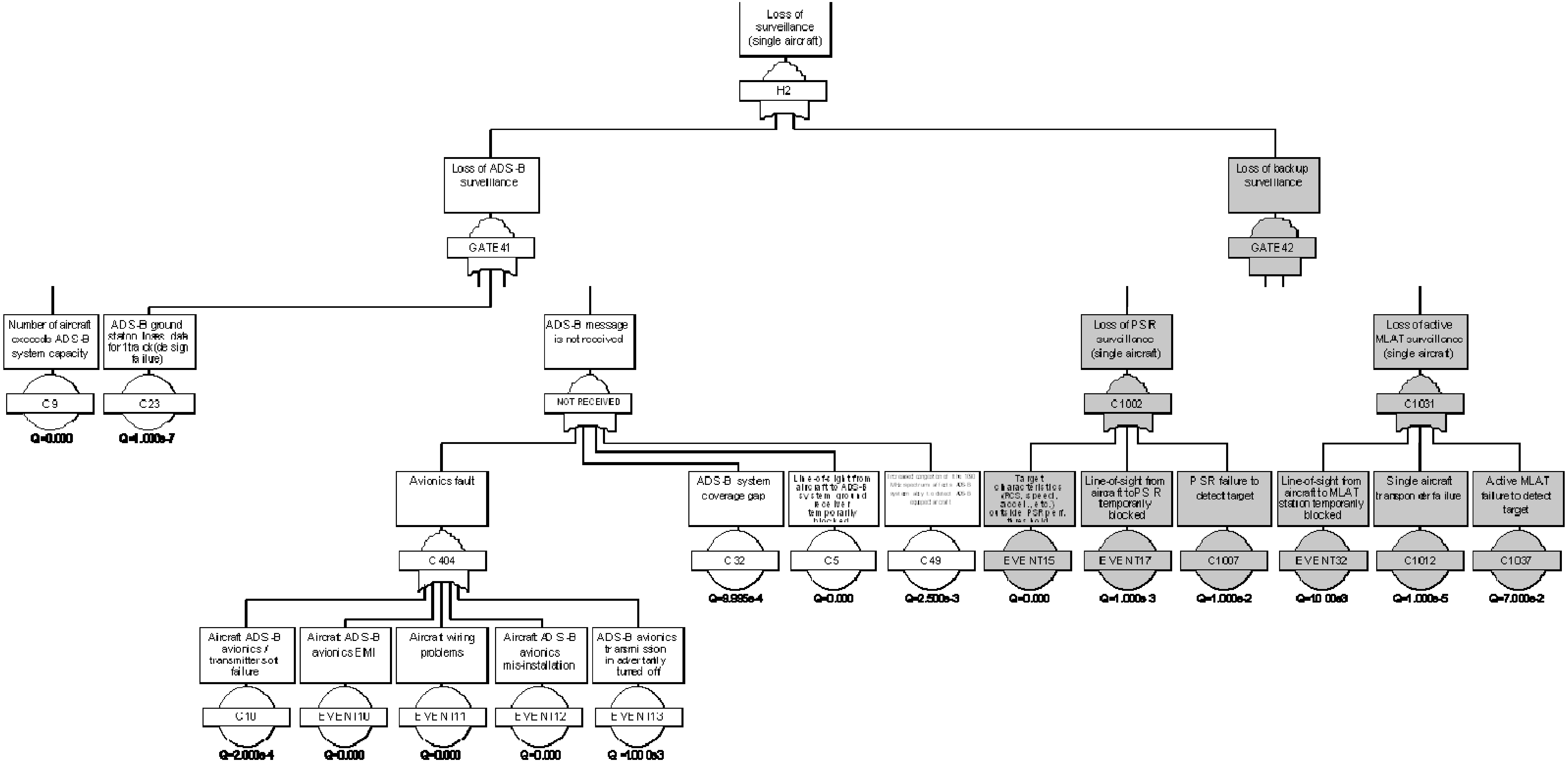


Figure C5-8: Strategy 3 - Hazard H2

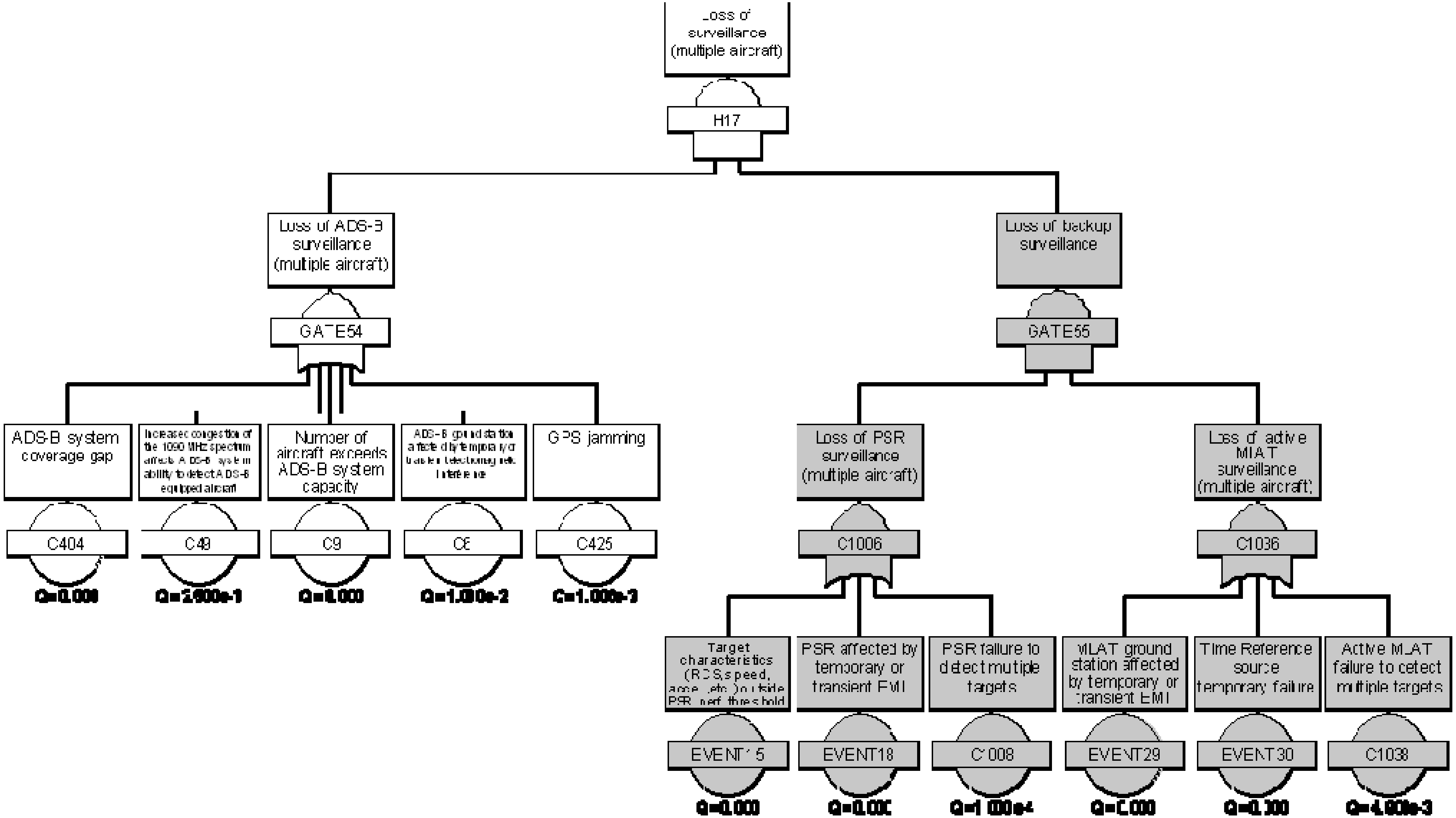


Figure C5-9: Strategy 3 - Hazard H17

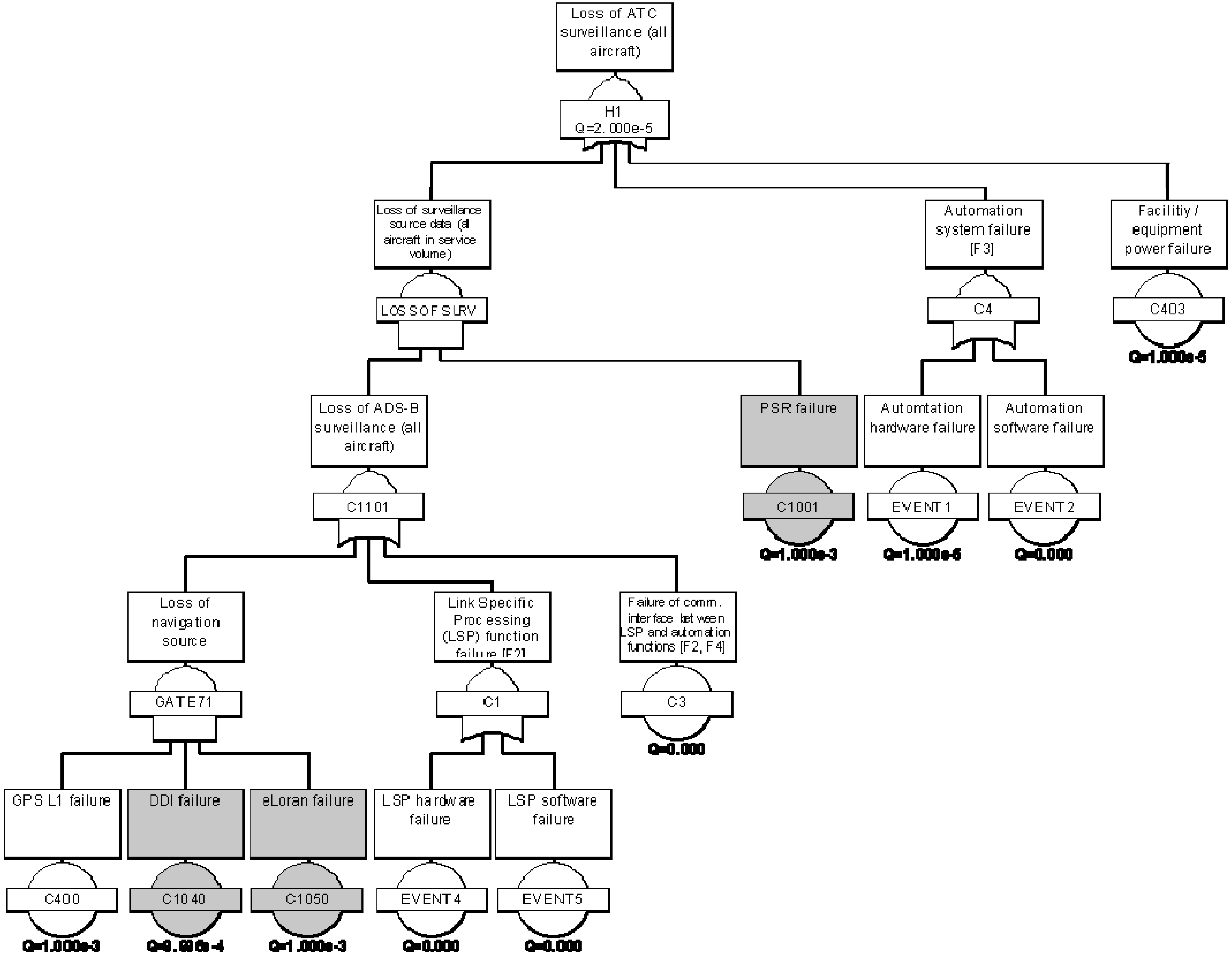


Figure C5-10: Strategy 4 - Hazard H1

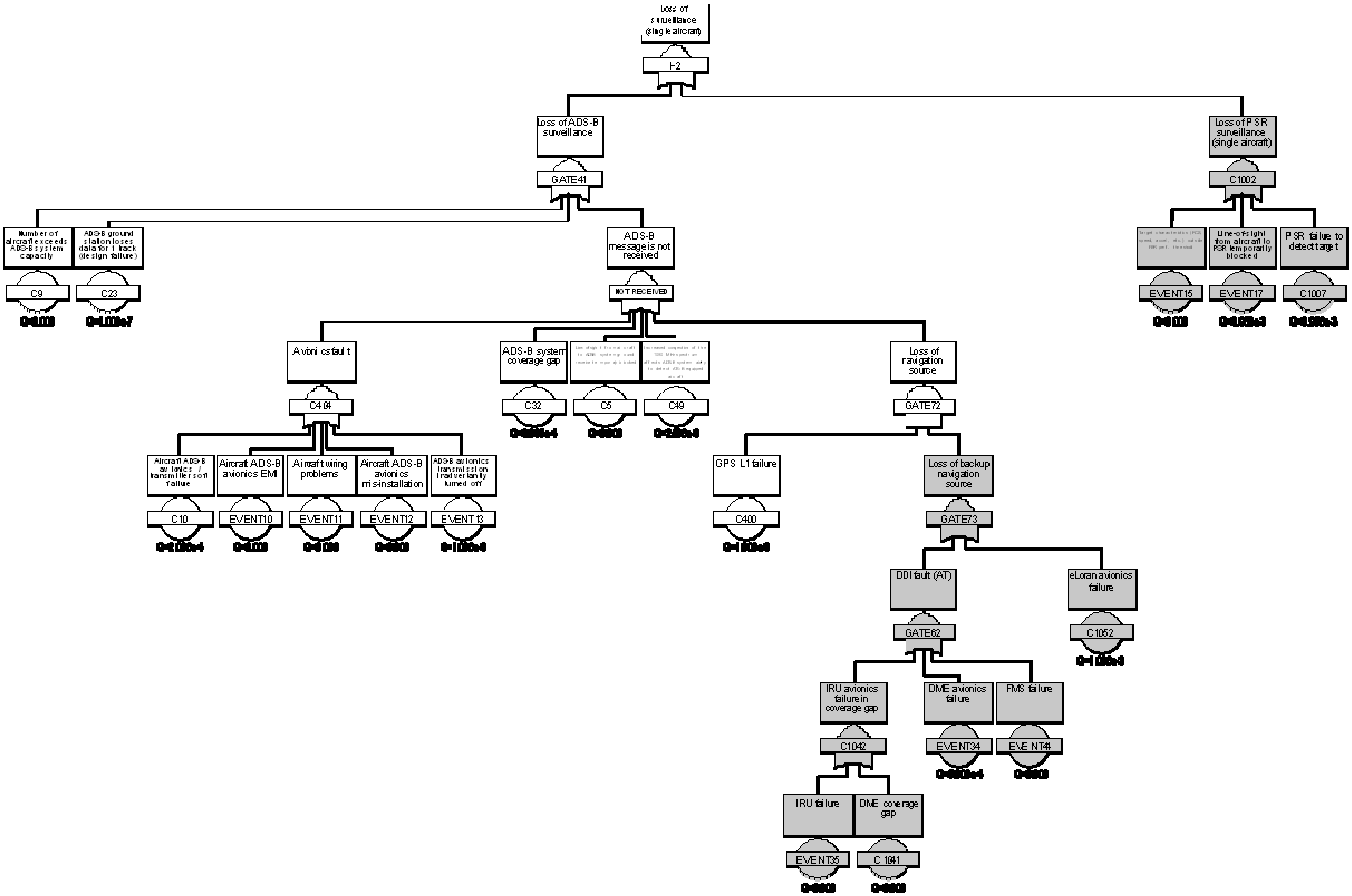


Figure C5-11: Strategy 4 - Hazard H2

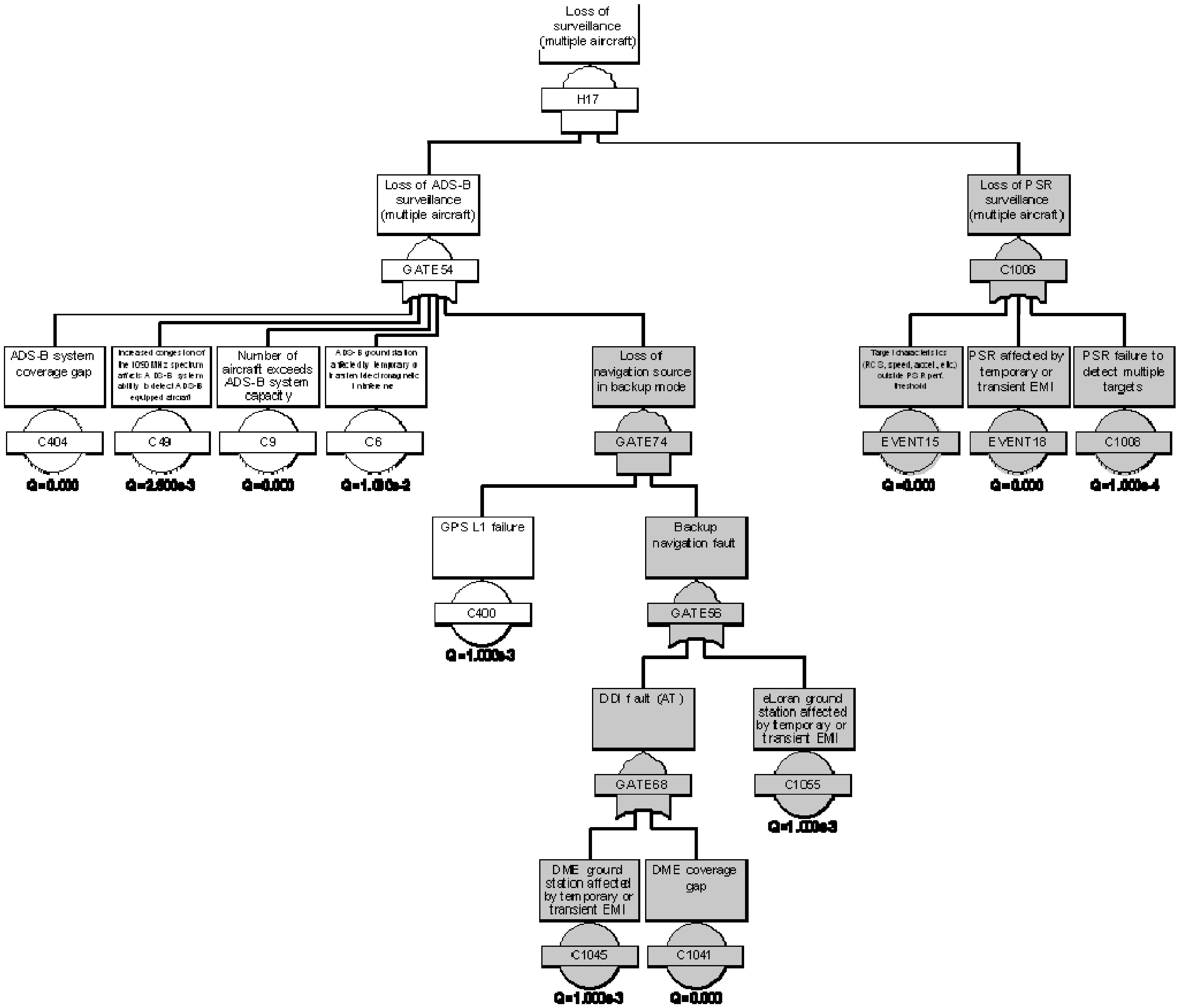


Figure C5-12: Strategy 4 - Hazard H17

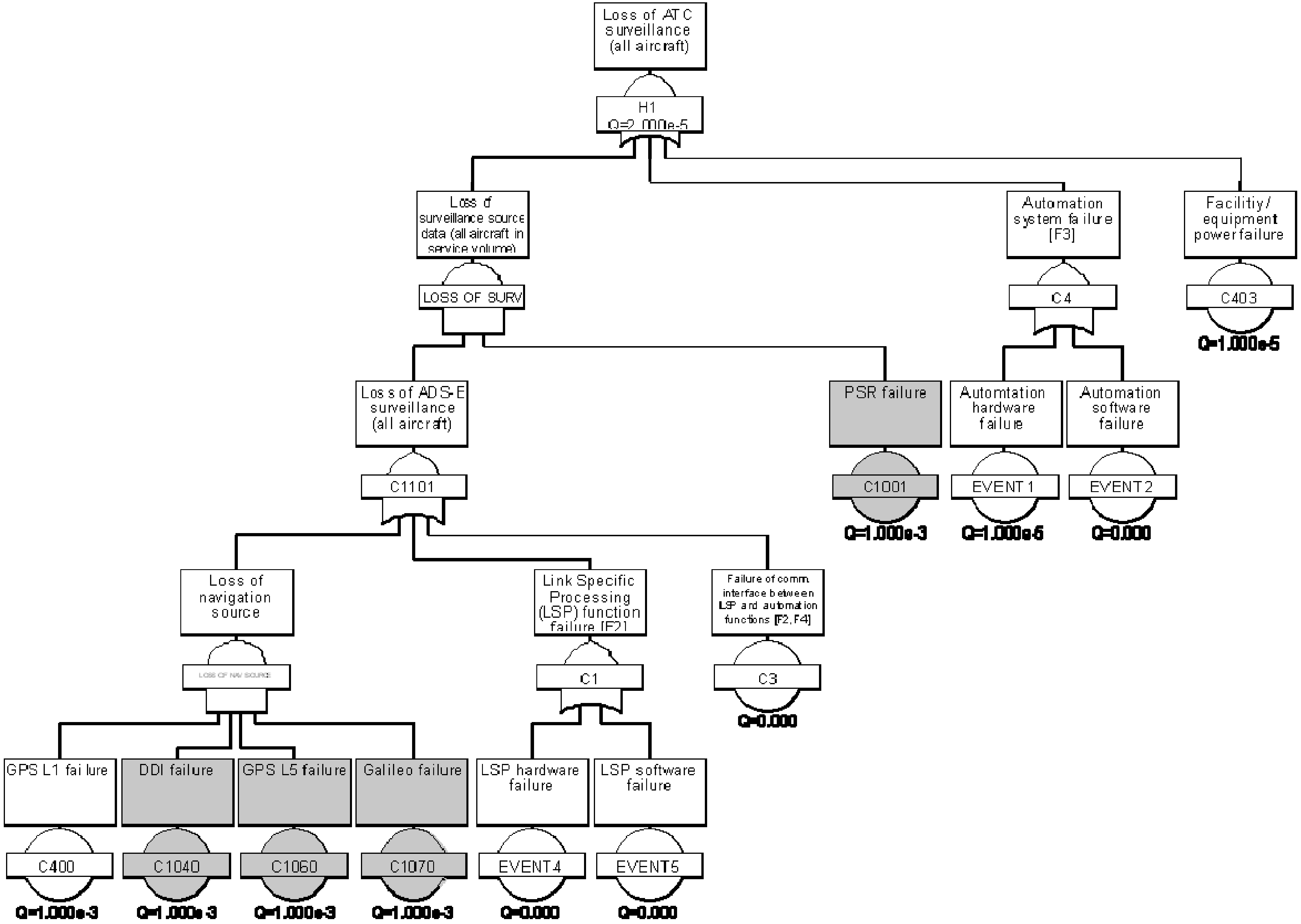


Figure C5-13: Strategy 5 - Hazard H1

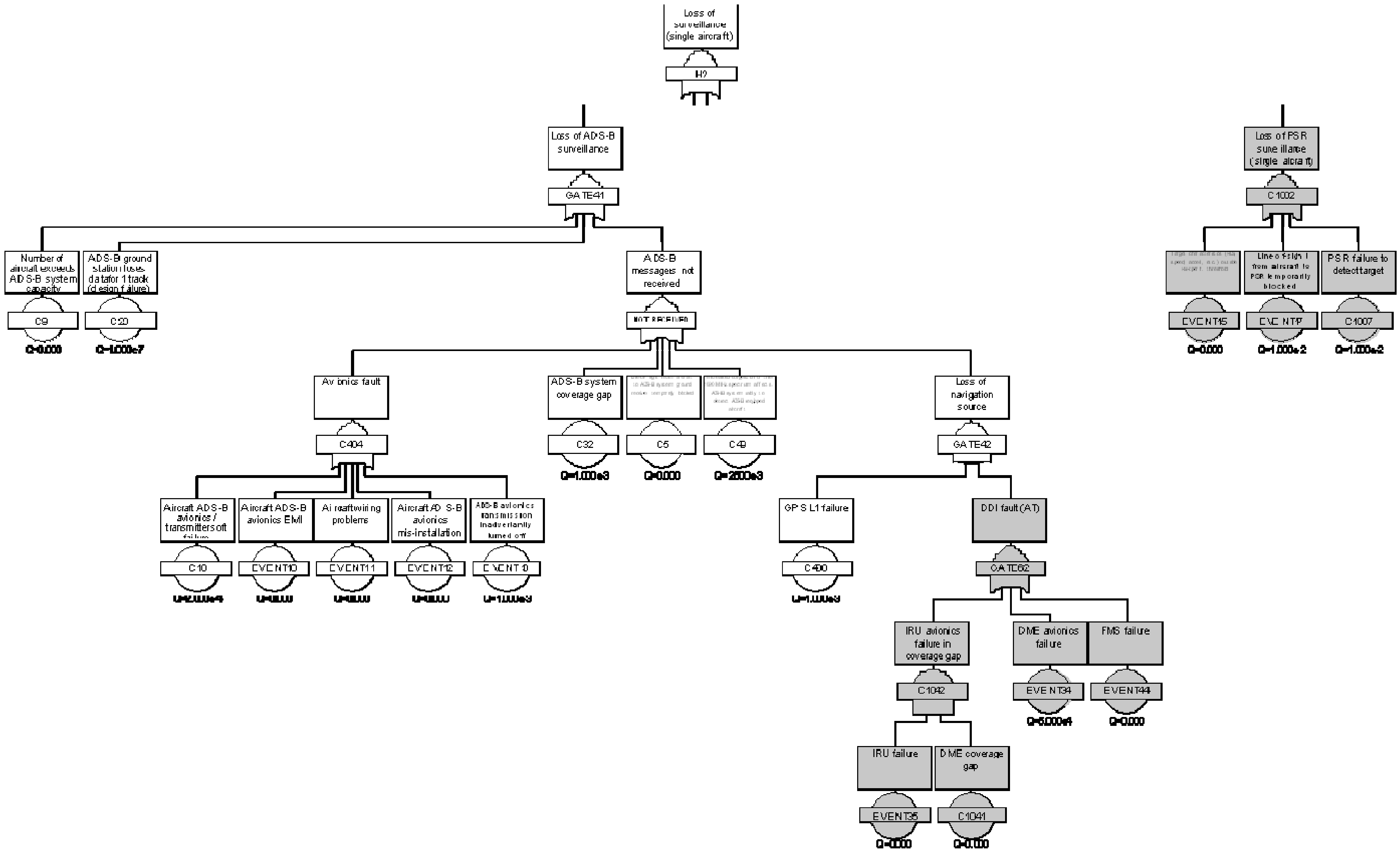


Figure C5-14: Strategy 5 - Hazard H2

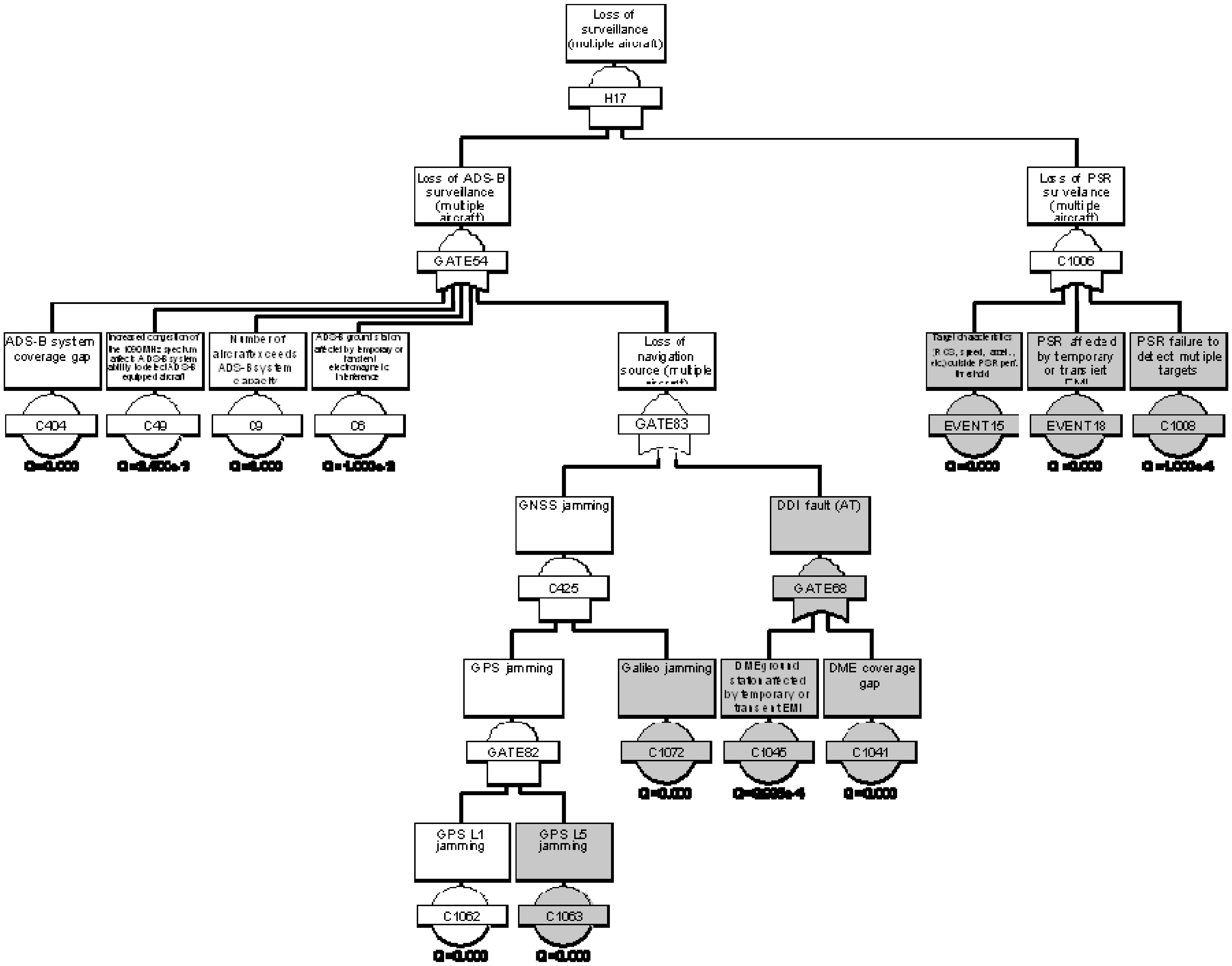


Figure C5-15: Strategy 5 - Hazard H17

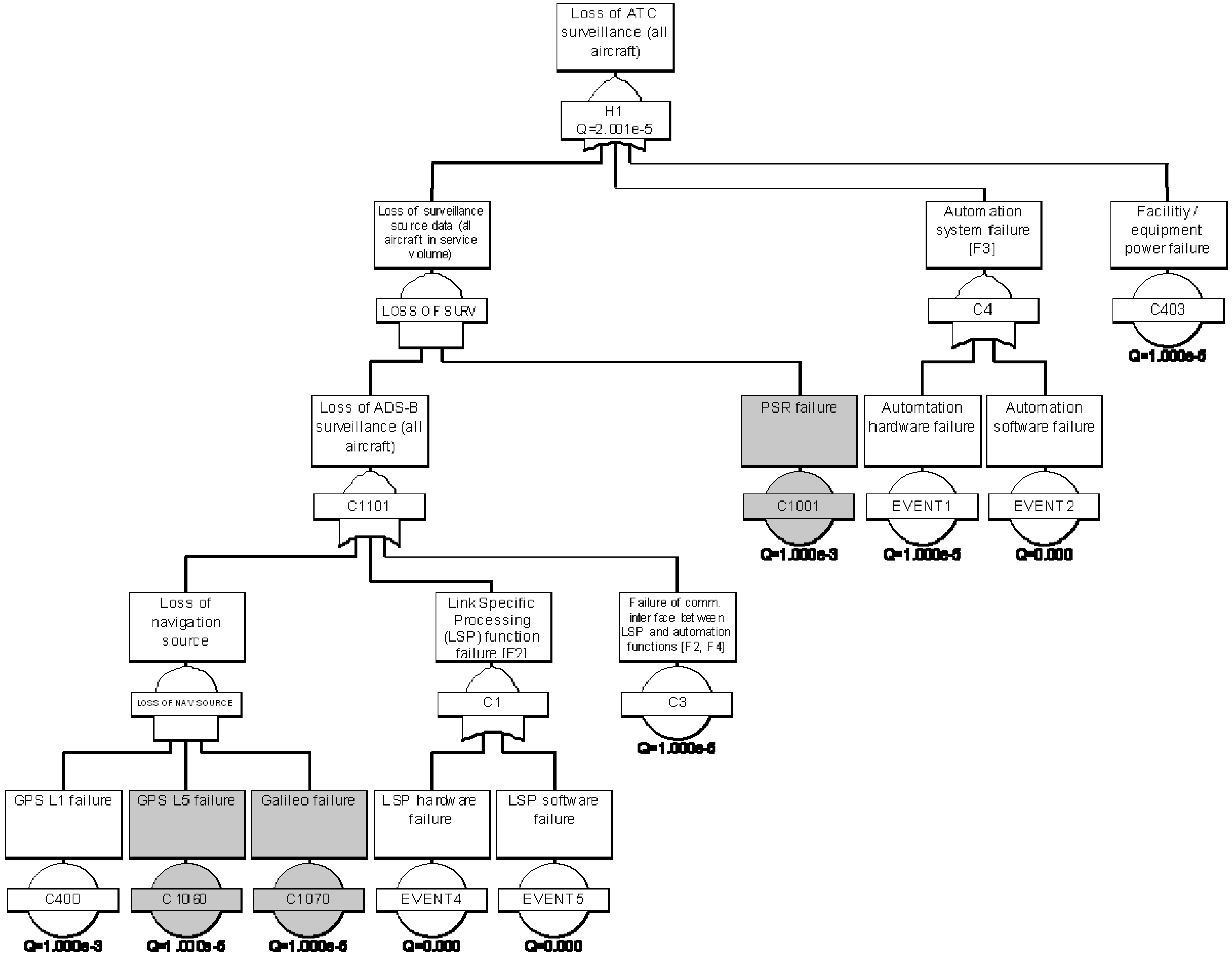


Figure C5-16: Strategy 6 - Hazard H1

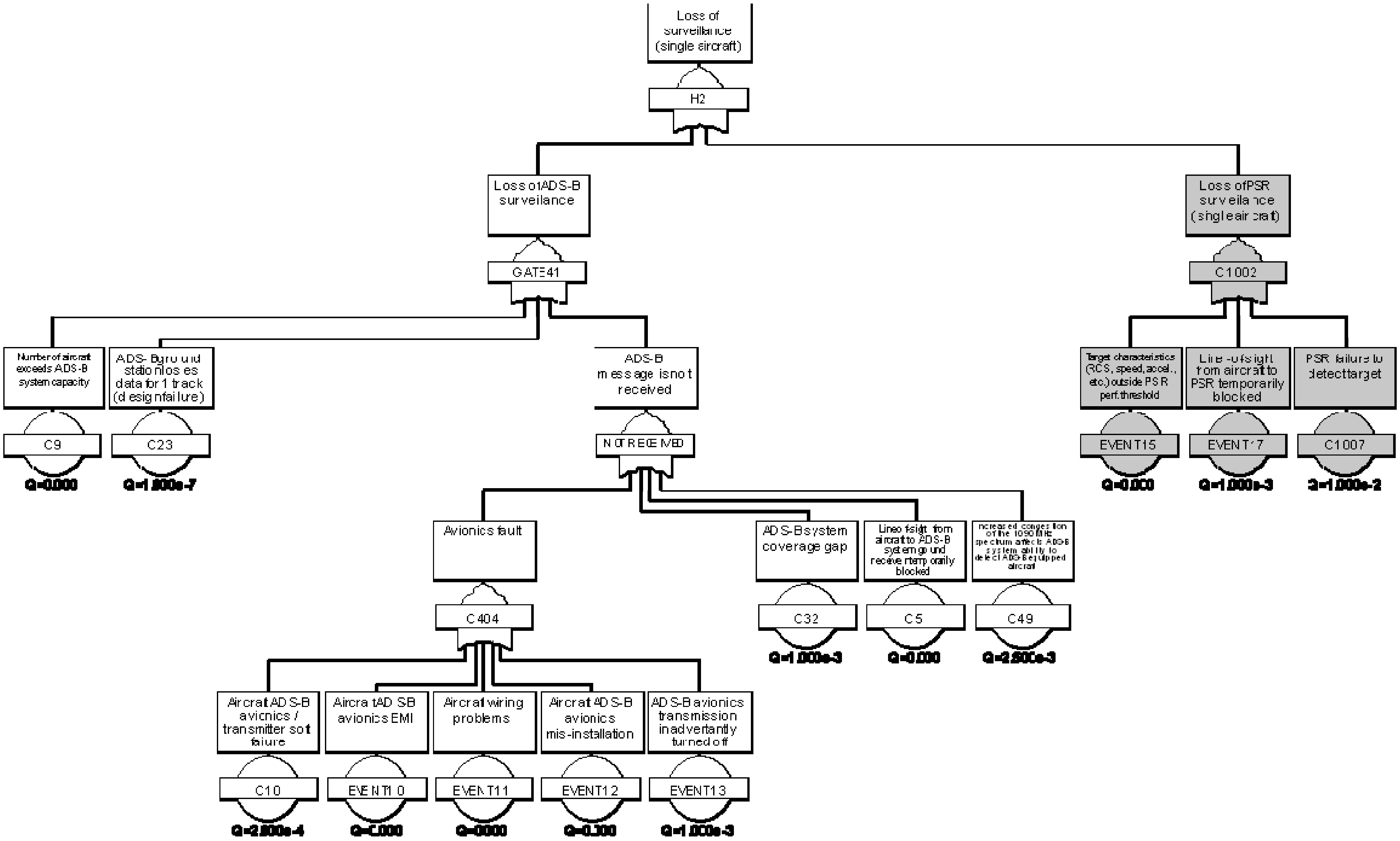


Figure C5-17: Strategy 6 - Hazard H2

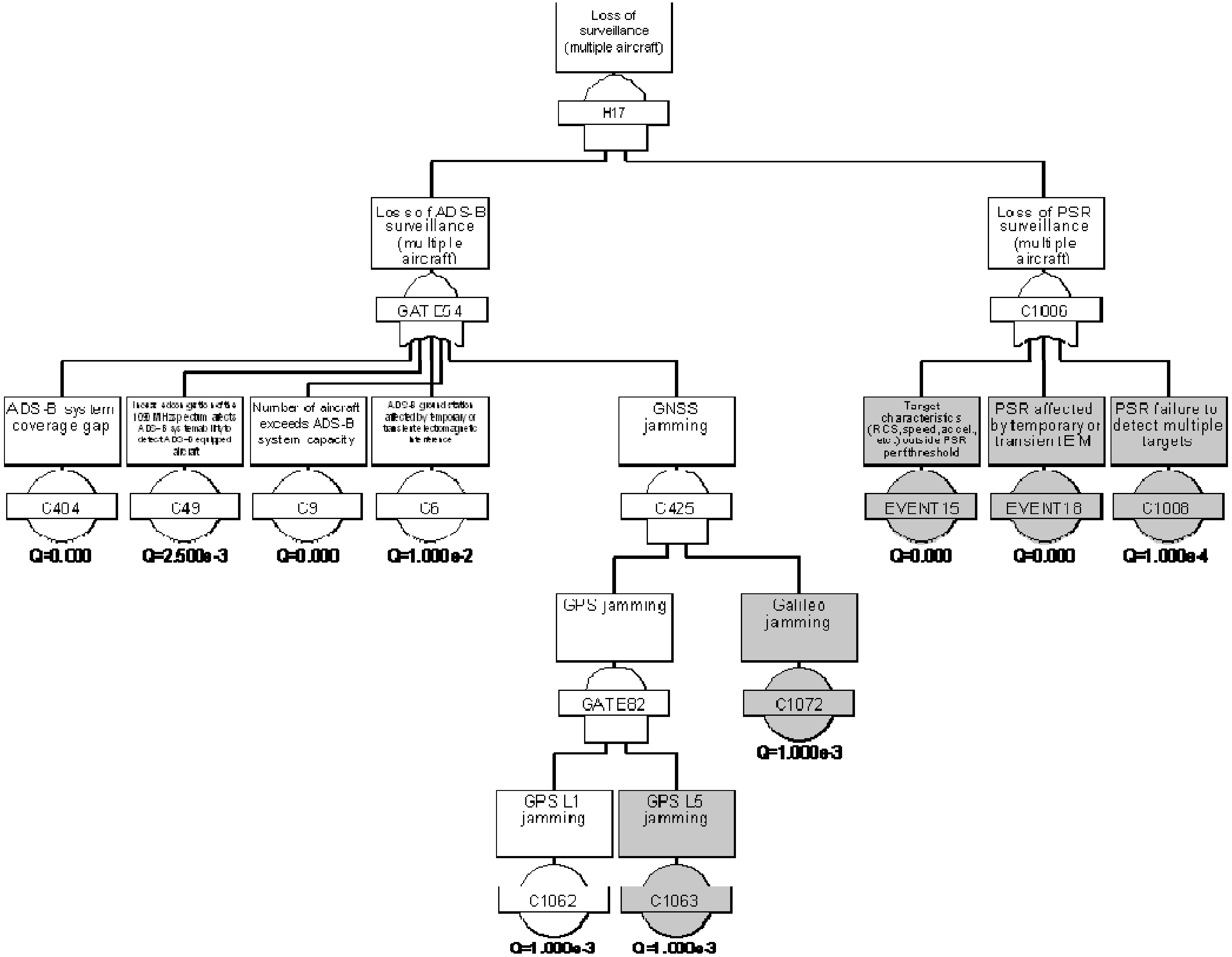


Figure C5-18: Strategy 6 - Hazard H17

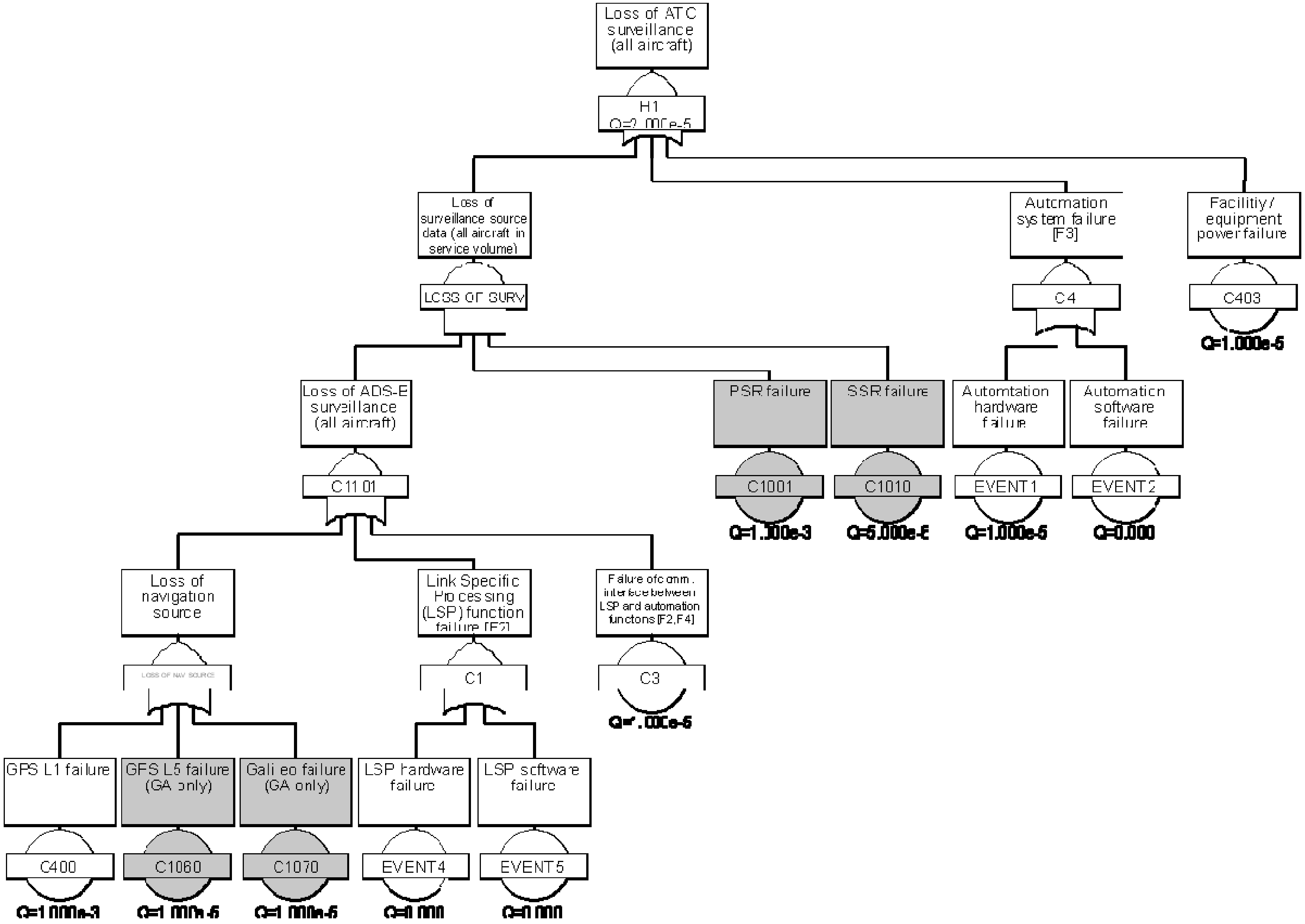


Figure C5-19: Strategy 7 - Hazard H1

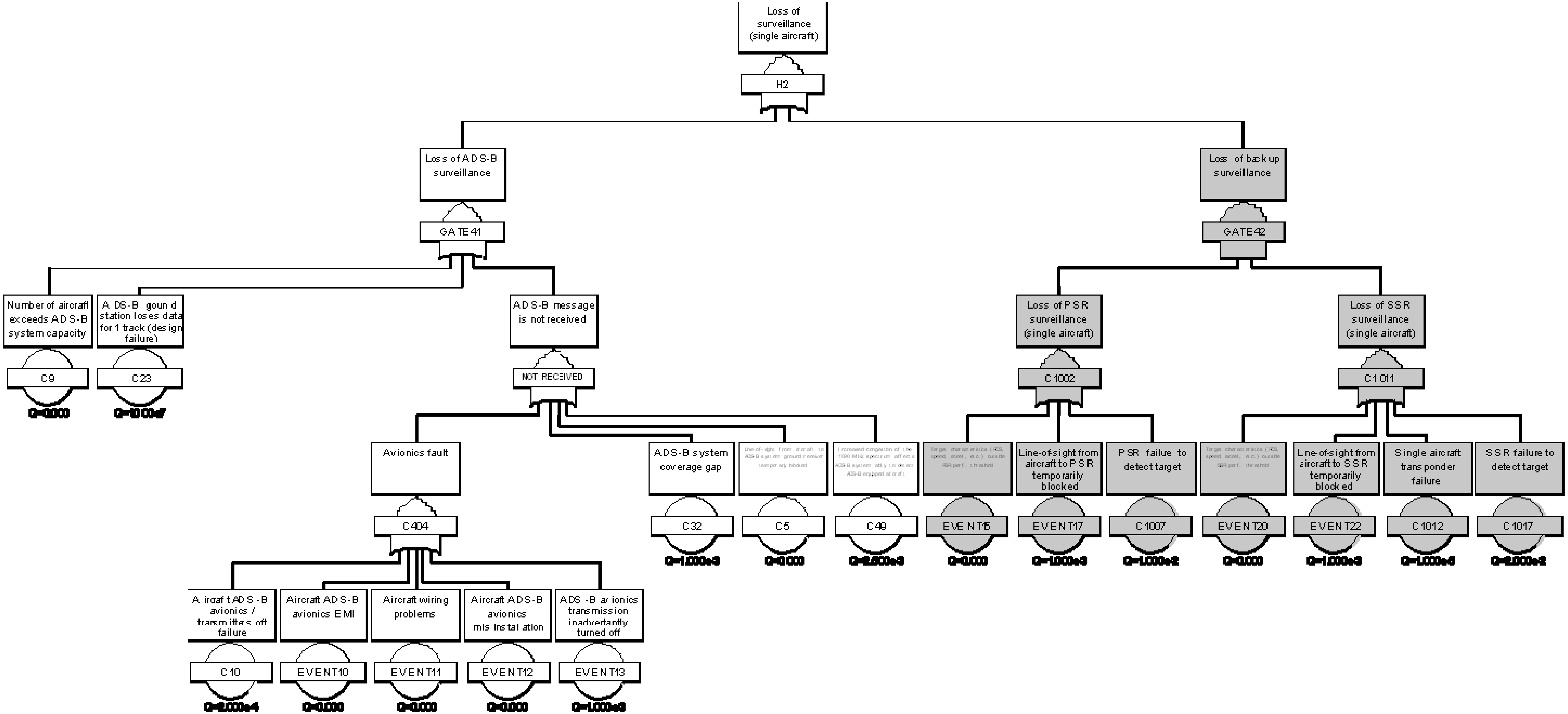


Figure C5-20: Strategy 7 - Hazard H2

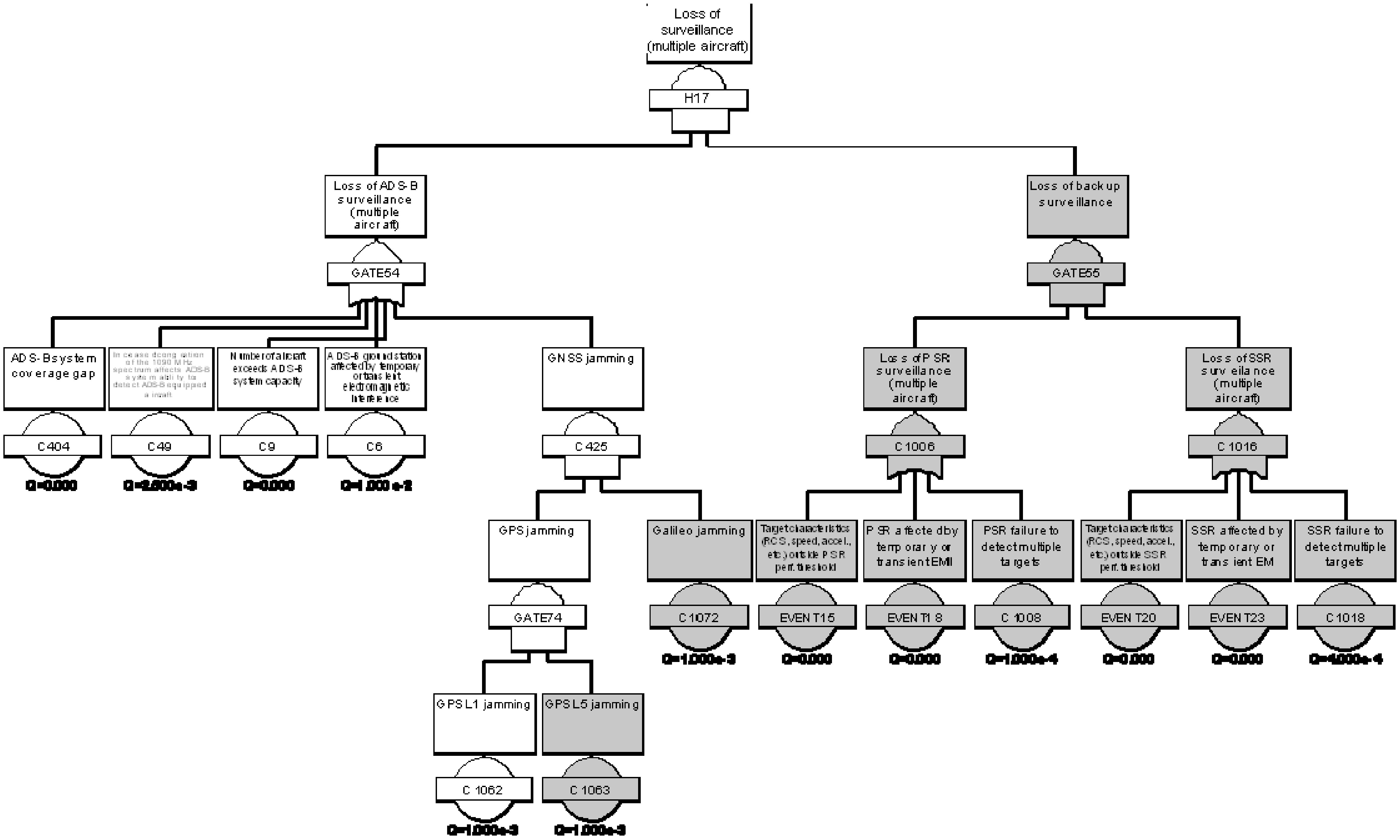


Figure C5-21: Strategy 7 - Hazard H17

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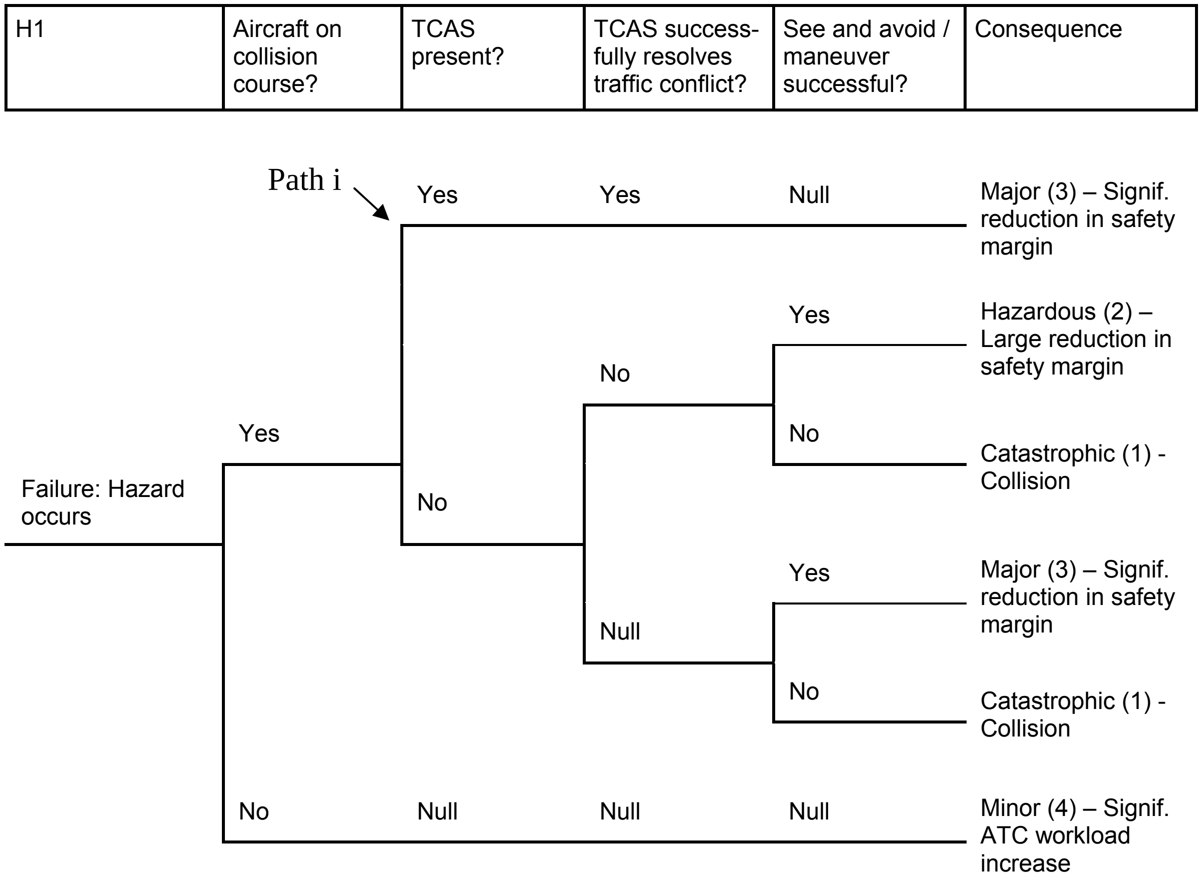

Figure C5-22: Event Tree for Hazard H1

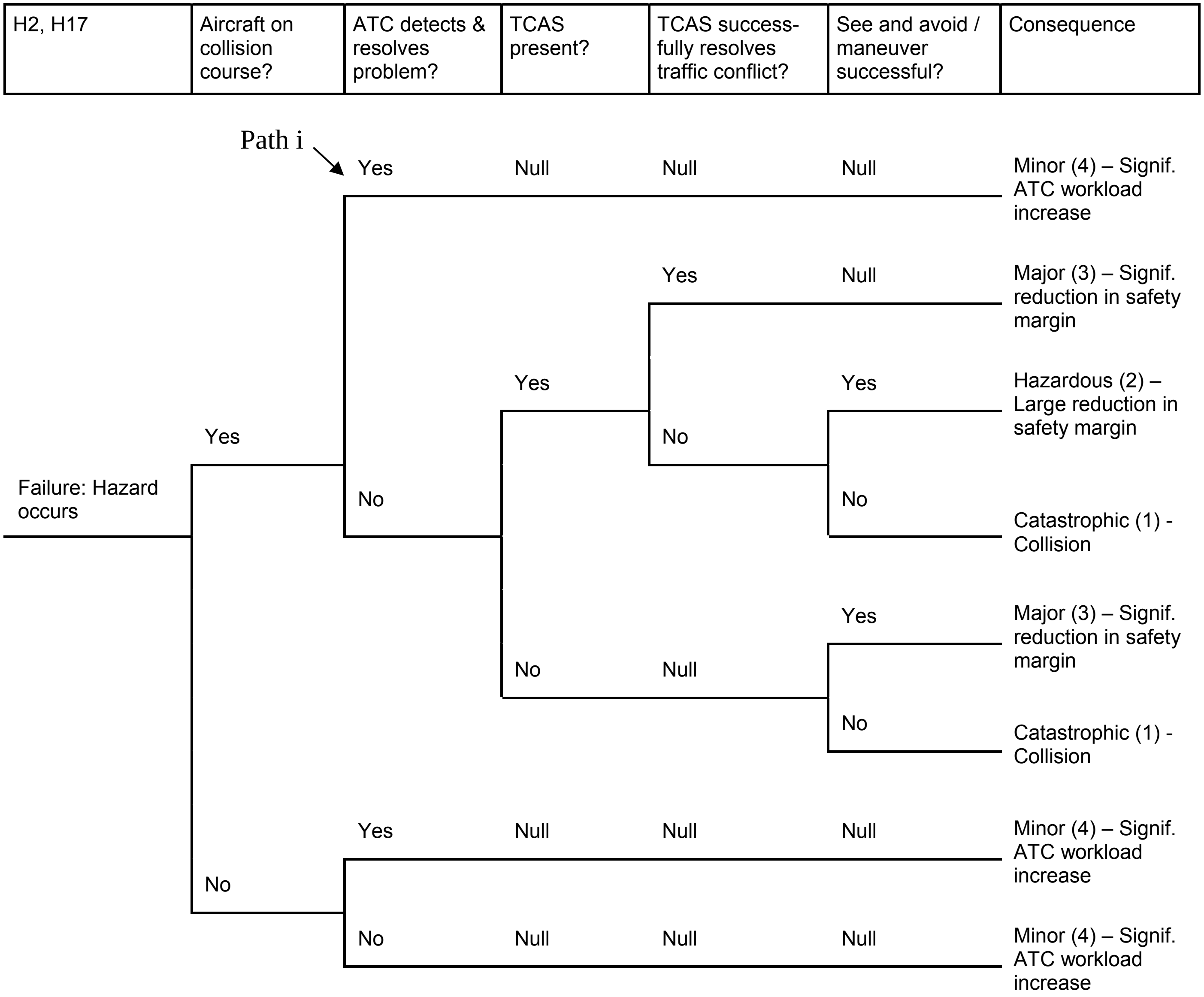

Figure C5-23: Event Tree for Hazards H2, H17

Table C5-2: Event Tree Paths for Hazard H1

Event Tree Path	On collision course?	Likelihood	TCAS equipped?	Likelihood	TCAS successful?	Likelihood	See & avoid successful?	Likelihood	Event Tree Calc. Likelihood	Severity
i	Y	1.00000E-06	Y	0.6	Y	0.9	Null	N/A	5.40000E-07	3
ii	Y	1.00000E-06	Y	0.6	N	0.1	Y	0.001	6.00000E-11	2
iii	Y	1.00000E-06	Y	0.6	N	0.1	N	0.999	5.99400E-08	1
iv	Y	1.00000E-06	N	0.4	Null	N/A	Y	0.001	4.00000E-10	3
v	Y	1.00000E-06	N	0.4	Null	N/A	N	0.999	3.99600E-07	1
vi	N	9.99999E-01	Null		Null		Null		9.99999E-01	4

<u>Note</u>: Event tree path ii is considered "not credible" based on likelihood < = 10^{-11}

Table C5-3: Event Tree Paths for Hazard H2

Event Tree Path	On collision course?	Likelihood	ATC detects & corrects?	Likelihood	TCAS equipped?	Likelihood	TCAS successful?	Likelihood	See & avoid successful?	Likelihood	Event Tree Calc. Likelihood	Severity
i	Y	1.00000E-06	Y	0.9	Null	N/A	Null	N/A	Null	N/A	9.00000E-07	4
ii	Y	1.00000E-06	N	0.1	Y	0.6	Y	0.9	Null	N/A	5.40000E-08	3
iii	Y	1.00000E-06	N	0.1	Y	0.6	N	0.1	Y	0.001	6.00000E-12	2
iv	Y	1.00000E-06	N	0.1	Y	0.6	N	0.1	N	0.999	5.99400E-09	1
v	Y	1.00000E-06	N	0.1	N	0.4	Null	N/A	Y	0.001	4.00000E-11	3
vi	Y	1.00000E-06	N	0.1	N	0.4	Null	N/A	N	0.999	3.99600E-08	1
vii	N	9.99999E-01	Null		Null		Null		Null		9.99999E-01	4

<u>Note</u>: Event tree paths iii and v are considered "not credible" based on likelihood < = 10^{-11}

Table C5-4: Event Tree Paths for Hazard H17

Event Tree Path	On collision course?	Likelihood	ATC detects & corrects?	Likelihood	TCAS equipped?	Likelihood	TCAS successful?	Likelihood	See & avoid successful?	Likelihood	Event Tree Calc. Likelihood	Severity
i	Y	1.00000E-06	Y	0.999	Null	N/A	Null	N/A	Null	N/A	9.99000E-07	4
ii	Y	1.00000E-06	N	0.001	Y	0.6	Y	0.9	Null	N/A	5.40000E-10	3
iii	Y	1.00000E-06	N	0.001	Y	0.6	N	0.1	Y	0.001	6.00000E-14	2
iv	Y	1.00000E-06	N	0.001	Y	0.6	N	0.1	N	0.999	5.99400E-11	1
v	Y	1.00000E-06	N	0.001	N	0.4	Null	N/A	Y	0.001	4.00000E-13	3
vi	Y	1.00000E-06	N	0.001	N	0.4	Null	N/A	N	0.999	3.99600E-10	1
vii	N	9.99999E-01	Y	0.999	Null	N/A	Null	N/A	Null	N/A	9.99999E-01	4
viii	N	9.99999E-01	N	0.001	Null	N/A	Null	N/A	Null	N/A	9.99999E-04	4

<u>Note</u>: Event tree paths iii, iv, and v are considered "not credible" based on likelihood < = 10^{-11}

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Appendix D: Initial ADS-B Surveillance Applications

ATC Surveillance. This application will use ADS-B surveillance information as a qualified surveillance source to provide ATC services throughout the NAS. ATC will use ADS-B surveillance information in the same manner as current cooperative surveillance system information is used, e.g., to assist aircraft with navigation, to separate aircraft, and to issue safety alerts and traffic advisories. ADS-B surveillance informationwill be used by ATC automation system functions, e.g., tracking and conflict alerting. Implementation areas include surface, terminal, en route, and oceanic domains.

Airport Surface Situational Awareness (ASSA). This application will reduce the potential for deviations, errors, and collisions through an increase in flight crew situational awareness while operating an aircraft on the airport movement area. Flight crews will use a cockpit display to increase awareness of other traffic on the airport movement area. Additionally, the display may be used to determine the position of ground vehicles, e.g., emergency vehicles and airport maintenance vehicles.

Final Approach Runway Occupancy Awareness (FAROA). This application will use a cockpit display to depict the runway environment and display traffic from the surface up to approximately 1,000 feet above ground level on final approach. It will be used by the flight crew to help determine runway occupancy, thereby reducing the likelihood of flight crew errors associated with runway occupancy and improving the capability of the flight crew to detect ATC errors.

Enhanced Visual Acquisition (EVAcq). This application uses a cockpit display to enhance out-of-the-window visual acquisition of air traffic. Flight crews will refer to the display during the instrument scan to supplement visual observations. The display can be used to either initially detect an aircraft or to receive further information on an aircraft that has been reported by ATC. The application will provide the flight crew with the relative range, altitude, and bearing of other aircraft.

Enhanced Visual Approach (EVApp). This application will enhance successive approaches for aircraft cleared to maintain visual separation from another aircraft on the approach. This will allow visual approach procedure operation arrival rates to be maintained, even during periods of reduced visibility or obstructions to vision (haze, fog, sunlight, etc). To achieve this, flight crews will be supported by a cockpit display of nearby traffic providing continually updated identity and position information of relevant traffic. Additional information such as range and speed will be provided to assist flight crews in monitoring their distance from the preceding aircraft. The display may also be used to monitor aircraft on approach to parallel runways.

Conflict Detection (CD). This application will provide alerting and relevant traffic information to help the flight crew identify conflicts with other aircraft based on current flight states and intentions. Aircraft equipped with a cockpit display will have the capability to display aircraft location and intent, and will alert pilots of developing conflicts. Also, the long surveillance range afforded by ADS-B will enable alerts to be issued in time to resolve conflicts with minimum disruption to the flight path. NOTE: This application is an ADS-B-enabled capability for properly equipped aircraft, and is not intended as a TCAS replacement.

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Appendix E: Technical Team and Steering Committee Membership

Surveillance/Positioning Backup Strategy Technical Team

Member	Organization	Role
James Baird	FAA ATO-P	Team Lead
George Ligler	PMEI	Team Facilitator
Jonathan Hammer	MITRE/CAASD	Team Secretary
Shahan Stepanian	MCRI	Cost Analyst
Avani Pandya	MCRI	Cost Analyst
Jennifer Lamont	FAA ATO-E (CTR)	Safety Analyst
Mark McCoy	FAA ATO-E (CTR)	Safety Analyst
Ray McDonald	FAA ATO-E (CTR)	Radar, Multilateration SME
James Carroll	Volpe NTSC	eLoran SME
Jack Kraemer	Volpe NTSC	eLoran SME
Dan O’Laughlin	MITRE/CAASD	SATNAV SME
Robert Saffell	Rockwell-Collins	AT Avionics SME
Joel Wichgers	Rockwell-Collins	AT Avionics SME
Tom Mosher	Garmin	GA Avionics SME
Sally Frodge	FAA ATO-W	Navigation SME
David Olsen	FAA ATO-P	Navigation SME
Chris Moody	MITRE/CAASD	ADS-B SME
Gus Waters	FAA ATO-T	Air Traffic User/Eval
Paul Lipski	FAA AVS/AIR	Certification (Surv) User/Eval
Bruce DeCleene	FAA AVS/AIR	Certification (Nav) User/Eval
Bill Flathers	AOPA	GA User/Eval
George Wilson	Delta Airlines	AT User/Eval
Milton Clary	USAF/Pentagon	DoD (Nav) User/Eval
Robert Manning	USAF/Pentagon	DoD (Surv) User/Eval
William Thedford	USAF/Hanscom	DoD (Avionics) User/Eval
Wayne Buhrman	JHU APL	Independent Assessment

Other Participants

Ken Alexander	FAA AVS/AIR
Bradford Benjamin	FAA ATO-T
Jacob Dorsey	ATO-T
Leo Eldridge	FAA ATO-W
Mike Huffman	FAA ATO-T
Ken Kepchar	FAA ATO-P
Jim Linney	FAA ATO-T
John Marksteiner	FAA ATO-E
Gary Paull	MCRI
Robert Pomrink	FAA ATO-E (CTR)
Steve Ramdeen	FAA AVS/AIR
Steve VanTrees	FAA AVS/AIR
Pat Zelechoski	FAA AVS/AFS

Surveillance/Positioning Backup Strategy Steering Committee

Member	Organization
Vincent Capezzuto	FAA ATO-E
Rick Heinrich	Rockwell-Collins
Tony Broderick	Consultant
Mark Cato	ALPA
Scott Foose	RAA
Dave Hamrick	MITRE/CAASD
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Appendix F: Acronyms and Abbreviations

AC	Advisory Circular
ADS-B	Automatic Dependent Surveillance-Broadcast
ADS-R	Automatic Dependent Surveillance-Rebroadcast
AGL	Above Ground Level
ASDE	Airport Surface Detection Equipment
ASF	Additional Secondary Factor
ASR	Airport Surveillance Radar
ASSA	Airport Surface Situational Awareness
ASTERIX	All-Purpose Structured Eurocontrol Radar Information Exchange
AT	Air Transport
ATC	Air Traffic Control
ATCBI	Air Traffic Control Beacon Interrogator
ATMAC	Air Traffic Management Advisory Committee
CAIV	Cost as an Independent Variable
CD	Conflict Detection
CDTI	Cockpit Display of Traffic Information
CENRAP	Center Radar ARTS Presentation
CIP	Capital Investment Plan
CONOPS	Concept of Operations
CONUS	Continental United States
CRI	Cross rate interference
CSA	Comparative Safety Analysis
DME	Distance Measuring Equipment
DoD	Department of Defense
drms	Distance Root-Mean-Square
ECD	Envelope-to-Cycle Difference
E-field	Electric Field
eLoran	Enhanced Loran
ES	1090 MHz extended squitter
ESL	Economic Service Life
EVAcq	Enhanced Visual Acquisition

EVApp	Enhanced Visual Approach
F&E	Facilities and Engineering
FAA	Federal Aviation Administration
FAROA	Final Approach Runway Occupancy
FCC	Federal Communications Commission
FIS-B	Flight Information Service - Broadcast
FL	Flight Level
FMS	Frequency Management System
fPR	Final Program Requirements
ft	Foot/Feet
FY	Fiscal Year
GA	General Aviation
GBAS	Ground-Based Augmentation System (satellite)
GLONASS	Global Navigation Satellite System (Russian)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRI	Group Repetition Rate
HAA	Height Above Airport
HAL	Horizontal Alert Limit
HDOP	Horizontal Dilution of Precision
HEA	Harbor Entrance Approach
H-field	Magnetic Field
HFOM	Horizontal Figure of Merit
ICAO	International Civil Aviation Organization
ID	Idnetification
IFR	Instrument Flight Rules
IRU	Inertial Reference Unit
JRC	Joint Resources Council
kHz	Kilohertz
kW	Kilowatt
LAN	Local Area Network
LDC	Loran Data Channel
LEMS	Loran Enhanced Monitoring System

LICOS	Loran Information, Control, and Operations System
Loran	Long Range Navigation
LSP	Link Specific Processing
MASPS	Minimum Aviation System Performance Standard
MHz	Megahertz
MLS	Microwave Landing System
MMR	Multi-Mode Receiver
Mode S	Mode Select
MOPS	Minimum Operational Performance Standard
MSL	Mean Sea Level
MW	Megawatt
NAC	Navigation Accuracy Category
NAS	National Airspace System
NIST	National Institute of Standards and Technology
nmi	Nautical Mile
NOTAM	Notice to Airmen
NPA	Non-Precision Approach
nsec	Nanosecond
NTIA	National Telecommunication and Information Administration
O&M	Operations and Maintenance
OEP	Operational Evolution Partnership
OMB	Office of Management and Budget
PARC	Performance-Based Aviation Rulemaking Committee
PHA	Preliminary Hazard Analysis
PSR	Primary Surveillance Radar
p-static	Precipitation Static
RAIL	Remote Automatic Integrated Loran
RAIM	Receiver Autonomous Integrity Monitor
RF	Radio Frequency
RFI	Radio Frequency Interference
RMS	Remote Monitoring Subsystem
RNAV	Area Navigation
RNP	Required Navigation Performance

RO	Receive Only
RT	Receive/Transmit
RTCA	RTCA
SATNAV	Satellite Navigation
SBAS	Satellite-Based Augmentation System
SBS	Surveillance and Broadcast Services
sec	Second(s)
SLEP	Service Life Extension Program
SNR	Signal-to-Noise Ratio
SoL	Safety of Life
SSR	Secondary Surveillance Radar
STARS	Standard Terminal Automation Replacement System
TCAS	Traffic Collision and Avoidance System
TCS	Transmitter Control Set
TD	Time Difference
TDOA	Time Difference of Arrival
TFE	Time and Frequency Equipment
TIS-B	Traffic Information Service - Broadcast
TOA	Time of Arrival
TOT	Time of Transmission
TSO	Technical Standard Order
UAT	Universal Access Transceiver
UPS	Uninterruptible Power Supply
USNO	U.S. Naval Observatory
UTC	Coordinated Universal Time
VFR	Visual Flight Rules
VOR	Very High Frequency Omnirange
WAAS	Wide Area Augmentation System
WBS	Work Breakdown Structure
WRC	World Radio Conference

Appendix G: References

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Appendix H

Independent Assessment of the Surveillance/Positioning Backup Strategy Alternatives Analysis for the Surveillance and Broadcast Services Program

by the
Johns Hopkins University Applied Physics Laboratory

As part of the Surveillance and Broadcast Services program, a preliminary hazard analysis was performed to identify potential risks to the ADS-B service. One of the risks identified as a result of this analysis was the potential loss of ADS-B surveillance for multiple aircraft due to an interruption of the GPS L1 frequency. A study was undertaken to recommend a backup strategy for mitigating the impact of a loss GPS to the ADS-B service. As part of this study, an impartial, independent assessment was performed to provide assurance that the process used to select a particular mitigation strategy was properly executed and the resulting recommended strategy was appropriate given the conclusions reached by the technical team.

A technical team, made up of subject matter experts, representatives from key user groups and support analysts was formed to perform the study. A steering committee formed by the RTCA Air Traffic Management Committee (ATMAC) provided direction and guidance to the technical team. Representatives of the technical team periodically briefed the steering committee to provide status as well as receive direction and guidance. During the course of the study, technical team members consulted additional subject matter experts as required, to ensure a complete and thorough analysis of all viable strategies that could potentially mitigate the identified risk.

The technical team followed the FAA trade study process as defined in the System Engineering Manual in a disciplined fashion to ensure an objective comparison of the potential alternatives to arrive at the most balanced technical solution(s). The team worked cohesively as a group and was not influenced by outside interests. All working assumptions developed by the team were vetted by the steering committee.

Evaluation criteria were developed to aid in scoring of the various strategies. Weighting of the evaluation criteria was done by the steering committee and used in the scoring process. Strategies were then formulated based on projected performance, availability of key technologies, current NAS evolution plans, and inputs from the Steering Committee. The list of strategies was down-selected based on the technical team's assessment of the viability of the strategy, resulting in a final list containing seven strategies that were coordinated with the Steering Committee for scoring purposes.

A sensitivity analysis was performed on each of the metrics to assess how the weighting of each metric impacted the overall score for each strategy. This analysis provided confidence that small variations in the weighting factors did not significantly impact the overall ranking for the strategies.

The technical team report addresses the risk and provides a viable mitigation to the loss of the ADS-B service due to an interruption of GPS. A review of the complete report is essential to assure the reader that a feasible mitigation strategy to the loss of GPS exists. As with any recommendation, careful evaluation of the guidelines and assumptions is critical for full understanding of the conclusions reached.