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Analysis of Using Three Nautical Miles as the Minimum Separation Standard for Targets at Intermediate Distances from an Air Surveillance Radar-11 (ASR-11)

Flight Systems Laboratory
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12. Abstract

The Terminal Airspace Organization, AJT-22, requested analytical support from the Flight Systems Laboratory, AFS-450, to re-examine the separation standards that are applicable to terminal use of the ASR-11. This study is to include, but will not be limited to: target separation, target resolution, vertical application, rules on the use of passing and diverging, the minimum separation from obstructions, minimum separation from adjacent airspace, and, if applicable, edge of scope separation. The performance of the ASR-11, with its suggested usage and any associated criteria for this usage, will be compared against the performance of similar systems that are allowed to be used in a similar manner today. The comparison will be from a safety aspect in order to facilitate the Safety Management System (SMS) process applicable to the Air Traffic Organization (ATO).

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Executive Summary

The Terminal Airspace Organization, AJT-22, has requested analytical support from the Flight Systems Laboratory, AFS-450, to re-examine the separation standards that are applicable to terminal use of the ASR-11. This study is to include, but will not be limited to: target separation, target resolution, vertical application, rules on the use of passing and diverging, the minimum separation from obstructions, minimum separation from adjacent airspace, and, if applicable, edge of scope separation. The performance of the ASR-11, with its suggested usage and any associated criteria for this usage, will be compared against the performance of similar systems that are allowed to be used in a like manner today. The comparison is from a safety aspect in order to facilitate the Safety Management System (SMS) process applicable to the Air Traffic Organization (ATO).

Increasing the usability of the existing installed infrastructure provided by the ASR-11 could increase the efficiency of the NAS at a very low cost to the FAA, if the performance can be proven equivalent or better than that provided by the existing systems allowed to use the Terminal Separation Standard at these increased ranges.

Current FAA Standards, as per FAA Order JO 7110.65, paragraph 5-5-4, Radar Separation Minima for Broadband Radar Systems or Digital Terminal Automation Systems, permit the use of Terminal Area Separation Minima of 3 NM when using a Air Surveillance Radar-11 (ASR-11) surveillance radar (which contains a Monopulse Secondary Surveillance Radar or MSSR) within a 40 NM radius of the radar antenna. This is in contrast to a similar system, specifically the ASR-9 with a Mode S, which is allowed as per the same paragraph in the order to apply Terminal Area Separation Minima of 3 NM out to a range of 60 NM from its' antenna. This study shows that performance of the ASR-11 Monopulse Secondary Surveillance (Beacon) System (MSSR) is equivalent to the performance of an ASR-9 with Mode S. Thus, the limitations that have been placed on the ASR-11 are unnecessarily restrictive for properly performing transponder equipped aircraft. Allowing the use of the Terminal Separation Standard Minima of 3 NM for these aircraft, at ranges from the radar of up to 60 NM from the sensor antenna, should incur no greater risk or hazard than the currently allowed application of the 3NM Separation Standard Minima for the ASR-9 with Mode S. This study also investigated using a 3 NM Separation Standard Minima for aircraft with search-only data reports (non-beacon equipped or performing). The data that was collected and processed for this purpose for the ASR-11 primary radar did not yield definitive comparability to the performance of the ASR-9 primary radar. It is therefore recommended that the current practice of requiring a 5 NM Minimum Separation Standard be continued for search-only targets whose range is reported to be greater than 40 NM from the reporting ASR-11 sensor antenna, and that 3 NM be utilized as the minimum separation standard for properly performing and equipped aircraft that are travelling within a 60 NM radius of the ASR-11, whose beacon data is being output from the sensor.

Overall, the ASR-11 MSSR Beacon performed in an equivalent manner to the ASR-9 with Mode

S, for all tested cases. The primary ASR-11 search radar could not be shown to have equivalent performance due to known problems with false alarm rate and target resolution. The portion of the study that examined clearance from obstructions for the ASR-11 beacon data could not use a comparative approach, since there was no formal study to assess the ability of the ASR-9 with Mode S to be used in this manner. This study shows that, if the conditions at the end of Section 3.7 are met, using a 3 NM clearance from obstructions for properly transponder equipped and performing aircraft, should incur no additional risk to the NAS, for the ASR-11 or the ASR-9 with Mode S.

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1.0 Introduction

Current FAA Standards, as per FAA Order JO 7110.65, paragraph 5-5-4, Radar Separation Minima for Broadband Radar Systems or Digital Terminal Automation Systems, permit the use of Terminal Area Separation Minima when using an ASR-11 surveillance radar (which contains a Monopulse Secondary Surveillance Radar) within a 40 NM radius of the radar antenna. This is in contrast to a similar system, specifically the ASR-9 with a Mode S, which is allowed as per the same paragraph in the order to additionally apply Terminal Area Separation Minima of 3 NM within 60 NM of the radius of the antenna. It is opined that the limitations placed on the ASR-11 may be unnecessarily restrictive and that it may be proven to be usable at the Terminal Separation Minima at greater distances from the radar antenna under certain circumstances and conditions. Increasing the usability of the existing installed infrastructure provided by the ASR-11 could increase the efficiency of the NAS at a very low cost to the FAA, if the performance can be proven equivalent or better than that provided by the existing systems allowed to use the Terminal Separation Standard at these increased ranges.

The Terminal Airspace Organization, AJT-22, has requested analytical support from the Flight Systems Laboratory, AFS-450, to re-examine the separation standards that are applicable to terminal use of the ASR-11. This study is to include, but will not be limited to: target separation, target resolution, vertical application, rules on the use of passing and diverging, the minimum separation from obstructions, minimum separation from adjacent airspace, and, if applicable, edge of scope separation. The performance of the ASR-11, with its suggested usage and any associated criteria for this usage, will be compared against the performance of similar systems that are allowed to be used in a similar manner today. The comparison will be from a safety aspect in order to facilitate the Safety Management System (SMS) process applicable to the Air Traffic Organization (ATO).

1.1 Purpose and Structure of This Report

This report will focus on the examination of the likenesses and differences of the ASR-11, when compared to the reference system of an ASR-9 with Mode S to determine if they are comparative equivalent systems. The primary or search radar subsystem will be considered separately from the secondary or beacon radar subsystem. Each subsystem will then be further broken down to consider its range and azimuth position components individually. The outcome of these comparisons will then be analyzed to determine their impact on the types of operations and conditions requested in the memorandum that originated this study, from which recommended usage and suggested restrictions will be made.

1.2 Background

Current FAA Standards, as per FAA Order JO 7110.65, paragraph 5-5-4, Radar Separation Minima for Broadband Radar Systems or Digital Terminal Automation Systems, permit the use of Terminal Area Separation Minima when using the ASR-11 surveillance radar (which contains a Monopulse Secondary Surveillance Radar, (MSSR)) within a 40 NM radius of the radar antenna. This is in contrast to a similar system, specifically the ASR-9 with a Mode S, which is allowed as per the same paragraph in the order to additionally apply Terminal Area Separation Minima of 3 NM within 60 NM of the radius of the antenna. It is opined that the limitations placed on the ASR-11 may be unnecessarily restrictive and that it may be proven to be usable at the Terminal Separation Minima at greater distances from the radar antenna under certain circumstances and conditions. Increasing the usability of the existing installed infrastructure provided by the ASR-11 could increase the efficiency of the NAS at a very low cost to the FAA, if the performance can be proven equivalent to or better than that provided by the existing systems allowed to use the Terminal Separation Standard at these increased ranges.

The exact reasons for the restricted use of the ASR-11 when compared to functionally similar systems are difficult to determine with certainty. However, research and anecdotal evidence suggests that the following factors may have influenced this decision:

1. 7110.65 Wording: Air Traffic Order 7110.65 is written to allow an ASR-9 with Mode S to utilize a 3 NM separation standard minima between 40 NM and 60 NM range from the antenna. At the time this decision was made, Air Traffic Controllers were trained on the meaning of the term “Mode S radar”, but had not been trained on the meaning of the term “monopulse radar”. This decision therefore resulted in savings of Air Traffic Controller training dollars.
2. Search / Primary Radar System Performance Differences: The ASR-11 is known to have different target resolution capabilities than its predecessor, the ASR-9. This difference will be further addressed in Section 3.2 of this document.
3. Different Adapted Alarm Thresholds on the NAS Automation Platforms: The ASR-11 was adapted into the NAS Automation platforms using different and less restrictive window tolerances for alarm generation, than those used for the ASR-9. This will be discussed further in Section 3.2.

The Terminal Airspace Organization, AJT-22, has requested analytical support from the Flight Systems Laboratory, AFS-450, to re-examine the separation standards that are applicable to terminal use of the ASR-11. This study is to include, but will not be limited to: target separation, target resolution, vertical application, rules on the use of passing and diverging, the minimum separation from obstructions, minimum separation from adjacent airspace, and, if applicable, edge of scope separation. The performance of the ASR-11, with its suggested usage and any associated criteria for this usage, will be compared against the performance of similar systems that are allowed to be used in a similar manner today. The comparison will be from a safety aspect in order to facilitate the Safety Management System (SMS) process applicable to the Air Traffic Organization (ATO).

2.0 Analytical Method

For this study, the performance of the ASR-11, with its suggested usage and any associated criteria for this usage, will be compared against the performance and usage of the ASR-9 with Mode S, since it is a similar system that is allowed to be used in a similar manner to what is desired for the ASR-11. This will be accomplished by an examination of the performance of the two subsystems that comprise the ASR-11, namely the beacon and the search subsystems. This will be followed by sections that analyze the impact of the results of the subsystem level performance comparison on each type of operation and situation documented in the original request, and make recommendations as to their criteria for usage.

The specific areas of the ASR-11 and the ASR-9 with Mode S that are deemed critical to a thorough and complete comparison of the two systems are as follows:

- Architecture: How each system is built and the process that it goes through to collect and output target information such as position. How each system interfaces into the NAS Automation Platform. The update rate of each sensor.
- Automation Processing: How the data from each of these sensors is processed once it gets into the NAS Automation Platform. This includes:
    - Processing of the data for display
    - Any modification of the data such as:
        - Registering the sensor to a common frame of reference
        - Registering the sensor to other received sensors
    - Validating the quality of the data and health of the reporting sensor
        - Status (Health) Checks
        - Alarms (with thresholds)
        - Alerts (with thresholds)
- Reporting Latency: This value is specified by the NAS-SR-1000, boresight-to-glass requirement. It gives a window for the 'freshness' of the data received from a sensor.
- Sensor Error Sources: To include the following:
    - Registration Errors:
        - Location Bias
        - Azimuth Bias
    - Range Errors:
        - Radar Bias
        - Radar Jitter
    - Azimuth Errors:
        - Azimuth Jitter
    - Output Format /Quantization Errors:
        - Range
        - Azimuth
    - Transponder Error Sources
        - Mode S
        - ATCRBS
- Other Performance Considerations:
    - Target Resolution

- Current System Usage
- Planned or Desired System Usage

Each of these areas will be examined within this report, with specific detail and consideration given to any where differences are noted between the ASR-11 and the reference system of an ASR-9 with Mode S.

This report is the culmination of many bodies of work on each of these systems independently as well as documents that address both the ASR-11 and the ASR-9 with Mode S. The analyses flow from the review and inclusion of information from the following referenced sources:

1. Mode Select beacon System – Academy Drawings and Tables, August 2006
2. JO 6365.3 – Maintenance of the Mode Select (Mode S) Beacon System, September 14, 1994
3. TI 6310.56 – Digital Airport Surveillance Radar ASR-11, System Manual for MSSR System, 7/5/2006
4. Department of Transportation Federal Aviation Administration Airport Surveillance Radar ASR-11 Final Operation Test Report, October 2003
5. Digital Airport Surveillance Radar System Specification and SRD Cross-Reference, Revision E, 6 September, 2007, Raytheon
6. Order 6365.1A – U.S. National Standard for the Mode Select Beacon System (Mode S), 1/3/83
7. JO 6310.19A – Maintenance of Airport Surveillance Radar (ASR-9), 12/4/2008
8. Project ATC-323 – Required Surveillance Performance Accuracy to Support 3-Mile and 5-Mile Separation in the National Airspace System, 1 November 2006, *S.D. Thompson, J.W. Andrews, G.S. Harris. K.A. Sinclair,* MIT/LL
9. Powerpoint Presentation "ASR-11 Three nmi Separation", November 2009?, *Mike Huffman, Karl Roulston*
10. ASR-11 MSSR Standalone OT Results Memo, January 14, 2010, *MW Prata*
11. Comparison of ASR-9 and ASR-11 Radar Azimuth Error v1 Study, 9/22/2010, *Colin Mayer and Dr. Panos Tzanos, MIT Lincoln Laboratory*
12. Surveillance Accuracy Requirements in Support of Separation Services, *Steven D. Thompson and James M. Flavin*, MIT/LL, as published in Vol. 16, No. 1, 2006 Lincoln Laboratory Journal
13. DR033 Range Zero Investigation at ACY 28th June to 1st July 2010, *W. H. Menown, G.A.Cowie,* Raytheon Systems Limited
14. SRTQC Email Transactions for Factual Verification, *Preston Barber*

3.0 System Likenesses and Differences (ASR-11 vs. ASR-9)

There have been several inquiries regarding the use of surveillance data provided by the ASR-11 radar and its included beacon to allow the application of a minimum separation standard of 3NM for targets flying between 40 and 60NM of the antennae. In order to frame the discussion and recommendations, we will first examine the current usage of the ASR-11 and its likeness and differences to other surveillance data systems that are allowed to be used in this manner, specifically the ASR-9 with Mode S.

- *Architecture:* Both the ASR-9 with Mode S and the ASR-11 (which includes a monopulse beacon processor) are collocated primary radar with monopulse beacon processing. They collect data in very similar manners. They both use the same basic method to transmit their output to the NAS Automation Platforms, and they both use the same basic data format for transmission. They both have similar technical specifications including the following:
    - *Coverage Volumes*:
        - *Range*: 0.5 NM to 60NM
        - *Azimuth*: 360° of coverage
    - *Update / Scan Rate*: 4.8 seconds per revolution

  There are some differences between the systems in their architectures as well (i.e. coverage altitudes and processing methods). These will be addressed in the subsystem sections of 3.1 and 3.2, for the primary and secondary radar components individually.
- *Automation Processing*: The data from the ASR-9 with Mode S and the ASR-11 are processed in very similar ways in the NAS Automation Platforms.
    - *Processing for Display:* The data from both of the surveillance sensors passes through the same type of process for display. There could be differences in how each sensor is adapted into the NAS Automation Platform. However, since both the of the surveillance sensors in question are currently using a 3 NM Separation Standard Minima at closer ranges to their respective antenna, these differences are thought to be minimal and inconsequential to this particular analysis.
    - *Data Modification:*
        - *Registering the sensor to a common frame of reference*: This involves modifying the received data from the received frame of reference of radar slant range into a System Plane reference for display. This concept is new for Terminal Area Automation Platforms with the advent of ADS-B with Fusion modifications being integrated into the systems. SBS Program Office Requirements for each of the Automation Platforms should ensure that the errors created by this process are in the proper range, and the ASR-9 with Mode S will go through the same process as that used for the ASR-11. Although currently there are some known deficiencies in meeting all of the testing criteria using the newly modified CARTS Automation Platform, these should be resolved in the near future by additional modification and testing.
        - *Registering the sensor to other received sensors.* In the traditional single-sensor slant range display mode sensor registration is not expected to be a problem for Terminal NAS Automation Platforms. The two sensors are handled in an identical manner when they are displayed to the Air Traffic Controllers. Key Sites for STARS and CARTS have recently gone into

service with modifications to accept ADS-B as a surveillance sensor, and to operate in a multi-sensor mode, with Fused Tracked output displayed for the control of air traffic. These modified NAS Automation Platforms contain new registration processes, with each system utilizing a unique algorithm. However, within each Automation Platform both surveillance sensors go through a similar process. There are some concerns in this area that are scheduled to be addressed, which have not been addressed fully at this time, such as:

- Ensuring that the process does not become overly reliant on any one sensor (such as ADS-B), and that enough time has elapsed between the computation of the registration values and their application to the system data to ensure that the ADS-B data used for the registration process was not faulty. (Allowing the ADS-B Time-To-Alert to have expired)

The handling of the ASR-9 with Mode S and the ASR-11 by STARS and the non-STDM Mode of CARTS should be equivalent to one another, and the residual bias requirements published by the SBS Program Office against which the system was tested, should be sufficient to ensure equivalent performance in this area.

- *Validating the quality of the data and health of the reporting sensor Status, Alert, and Alarm Monitoring:* Both the ASR-9 with Mode S and the ASR-11 (which includes a monopulse beacon processor) send a combination of status messages and test targets that are used for continuous monitoring of each system's data quality or "fitness" to be used as a surveillance sensor in the NAS Automation Platforms. These are measured against expected/desired results and settings, sometimes with an included window of tolerance to set a data/sensor quality threshold. When the tolerance windows or the quality thresholds are breached, the system will:
  - Invoke another process to scrutinize the data at a finer level of detail, and/or
  - Create alerts/alarms to the air traffic controllers and/or maintenance personnel, and/or
  - Initiate a pre-programmed backup mode, to choose another available sensor as the data source, or to remove the sensor data from the system display presentation.
  - Alerts and alarms are also sent to other maintenance coordination points and storage systems to determine nationwide NAS health and for historical analyses and storage.
  - *Note: Although both of the systems are subjected to the same basic continuous monitoring process, some of the alarm thresholds and criteria against which they are measured to determine data quality differ between the two systems. This will be further discussed in Section 3.2.*

- *Reporting Latency:* Since this value is specified by the NAS-SR-1000, boresight-to-glass requirement, both sensors are tested to the same criteria in each of the NAS Automation Platforms, and are therefore, considered equivalent in this area.
- *Sensor Error Sources:*
  - *Registration Errors:*
    - Location Bias – This is not a function of the surveillance sensor itself, but an error caused by improper or inaccurate radar siting, and should therefore be considered equivalent between the ASR-9 with Mode S and the ASR-11.
    - Azimuth Bias – This is a function of registering the alignment of each sensor to the Automation Platform, and was addressed in the "Data Modification" bullet above. The sensors go through equivalent alignment processes for azimuth bias correction, which is already being done on each platform for each sensor, and should therefore have an equivalent effect.
  - *Range Errors:*
    - Radar Bias - This is a function of registering the alignment of each sensor to the Automation Platform, and was addressed in the "Data Modification" bullet above. The sensors go through equivalent alignment processes for bias correction, which is already being done on each platform for each sensor, and should therefore have an equivalent effect.
    - Radar Jitter – This is an area that is handled differently by the primary or search radar versus the secondary or beacon radar. Although the architectures between the two different sensors appear to be very similar in this area, it will be further addressed in sections 3.1 and 3.2.
  - *Azimuth Errors:*
    - Azimuth Jitter – This is the area of greatest concern for examination to ensure equivalency between the ASR-9 with Mode S and the ASR-11. It is also an area that is handled in a different manner by the primary or search radar versus the secondary or beacon radar. It will be further addressed in sections 3.1 and 3.2.
  - *Output Format /Quantization Errors*:
    - Data from the ASR-9 with Mode S and from the ASR-11 are both output in the same data format, with the same resolution for beacon and search targets, at this time. Therefore, both radars are deemed equivalent in this area.
  - *Transponder Error Sources:*
    - Although the Mode S Transponder and the ATCRBS Transponder have different error characteristics from one another, both of these errors are independent of the receiving surveillance sensor, and experienced and compensated for in much the same way by the ASR-9 with Mode S and the ASR-11. Therefore, both systems are deemed equivalent in this area.
- *Other Performance Considerations:*
  - *Target Resolution:* There are significant differences between the primary or

search processing target resolution versus the secondary or beacon processing target resolution as well as some other notable differences between the two systems. This will be further discussed in section 3.1 and 3.2 of this document.

- *Current System (Minimum Separation Standard) Usage:* Both the ASR-9 with Mode S and the ASR-11 (which includes a monopulse beacon processor) are used as surveillance sensor sources for many NAS Automation Platforms in Air Route Traffic Control Centers (ARTCCs) and Terminal Radar Control Facilities (TRACONs), and both are allowed to be used in a multi-sensor/mosaic display mode with a minimum separation standard of 5 NM, or in a single-sensor display mode out to a range of 40 NM from the sensor with a minimum separation standard of 3 NM, as per the current 7110.65 Order. The ASR-9 with Mode S is allowed to be used with a 3 NM minimum separation standard between 40 to 60 NM from the sensor, while the ASR-11 has been limited to using a 3 NM separation standard minima within 40 NM of the ASR-11 antenna. This appears to have come about as the result of several separate factors, including the wording of the 7110.65, which reportedly was associated with concerns over training issues, some noted performance differences between the ASR-11 versus the ASR-9, which will be addressed in Section 3.1 for beacon differences and in Section 3.2 for the search differences, and some alarm thresholds on the NAS Automation Platforms that were set to tolerances much larger for the ASR-11 than the settings for the ASR-9.

3.1 Secondary Radar (Beacon) Analysis

Comparison of the Condor MSSR, which is the included beacon system in the ASR-11, with the Mode S is critical to the determination of the acceptable equivalency of the two systems, and thus the extended usability of the ASR-11 at the lower separation standard minima. This section will examine the architectures, the internal processing, and error characteristics of each subsystem.

- *Architecture:* Both the Mode S and the Condor MSSR (beacon system in the ASR-11) perform monopulse beacon processing as their preferred mode. The monopulse beacon processing produces better azimuth accuracy of target position than the previous beacon processing method of using a sliding window. The sliding window method was used on earlier beacon systems, and is still used as the backup mode of operation for the Mode S and the ASR-11.
    - *Coverage Volumes*: (Ref . 6365.3 for Mode S and 6310.56 and SSSRevE_6_Sept_2007 for ASR-11)
        - *Range*: Although the Mode S and the Condor MSSR can both be tuned to provide coverage further out in range (out to a maximum of 120 NM for the ASR-11's Condor MSSR and out to 255 NM for the Mode S), the

configurations examined in this report will be limited to systems with a maximum range of 60 NM.

- *Azimuth*: 360° of coverage
- *Altitude*: 0 to 60,000 feet above ground level (AGL) by specification requirements. However, an examination of FAA's Test Plan for the ASR-11 in Table 3.6-1 indicates the ASR-11's MSSR Detection Volume was only planned to be tested from 0-25,000 feet AGL. The "Final Operational Test Report", on the other hand, gives detection probability values up to around 40,000 feet, as shown in Figure 1 below, which is a re-print of Figure 4.1.1.8-32 from the final operational test report dated October 31, 2003.

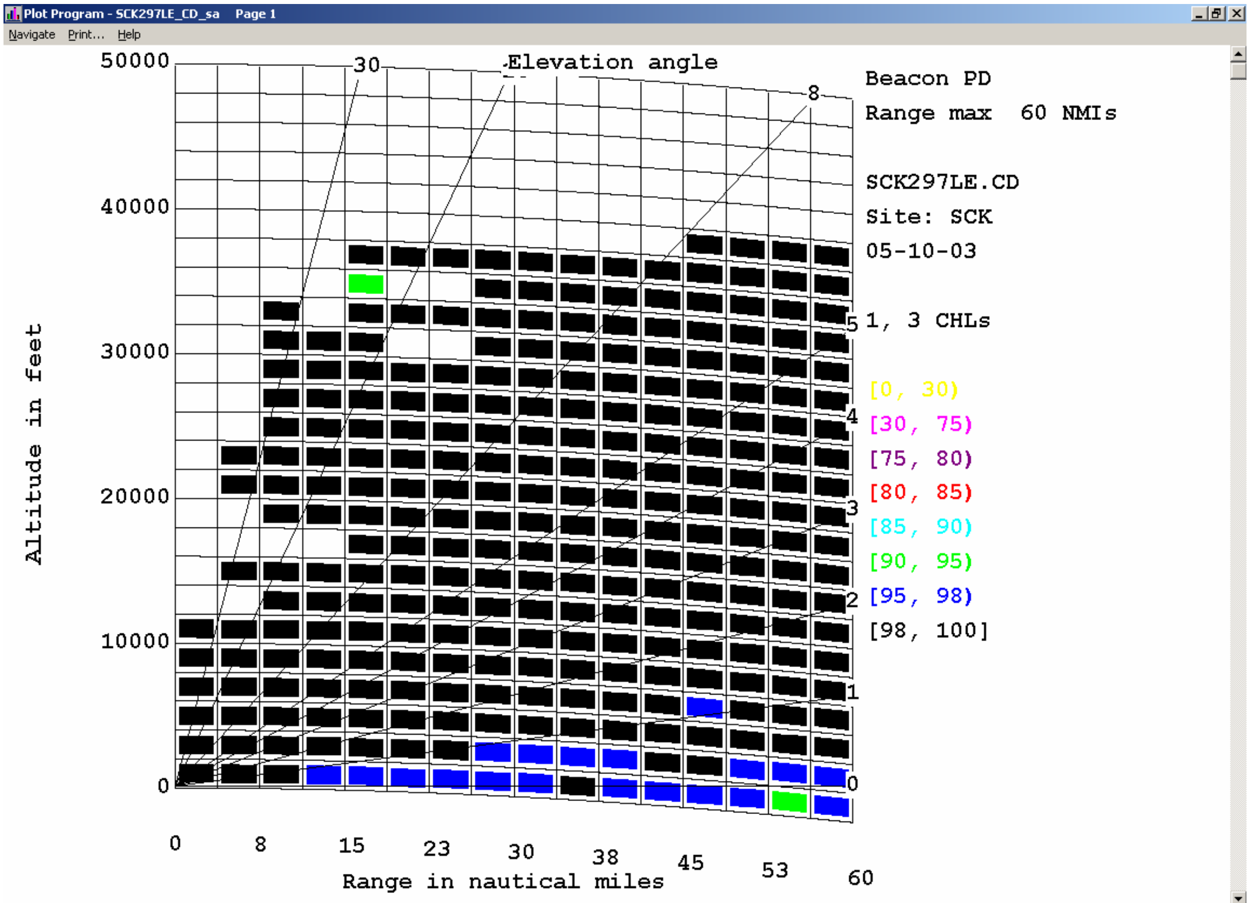


Figure 1: Beacon coverage provided by the ASR-11

The ASR-11 has been deployed and in use at multiple locations to provide Air Traffic Control Services for many years. This provides an opportunity to view the coverage that is provided by the ASR-11 by collecting empirical data. At the request of the FAA for this report, MIT/ Lincoln Laboratory created and analyzed a large volume of beacon data to determine the comparative characteristics of beacon data collected from an ASR-11 with the characteristics of beacon data for an ASR-9 with Mode S, to verify the likenesses and differences of the two data sets. This large scale analysis of radar errors was quickly achieved by Lincoln Laboratory through use of the same data and process from a Radar Error Study previously accomplished at the request of the SBS program Office. Lincoln Laboratory collected 14 days of radar data through the RADES Network, totaling 8.5 million data points from sixteen different radars. The sixteen different radars were equally split with eight ASR-9s equipped with Mode S and eight ASR-11s. This allowed them to produce the following spatial density plot of the data shown in Figure 2 below. It shows the spatial distribution of the ASR-9 and ASR-11 data sets. The plot shows very similar spatial distribution for the two data sets, with the vast majority of reports coming from aircraft flying at altitudes of 30,000 to 40,000 feet and elevation angles between 5 and 15 degrees.

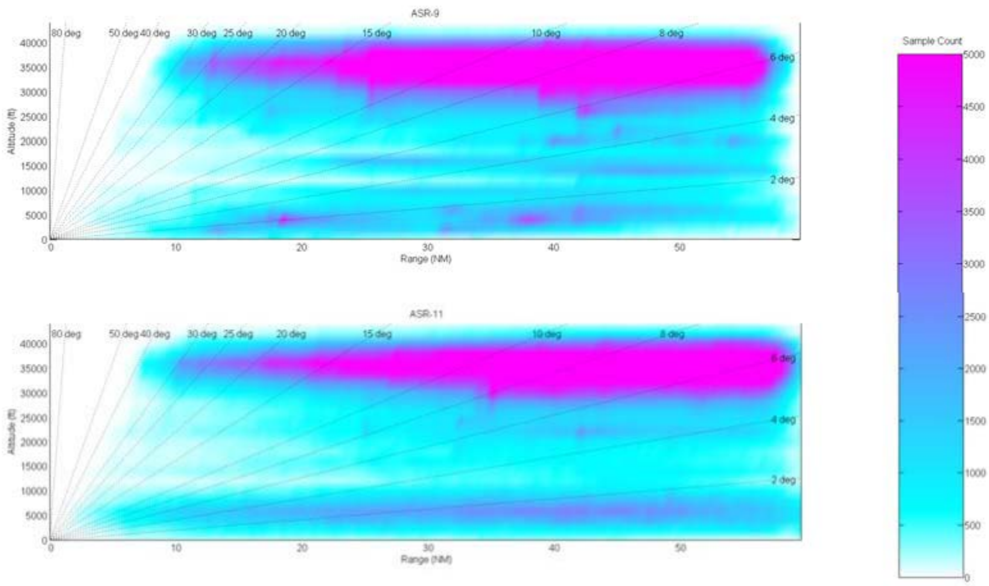


Figure 2: Spatial density plot

- *Update / Scan Rate*: 4.8 seconds per revolution
- *Probability of Detection*: Both systems consistently operate in the 97% to 99.5% range, with false alarm rates measured at less than 0.07%, when properly sited and optimized. This element and the related element of False Alarm Rate for beacon were tested and passed in the Final Operation Test Report, dated October 3, 2003, and need not be further addressed in this document.
- *Frequency*: Both systems operate on a transmit frequency of 1030 MHz, and on a receive frequency of 1090 MHz.

Although the systems have very similar architectures, there are some significant differences. One of the differences between the two architectures is intuitive from the naming of the two systems. They are both MSSRs, but the Mode S does perform Mode S or Mode Select processing. The Condor MSSR which is part of the ASR-11, was manufactured with a requirement that it be upgradeable to Mode S, but this capability is not incorporated into the current system. Mode S versus MSSR processing, and the subtle performance differences between them will be covered in the "Internal Processing" discussion that follows, and in the "Comparative Differences" paragraph.

- *Internal Processing*: The data from the ASR-9 with Mode S and the ASR-11 are processed in very similar ways.
  - *Monopulse*: The ASR-9 with Mode S and the Condor MSSR in the ASR-11 beacon systems use monopulse processing. Monopulse processing provides improved azimuth accuracy in the target output through the use of sum and difference computations on the receive antenna. Where they are different however, is that the Mode S system can perform a directed interrogation, addressing each aircraft within its coverage volume independently. This provides an advantage in avoiding "garbled" beacon replies. The garbled condition can occur when the replies of two aircraft arrive at the receive antenna overlapping with one another in a manner such that the pulses within the report cannot be separated from one another well enough for a proper decode of the pulses. This condition is normally temporary, as the affected aircraft do not remain in a relative geometry that is conducive to this type of error for an extended period of time. The fact that the Mode S beacon is much less prone to this error condition led to claims of greatly improved azimuth performance in the Mode S specification, when compared to those of the ASR-11. These claims have not been tested and do not appear in the data collected, because the error characteristics of both systems are limited to the quantization or resolution of their output data format. This will be examined further in the azimuth error characteristics discussion later in this section of the report.
- *Automation Processing:*
  - *Status, Alert, and Alarm Monitoring:* It is believed that the adaptation thresholds, window tolerances, and other status checks, alert and alarm criteria, thresholds, tolerances and monitoring for the beacon processing of the ASR-11 and the ASR-9 with Mode S in the NAS Automation Platforms is equivalent. This needs to be validated and verified by OSF personnel prior to allowing the ASR-11 beacon to use a 3 NM Minimum Separation Standard for targets between 40 NM and 60 NM of the antenna. Once the verification of the equivalency of the alarm and alert criteria is satisfied, it is recommended that the 7110.65 be re-written to allow the usage of a 3 NM Minimum Separation Standard for ASR-11 beacon targets out to a distance of 60 NM from the reporting antenna.

- *Beacon Sensor Error Sources:*
  - *Registration Errors:*
    - Location Bias – This is not a function of the surveillance sensor itself, but an error caused by improper or inaccurate radar siting, and should therefore be considered equivalent between the ASR-9 with Mode S and the ASR-11.

- Azimuth Bias – This is a function of registering the alignment of each sensor to the Automation Platform, and was addressed in the "Data Modification" bullet above. The sensors go through equivalent alignment processes for azimuth bias correction, which is already being done on each platform for each sensor, and should therefore have an equivalent effect.

- *Range Errors:*
  - Radar Bias - This is a function of registering the alignment of each sensor to the Automation Platform, and was addressed in the "Data Modification" bullet above. The sensors go through equivalent alignment processes for azimuth bias correction, which is already being done on each platform for each sensor, and should therefore have an equivalent effect.
  - Radar Jitter – The range that is output in the beacon target message is derived by the time between the transmission of the 1030 MHz interrogation pulses and the receipt of the reply pulses from the aircraft. This processing is the equivalent between the ASR-11's Condor MSSR and the Mode S. The specifications for both systems are identical in this area and both systems have been successfully tested through Operational Test and Evaluation to verify this.
- *Azimuth Errors:*
  - Azimuth Jitter – This is the area of greatest concern for examination to ensure equivalency between the ASR-9 with Mode S and the ASR-11. The error that is listed for the Mode S Performance as per 6365.3 Paragraph 30.1 is 0.022 degrees. However, it is also noted that, due to the output data format, the azimuth performance will be limited by the resolution in the message of 0.088 degrees. This is similar to that listed and tested for in the ASR-11, 0.08 degrees rms. This means, that from an operational perspective, if the Condor MSSR and the Mode S both meet the test criteria of 0.08 degrees or less azimuth error, then in today's operational environment, they can be deemed as operationally equivalent in azimuth error. The current Common Digitizer (CD-2) output data format limits realization of the benefits of the Mode S capabilities. If a higher resolution output format (such as Asterix) is allowed in the future, this performance equivalence may need to be re-examined. This should however, only improve the performance characteristics of one or both systems and would not be expected to limit the continued use of either system for operations in place at the time of the data format change.
  - The goal of this study is not to measure the performance of each of these systems against their system specification, but to compare the performance of the two different systems. The ASR-9 with Mode S is currently allowed to use the minimum separation standard of 3 NM at distances between 40 NM and 60 NM from its antenna. If the ASR-11's Condor MSSR performance can be proven equivalent or better than that of the Mode S, it is reasonable to assume that its beacon data output can

safely be used in the same manner. To determine this, a large scale analysis of empirical data was examined, and a report generated by MIT/Lincoln Laboratory for the FAA. This report titled "Comparison of ASR-9 and ASR-11 Radar Azimuth Error v.1" by Mayer and Tzanos is included as Appendix A, with a few figures copied into this report for the reader's convenience. For this effort, MIT collected 14 days of radar data through the RADES Network, totaling 8.5 million data points from 16 different radars. The sixteen different radars were equally split with eight ASR-9s equipped with Mode S and eight ASR-11s. This data was then filtered to include only those tracks that appeared to be attempting to fly a straight and level path. Then a straight line was fit down the middle of the path, assuming this was the aircraft's intended trajectory. Errors were measured based upon the distance from the derived "straight line path" and then split into range and azimuth components. These errors were summarized and compared for the ASR-9 with Mode S group of sensors and for the ASR-11 group of sensors. These summary plots and statistics are then broken out into range groupings, with the grouping between 40 NM and 60 NM from the sensors being the most critical to this discussion. This plot is re-printed as Figure 3 below. This plot contains a Cumulative Distribution Function (CDF) and Probability Distribution Function (PDF) of the errors for both the ASR-9 with Mode S and the ASR-11. The ASR-9 / Mode S error PDF is represented by the light-blue histogram and the ASR-11 PDF is represented by the red outlined histogram. The ASR-9 / Mode S error CDF is plotted as a blue line and the ASR-11 error CDF is plotted as a red line. The right y-axis refers to PDF density values, while the left y-axis refers to the CDF density values. The statistical standard deviations of the ASR-9 and ASR-11 distributions are recorded in the plot legend.

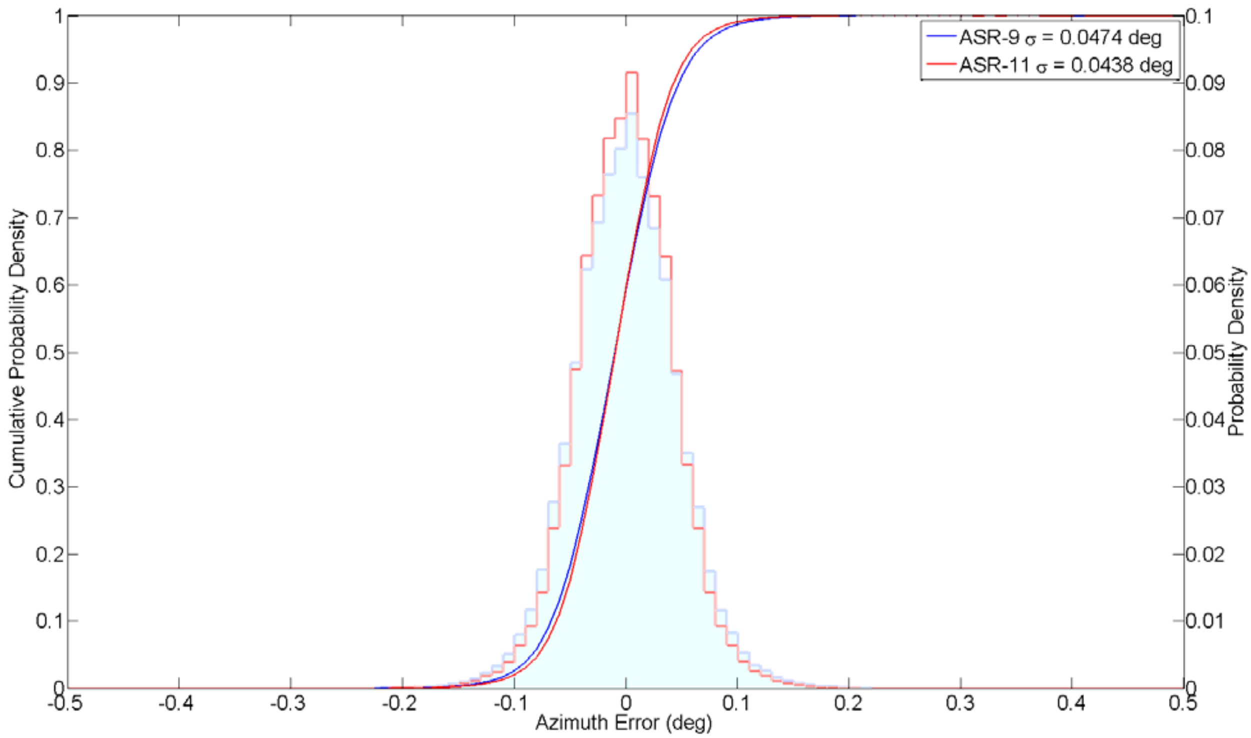


Figure 3: Estimated azimuth error distributions for ASR-9 and ASR-11 for reports 40-60 NM from the radar

For this error distribution plot, the closer the lines and the distributions stay to zero (deg), the better the performance of the sensor. For this case, the ASR-11s performed better than the ASR-9 with Mode S. Note that the red ASR-11 PDF distribution and CDF line are both closer to zero than the blue distribution and line for the ASR-9 with Mode S. The data in the upper right-hand corner of the plot that shows that the standard deviation of the azimuth error for the ASR-9s with Mode S was 0.0474 degrees, which is higher than that for the ASR-11, which came in at 0.0438 degrees, or closer to zero degrees. The distributions shown in this plot for the ASR-9 with Mode S as compared to the ASR-11 are similar enough to be considered equivalent for azimuth performance.

Errors caused by the alignment process of the Monopulse Secondary Surveillance Radar (MSSR) are another area to consider in determining if the sensors have equivalent azimuth error characteristics. Monopulse beacon radar use a CPME, which is located at or near the ground level for alignment of the sum and difference curves that produce the improved azimuth accuracy. Since the curves are optimized from an object that is located at or near the ground, the concern is that the azimuth performance may degrade or be prone to larger errors at higher elevations and / or elevation angles. This was also examined in the MIT/LL report located in Appendix A which looked at about 8.5 million points of data collected over a 14 day period from the 84th Radar Evaluation Squadron (RADES) Network. Figure 4 below shows that the sensors performed very close to one another at lower elevation angles, but above approximately 40 degrees, the two curves began to diverge, with the ASR-11 experiencing less azimuth error than the ASR-9 with Mode S.

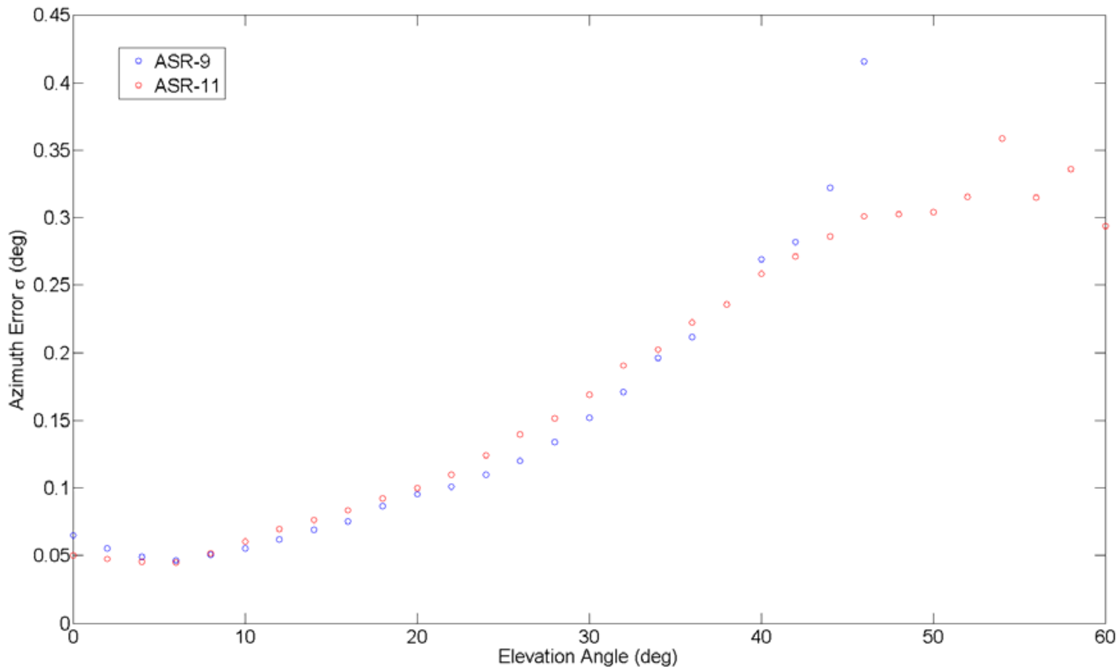


Figure 4: Estimated azimuth error vs. elevation angle

It should be noted that the number of reports received at the higher elevation angles where the two curves appear to diverge is reasonably small, somewhere around 3,500 out of 4,000,000 reports.

In fact, through the MIT/LL Report, it was shown that the elevation angle has a larger effect on the azimuth error than the range or the altitude of the target in a general sense, as is illustrated by the colormap plot re-printed from the Appendix A MIT/LL Report in Figure 5 below:

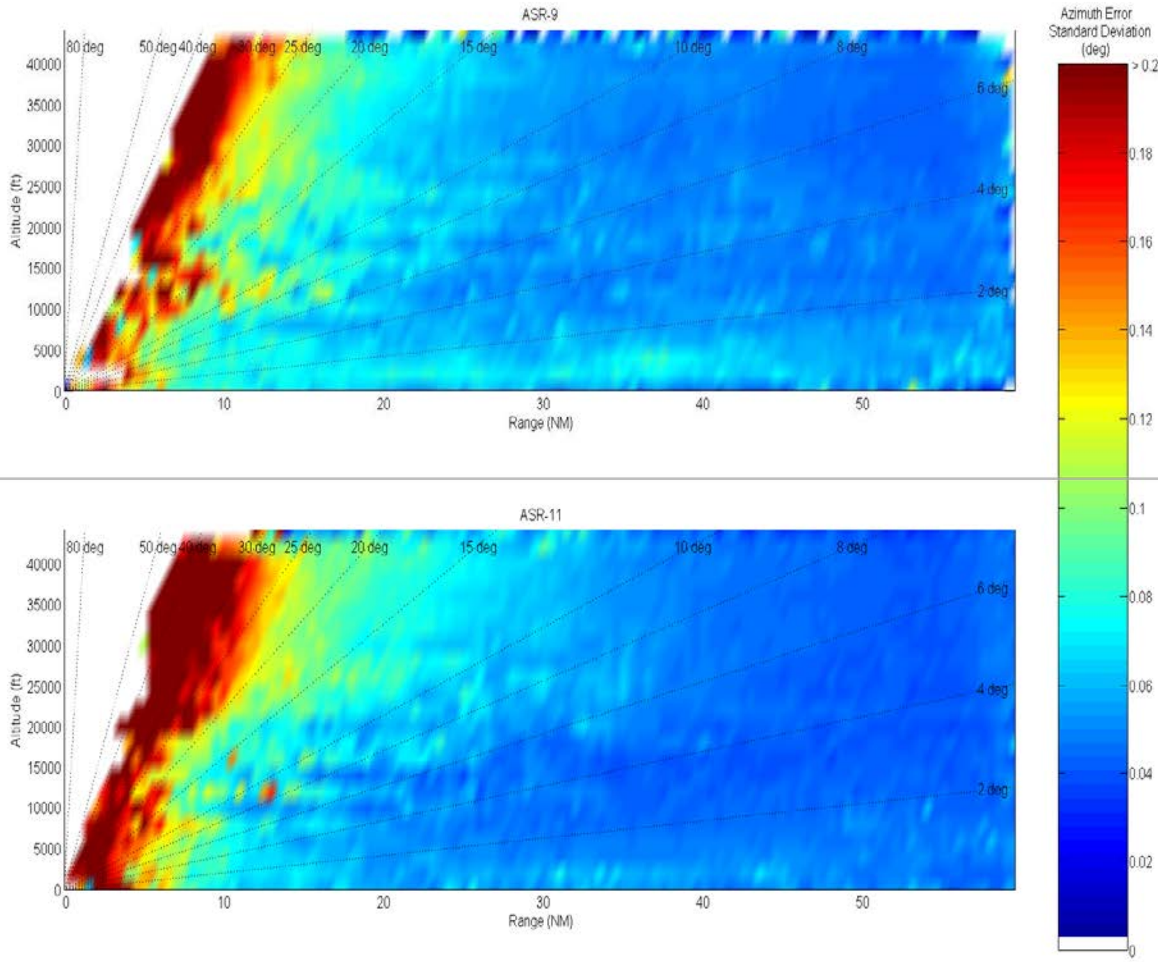


Figure 5: Estimated azimuth error vs. range and altitude

The azimuth error is shown in Figure 5 above, with the top half representing the ASR-9 with Mode S, and the bottom half representing the ASR-11. The x-axis represents the range of the target, with the y-axis showing the corrected altitude of the target using Mode C. The data was processed using 0.5 NM cells by 2,000 feet, and then smoothed. The color-bar down the right side of the plot is the legend for the color-coded standard deviation value computed for each cell, with dark blue representing the lowest or best standard deviation of the azimuth error, and red representing the highest or worst standard deviation of azimuth error, extending up to greater than 0.2 degrees. White areas in the plot are created at locations where no target data was received. It is clear from these plots that there is a degradation effect on the radar azimuth accuracy for both sensors from elevation angle, but this appears to be related to the edge of the radar beam and does not appear to impact the area of the plots that are pertinent to the comparative equivalency of the two sensors, based upon azimuth errors between 40 NM and 60 NM from the antenna. In this plot, the errors for the ASR-11 look somewhat less or better for azimuth than they do for the ASR-9 with Mode S, such that the two sensors can be said to be equivalent for the purposes of this study.

- *Output Format /Quantization Errors*:
  - Data from the ASR-9 with Mode S and from the ASR-11 are both output in the same basic data format, with the same resolution for beacon targets, at this time. Therefore, both radars are deemed equivalent in this area.
- *Transponder Error Sources:*
  - Although the Mode S Transponder and the ATCRBS Transponder have different error characteristics from one another, both of these errors are independent of the receiving surveillance sensor, and experienced and compensated for in much the same way by the ASR-9 with Mode S and the ASR-11. Therefore, both systems are deemed equivalent in this area.

- *Other Performance Considerations:*
  - *Target Resolution*: The processing of the Mode S and the Condor MSSR in the ASR-11 are similar enough that they are expected to maintain equivalency in this area. The ASR-11, as per the DASR System Specification Rev-E states that the Condor MSSR will be able to resolve two identical targets that are within 0.05 NM of one another in slant range, which are separated by at least 2.1 degrees (approx. 2.2 NM apart at 60 NM from the antenna) at least 95% of the time, and resolve two unique targets (having at least one unique beacon data field) that are within 0.05 NM of one another in range and are separated by at least 1.5 degrees (approx. 1.5 NM apart at 60 NM from the antenna) at least 99% of the time. This capability was tested and as per the Final Operational Test Report Dated October 31, 2003, Section 4.1.11.9, both tests met or exceeded the listed requirements. Passing these tests should be sufficient for safely allowing the beacon portion of the system to be used for a 3 NM minimum separation standard out to 60 NM from the ASR-11 antenna. The comparative assessment to the Mode S System becomes more difficult at this point. The Mode S secondary radar uses monopulse processing and is allowed to use a 3 NM minimum separation standard out to 60 NM from the ASR-9 antenna for targets equipped with Mode S beacon transponders and for ATCRBS beacon transponders. Mode S beacon radar target resolution performance for ATCRBS transponders should be roughly equivalent to that of the Condor MSSR for the ASR-11. However, Mode S beacon radar target resolution for targets with a Mode S transponder would be expected to be superior to that of either the ASR-11's Condor MSSR or the Mode S beacon radar when processing ATCRBS target, due to the ability to directly address each target within its coverage volume. This makes the Mode S beacon radar much less prone to the error condition known as "garbling", where two targets are in such close proximity that the radar cannot successfully extract the code pulses for the two targets from one another. With the additional Mode S

benefit taken into account, since the system is currently used with a 3 NM separation standard minima out to 60 NM from the antenna, regardless of whether or not the aircraft can participate in the directed interrogations which require equipage with a Mode S (versus ATCRBS) transponder, the Condor MSSR with the ASR-11 and the ASR-9 with Mode S are deemed equivalent for beacon target resolution.

- *Future System (Minimum Separation Standard) Usage:* The ASR-11 with the Condor MSSR is determined to have equivalent performance to an ASR-9 with Mode S, and provided that the adaptation thresholds, window tolerances, and other status checks, alert and alarm criteria, thresholds, tolerances and monitoring can be proven equivalent, using a 3 NM Minimum Separation Standard out to 60 NM from the antenna, is not expected to increase the risk associated with aircraft operations above the level experienced at like ranges on the ASR-9 with Mode S today. There is one cautionary note, however for usage of a new mode of operation included in the version of CARTS software that includes ADS-B with Fusion. The new mode is titled System Track Display Mode (STDM). This mode of operation does not function in an equivalent manner to the legacy CARTS mode in the display of beacon-only targets to Air Traffic Controllers. On the legacy CARTS system, as was the case for all legacy Terminal Automation platforms, beacon target reports were published to the display as soon as they were received and could be processed. The STDM mode of CARTS has modified this, by choosing to filter out or not display 'untracked' beacon-only targets. This creates a situation where data from aircraft in flight in suppressed or delayed in getting to the display of the air traffic controller. This change has not been addressed nor evaluated that we are aware of, and is therefore CARTS STDM Mode is not recommended for usage for any of the separation reductions analyzed in this study. If this mode is changed to operate without filtering out 'untracked' beacon-only targets, or this mode is tested and proven to perform at an equivalent or better margin of safety when compared to the legacy systems, this recommendation needs to be re-assessed.

3.2 Primary Search Radar (PSR) Analysis

Creating tracks from primary search radar reports relies exclusively on time and geographic coincidence. This makes comparison of the primary search target reports a more challenging or at least less exacting process than filtering through tracks of beacon targets. Beacon targets are easier to form into correlated tracks, particularly in post-processing, where the data is static and known. Forming tracks from PSR data is prone to errors. Add to this the fact that search targets contain only range and azimuth position information in radar slant-range, with no altitude information or other fields for matching to an existing track, and the process becomes even more difficult. The process that was used previously in the MIT/LL Report for beacon track processing is unusable for the search data. This makes the primary search radar (PSR) analysis wholly reliant on data from controlled flight tests for the derivation of error statistics, as opposed to the 8.5 million data points from Targets of Opportunity (TOO) that were used for the beacon analysis.

This study will examine the controlled flight tests and results from the Final Operational Test Report, dated October 31, 2003, as well as the additional data provided in Report DR033. While testing the modified STARS system with ADS-B and Fusion at Philadelphia, Raytheon made a modification to the adaptation of the ASR-11 parameters. This change repaired recorded tracker anomalies. Pursuant to this, Raytheon agreed to produce a report documenting the factory re-test of the ASR-11 that was to prove the performance of the ASR-11 PSR to support this change. This report is the referenced DR033 Report. The results of this Report will be considered in this discussion to determine if the testing and findings support the equivalency of the performance of to ASR-9 PSR and thus support a reduction of the current Separation Standard Minimum for the ASR-11 Primary Search Radar (PSR).

- *Architecture:* As per DASR System Specification Rev-E for the ASR-11 (p.6-14 to 6-34) and 6310.19A for the ASR-9 (p.5, 31&32)
    - *Coverage Volume:*
        - *Range*: Slant range from 0.5 NM to 60 NM from the antenna
        - *Azimuth*: 360^{o} of coverage
        - *Altitude*: The ASR-9 has a maximum altitude coverage requirement of 25,000 feet, and the ASR-11 has a maximum altitude coverage requirement of 24,000 feet.
    - *Update / Scan Rate*: 4.8 seconds per revolution
    - *Probability of Detection*: Both PSR systems should perform consistently in the 80% Probability of Detection range for targets "in the clear." This element was tested and passed except for the one degraded mode case for the ASR-11 in the Final Operation Test Report, dated October 3, 2003. There are some concerns regarding the performance of the ASR-11 in this area and in the related area of False Alarm Rate, which did not pass the requirements in the Final Operational Test Report [4]. A plot of the probability of detection of the ASR-11 PSR from the Willow Grove radar operating in a degraded mode is shown as Figure 6, re-printed from the Operational Test Report for discussion.

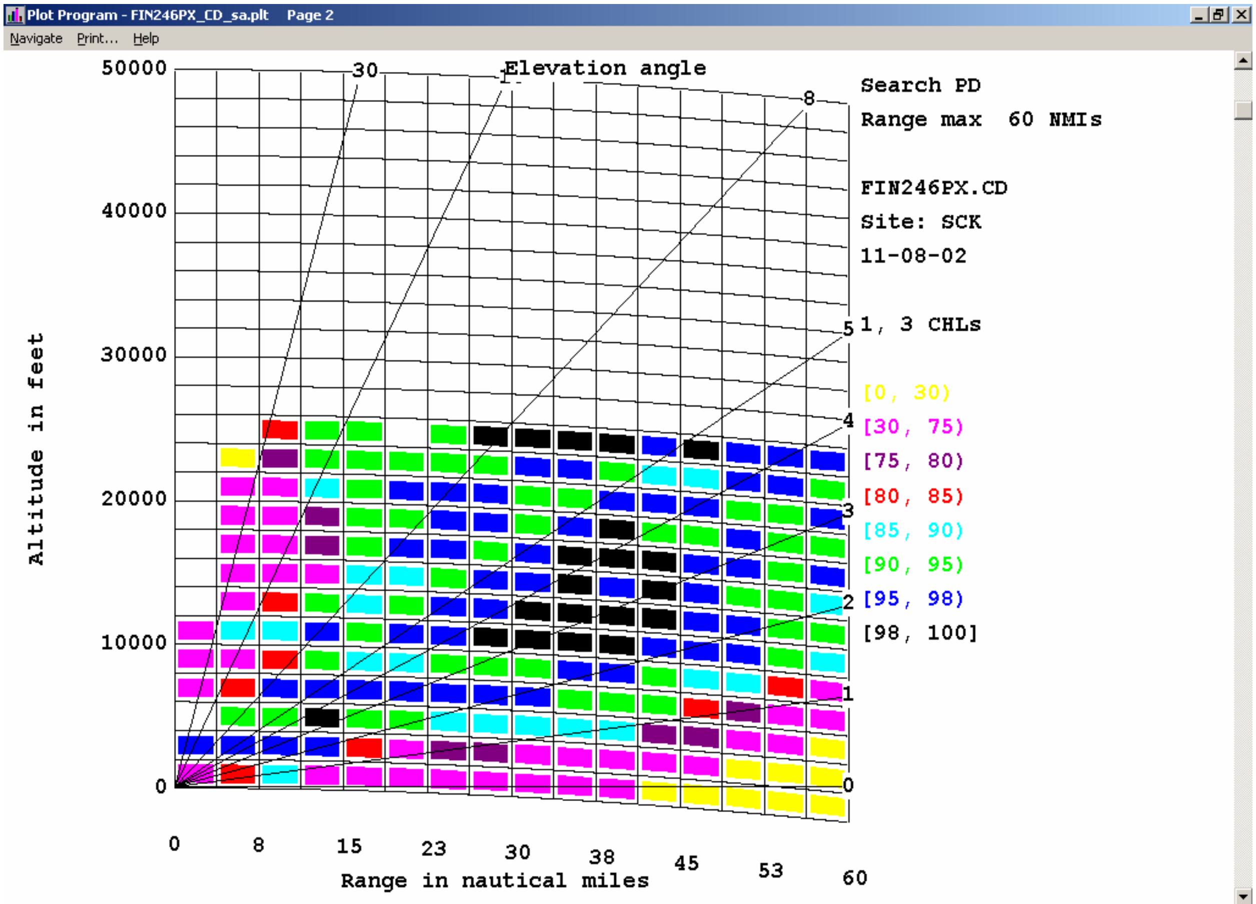


Figure 6: Stockton Run 246 PSR Plot detection - CP - 7 Tx modules online

Note that the Probability of Detection is given by the color of the block within each range and altitude cell, with the legend for interpretation located down the right-hand side of the plot. The yellow color is difficult to see in the legend, but it signifies that the probability of detection in the block was measured to be somewhere between 0% and 30%. This increases up to the maximum value of between 98% and 100% probability of detection for black colored blocks. Even though this plot is from a degraded mode of operation for the ASR-11, it is shown here to illustrate what a surveillance system passing an averaged probability of detection value may or may not mean. There is a significant difference between the safety of a system that detects or 'sees' 100% of the targets, but only receives them 80% of the time versus a system that only receives data on 80% of the targets and does not detect nor display 20% of the targets. Targets that are detected and tracked at an Automation Display can be 'coasted' through areas of spotty coverage. Targets that are not detected will not be displayed on the Automation display, and therefore pose a safety hazard to the NAS. This makes the 100% of the targets, but only 80% of the time, preferably, from a safety perspective, versus a system that will never detect 20% of the targets. In the drawing above, there are areas where the probability of detection is so low at distant ranges and low altitudes, that the PSR-only data in this area should not be heavily relied upon. This is typically an exercise which is performed during infrastructure planning and while siting the radar. The inconsistent probability of detection for the ASR-11 combined with the issues with the false alarm rate, make it an unlikely candidate for the reduction of an existing separation standard at this time.

The Final Operational Test Report states that an "Action Plan" will address the noted deficiencies of target resolution and false alarms. Research into the status of the "Action Plan" indicated that attempts to repair these deficiencies have been unsuccessful. These problems still persist today. The current plan is to replace the signal processor in the ASR-11 to correct these deficiencies. ASR-11 Build 12, the software change to correct the performance deficiencies (using advance clutter mapping and Doppler filtering) is projected to undergo 'key site' testing somewhere around March of 2012. System testing for the ASR-11 PSR after this modification is complete, may build a case for equivalency to an ASR-9, but at this time, the ASR-11 does not meet equivalency in this area.

- o *Frequency*: Both systems operate as S-band radar, within the range from 2.7 to 2.9GHz.

- *Internal Processing*: The ASR-9 PSR and the ASR-11 PSR use very similar technologies for the reflected RF or search detection path, with the exception that the ASR-9 was designed with better clutter mapping and Doppler filtering capabilities to reduce false targets or clutter. The Final Operational Test Report [4] shows the ASR-11 failed the required tests for False Alarm Rate. The report states that an "Action Plan" would be initiated to address these noted deficiencies. As was explained in the "Probability of Detection" paragraph above, a fix is being worked for these issues, but will not be in place until ASR-11 Software Build 12 is fully implemented and tested. At the time of this report, the ASR-11 does not meet equivalency in this area.

- *Automation Processing:*
  - o *Status, Alert, and Alarm Monitoring:* Radar systems typically employ a variety of test targets to check out individual processing paths of the system. For the RF/Primary surveillance path, some systems utilize RF reflectors that are set at fixed and known locations to verify the entire primary radar processing path. Some systems additionally inject an RF test target into the feedhorn of the primary radar antenna to test out the receiver processing path. Likewise, the secondary surveillance radar or beacon processing path has test targets. The end-to-end test for the secondary processing path was traditionally performed by using a beacon Position Adjustable Range Reference Oriented Transponder (PARROT), which is a component of the Radar Beacon Performance Monitor (RBPM), but it is now more commonly performed using the Calibrated Performance Monitoring Equipment (CPME). Both of these systems are installed externally to the radar

facility under test, and are used to test out the full processing path for the secondary surveillance radar or beacon system. Both the beacon and the search processing paths also make use of a digitally generated test target that tests out the respective digital processing paths of each system. These targets are generated at fixed locations and should create one target for each path on each rotation or scan of the antenna. The test targets names are acronyms that both end in RTQC for the Real-Time Quality Control targets or RTQC. The search or primary surveillance target being the SRTQC, and the beacon or secondary target is the BRTQC. These test targets are checked and verified at the radar site, and many of them are also sent out of the radar as a part of the main output stream to the NAS Automation Platforms that receive surveillance services from the radar. These test targets are used for continuous monitoring of each system's data quality or "fitness" to be used as a surveillance sensor in the NAS. The ASR-9 and the ASR-11 radar systems output several test targets that are used to verify the operational status of the system and to provide a rough check on the quality of the data that it produces. The types of test targets for the ASR-9 and the ASR-11 are very similar to one another, but there are some reported differences in this area, particularly regarding the measurement for the PSR SRTQC location and window of tolerances for alerts / alarms. This introduces some differences between an ASR-9 and an ASR-11.

- *SRTQC Placement*: There has been some confusion about the placement of the SRTQC location as it was adapted into the NAS Automation Platforms. The SRTQC test target is used for testing of the quality of the ASR-11 PSR data and the health of the ASR-11 for usage as a surveillance sensor in the NAS. Anecdotal evidence suggests that the location may have been improperly adapted due to miscommunications at most if not all of the NAS Automation Platforms receiving ASR-11 data. This study will not examine the details behind this, the truth of any claims or the current status of the adapted sensors in the NAS. The goal of this study, in this area, is to identify this as an area to be investigated by the appropriate ATO personnel, and to publish the correct method by which to compute the location of the SRTQC, courtesy of AJW-14, included here as Appendix C. It is suggested that this adaptation parameter and the window of tolerance associated with any alerts or alarms based upon this parameter be checked and corrected, if necessary, at any and all NAS Automation Platforms, prior to the modification of any separation standards currently in use at the facility. Once these are checked and / or have been corrected, they should be deemed equivalent to those used for the ASR-9.
- *Expanded SRTQC Window of Tolerance:* There is also evidence to suggest that the adapted Window of Tolerance used to create alarm and alert criteria thresholds for the SRTQC was much larger for the ASR-11 than that used for the ASR-9. This may have resulted from attempt to

reduce alarms and alerts that were in reality caused by a misplacement of the SRTQC location that was discussed in the previous paragraph. When a radar is interfaced into a NAS Automation Platform, the location and existence of the RTQCs is one of the continuous quality checks performed on surveillance sensors to determine the quality and hence usability of the service that they provide, by verifying the SRTQC location. This has the effect of making the ASR-11 less sensitive than the ASR-9 to the detection of an azimuth error. If the ASR-11 SRTQC Windows of Tolerance are corrected (which would require that the SRTQC locations be adapted correctly as well) to match those used in the ASR-9, the two systems would be considered equivalent in this area.

- *Radar Sensor Error Sources*:
  - *Registration Errors:*
    - Location Bias – This is not a function of the surveillance sensor itself, but an error caused by improper or inaccurate radar siting, and should therefore be considered equivalent between the ASR-9 and the ASR-11.
    - Azimuth Bias – This is a function of registering the alignment of each sensor to the Automation Platform, and was addressed in the "Data Modification" bullet above. The sensors go through equivalent alignment processes for azimuth bias correction, which is already being done on each platform for each sensor, and should therefore have an equivalent effect.
  - *Range Errors:*
    - Radar Bias - This is a function of registering the alignment of each sensor to the Automation Platform. The sensors go through equivalent alignment processes for bias correction, which is already being done on each platform for each sensor, and should therefore have an equivalent effect.
    - Radar Jitter – The range that is output in the beacon target message is derived by the time between the transmission of the Radio Frequency (RF) transmission pulses and the receipt of the RF energy bouncing back off of the aircraft. This processing is the equivalent between the ASR-11 and the ASR-9. The specifications for the ASR-11 were tested in the Final Operational Test Report [4] by controlled flight tests and the results came in at 134 feet rms including bias, which was well below the maximum allowable error of 275 feet rms. The ASR-11 and the ASR-9 are deemed equivalent in these areas.
  - *Azimuth Errors:*
    - Azimuth Jitter – The specification for the ASR-11 required that the azimuth error for the ASR-11 PSR be limited to a maximum of 0.16^{o} rms, including bias. This was tested in the Final Operational Test Report [4], and during non-range resolution flights, the results showed that the measured rms azimuth error was 0.1425^{o}. This exceeded the specified

requirement, and is considered equivalent to the performance of the ASR-9.

- *Output Format /Quantization Errors*: The ASR-11 and the ASR-9 use the same output data format for delivering data to the NAS Automation Platforms, therefore they are deemed equivalent for range and azimuth quantization errors.

- *Other Performance Considerations:*
  - *Target Resolution:* Target resolution is the ability of the surveillance sensor to distinguish between and therefore output two target reports when two targets fly in close proximity to one another in range and / or in azimuth. This is another area of difficulty for the ASR-11 PSR. As per the Final Operation Test Report [4], it did not meet the specification of being able to resolve two aircraft at the same range and separated in azimuth by 2.6^o 80% of the time. It did however, successfully resolve two aircraft 80% of the time that were at the same range and separated in azimuth by 2.9^o. The significance of this 0.3^o difference in performance can be seen by examining the separation distance in NM at the current maximum range at which a 3 NM minimum separation standard is allowed for the ASR-11 of 40 NM and the range at which this separation standard is desired to be used, 60 NM. This can be computed by computing the circumference of the coverage volume at the desired range, dividing it by 360^o, and then multiplying by the specified and the actual azimuth resolution values for each range.
    - Target Separation in NM for the Target Resolution, at Range ‘r’
      - $S = ((2 * \prod * r) / 360^o) *$ Target Resolution

Table 1: Target Separation in NM for the Target Resolution, at Range ‘r’

Target Resolution	@ 40 NM Range from Antenna	@ 60 NM Range from Antenna
2.6^o	1.82 NM	2.72 NM
2.9^o	2.02 NM	3.04 NM

The ASR-11 does not meet comparative equivalency to the ASR-9 for Target Resolution. The ASR-11 did not meet its specified requirements for target resolution, and close to the maximum processed range for the sensors under consideration, Table 1 above shows that the ASR-11 would not be capable of resolving two targets spaced at or near the 3 NM Minimum Separation Standard. It is not known if any of the planned processing improvements for the ASR-11 will affect the azimuth target resolution capabilities of the PSR. If they do, this area would need to be re-examined to determine if it meets equivalency to an ASR-9.

  - *Future System (Minimum Separation Standard) Usage:* Due to a failure to meet an equivalent level of performance to an ASR-9, as shown by excessive false targets recorded and the failure to meet target resolution parameters in the Final Operational Test Report [4], combined with known issues with SRTQC checks in the NAS Automation Platforms, it is not recommended to expand the use of 3 NM Minimum Separation Standard beyond the current limit of 40 NM for the ASR-11 PSR at this time.

3.3 Target Separation

The data shows that the performance of the monopulse beacon system of the ASR-11 is sufficiently similar to the performance of the ASR-9 with Mode S, for the two systems to be considered comparative equivalents. Therefore allowing a reduced separation standard minimum of 3 NM for beacon targets that are located at a distance between 40 NM and 60 NM range from the ASR-11 antenna is not expected to incur any additional risk than using the ASR-9 with Mode S at the same separation standard and at similar distances from the antenna as is allowed in the NAS today.

The data shows that the performance of the ASR-11 PSR is not currently equivalent to the performance of an ASR-9 PSR. It is therefore not recommended to allow the expanded use of a 3 NM separation standard at distances exceeding those in use today.

3.4 Target Resolution

The data shows that the performance of the MSSR of the ASR-11 is sufficiently similar to the performance of the ASR-9 with Mode S, for the two systems to be considered comparative equivalents. Therefore allowing a reduced separation standard minimum of 3 NM for beacon targets that are located at a distance between 40 NM and 60 NM range from the ASR-11 antenna is not expected to incur any additional risk than using the ASR-9 with Mode S at this standard and distance from the antenna as is allowed in the NAS today.

The data shows that the performance of the ASR-11 PSR did not meet its specification requirement in this area and is not currently equivalent to the performance of an ASR-9 PSR. It is therefore not recommended to allow the expanded use of a 3 NM separation standard at distances exceeding those in use today.

3.5 Vertical Application

From a comparative surveillance sensor standpoint, when MSSR altitude data has been received, decoded correctly and validated, there is no difference between the ASR-11 and the ASR-9. The data source is the same in both cases, the altimeter on-board the aircraft. There is also little effect based upon range or distance from the reporting sensor, regarding the accuracy of the data received, since it is sent to the surveillance sensor as coded pulses in a beacon reply. The only significant difference that range from the reporting sensor has on the vertical information received at the radar, is based upon the probability of detection or receiving a reply at all. This does vary with range, with close in ranges near the edge of the transmit beam and at low altitudes farther out in range performing the worst. But, it is not different based upon the minimum lateral separation standard in use, nor does it vary based upon whether the aircraft is 40 NM from the antenna or 60 NM. The factors that do affect the pressure altitude errors are: the pilot's ability to maintain a particular altitude, the distance (both laterally and vertically) from the altimeter to the reporting weather station, and cold temperature variations. Since none of these is affected by allowing the ASR-11 MSSR to utilize a reduced separation standard beyond 40 NM from the antenna, this change alone would not be expected to increase the risk to the NAS above what is experienced today for continued application of existing vertical separation criteria.

3.6 Use of Passing and Diverging

Since the ASR-11 MSSR and the ASR-9 with Mode S meet criteria for comparative equivalency, using their beacon targets in the same manner for Passing and Diverging Operations, within 60 NM of the reporting sensor for the same operations that are in place, is expected to incur no additional risks to the NAS. Passing and Diverging Operations are only partially dependent upon the performance of the reporting surveillance sensors. These types of operations are additionally dependent upon the operation and processing of the NAS Automation Platform used to display the targets to the Air Traffic Controller. Passing and Diverging Operations are unique, because they rely upon traditional distance-based separation standards at the beginning of the operation (3 NM lateral separation minimum between targets and / or 1,000 feet vertical separation between the aircraft). But, after the symbol representing one of the aircraft is seen to cross or pass the projected path of the other aircraft, the operation is based solely on continued divergent paths and 'green between' on the display (ensuring that the two target symbols for the aircraft do not touch or merge together on the display.

This is not expected to be a problem or cause any additional risks when performed on the legacy terminal automation platforms of STARS and CARTS, but it may pose additional risks with the newly modified "ADS-B with Fusion Tracking" versions of these systems.

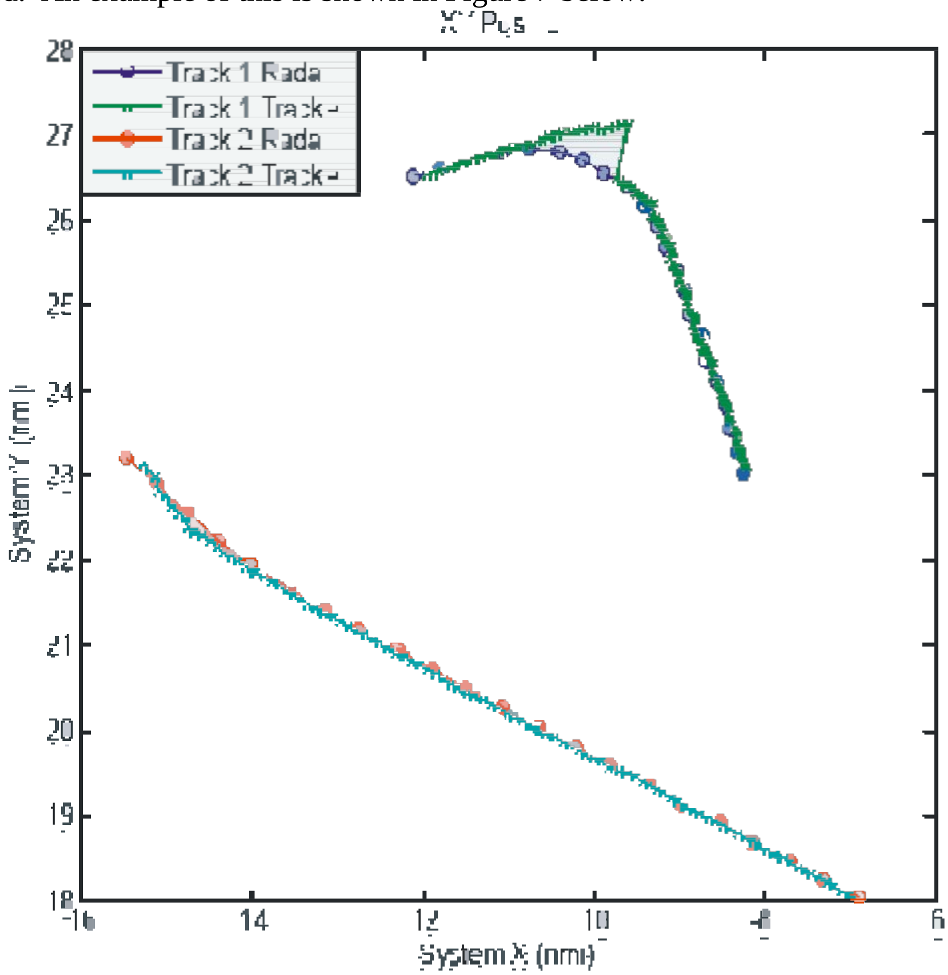
The CARTS and the STARS Automation Platforms were recently modified to accept ADS-B and to use Fusion Tracking while operating in a multi-sensor mode. Fusion Tracking with multiple sensors, if it can be optimized correctly, may provide some distinct benefits to the NAS, particularly in the area of track continuity through individual sensor failures, and a faster effective track update rate. However, creating a Fusion Tracker that is optimized correctly is a non-trivial task, and there are some significant challenges that must be addressed for it to produce improved results. Two of the most difficult challenges are minimizing the residual bias errors between sensors through accurate registration, and minimizing tracker lag.

- *Registering the Sensors:* The sensor registration process is not a new concept for NAS Automation Platforms. A registration process has been available in various forms for years. In most cases this process has been run by maintenance personnel on a periodic basis, and the decision as to whether or not to 'manually' apply the suggested registration corrections computed the registration process was left up to their discretion. In single sensor mode, which has been the standard mode of operation for legacy NAS Terminal Automation Platforms until the ADS-B related modifications, misaligned sensors could only affect the system if they were being used, which in most cases, only occurred on the failure of the preferred sensor, which was infrequent. With fusion tracking, this is no longer the case, misaligned sensors can not only dilute or reduce the accuracy of the reported tracks, they can also cause track de-correlation and add to tracker lag, which can create an unsafe condition where the displayed track does not 'agree' with the reported positions being received. For this reason, both of the modified Terminal Automation Platforms, STARS and CARTS, have now moved to an automatic and dynamic registration process. They were both tested and measured against 'residual bias requirements' published in the SBS Program Office's Automation Requirements Document. There are remaining concerns in the operation of both of the modified versions of the Terminal Automation Platforms. The vendors are aware of these concerns, and are working on them as program improvements. These include:

- Ensuring that the process does not become overly reliant on any one sensor (such as ADS-B), and
- The related concern that 'health checks' need to be performed on each sensor to determine its eligibility to participate in the Fusion Tracker.

In algorithms where ADS-B is the preferred sensor a time delay needs to be in place between the computation of the registration values and their application to the system data ensure that the ADS-B data used for the registration process was not faulty by allowing the ADS-B Time-To-Alert to expire. For algorithms that register sensors to one another, additional 'health checks' of the participating sensors need to be in place to ensure that a 'healthy' sensor is not misaligned by registration with one that is 'unhealthy.' This last concern has always existed at some level, but is even more of a concern because the new processes are designed to be run and applied automatically, as opposed to being manually run, without humans to validate that the sensor(s) 'look' normal or okay, and because in the fusion environment, the effects of a faulty sensor may no longer be obvious to the Air Traffic Controller, as it has been in the past with single-sensor mode.

- <u>Tracker Lag:</u> Tracker lag is the most challenging problem in multi-sensor tracking. Just as in the radar system there is always a performance trade-off between the probability of detection and the false alarm rate. With trackers, the trade-off is a stable smoothed track in the presence of position jitter or noise and the detection of a state change, such as going from a turn to straight flight or vice versa. In the worst cases, the tracker will not correlate the new position reports for an existing track with the track, and will continue to 'coast' on its predicted path. In some cases the de-correlated reports will not be shown on the Air Traffic Controller's display until enough additional reports have been received to form a new track. This causes a highly undesirable situation that can pose a significant risk to the NAS, in which the Automation Platform has lost "situational awareness" by 'losing' targets, which then prevents the Air Traffic Controller from maintaining 'situational awareness', and may prevent them from performing their risk mitigating functions of ensuring that the aircraft under their control follow instructions as directed, and commanding evasive maneuvers when a potentially dangerous condition appears. Both the STARS and the CARTS Automation Platforms with ADS-B and Fusion Tracking modifications exhibited tracking problems, including tracker lag, on the operational data that was collected and analyzed. An example of this is shown in Figure 7 below:



In this example, the tracker lag is shown in the top right-hand corner of the plot. The dark green 'X' indicates the tracker update that would be shown on the Air Traffic Controller's Display, while the blue 'O' represents the radar reported position that may not be shown to the Air Traffic Controller on some of the new modified systems. The CARTS and the STARS underwent further modification and testing to repair these anomalies. Many of the follow-on test results look promising to repair many of these issues, but some of them are not installed on the versions of the software that was recently approved for the In Service Decision, and are planned for later testing and deployment.

- There is also concern that the latest version of the CARTS software with these modifications that also include a System Track Display Mode (STDM), which did not successfully pass the test criteria that were designed to test out its safety for turning operations, such as passing and diverging. The vendor is aware of these issues, and has a planned improvement to attempt to address these concerns. Due to this issue, this mode of operation is not recommended for use on any operations that may be impacted by this deficiency, to include Passing and Diverging, or other operations where aircraft travel in close proximity to one another, where a delay or lag in the system display may prevent or delay the Air Traffic Controller from performing their risk mitigation functions.

- A lack of sensor ‘health checks’ prior to allowing a sensor to be used as a reference for other sensors to be registered against and prior to allowing it to contribute to the fused tracked position shown on the display to controllers is another concern previously identified in “Registering the Sensors” above. In the legacy single-sensor Terminal Automation Platforms, if a surveillance sensor failed or had significantly degraded performance, it was typically easy to tell that the sensor was faulty and which sensor was faulty by directly viewing the Air Traffic Controller’s Display. This has changed in the new multi-sensor Fusion Tracking environment, where the Air Traffic Controller will not be shown which sensors are contributing to the track information on the display. To prevent one faulty sensor from causing the positions of all or multiple displayed tracks to degrade, the Terminal Automation Platforms need to perform additional ‘health’ and Fusion tracker eligibility checks on the data from each surveillance sensor prior to using a sensor as a reference for registration computation or for tracking and display. It should be verified that STARS and CARTS which include ADS-B and Fusion Tracking contain these types of system safeguards and that they are properly functioning prior to using them for Passing and Diverging or other similar operations that are heavily reliant upon the Air Traffic Controller being aware of unplanned aircraft turns or failure to turn quickly.

STARS and CARTS legacy Terminal Automation Platforms should be able to be used for Passing and Diverging with ASR-11 beacon data between 40 NM and 60 NM from the antenna, without incurring additional risk to the NAS, above what is experienced at the same ranges for this type of operation when using an ASR-9 with Mode S today. Once these issues, including the CARTS planned improvements, are implemented and tested in the new CARTS and STARS Automation Systems with ADS-B and Fusion Tracking, and the test results determine that there is no added delay in publishing the correct aircraft position to the display through added tracker lag, and that there is no additional risk of faulty data being published to the Air Traffic Controller’s display and similar risk of faulty data to the legacy systems, that has a lower chance of being detected, then they should be allowed to be used for passing and diverging as well as similar operations as well, with no additional risk to the NAS beyond what is experienced today.

3.7 Minimum Separation from Obstructions

This study examines if it is reasonable to reduce the current lateral separation from obstructions, based upon radar processing improvements. Vertical separation from obstructions is not addressed, since the vertical position is an encoded representation of the barometric pressure sensors on-board the aircraft and would not be impacted by improved radar processing accuracy.

Since a reduction in the aircraft-to-aircraft separation standard minima was previously approved for aircraft travelling between 40 NM and 60 NM from an ASR-9 radar with Mode S, it seems intuitive to some that the separation from obstructions should also be safely reduced to the same 3 NM minimum separation standard. However, taking into account the fact that it is easier to hit a fixed target than it is to hit a moving target, casts doubt on conclusions from intuitive assumptions alone. Deriving a level of risk associated with these types of operations is a non-trivial task and requires research to determine the appropriate nominal scenarios to simulate and the nominal parameters to address in these scenarios. Determination of the nominal parameters requires research through multiple FAA Orders to determine: (1) How obstacles are created and drawn on the Radar Video Maps; (2) How the Radar Video Maps are aligned to the Automation Display; (3) The resolution of the Automation Display; and (4) How the radar data is aligned to the Automation Display. Simulations of these scenarios with their nominal parameter settings will then be run with randomly seeded distributions enough times to create a large data set from which a probability of Test Criteria Violation (TCV rate) can be determined.

AFS-450 has fast-time simulation tools that can be used to perform thousands to millions of runs in a 'Monte Carlo' simulation to answer these questions. These simulations include error distributions for surveillance sensors, error distributions for navigational errors, aircraft aerodynamic models and atmospheric models. This allows the creation and execution of specific scenarios to predict how often, given the errors and their frequency in the system, the aircraft, while attempting to maintain a 3 NM separation from an obstacle, would be expected to come within 500 feet of the obstacle, and how often this would be expected to occur. This will allow the derivation of a predicted risk associated with this operation. There are two scenarios that are being processed for this purpose. Scenario 1, shown in Figure 8 is meant to represent a typical scenario, where the aircraft trajectory is tangential to the obstacle at the minimum separation distance. Scenario 2, shown in Figure 9 is intended to represent a scenario in which the aircraft travels on a heading toward the obstacle and then executes a 90 degree turn away from the obstacle at the minimum separation distance from the obstacle, as could be experienced on a departure course where there are mountains or other obstacles that must be avoided on a direct heading off of the runway end.

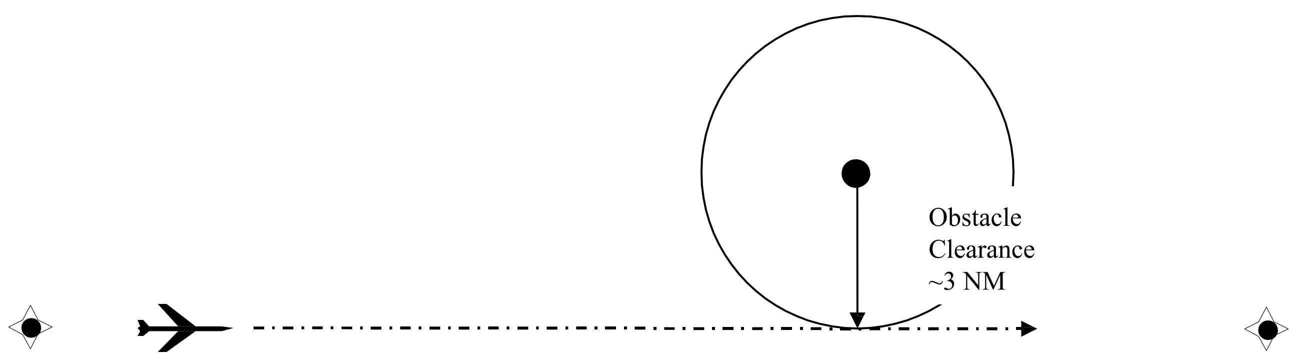


Figure 8: Scenario 1 Tangential Flight Past Obstacle Clearance

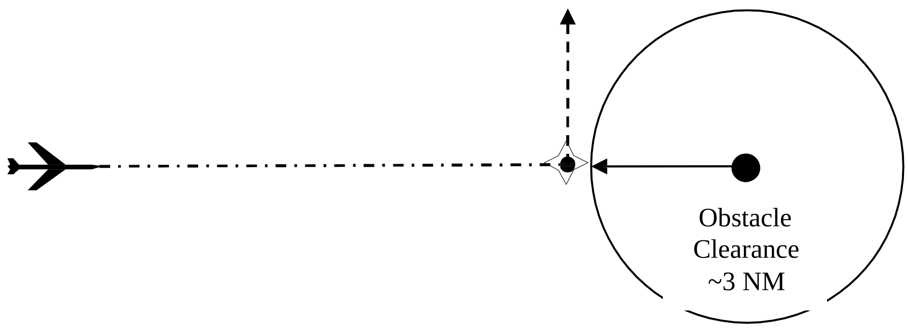


Figure 9: Scenario 2 Turning Flight At Obstacle Clearance Boundary

For Scenario 1 simulations an RNP 2.0 capability was used to create a nominal assumption for aircraft performance to account for aircraft that may be subjected to inertial drift or may be flying at greater distances from a VOR or DME. It is noted that the operation is dependent upon an air traffic controller being able to maintain a distance between the displayed aircraft position and the displayed obstacle position. Aircraft performance becomes most critical for safety during the time in between displayed position updates made by a fresh surveillance report. It is thought that aircraft flying on the outer bounds of their RNP value are subjected to a slow drift and heading change that would typically be noticed and corrected by air traffic controller intervention. This intervention is difficult to model within the simulation, since the timing of an intervention could be affected by many factors, including controller experience and workload. For this simulation, it was determined that the heading inaccuracy or trajectory drift would be noticeable and corrected at least by the time the symbol representing the aircraft on the display crossed over the line or circle representing the obstacle's clearance area. The simulation used an air traffic controller model that gave the aircraft a 45^{o} heading change away from the obstacle if the displayed symbol of the aircraft penetrated the obstacle's clearance area. The timing of the symbol crossing this threshold is affected by the update rate and performance of the reporting sensor, which can be affected by the probability of a missed detection during the operation. This simulation was treated as an impromptu flight between two waypoints, to create the nominal case experienced in the NAS. If this scenario was treated as a part of a published procedure or route, it would be subjected to the TERPs design criteria and would contain additional protection buffers for the primary and secondary areas, and would not represent a reasonable 'worst case.' These simulations were run using a uniform distribution of aircraft velocities which ranged from 200 to 400 knots.

Scenario 2 simulations were treated similar to a published departure procedure, and include additional protected areas around the waypoints, equivalent in size to the minimum RNAV/RNP performance level of the aircraft that is allowed to fly the procedure. This scenario was split into

Scenario 2a, to include the smallest waypoint protection area, with a stringent RNP 0.3 requirement, and Scenario 2b, which contains nominal performance of RNP 2.0, with the largest waypoint protection area. Aircraft in these simulations were held at 200 knots to approximate a reasonable maximum speed thought to be appropriate for these types of turning operations.

The simulation and modeling tool used for this study was ASATng. Error distributions were applied for flight technical error (FTE), which implemented the chosen Required Navigation Performance (RNP) level for the simulation, and for the ASR-11 surveillance sensor, which utilized the FAA standard radar error distribution model to create a reasonable worst-case surveillance error for the MSSR beacon data. (The ASR-11 MSSR was shown to perform better than this model in the MIT/LL Report included in Appendix A.) The simulation is not programmed to model the errors in the display of the obstacles shown to the Air Traffic Controller, relative to the displayed aircraft location, nor the error between the surveillance sensor and the Air Traffic Controller display. These are modeled by determining reasonable worst-case value assumptions for each of the variables, and reducing the effective minimum separation circle drawn around the obstacle by this error amount.

Four different errors were incorporated in the simulations in this manner. The variables of interest were errors from: (1) obstacle location or survey inaccuracies, (2) errors from a misalignment between the radar video maps and the display, (3) errors caused by translating the different data sources from one frame of reference to another (which is necessary to properly display the data on the same screen), and (4) errors between the alignment of the surveillance sensor and the display.

Obstacle Survey Errors: In today's modern NAS Automation environment which uses digital radar video maps, obstacle data or information used in the NAS is stored in *.dof files, which are housed in databases. There are two primary databases used as Aeronautical Information resources, each maintained in a slightly different way, and used for a slightly different purpose. These are AVNIS and NACO. AVNIS is typically used to develop and check TERPS criteria and TERPS surfaces for aircraft procedures. NACO is used as input to the process that produces Radar Video Maps. Obstacle data is sent to the Sector Design and Analysis Tool (SDAT). SDAT uses the locations from the obstacle data files to draw circles around these locations, to create the polygons which become the Radar Video Map. The way in which these polygons are drawn for Radar Video Maps is different from the way TERPs treats obstacles for surface and procedural development. The polygons produced for the Radar Video Maps, do not take the accuracy codes of the obstacles from the *.dof into account when creating the circle or polygon around the obstacle, which will be used as a separation distance marker by air traffic control. SDAT draws a circle or cylinder around obstacles based upon the obstacle's distance from the closest radar. It creates a 3 NM radius circle for objects within 40 NM of an MSSR, and a 5 NM radius circle for obstacles beyond 60 NM of the radar.

This may be an artifact left in the system from older technologies that used Analog Video Maps, and when the surveillance sensor created target reports for fixed objects. Before the implementation of the newer Digital Terminal Automation Systems (DTAS), which includes the CARTS, STARS, and the MEARTS Terminal Automation Platforms, radar video maps were aligned to magnetic north on many displays, and the maps would experience drift over time. There were many checks and verifications needed to ensure that the maps and the data displayed on them remained aligned properly with one another. Map accuracies were held to 1% at maximum display range, and airport magnetic variations up 6 degrees were allowed, with radar magnetic variations up to 2 degrees, as per Order 7910.1, Video Mapping Program. This was prior to radar surveillance sensors having the capability to filter clutter by maps, geographic filters, and Doppler filtering. This capability reduced the amount of clutter shown on an Air Traffic Controller's display, but it also removed all fixed or non-moving search targets from the surveillance data. The fixed targets, when present, had been used for map alignment and were checked by both the air traffic controller and the maintenance technician. The need for these checks largely went away when the FAA moved to using DTAS systems with Digital Maps. The digital maps did not experience the drift associated with the older analog maps, and the needed map features, such as obstacles, were drawn directly onto the map, as opposed to being received and displayed via radar reports. It also created a new problem, when the aircraft and the obstruction position were both being reported by the radar, they shared a common frame of reference and thus experienced similar errors. With the newer technologies and maps, the errors experienced by the aircraft's target data were different than the errors experienced by the obstacle data, which was now tied to the Radar Video Map, as opposed to a reporting radar.

Initially it was thought that the process to draw the obstacles on the Radar Video Maps would be similar to the process used for creating Minimum Vectoring Altitude (MVA) and Sectional Charts. Both of these charts require that the obstacles either meet the surveyed accuracy code of 5E (no greater than 500' horizontal error, and no greater than 125' vertical error), or additional separation buffers will be applied. However, through discussions with several different organizations involved with different phases of the process, it was determined that the Radar Video Maps are drawn using the Sector Design and Analysis Tool (SDAT) which does not consider the accuracy code of the obstacle when drawing the circles on the map. SDAT creates a 3 NM radius circle for objects within 55 NM of an MSSR, and a 5 NM radius circle for obstacles beyond 55 NM of the radar. This method does line up somewhat with the separation from obstruction standards listed in the 7110.65R, but it has drawbacks as well. By drawing the same size of circle regardless of the accuracy of the obstacle being represented, it is difficult to claim a standard separation distance is being maintained.

By basing the radius of the circle which represents the obstacle on the Air Traffic Controller's display on the distance from the radar, the minimum separation standard from the obstacle is allowed to vary from obstacle to obstacle by the error in the surveyed position of the obstacle. The positional error of the aircraft will be affected by the distance of the aircraft from the reporting sensor. The error of the obstacle on the Air Traffic Controller's display has no correlation to its distance from any radar. Obstacles are fixed objects that are filtered from the output of modern radar as clutter (through the use of geographic filters, clutter maps and Doppler filters), and are displayed to controllers as circles drawn on the Radar Video Map. If there is no limit placed on the surveyed errors for obstacles that are drawn on the Radar Video Map, the minimum separation standard that is applied as clearance around the object can vary effectively as much as the maximum allowed survey error. For the worst case, where the surveyed error is unknown, the separation from that obstacle is also unknown. For obstacles that have a surveyed error of category 8H, the effective minimum lateral separation standard in use could be less than 2 NM, when other systems errors are considered, due to the 1 NM horizontal error possible for this category. This also means that an obstacle with a 1A category or surveyed to a lateral accuracy within 20 feet, could have a 5 NM standard in use around it. The current method of drawing circles of differing radii based upon the distance between the obstacle and the reporting radar makes some sense from the single-sensor legacy mode of operation, where there is a correlation between the accuracy of the reported aircraft position and the distance from the radar, but it does not provide for standardized separation from the obstacle or obstruction since the accuracy of the obstacles position is not taken into account.

From a safety perspective, it becomes impossible to derive a target level of safety or a comparative safety assessment based upon obstacles with unknown accuracy. In order to create a path for facilities who can derive significant benefits from a reduction in the separation from obstacles, it was decided to set forth an assumption that creates a requirement for facilities to use the reduced separation, through an area, that all of the obstacles that are within the reduced obstruction clearance area be surveyed to a known lateral accuracy of a category 5 or 500'. So that the obstacle survey error used in this study is 500'.

It is further noted, that with the advent of fused tracked displays for the various systems, the method of drawing a cylinder around the obstacle based upon its distance from any radar or surveillance sensor has no logical basis for safety or usability for Air Traffic purposes. In Terminal Automation Systems with Fusion Tracking, the display symbol will be a filled circle to indicate that the data received for the target allows the usage of a 3 NM minimum separation standard, and a hollow or non-filled circle will indicate that a 5 NM minimum separation standard should be used. This requires that consistent separation standards be applied to pair- wise groups of targets as opposed to the previous sector-wide basis. This means that, for obstructions, the air traffic controller will need to use a 3 NM circle or a 5 NM circle for the correct separation distance minima, based upon the target equipage and data quality. Therefore, it is suggested that Radar Video Maps be modified to include both of these circles and Air Traffic Controllers be trained to use the correct circle for separation under the proper circumstances.

It is assumed that all of the Terminal NAS Automation Platforms that reduce the Obstruction Clearance based upon this study will use Digital Radar Video Maps with a minimum display resolution of 2048x2048 pixels, and that they include an alignment procedure that is accomplished at a resolution such that the width of each pixel will not represent a distance exceeding 150', and there are Beacon PARROT / CPME location adapted to monitor the health of the surveillance sensors used to monitor the aircraft flying in the vicinity of the obstacles in the Terminal Automation Platform, and that the azimuth tolerance for these locations is not allowed to drift by more than +/- 1 ACP (2 ACPs total error), without generating an alarm to the Air Traffic Controller.

Map Alignment Errors: Digital map alignment is now performed by maintenance personnel at the air traffic control facility by using an aligned master map, sometimes called a fixed target map, and aligning all other maps to this on the 2048x2048 pixel displays. Once aligned the maps do not move unless there is a manual change to the system. It is assumed that the worst case error experienced due to this is 3 pixels. This would allow for an expectation that there would be some 'green between' the map features at this point and therefore very easy to distinguish the map misalignment visually. For the purposes of this study, it is further assumed that the pixel width at the resolution used for map alignment, is approximately 150 feet, which would equate to roughly 50 NM of displayed screen width. This gives a reasonable 'worst-case' map alignment error of 450' for our study.

Data Translation Errors: These errors occur in the system when data from differing frames of reference have to be translated so that they can be shown on the same display. CARTS, for example, when using a single-sensor or radar slant range display mode it is using a Lambert Conical Conformal Projection to create a 2 dimensional display of the aircraft. Fusion or multi-sensor displays in the FAA generally use a Stereographic Plane projection for their displays. The errors caused by this are typically very small, on the order of tens of feet, but to consider a reasonable 'worst-case' for this, 50' is assumed for this error.

Surveillance Sensor Display Alignment Errors: The terminal automation platforms are adapted with a window of tolerance for the radar alignment to the display through the usage and checking of radar beacon PARROTs and CPMEs. The window of tolerance, which if exceeded, will cause a system alarm to be generated is 2 Azimuth Change Pulses (+/- 1 ACPs). At the maximum terminal radar range of 60 NM, this creates a reasonable 'worst-case' error of 0.183 NM.

It is noted that the tolerance chosen for this report is in agreement with the residual bias requirement of +/- 1 ACP for NAS Automation Platforms that perform fusion tracking with ADS-B. These studies were also run with the less stringent setting of +/- 2 ACPs which is in use as the tolerance on some NAS Automation Platforms. When the larger azimuth tolerance window of 4 ACPs is used, the larger errors allowed at maximum ranges cause Scenario 2b (fly- by of an obstacle using an RNP 2.0 aircraft) failing the TLS in the simulations, even when the predicted frequency of the operation is taken into account. For this reason, the lower tolerance was chosen as a requirement for the reduction of the clearance from obstructions in this report.

The errors discussed above could exist in any direction from the obstacle, and can thus be added to one another and represented as being in all directions for the nominal case. Figure 10 illustrates the way these errors affect the minimum separation distance or protection buffer around a point obstacle with a protection buffer of 3 NM radius, labeled **R**. The system errors between the obstacle and the received target data from the radar are shown as a concentric circle around the obstacle of radius **d**, where **d** represents the sum of the nominal errors that could be present at the display of the Automation Platform.

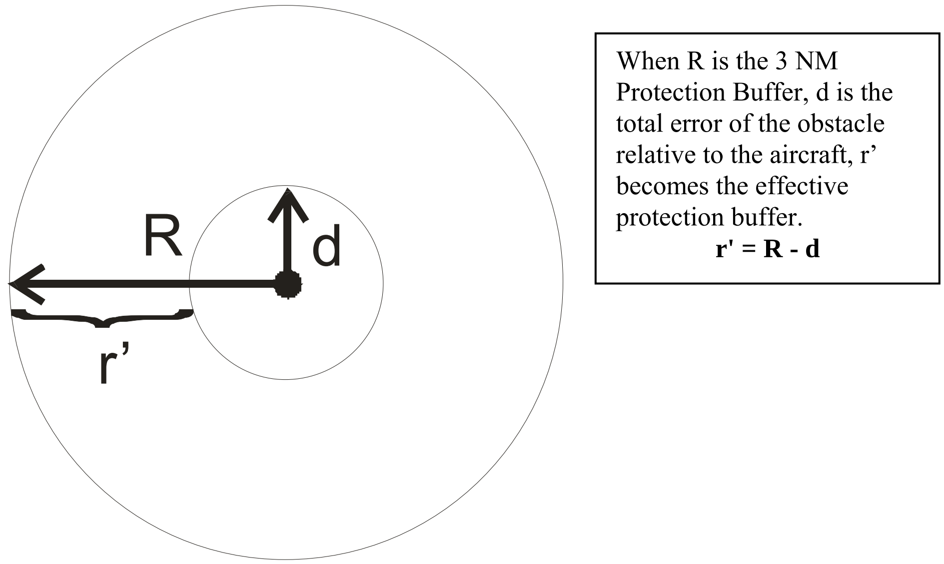


Figure 10: Effective Protection Buffer Distance Allowing for System Errors

The risk associated with flying too close to the effective protection buffer, shown in Figure 10 as the circle with radius **d**, can be equivalently modeled using a point obstacle and reducing the radius of the original protection buffer **R**, by the distance **d**, as shown in Figure 11.

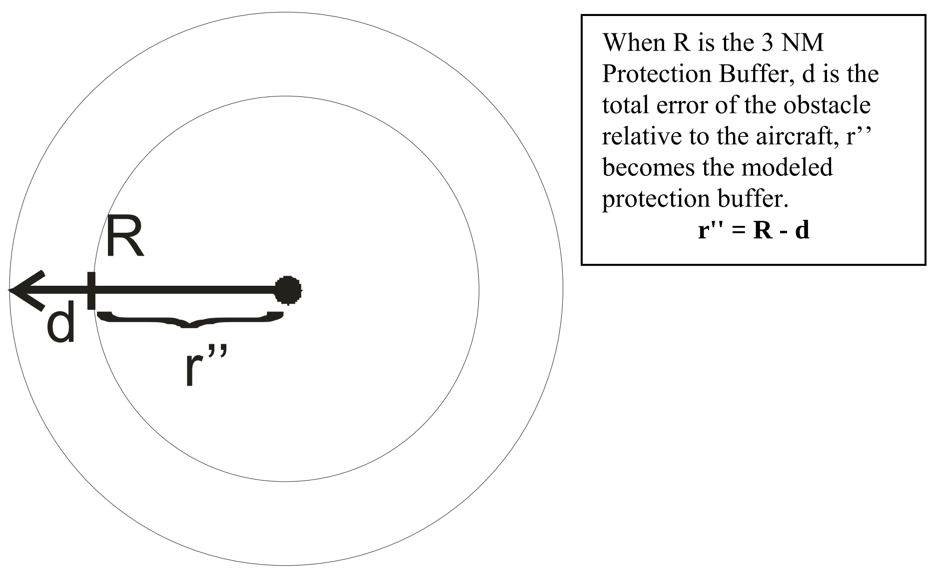


Figure 11: Modeled Equivalent Protection Buffer Distance Allowing for System Errors

To find **r'',** the system errors must be totaled to get **d**. The sum of the errors for nominal obstacle accuracy, map alignment and data translation of 500', 450', and 50' gives us a total of 1000' to be subtracted from the 3 NM separation from obstruction value to give a new separation clearance of 2.83 NM. From this value the 'Surveillance Sensor Display Alignment Error' of 0.183 NM is subtracted, resulting in a **d** of 2.65 NM, which will be used as the minimum separation distance from obstructions for testing in Scenario 1 of this study. For Scenario 2, it was felt that the only procedure that would include direct flight to an obstacle boundary as depicted, would be in cases where there was no other option, as in a departure procedure where terrain exists off the end of the runway, and that in these cases, a waypoint would be created just outside of the obstacle minimum separation boundary. Additional separation is added around waypoints based upon the RNP Level that is required to fly the procedure. The worst case additional separation between the protected area around the obstacle and the waypoint would be 0.3 NM, but only an RNP 0.3 capable aircraft would be allowed to fly this procedure. For this reason, Scenario 2 was split into two different cases. In Scenario 2a, 0.3 NM was added to the boundary for the waypoint, resulting in a 2.95 NM protected area around the obstacle, and an RNP 0.3 aircraft was used to fly the procedure. Scenario 2b included an additional 2 NM around the waypoint, for a 4.65 NM protected area around the obstacle, and was flown with the worst case RNP 2.0 aircraft performance.

The RNP flight values are applied as randomly seeded drift errors chosen from within the distribution of the selected performance level of the scenario at the beginning of each flight or run of the Monte Carlo software that affect the entire flight path. (In other words, every position update of the aircraft is not randomly seeded based upon the distribution, as this would cause an unrealistic flight pattern where the aircraft would “jump” from one position to the next as opposed to resembling normal aircraft flight.)

In Figure 12 the green lines show a small sample of the ‘true positions’ of RNP 2.0 tracks output for Scenario 1 from ASATng. The circle represents the 2.65 NM derived protection area around the obstacle in the center of the circle. The pink dots indicate when the Air Traffic Controller in the scenario commanded the 45^{o} heading change for those tracks that penetrated the protected area around the obstacle. Note that most of the tracks flew past the obstacle as shown near the bottom of the figure.

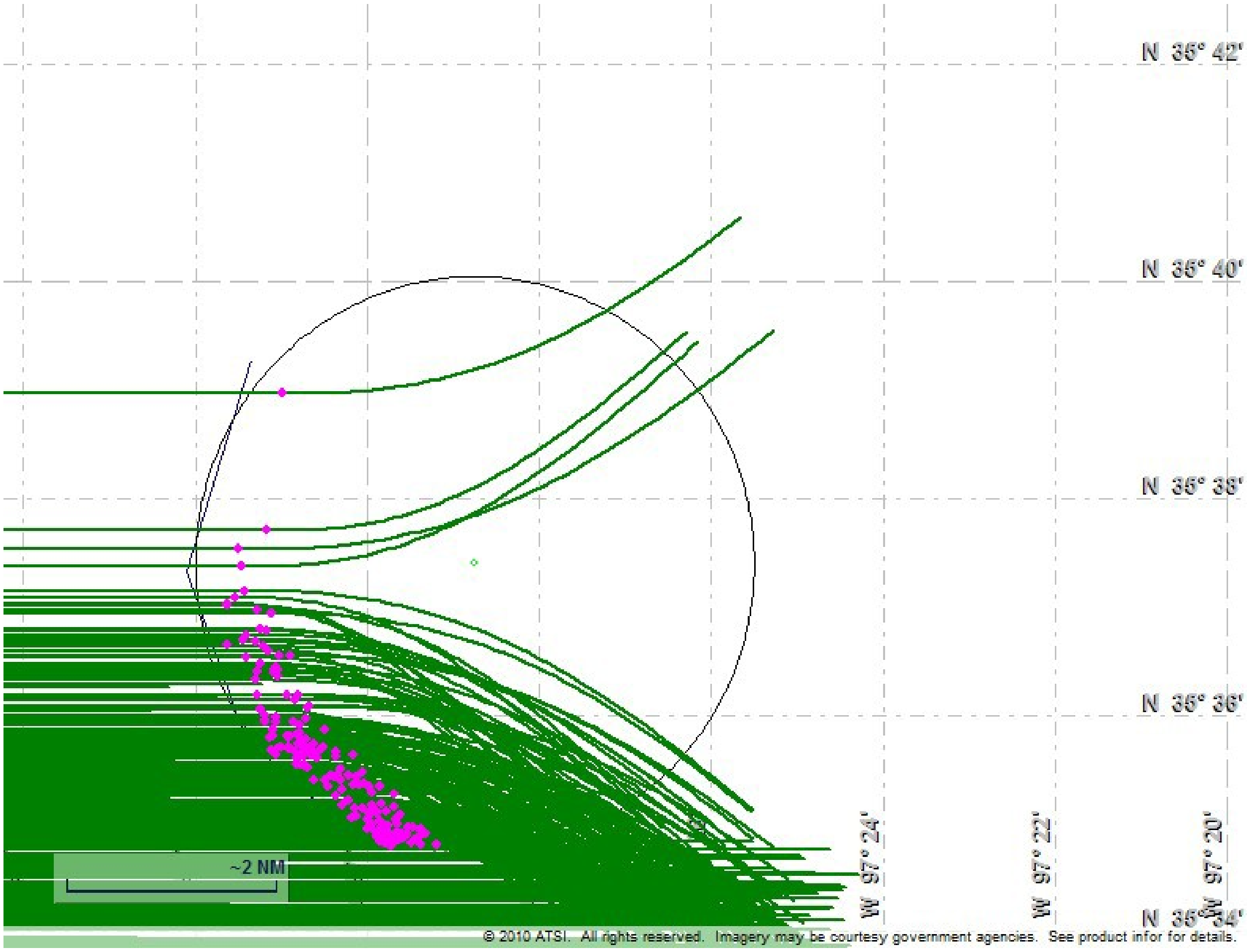


Figure 12: Scenario 1 Sample Tracks Tangential Flight Past Obstacle Clearance

Data was collected for the closest lateral distance between the obstacle and the aircraft for each of 553,474 flights. This data was then fit to a Beta distribution using ExpertFit software as shown in Figure 13. The TCV rate computed for this operation, using a 500' TCV is estimated to be $1.04x10^{-12}$, which exceeds the current Target Level of Safety (TLS) specified for SMS of $1x10^{-9}$. For the purposes of this paper, the units for the TLS metric are assumed to be a per operation number, which is more conservative than the alternative per flight hour assumption.

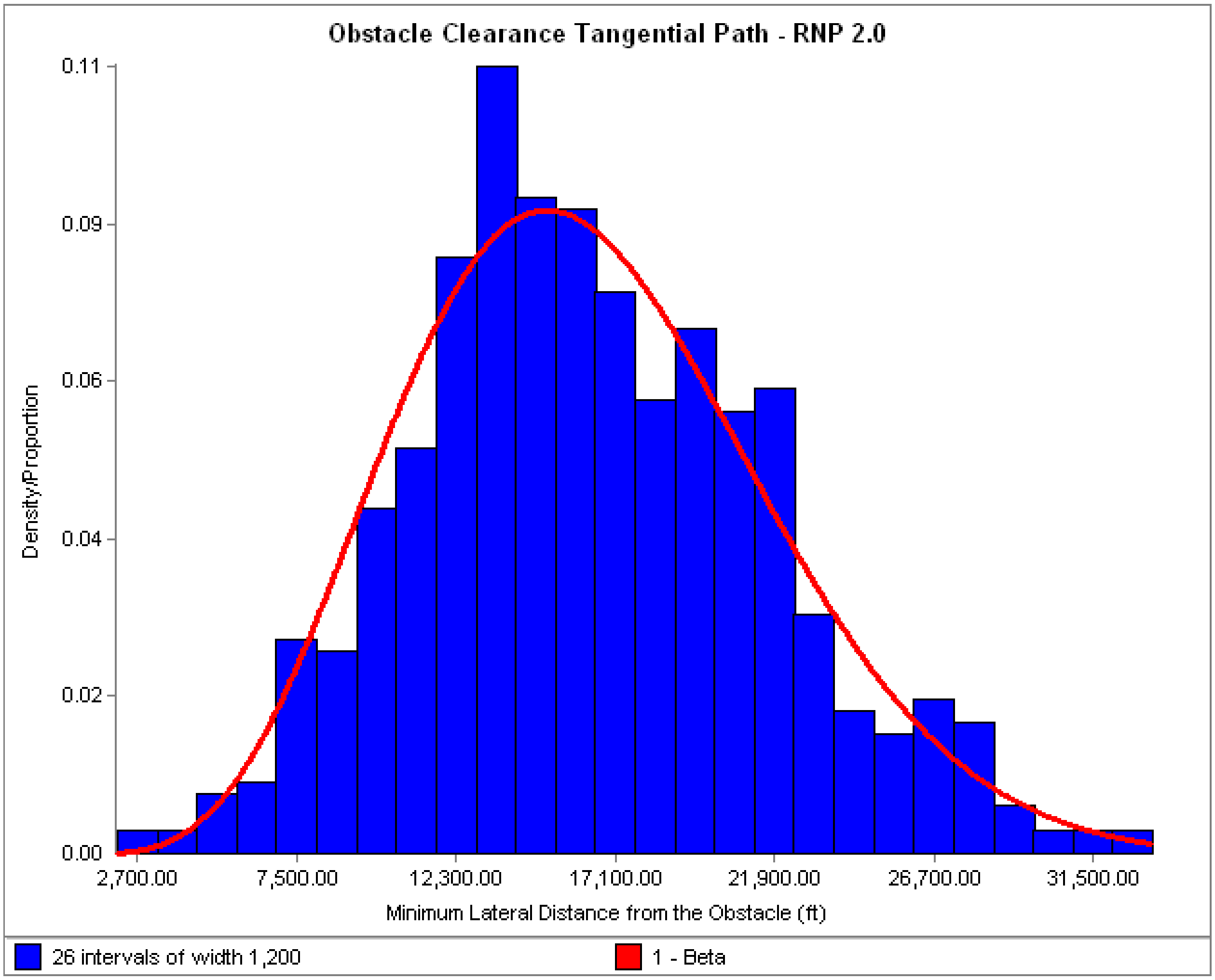


Figure 13: Scenario 1 Tangential Flight Obstacle Clearance Histogram

In Figure 14, sample tracks from Scenario 2a are shown for RNP 0.3 aircraft flying a procedure head-on toward an obstacle with a 90^{o} turn at a waypoint whose protected area is placed to abut the edge of the obstacle's protected boundary. Note that this procedure is not dependent directly upon surveillance performance / accuracy or controller intervention.

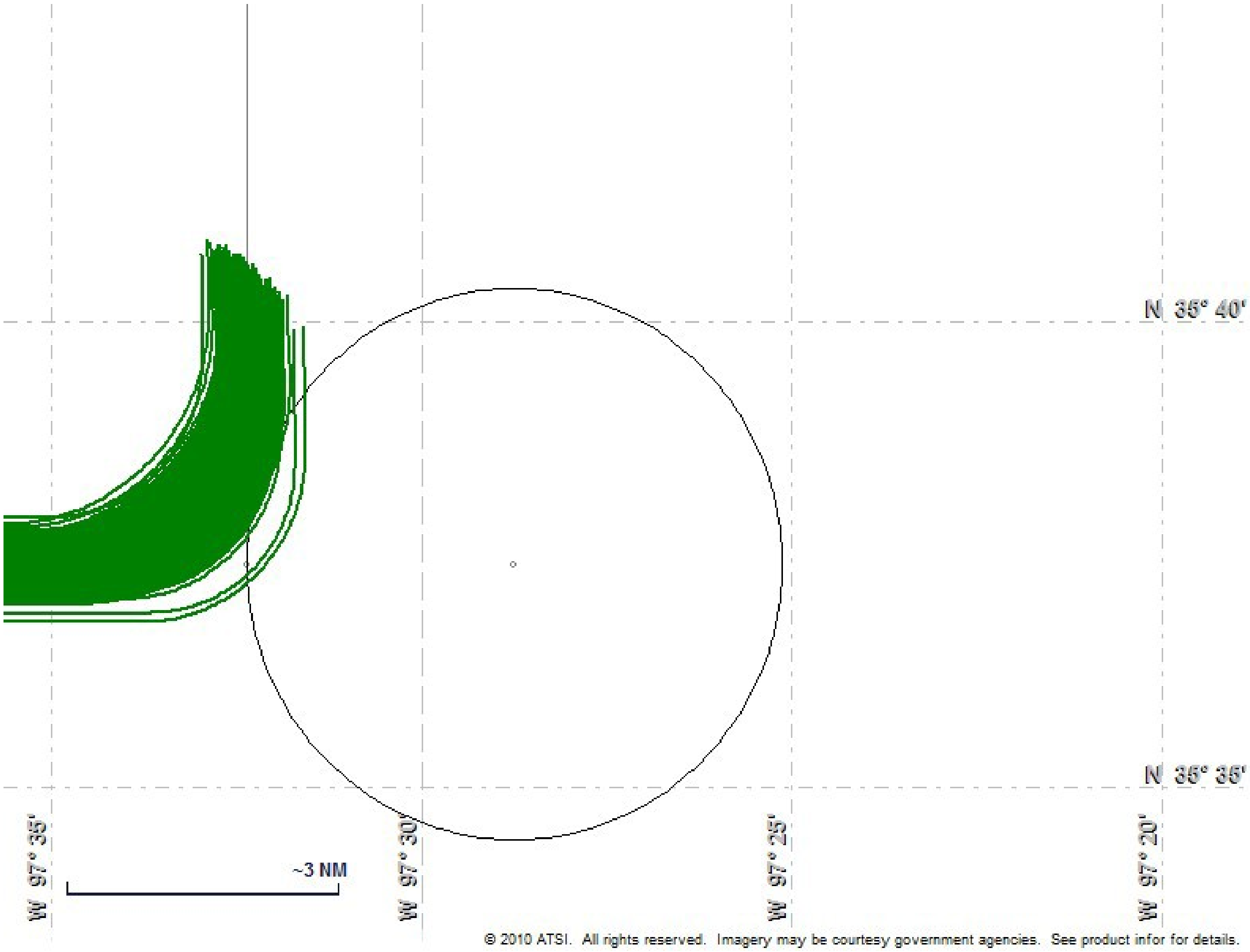


Figure 14: Scenario 2a Turning Flight At Obstacle Clearance Boundary – RNP 0.3

Data was collected for the closest lateral distance between the obstacle and the aircraft for each of 748,595 flights. This data was then fit to a Normal distribution using ExpertFit software as shown in Figure 15. The TCV rate computed for this operation, using a 500' TCV is estimated to be 3.89×10^{-48}, which exceeds the current Target Level of Safety specified for SMS of 1×10^{-9} per operation.

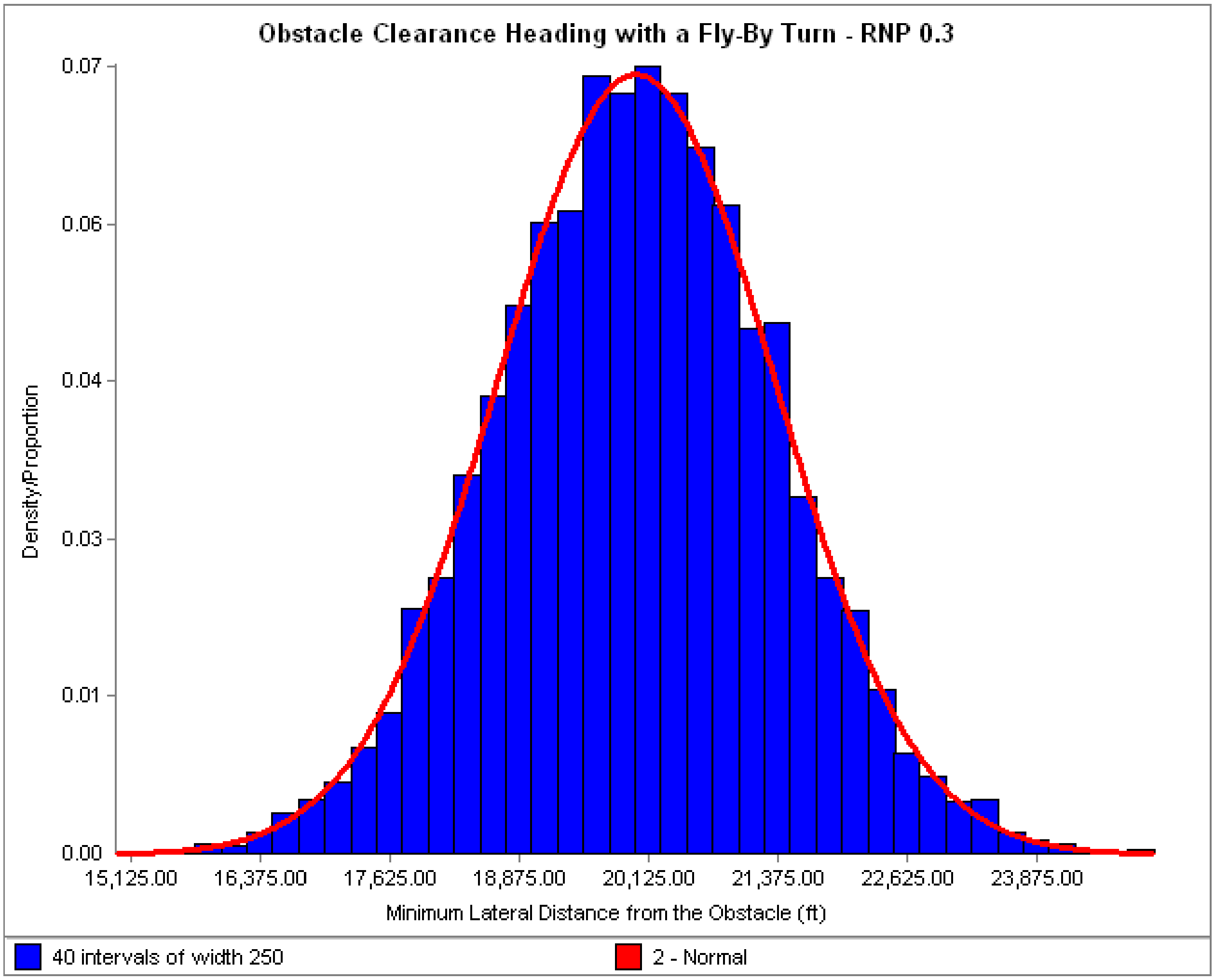


Figure 15: Scenario 2a Turning Flight At Obstacle Clearance Boundary (RNP 0.3) Histogram

In Figure 16, sample tracks from Scenario 2b are shown for RNP 2.0 aircraft flying a procedure head-on toward an obstacle with a 90° turn at a waypoint whose protected area is placed to abut the edge of the obstacle's protected boundary. Note that this procedure is not dependent directly upon surveillance performance / accuracy or controller intervention.

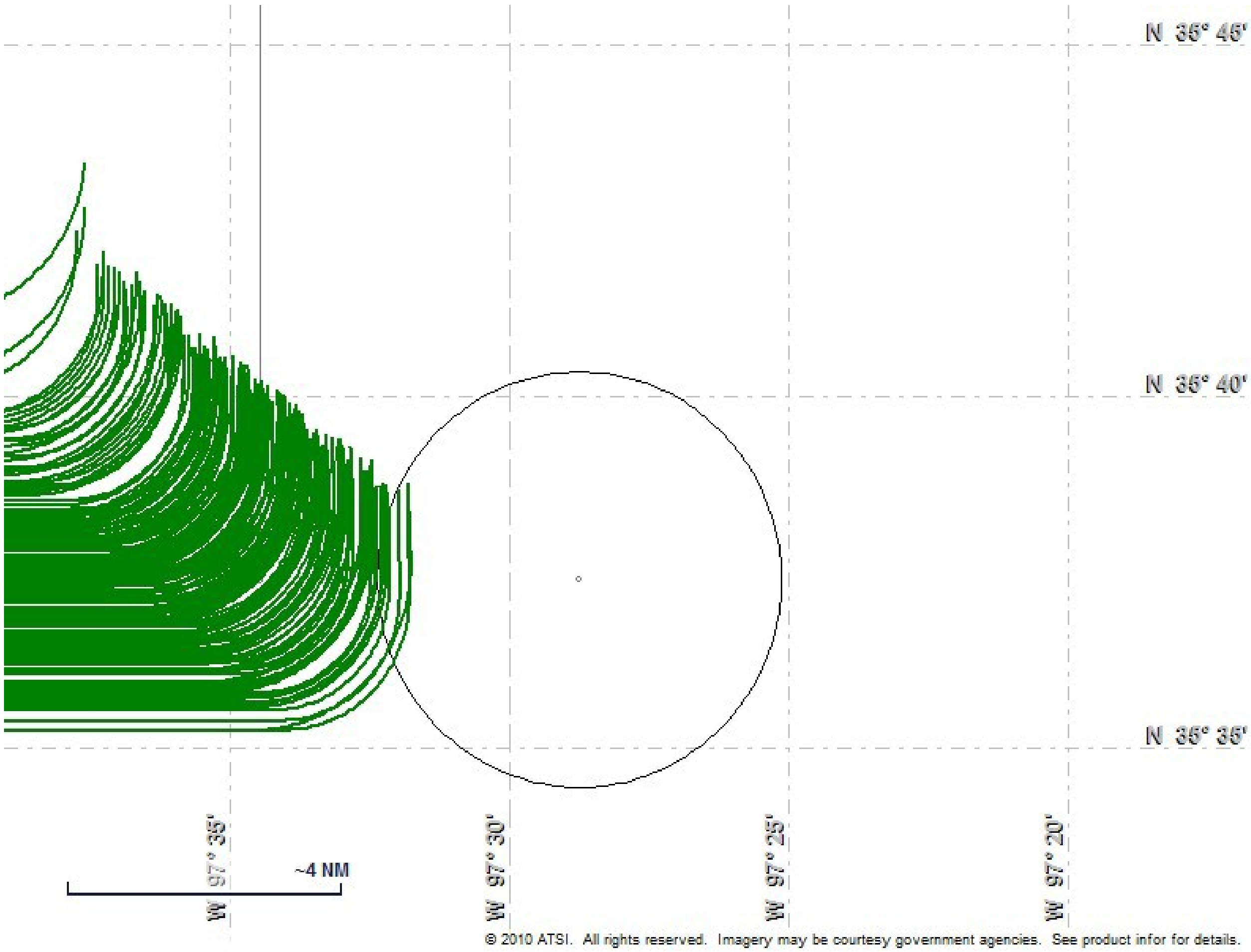


Figure 16: Scenario 2b Turning Flight At Obstacle Clearance Boundary – RNP 2.0

Data was collected for the closest lateral distance between the obstacle and the aircraft for each of 434,039 flights. This data was then fit to a Beta distribution using ExpertFit software as shown in Figure 17. The TCV rate computed for this operation, using a 500’ TCV is estimated to be $1.6x10^{-8}$, which does not appear to meet the current Target Level of Safety specified for SMS of $1x10^{-9}$ per operation. However, this type of nominal operation is thought to occur on an infrequent basis in the NAS, such that when the fact that less than one out of every thousand operations performed in the NAS are thought to be represented by this nominal case, and particularly by an aircraft performing at this degraded level of navigation performance, the $1.6x10^{-8}$ becomes $1.6x10^{-11}$ per operation, which exceeds the TLS requirement specified in SMS.

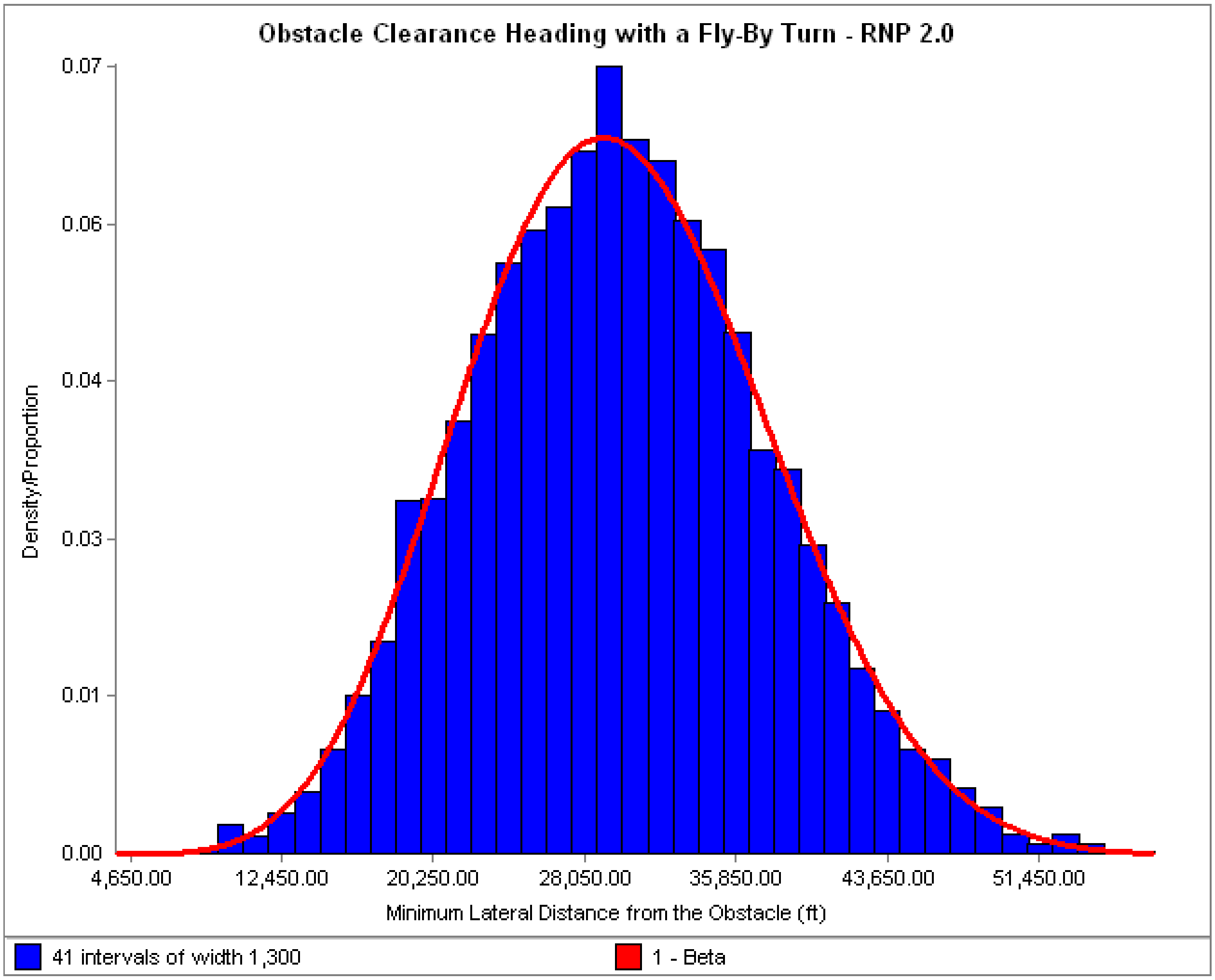


Figure 17: Scenario 2b Turning Flight At Obstacle Clearance Boundary (RNP 2.0) Histogram

Provided that:

- The Terminal NAS Automation Platforms that reduce the Obstruction Clearance based upon this study use Digital Radar Video Maps with a minimum display resolution of 2048x2048 pixels, and
- Include an alignment procedure that is accomplished at a resolution such that the width of each pixel will not represent a distance exceeding 150’, and
- Will contain Beacon PARROT / CPME location adapted to monitor the health of the surveillance sensors used to monitor the aircraft flying in the vicinity of the obstacles in the Terminal Automation Platform, and
- The azimuth tolerance for these locations is not allowed to drift by more than +/- 1 ACP (2 ACPs total error), without generating an alarm to the Air Traffic Controller, and
- All obstacles within the volume of airspace using the reduced separation minimum from obstruction of 3 NM are surveyed to an accuracy code of at least a Category 5 (or 500’), and

- That the surveillance sensor in use is an ASR-9 with Mode S, beacon data from an ASR-11 or of equivalent performance in all of the critical areas listed earlier in this document to these systems, to include probability of detection, target resolution, update rate, etc…, and
- That the aircraft and obstruction are both within the coverage volume of the radar and within 60 NM of the antenna of the reporting radar.

All scenarios tested appear to surpass the Target Level of Safety, and thus reducing the clearance from obstructions for these sensors to a minimum separation distance of 3 NM, under these conditions is not expected to incur an unacceptable level of risk to the NAS.

3.8 Minimum Separation from Adjacent Airspace

The Minimum Separation from Adjacent Airspace, as described in JO 7110.65R, paragraph 5-5-10 has two separate cases that will be addressed. The first case to be considered is for radar-controlled aircraft separation from adjacent airspace where radar separation is being applied, where there has been no coordination between the controllers. For this case, the primary concern is to maintain half of the minimum allowable separation standard from the adjacent airspace. In this way, it would be ensured that each aircraft pair, even when located in different, adjacent airspace would still maintain at least the minimum separation standard. The ASR-9 with Mode S and the beacon targets from an ASR-11 should be allowed to use one-half of their recommended aircraft-to-aircraft minimum separation standard of 3 NM for this purpose, for aircraft within a 60 NM radius of the antenna, or 1 ½ NM minima.

The second case is separating radar-controlled aircraft from the boundary of airspace in which non-radar separation is being used. For this case the primary concern is to ensure that the aircraft maintain the full buffer provided by the minimum separation standard inside the radar-controlled airspace, to isolate the risk posed by the larger errors expected from non-radar airspace. The ASR-9 with Mode S and the beacon targets from an ASR-11 should be allowed to use their recommended aircraft-to-aircraft minimum separation standard of 3 NM for this purpose, for aircraft within a 60 NM radius of the antenna.

3.9 Edge of Scope Separation

The Minimum Separation from Edge of Scope, as described in JO 7110.65R, paragraph 5-5-11 sets criteria for separating radar-controlled aircraft climbing or descending through the altitude of an aircraft that has been tracked to the edge of scope until non-radar separation has been established. For this case the primary concern is to ensure that the aircraft maintain the full buffer provided by the minimum separation standard inside the radar-controlled airspace, to isolate the risk posed by the larger errors expected from non-radar airspace. The ASR-9 with Mode S and the beacon targets from an ASR-11 should be allowed to use their recommended aircraft-to-aircraft minimum separation standard of 3 NM for this purpose, for aircraft within a 60 NM radius of the antenna.

4.0 Conclusion

The Terminal Airspace Organization, AJT-22, has requested analytical support from the Flight Systems Laboratory, AFS-450, to re-examine the separation standards that are applicable to terminal use of the ASR-11. This study is to include, but will not be limited to: target separation, target resolution, vertical application, rules on the use of passing and diverging, the minimum separation from obstructions, minimum separation from adjacent airspace, and, if applicable, edge of scope separation. The performance of the ASR-11, with its suggested usage and any associated criteria for this usage, will be compared against the performance of similar systems that are allowed to be used in a like manner today. The comparison is from a safety aspect in order to facilitate the Safety Management System (SMS) process applicable to the Air Traffic Organization (ATO).

Increasing the usability of the existing installed infrastructure provided by the ASR-11 could increase the efficiency of the NAS at a very low cost to the FAA, if the performance can be proven equivalent or better than that provided by the existing systems allowed to use the Terminal Separation Standard at these increased ranges.

Current FAA Standards, as per FAA Order JO 7110.65, paragraph 5-5-4, Radar Separation Minima for Broadband Radar Systems or Digital Terminal Automation Systems, permit the use of Terminal Area Separation Minima of 3 NM when using a Air Surveillance Radar-11 (ASR-11) surveillance radar (which contains a Monopulse Secondary Surveillance Radar or MSSR) within a 40 NM radius of the radar antenna. This is in contrast to a similar system, specifically the ASR-9 with a Mode S, which is allowed as per the same paragraph in the order to apply Terminal Area Separation Minima of 3 NM out to a range of 60 NM from its' antenna. This study shows that performance of the ASR-11 Monopulse Secondary Surveillance (Beacon) System (MSSR) is equivalent to the performance of an ASR-9 with Mode S. Thus, the limitations that have been placed on the ASR-11 are unnecessarily restrictive for properly performing transponder equipped aircraft. Allowing the use of the Terminal Separation Standard Minima of 3 NM for these aircraft, at ranges from the radar of up to 60 NM from the sensor antenna, should incur no greater risk or hazard than the currently allowed application of the 3NM Separation Standard Minima for the ASR-9 with Mode S. This study also investigated using a 3 NM Separation Standard Minima for aircraft with search-only data reports (non-beacon equipped or performing). The data that was collected and processed for this purpose for the ASR-11 primary radar did not yield definitive comparability to the performance of the ASR-9 primary radar. It is therefore recommended that the current practice of requiring a 5 NM Minimum Separation Standard be continued for search-only targets whose range is reported to be greater than 40 NM from the reporting ASR-11 sensor antenna, and that 3 NM be utilized as the minimum separation standard for properly performing and equipped aircraft that are travelling within a 60 NM radius of the ASR-11, whose beacon data is being output from the sensor.

Overall, the ASR-11 MSSR Beacon performed in an equivalent manner to the ASR-9 with Mode S, for all tested cases. The primary ASR-11 search radar could not be shown to have equivalent performance due to known problems with false alarm rate and target resolution. The portion of the study that examined clearance from obstructions for the ASR-11 beacon data could not use a comparative approach, since there was no formal study to assess the ability of the ASR-9 with Mode S to be used in this manner. This study shows that, if the conditions at the end of Section 3.7 are met, using a 3 NM clearance from obstructions for properly transponder equipped and performing aircraft, should incur no additional risk to the NAS, for the ASR-11 or the ASR-9 with Mode S.

Appendix A: Comparison of ASR-9 and ASR-11 Radar Azimuth Error Report from MIT/LL

Comparison of ASR-11 and ASR-9 Surveillance Radar Azimuth Error through Analysis of Targets of Opportunity Data

Colin Mayer and Dr. Panos Tzanos, MIT Lincoln Laboratory

Introduction

The radar systems discussed in this paper consist of primary radar with co-located beacon interrogators, referred to as Monopulse Secondary Surveillance Radar (MSSR). This analysis evaluates the performance of the beacon systems, and does not consider the performance of the primary radar. In this paper the terms ASR-11 and ASR-9 refer specifically and exclusively to the MSSR component of the radar system.

Current FAA regulation, Order JA 7110.65S 5-5-4, states that when using an ASR-11 with Monopulse Secondary Surveillance Radar, aircraft must be separated by a minimum of 3 nautical miles (NM) when less than 40 NM from the radar antenna and a minimum of 5 NM when 40 NM or more from the radar antenna. The same regulation extends the permitted use of 3 NM separation minima out to 60 NM for single sensor terminal systems using an ASR-9. The ASR-11 and the ASR-9 are similar monopulse systems therefore the 40 NM limit on terminal separation minima for the ASR-11 may be unnecessarily restrictive. Consequently, the FAA Flight Systems Laboratory, AFS-450, commissioned a study to evaluate ASR-11 performance and determine if the ASR-11 can support 3 NM separation minima at ranges of greater than 40 NM.

As part of this study, MIT Lincoln Laboratory was tasked with completing a large scale data analysis of ASR-11 performance. Lincoln Laboratory had previously developed an estimation algorithm that analyzes targets of opportunity data (radar reports without truth) to estimate radar azimuth error. This method enables analysis of large scale data sets without expensive flight tests. Lincoln Laboratory adopted a reference system approach that compares the performance of the new ASR-11 system, against the performance of the approved legacy ASR-9 system to determine if the ASR-11 performance is equivalent to or better than the approved legacy system. The following sections detail the analysis method, results and conclusions of Lincoln Laboratory's analysis.

Analysis Method

Estimating radar sensor azimuth error using data from targets of opportunity (TOO) requires the true location of the aircraft to be estimated from the source data. Lincoln Laboratory's method analyzes radar reports from aircraft traveling at nearly constant heading, velocity and altitude so it can utilize a priori knowledge of the aircraft behavior to accurately estimate true aircraft position.

Projection onto Stereographic Plane

Raw secondary radar data provides slant range (r), azimuth angle (θ), pressure altitude (alt), and time (t) information. Given TOO data that fits the assumption of flight at constant altitude, sequences of radar reports can be projected onto a stereographic plane. The location of the aircraft, as given by the radar, then can be considered to have (x, y, t) coordinates, instead of (r,θ ,alt,t).

Aircraft altitude is reported as Mode C pressure altitude from sea level on an average day, barometric pressure of 29.92 mm Hg. As local barometric pressure deviates from this standard, Mode C altitude reports become inaccurate. To ensure accurate position projections Mode C altitude reports are corrected to the true altitude using the local hourly barometric pressure and temperature.

Error Estimation Algorithm

The true trajectory of the aircraft is estimated as the line that best fits the data in a least-squares sense. An illustration of this procedure is shown in Fig. 1. To find the least-squares line, the algorithm finds the coefficients (a,b) that minimize the following distance metric:

$$\arg\min_{a,b} \sum_{i=1}^{m} [y_i - (a + bx_i)]^2 \qquad \textbf{(1)}$$

Where (x_i , y_i) is the x,y position of the aircraft at time t_i.

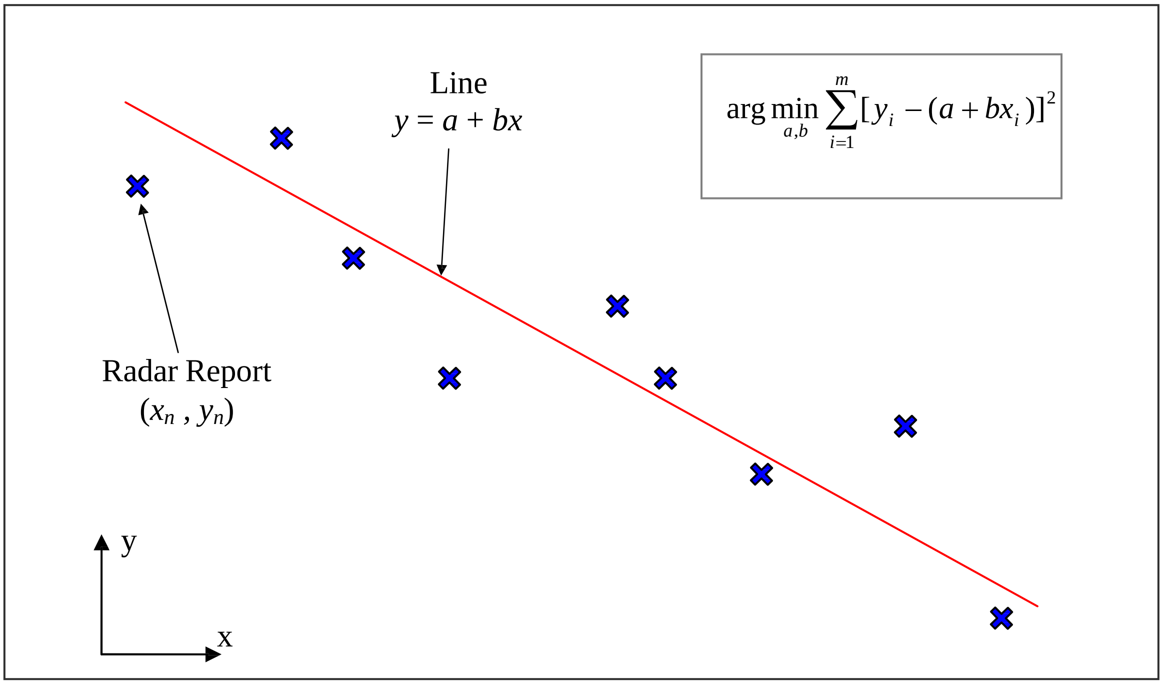


Figure 1: Least-squares best fit line

To estimate the true position of the aircraft at the time of each radar measurement, the algorithm finds the set of points (x'_i, y'_i) on the least-squares line that minimize the summed distance with the points (x_i, y_i), while the aircraft maintains a constant velocity v. More precisely, the following set:

$$\{(x'_i, y'_i) \mid \min_{x'_i, y'_i} \sum_i d_i, \frac{\sqrt{(x'_{i+1}-x'_i)^2+(y'_{i+1}-y'_i)^2}}{t'_{i+1}-t'_i} = v\} \qquad (2)$$

where d_i is the Euclidean distance between the points (x_i, y_i) and (x'_i, y'_i). This process is illustrated in Fig. 2. Note that this approach does not measure any bias effects and only measures random error characteristics.

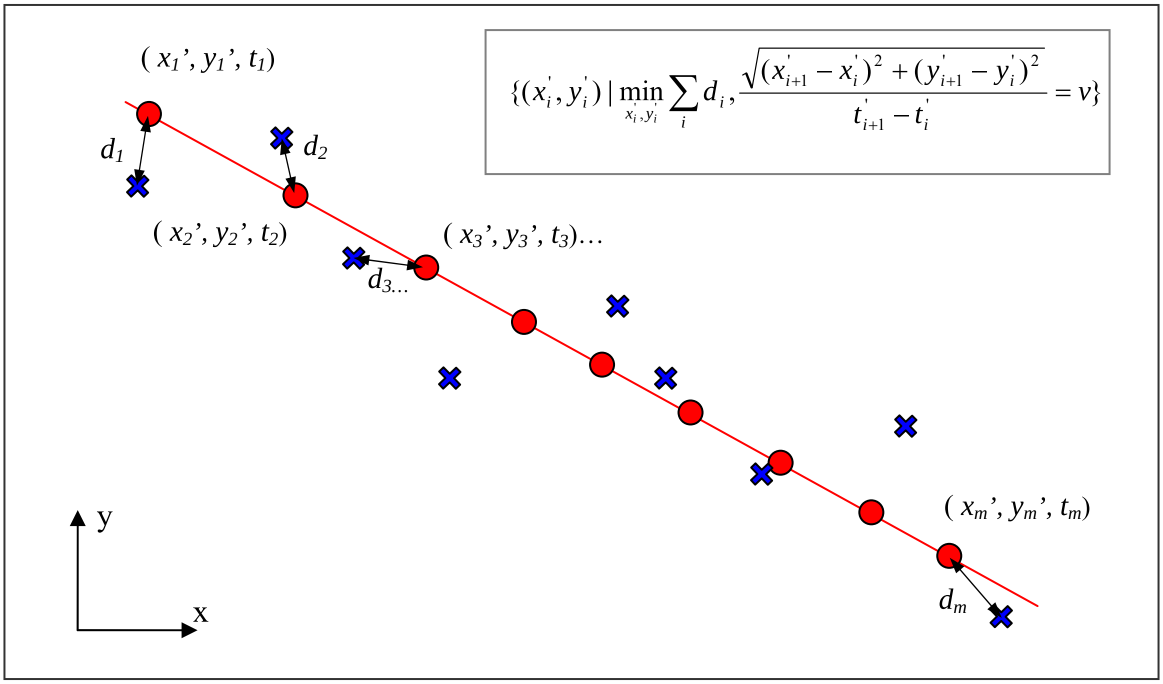


Figure 2: Sampling of estimated truth along best fit line

To calculate the radar azimuth error the set of estimated true positions (x_i', y_i') is converted into the radar coordinate systems (r, θ) and compared to the original radar reports. The estimated radar azimuth error for any given radar report is the difference between the radar reported azimuth and the estimated true azimuth.

Track Filtering Algorithm

A filtering algorithm was developed to complement the radar azimuth estimation technique by extracting tracks of straight and level flight at a constant velocity from large sets of data. Given a track of radar reports from a single sensor tracking a single aircraft, the algorithm returns the portions of the track (sub-tracks) where the aircraft was flying straight and level at a constant velocity. Straight and level flight at a constant velocity was assumed for sequences of radar reports where the calculated aircraft heading varied by no more than 2 degrees, the reported aircraft altitude varied by no more than 100 feet and the calculated aircraft groundspeed varied by no more than 30 knots.

Heading and groundspeed are not recorded in surveillance data and must be calculated from radar position reports. To calculate aircraft heading, the algorithm first smoothes the position reports using a using a locally weighted Gaussian kernel[1] smoother. It then calculates the instantaneous heading value (Eq. 3) for every report in the sequence. Finally, the calculated headings are smoothed and returned. To determine groundspeed, the algorithm calculates the instantaneous groundspeed (Eq. 4) for every report using the raw reported position. The algorithm removes any outliers and then smoothes the remaining calculated groundspeed values. Finally, the algorithm linearly interpolates the smoothed groundspeed values to the report times of the removed outliers to maintain the complete report sequence and returns all the values.

$$h(j) = \arctan\left(\frac{y_{j+1} - y_j}{x_{j+1} - x_j}\right) \quad \textbf{(3)}$$

$$v(j) = \frac{\sqrt{(y_{j+1} - y_j)^2 + (x_{j+1} - x_j)^2}}{t_{j+1} - t_j} \quad \textbf{(4)}$$

Once the heading and groundspeed values are calculated, the algorithm traverses the inputted track returning

[1] R.C. Gonzalez and R.E. Woods, "Digital Image Processing," 2nd Ed., Upper Saddle River, NJ: Prentice Hall, 2002

sequences of reports with minimum and maximum heading, groundspeed and altitude values within the corresponding thresholds.

The algorithm extracts all straight and level sub-tracks with unique starting points from a given track. Many tracks return overlapping sub-tracks and the results must be filtered to ensure a unique set of reports is returned. The algorithm employs a modified Floyd-Warshall algorithm[2] to determine the sequence of unique sub-tracks that contains the most reports. The Floyd-Warshall algorithm is a graph analysis algorithm that traditionally finds the shortest path in a weighted directed graph. For this application, it is modified to instead return the longest path. Sets of sub-tracks are stored as vertices in a graph with directional edges drawn between all non-overlapping sequential sub-tracks and weighted with the sequential sub-track's length (number of reports in the track). The modified Floyd-Warshall algorithm then processes the graph to determine the longest unique path. The longest path found is equivalent to the sequence of unique sub-tracks that contains the most reports.

Diagnostic plots can be generated for any track to verify the performance of the filtering method. An example set of diagnostic plots is shown in Figure 3. The left two plots and the top right plot offer a comprehensive view of the aircraft's position, while the bottom right plots show the smoothed calculated heading and groundspeed of the aircraft vs. time. The track in this example was filtered into two shorter sub-tracks of straight and level flight. The two sub-tracks can be seen highlighted in cyan and magenta in the position and altitude plots. It is apparent through comparison of the highlighted portions of the altitude plot and the heading plot that the straight sub-tracks correspond to the sections of flight when the aircraft follows a constant heading and altitude.

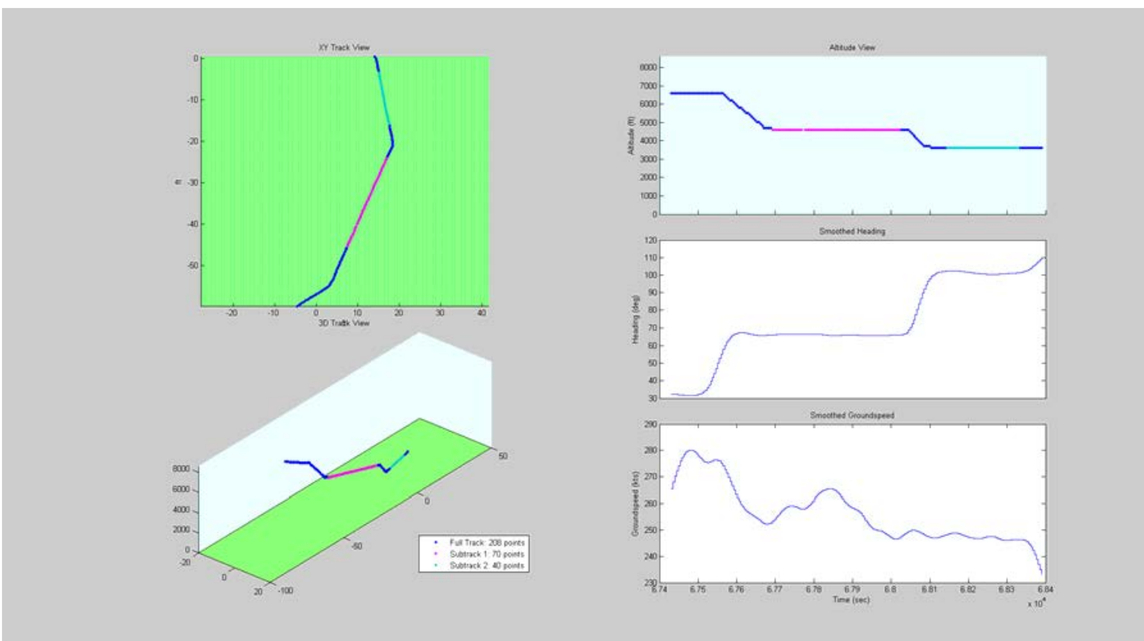


Figure 3: Straight track filtering algorithm

Validation

To validate the accuracy of the filtering and azimuth error estimation algorithms a large set of radar data with known truth was simulated. The data consisted of simulated radar reports from two different sensors with varying error characteristics. The first sensor was a traditional model of an ASR-9 with Gaussian azimuth jitter with zero mean and a 0.068 deg standard deviation. The second sensor was identical to the first, but the standard deviation of the azimuth jitter was increased to 0.08 deg. A total of 10,000 tracks were simulated for each sensor. The simulated

[2] T.H. Cormen, C.E. Leiserson, R.L. Rivest, and C. Stein, "Introduction to Algorithms," 2nd Ed., Cambridge, MA: The MIT Press, 2001

radar reports were then run through the filtering and estimation algorithms and the estimated azimuth error compared to the true (simulated) azimuth error. The results of the validation are shown in Figures 4 and 5. The blue bar graph represents the true (simulated) azimuth error distribution, while the red line represents the estimated azimuth error distribution. The standard deviation of each distribution is illustrated in the legend.

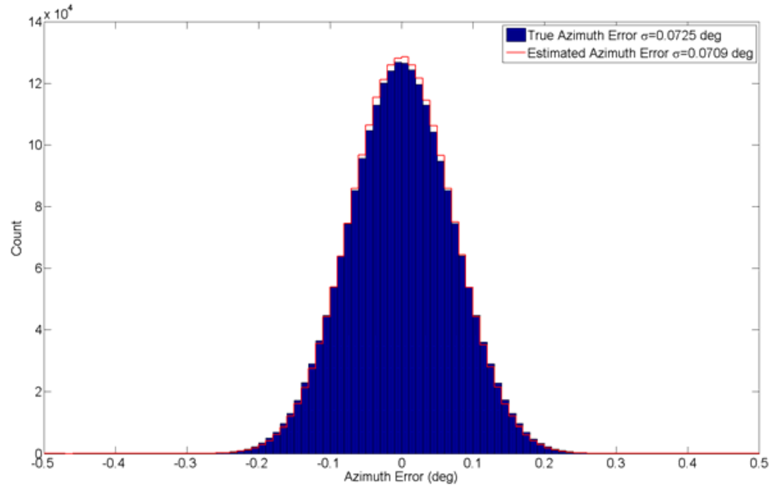


Figure 4: Validation results from simulated ASR-9 (σ = 0.068 deg)

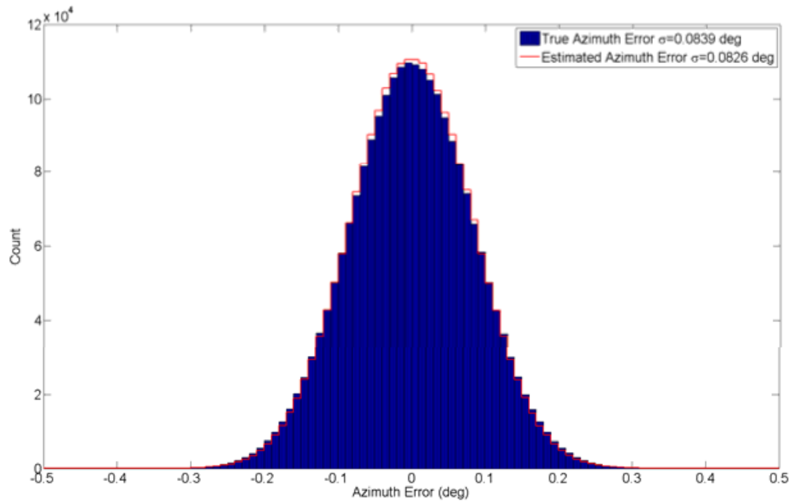


Figure 5: Validation results from simulated sensor with azimuth jitter σ = 0.08 deg

As depicted in Figures 4 and 5, the estimation algorithm accurately estimates both the size and shape of the azimuth jitter distribution for both sensor types. Additionally, it clearly distinguishes the slight differences in error characteristics between the two sensor types.

The following analysis looks at azimuth error dependence on range and elevation angle. To ensure the validity of those results, the algorithm performance must be shown to be independent of those factors. The plots in Figure 6 show the algorithm performance for the analysis of the simulated ASR-9 broken down by report range and elevation angle. The sensor model did not include any range or elevation angle dependence, so the distributions in each sub-plot look very similar.

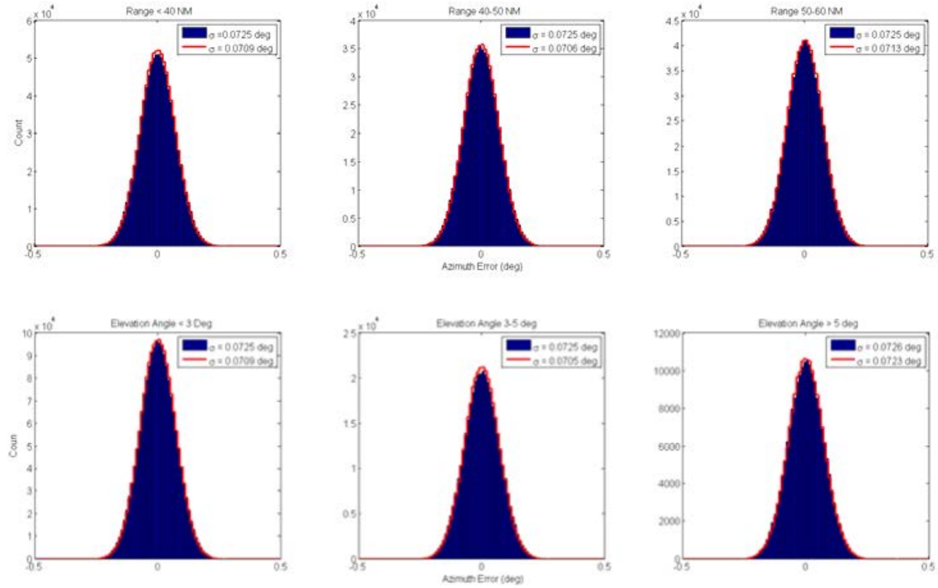


Figure 6: Range/elevation angle independence validation for simulated ASR-9 (σ = 0.068 deg)

The algorithm performance shows no dependence on range or elevation angle and can be used to estimate the azimuth error dependence on those same factors.

Analysis Results

Analysis was conducted on a collection of radar data supplied by the 84th Radar Evaluation Squadron (RADES). The data set consisted of 14 days of radar data from February 28th to March 13th, 2009. The local weather data needed for Mode C altitude correction was incomplete on some days. Data from radar without weather data on those days were not included in the analysis. Radar reinforced beacon reports were collected from a total of 16 different radar; 8 ASR-9 and 8 ASR-11. Table 1 lists the ASR-9 and ASR-11 sensors chosen for the analysis. The radar reports are analyzed and stored in a database using an automated process. Radar azimuth errors were calculated for all reports from ASR-11 sensors and for all monopulse reports from ASR-9 sensors. A total of 8,588,036 radar reports were analyzed; 4,334,946 from ASR-9 sensors and 4,253,090 from ASR-11 sensors.

Table 1: ASR-9 and ASR-11 radar sites

ASR-9	
Site Name	**Radar ID**
Baltimore (BWI)	BWI
Chicago OHare Intl	ORD
Logan Intl (Boston)	BOS
Los Angeles Intl - North	LAX
Manchester	MHT
New York (JFK)	JFK
Newark	EWR

ASR-11	
Site Name	**Radar ID**
Colorado Springs	COS
Columbia MO	COU
Lafayette	LFT
Saginaw	MBS
Stockton	SCK
Waco	ACT
West Palm Beach	PBI

Azimuth Error Comparison

Figures 7 to 9 show the estimated azimuth error distributions for the ASR-9 and ASR-11 surveillance radars. Figure 7 shows the results from the full data set. Figure 8 shows the azimuth errors for the subset of reports 40 NM or less from the radar antenna, the ranges where 3 NM separation minima is permitted for the ASR-11. Figure 9 shows the azimuth error for the subset of reports 40 NM to 60 NM the radar antenna, the extended range at which 3 NM separation minima is permitted for the ASR-9 but not for the ASR-11. Each plot contains a CDF and PDF of the errors for both the ASR-9 and the ASR-11. The ASR-9 error PDF is represented by the light-blue histogram and the ASR-11 PDF is represented by the red outlined histogram. The ASR-9 error CDF is plotted as a blue line and the ASR-11 error CDF is plotted as a red line. The right y-axis refers to PDF density values, while the left y-axis refers to the CDF density values. The statistical standard deviations of the ASR-9 and ASR-11 distributions are recorded in the plot legend.

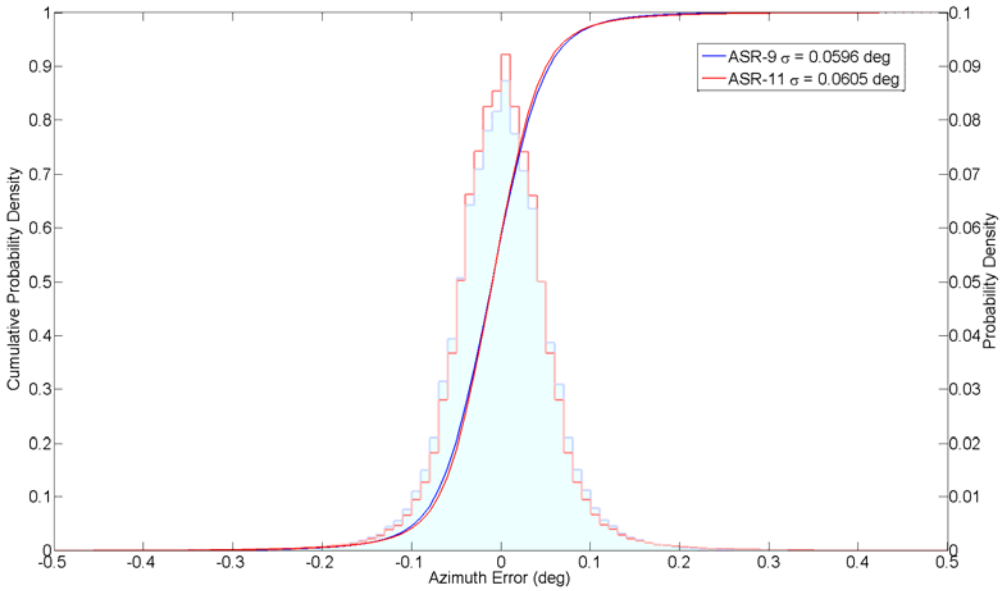


Figure 7: Estimated azimuth error distribution for ASR-9 and ASR-11 for reports 0-60 NM from the radar

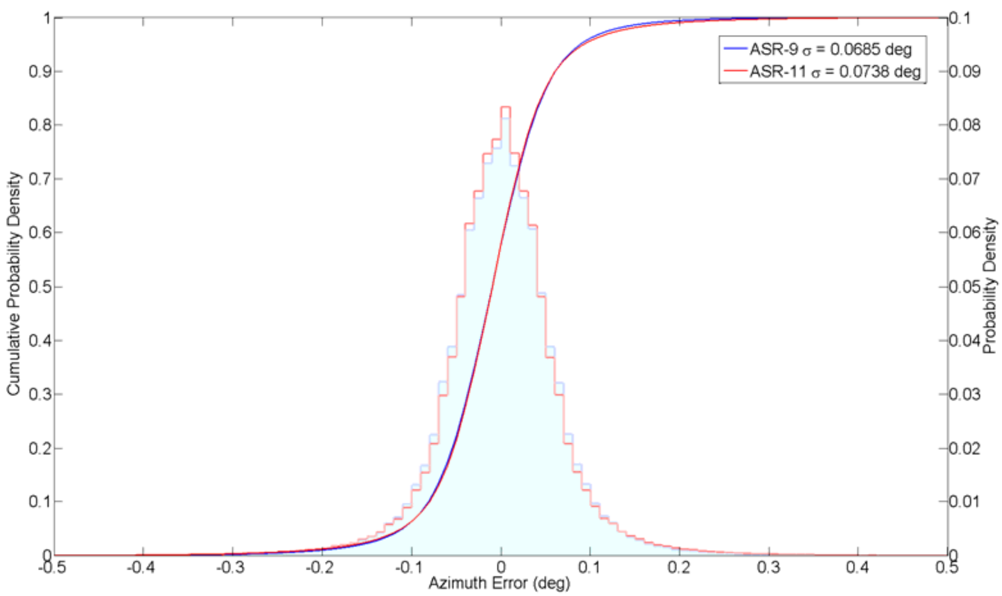


Figure 8: Estimated azimuth error distributions for ASR-9 and ASR-11 for reports less than 40 NM from the radar

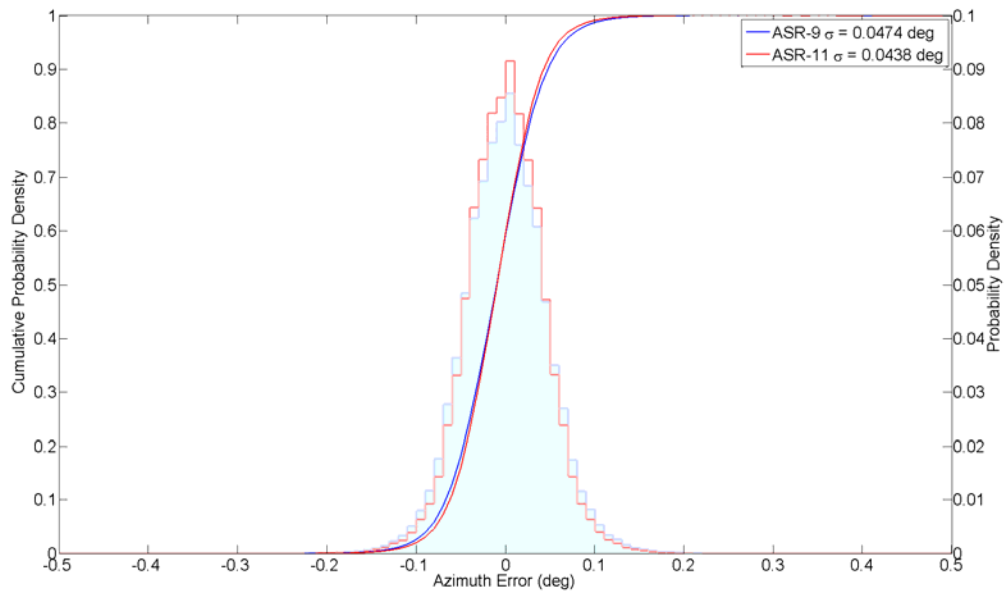


Figure 9: Estimated azimuth error distributions for ASR-9 and ASR-11 for reports 40-60 NM from the radar

Figure 10 plots the estimated azimuth error versus elevation angle for each sensor type.

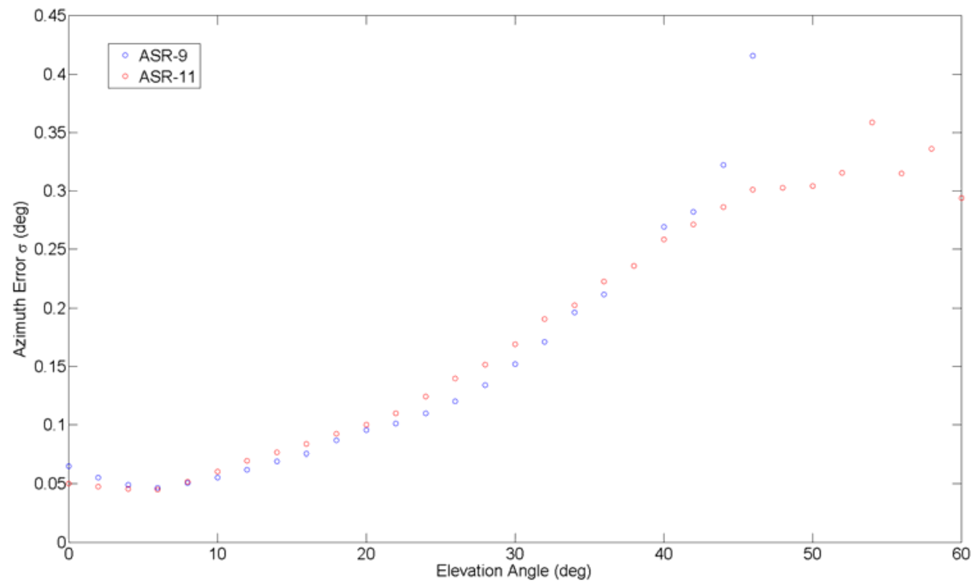


Figure 10: Estimated azimuth error vs. elevation angle

Figure 11 plots the estimated azimuth error as a function of range and altitude. The top plot contains the ASR-9 results, while the bottom plot contains results for the ASR-11. The x-axis represents the range of the targets and the y-axis the altitude of the targets. Dotted lines representing elevation angles are drawn on the plot for reference. The plots are broken down into cells 0.5 NM in range by 2,000 feet in altitude. Each cell is assigned a color corresponding to the magnitude of the standard deviation of the azimuth error of the reports in the cell. The colormap ranges from dark blue, representing small azimuth errors, to red, representing large azimuth errors (standard deviation of greater than 0.2 degrees). The colored cells are then interpolated to a finer resolution for a smoother image. The azimuth error value for each color is shown in the colorbar to the right of the plots. White-space represents areas where no target reports were recorded.

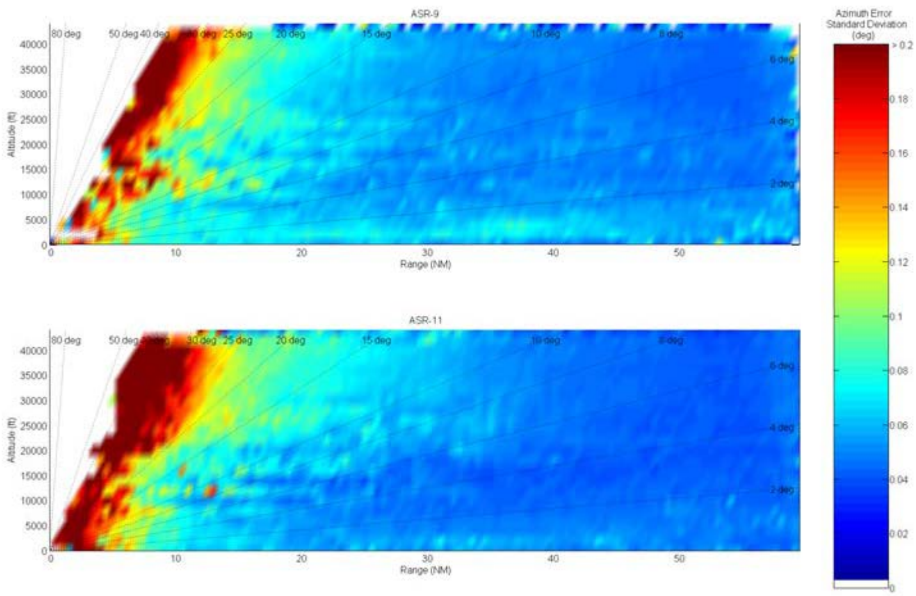


Figure 11: Estimated azimuth error vs. range and altitude

Figures 8 and 9 illustrate that the estimated azimuth error characteristics for the ASR-9 are nearly identical to those for the ASR-11. Most notably, ASR-11 azimuth errors for reports at ranges of 40 to 60 NM appear to be equivalent to the azimuth errors for the ASR-9 at the same ranges. This conclusion is reinforced in Figure 11, where the right halves of the ASR-9 and ASR-11 plots display the same error levels.

Figures 10 and 11 show azimuth error increases rapidly with elevation angle for both sensor types. This behavior is not unexpected as the monopulse tables used by both systems are calculated at low elevation angles, and may not be as accurate for reports received from higher elevation angles. The results are encouraging from an analysis perspective, as they demonstrate the analysis method capturing an expected degradation in performance.

The results show that for reports within 60 NM of the radar, elevation angle is the dominant factor in radar azimuth accuracy, while range and altitude have relatively little effect. Figure 8 shows both sensors having larger azimuth errors at short ranges compared to long ranges (Figure 9), but this behavior is an artifact of azimuth error dependence on elevation angle. Aircraft flying at the same altitudes will be at higher elevation angles relative to the sensors at short ranges than at long ranges, so subsequently the azimuth errors will be larger at short ranges.

Figures 10 and 11 show that for the data set analyzed, ASR-11 surveillance radar are capable of occasionally receiving reports at higher elevation angles than the ASR-9 surveillance radar. However, the number of reports received at high elevation angles (> 45 deg) by the ASR-11 was relatively small; roughly 3,500 out of 4,000,000 reports, and had minimal effect on the final results.

Data Characteristics

Figure 12 is similar to Figure 11, but illustrates the radar report density instead of azimuth error. It shows the spatial distribution of the ASR-9 and ASR-11 data sets. The plot shows very similar spatial distribution for the two data sets, with the vast majority of reports coming from aircraft flying at altitudes of 30,000 to 40,000 feet and elevation angles between 5 and 15 degrees.

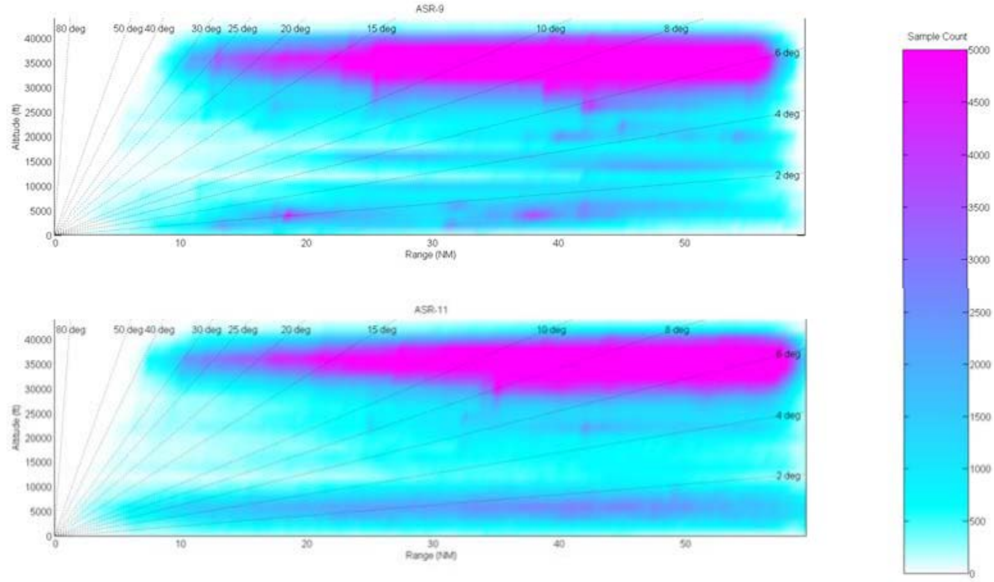


Figure 12: Spatial density plot

Figures 13 and 14 show azimuth error variation by sensor and date respectively. The plots are included to reinforce the consistency of the data and to show that no aberrant behavior from a single day or sensor influenced the results.

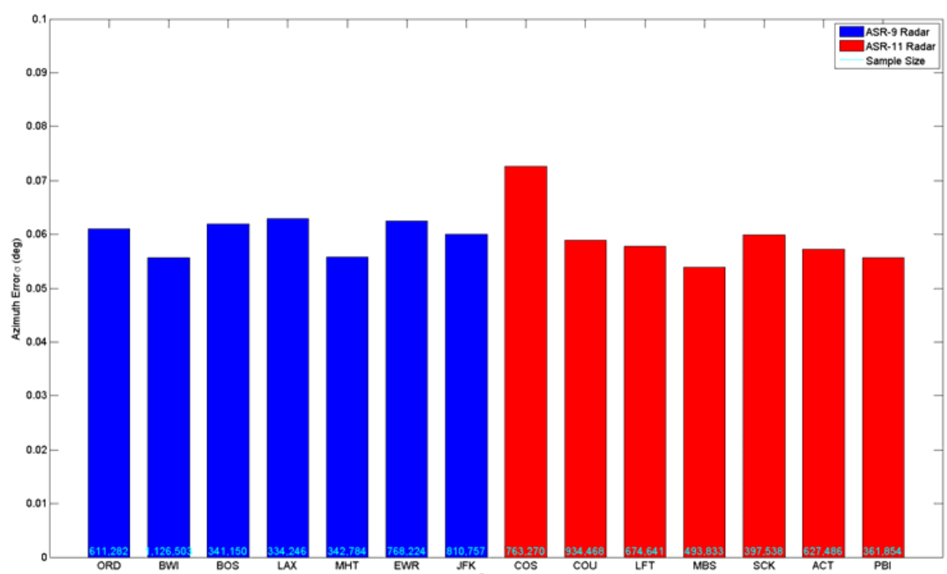


Figure 12: Azimuth error for individual radars

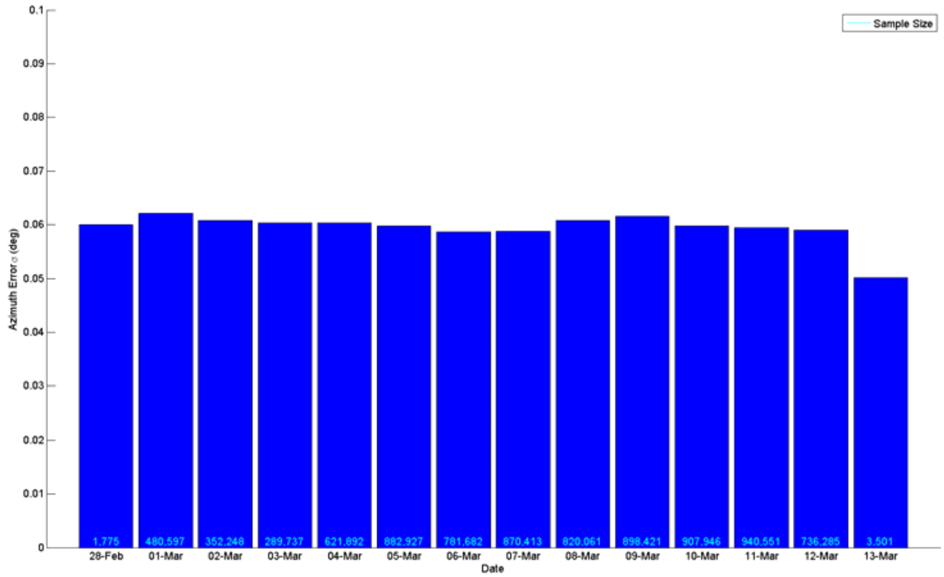


Figure 12: Azimuth error as a function of date

Conclusions

The estimated azimuth jitter for ASR-11 surveillance radar (σ = 0.0605 deg) is nearly identical to the estimated azimuth jitter for ASR-9 radar (σ = 0.0596 deg). In particular, for targets in the region of interest, 40 to 60 NM from the radar antenna, ASR-11 azimuth jitter (σ = 0.0438 deg) is equivalent to the ASR-9 azimuth jitter in the same region (σ = 0.0474 deg). The results of this analysis support the supposition that the 40 NM limit on 3 NM separation minima for ASR-11 surveillance radar is unnecessarily restrictive.

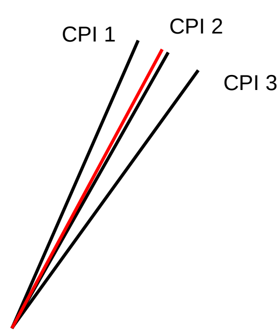
Appendix B: SRTQC Placement Paper – Preston Barber, AJW-14

SRTQC Placement

Questions regarding the accuracy of the SRTQC require some clarification and discussion. This paper is an attempt to describe how the SRTQC is reported in the ASR-11 and hopefully to address any azimuth reporting accuracy questions that may exist.

To discuss the accuracy error requirement (0.16^o rms) of the SRTQC we first must know where the SRTQC should be reported. To calculate this, we must discuss how the SRTQC is created.

The SRTQC is a soft test target and is defined in the customer adaptation data set. The user enters a range, in nmi, and azimuth, in degrees, for the software to generate the target. The ASR-11 has Coherent Processing Intervals of five pulses at four different PRFs that cycle through a sequence, but are 'free wheeling' (which basically means that the same CPI may not be at the exact same azimuth for every scan). The SRTQC is injected into three CPIs, the CPI immediately after the azimuth entered in the adaptation data, the next CPI after that, and the CPI immediately preceding the CPI after the azimuth entered into the adaptation data. To illustrate this the figure below represents the azimuth entered into the adaptation data in red, and the start of the three CPIs in black.



Since the ASR-11 uses four PRFs, the azimuth duration of each CPI will be different, so the total azimuth extent of the SRTQC will also vary. The four PRFs and azimuth durations for the PRFs are listed below.

PRF (Hz)	Interpulse Period (seconds)	5 Pulse (seconds)	Azimuth extent (degrees)	Azimuth extent (ACPs)
1008	0.000992063	0.004960317	0.37	4.23
757	0.001321004	0.00660502	0.50	5.64
898	0.001113586	0.005567929	0.42	4.75
694	0.001440922	0.007204611	0.54	6.15

For a target that exists for three CPIs, the targets total azimuth extent would be the summation of the three CPI azimuth extent. Since the ASR-11 cycles through the four PRFs, the target duration could be any one of four different CPI combinations (i.e. CPI 123, CPI 234, CPI 341, and CPI 412). The following table shows the azimuth durations for these CPI groupings.

CPIs	Duration (seconds)	Azimuth extent (degrees)	Azimuth extent (ACPs)
1 2 3	0.017133266	1.28	14.62
2 3 4	0.019377559	1.45	16.54
3 4 1	0.017732857	1.33	15.13
4 1 2	0.018769948	1.41	16.02

We will assume that the centroided azimuth for these targets is half of their total azimuth extent. Then to determine the reported position of the SRTQC, we can take the programmed azimuth, minus the first CPI duration for the CPI grouping used, plus half of the total target duration for the CPI grouping.

As an example, the Stockton SRTQC is programmed for 1.6 degrees, which is 18.2 ACPs. The following table lists the expected reported azimuths for the four CPI groupings.

CPIs	Duration (seconds)	CPI Previous Duration (seconds)	Expected Azimuth Position (ACPs)
1 2 3	0.017133266	0.004960317	21.28
2 3 4	0.019377559	0.00660502	20.83
3 4 1	0.017732857	0.005567929	21.01
4 1 2	0.018769948	0.007204611	20.06

The reported azimuths for the SRTQC should be approximately 20.75 degrees, assuming the CPI occurred immediately after the 18.2 ACP programmed value. Using this value for the expected position and calculating the rms error from a data sample taken in Stockton yields an error of 0.14 degrees, well within the specification limit.

Appendix C: DR033 Range Zero Investigation Report - Raytheon

Page 1 of 7

Raytheon Systems Limited Visit Report

DR033 Range Zero Investigation at ACY 28th June to 1st July 2010

Author: W. H. Menown.

Iss A released 9th July 2010, following review by G.A.Cowie.

Summary

The essence of DR033 is that the PSR reported Range position of the Flight Trial aircraft fell outside of the DASR specified limit by 5 feet, on the 14,000 feet inbound run of the Flight Trial. While the PSR Advanced Signal Data Processor (ASDP) showed improvement compared to the 27 foot error seen from the previous version SDP, an investigation report was raised as to why the PSR fell outside specification. The question of why the range aligNMent procedures allowed a bias of 157 feet to remain un-corrected was included in the investigation. The Radar bias hinges on the calibration at the MSSR, to get correct reported position.

Tom Healy's initial report included the following:

"6. Range Zero AligNMent in MSSR (based on cable length measurement at site)

A range zero misaligNMent in the MSSR could contribute to the range bias seen. The cable length from the RFCO on top of the MSSR cabinets to the LVA was measured. The cable length was 129 ft. The MSSR allows range zero aligNMent parameter settings in increments of 27 ft. It was discovered that the parameter setting in the ACY Condor MKII was 0x052F. Based on the measured cable length, it should have been 0x530. This small error (27 ft) does not account for the entire range bias seen in the accuracy analysis."

The measurement carried out recently at ACY for the allowance for the cable run from the Interrogator to the antenna agrees with Tom's assertion that 0x0530 should have been used . The difference of one SSR range gate (30 ft in AIR - 27ft in Cable) when aligning the PSR would have resulted in the PSR being aligned 30ft closer to the GPS position. When this is translated into the test results one can justify subtracting 30 ft from the PSR detections which will bring the PSR into specification.

Furthermore the range bias introduced by the MSSR verses the GPS range (consistent at 157 ft) is generated by the MSSR allowance of 3 microseconds (for TAD) verses the actual 3.2 microseconds at the King Air Transponder. If it is deemed the correct approach, the MSSR could make an allowance of 3.2 microseconds for TAD by a simple parameter change.

Instead of confirming an increasing change in the overall spread of Turn Around Delay from the ICAO standard of 3 μsec, the PSR Range Collimation aligNMent tool confirmed that the settings used for the Flight Trial were accurate, consistent and repeatable. This suggests that the majority of transponders have the same processing delay as the MRSM and the additional 0.2 μsec (98 feet) that has always been dismissed as a variation due to different transponders, should instead be removed as part of the MSSR Range Zero calibration.

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1 Test Plan

The investigation centred on agreeing the method of testing for the Transponder Turn Around delay and how it should be allowed for when calculating the true position of aircraft. Unfortunately, aircraft fitment of cables varies in length and the ICAO tolerance on the Turn Around Delay (TAD) at 0.5 µsec equate to 240 feet, so no attempt to compensate for the cables and variation in TAD has been made in the past. It remains unclear what cable length was between the Flight Trial King Air beacon antenna and its cable, but this factor may contribute to the difference between the MSSR and PSR measured ranges, especially if the cable dielectric constant is low and adds an unknown delay.

The radar site cable range offset is adjusted at the Interrogator Code Assembler in Range Units (IRU). A single RU is equivalent to 30.7 feet so the 157 feet range bias that is measured is about 5 RUs and checks are made to ensure everything ties up to within 4 RUs. It could not be established as to why the confidence check had such a large measurement error, given that most test equipment measurements can determine pulse rise times to 50 nsec. The tolerance of 62.5 nsec, due to a single RU clock uncertainty seemed to be a reasonable limit, so another 4 RUs could not be accounted for.

Various methods could be devised for measuring the time from the Interrogator generating the P3 rising edge to the first F1 pulse from a transponder. It was decided to explore these to get a measure of the errors involved.

Initially, the ACES Test equipment was used to generate a single report that could be timed on an oscilloscope to check the internal printing of the replies at the Interrogator from the Code Assemblers.

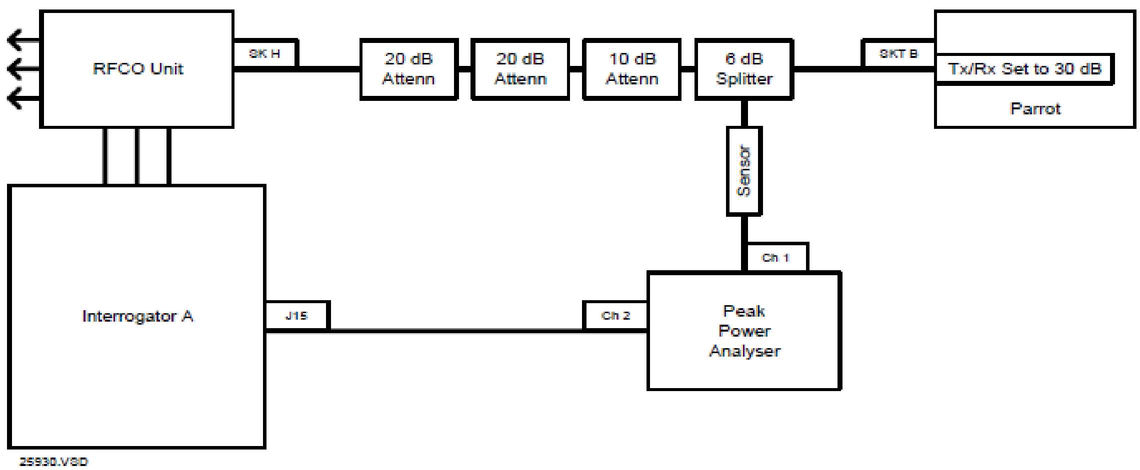

Figure 1 Turn Around Delay Measurement

The test configuration aim was to repeat that shown in the Figure 1 above. This has been copied from the SSR System Setting to work. The measurement could be reproduced by re-locating the MSSR Remote System Monitor (MRSM) from the Tech Centre to the same room as the Interrogator in Building 162. It was agreed that this would only be necessary if the ACES fixed target test could not expose the nature of the error in setting up the radar.

The MSSR range is adjusted to compensate for the cables from the Interrogator racks to the Antenna and was calculated to be 129 feet. The procedure then requires a cross-check, using the calibrated timing from a Ground fixed Transponder. The tolerance of the check is to within 122 feet. The cables at the ACY Test facility, so there was either a failure in the measurement procedure or in the assumptions of the cross-check, because a bias of 157 foot remained undetected before the Flight Trial was carried out. The problem facing the test team was that the Flight Trial aircraft, with its GPS positioning equipment, would not be made available to repeat the Flight trial again. Fundamental review of the setting-up procedure of the MSSR and the PSR was needed to explain the 157 foot error because it exceeds the cabling or propagation delays that could be allowed for.

The text in DR033 explains the calculations made from the Optimization Worksheet, and this had to be reviewed and repeated, to establish whether calculation errors had been made. Results are at Appendix A.Page 3 of 7

2 Initial Test Results

2.1 Calibration using the ACES.

The ACES scenario produced a single target at a delayed time of 30.6 μsec after the rising P3 pulse at the TX I/F Unit, 2.19NM. On the S300, with DP7 3 changed from 0527 to 0520, the report of 441 RUs was correct, supporting the work carried out for the RAF Lakenheath Range Zero checks. (R0-PRON.TML)
A repeat of measurements at the Mk2D with the ACES similarly produced the replies in the acceptable position.
Part of the problem with the test set up was the lack of accuracy that the Oscilloscope could provide. The tolerance of 0.1 μsec was considered excessive and the scope could not be relied upon to give the accuracy required. Furthermore it did not explain the error of about 0.02NM that had been seen with the MRSM.

2.2 Calibration with MRSM.

2.2.1 <u>MRSM set to Zero NM offset</u>

The Range Zero calculation at the Condor Mk2D Interrogator was repeated, but without the MRSM programmed range offset in place. The estimated effective cable length at the MRSM was 357 ft (i.e. 0.0588 NM).
Previously, the system had been set up with the delay set to 55 NMile, so:
Ro = Rd + Rc + Re = 55.0 NM + 0.0243 NM + 0.0588 NM = 55.0831 NMile
where Rd is the MRSM range delay, Rc is the MRSM TAD correction due to the response exceeding the expected 3 μsec by 0.3 μsec, and Re is the equivalent feeder cable length.
It had been established from tests at Harlow, that the MRSM delay could not be used in this formula. The delay of 55 NM translated to 54.984 NM according to the timing of the Interrogator in Air, producing an error of 0.0156 NM. Hence, the modified formula is:
Ro = Rc + Re = + 0.0243 NM + 0.0588 NM = 0.0831 NMile
The MRSM expected reported range Rr, should then be the same as the actual (physical distance between antennae) range, plus cables and TAD. Rp is the physical range calculation from the WGS84 measurements, was then calculated using the equation:
Rr = Rp + Ro = 1.0760 + 0.0831 = 1.1591 NM
It was suspected that the cabling offset at the Radar should have been increased by a RU, from DP7/8 3 =052F to 0530. Allowing for the Cable at the radar, the default setting of DP7/8 3 = 052B was increased by 1 RU to get the best MRSM reported range at the Interrogator. With the MRSM Range delay set to zero, the printed replies, with DP7/8 = 052C, were 234 RUs. (R0-SM1NM.TML)
This gave a reported range of 1.1834 NMile.
The difference between the reported and the predicted range was 0.0243 NMile too long.
The extra 0.0243 NMile in the reported range, when accurate Site Survey location is added to the MRSM Cabling calculation could not be explained. It was decided to remove the MRSM from the Tech Centre building and connect it direct to the Interrogator per the Figure 1 above.
On carrying out the tests in section 2.2.2 below, it was realised that if the Range Zero offset at the Interrogator was changed to allow for the 0.2 μsec time measured, then the calculation should not include the TAD of 0.3 μsec. However the cabling at the Interrogator to the LVA was 129 feet, which at 0.88 velocity factor, extends the effective cable to 147 feet. Then the calculated range becomes:
Rr = Rp + Ro = 1.0760 + 0.0588 = 1.1548 NM
The detected range would be 234, less 4 RUs for the cable to the LVA, less another 3 RUs for the 0.2 μsec Transponder response time discussed in Section 2.2.2. That would be 227 Rus or 1.148 NMile and close to the expected range.Page 4 of 7

2.2.2 MRSM checks at Building 162

Various problems occurred with trying to recreate a reliable test configuration that was similar to Figure 1 above. The replies could only be seen at the Interrogator Internal printing when the STC was disabled and the MRSM delay was set to 0.1NM.
Tests assuming that the pulses from the MRSM were triggered 3 µsec after the P3 pulse at the TX I/F Unit, confirmed that the default setting of the Mk2D were correct for no significant cabling. (R0-SM0-2.TML)
For example, at 4.52 µsec, the number of RUs to time the remaining 1.52 µsec, was 22 or 23, for a predicted number of 24.3. No measurable difference could be found between using the TX I/F Unit and the RF Couplers at the top of the rack. Only one Peak Power meter trace was used to display the forward and return pulses.
It was agreed that the tests carried out at Harlow, with the Mk2D and an MRSM, that concluded that the default parameter should have been a value of 0528, were wrong. The timing measurement tests had allowed for the Interrogator RX response, which is about 0.2 µsec. This has to be allowed for when calculating the timing of P3 to F1, as measured at the Top of the rack of the Interrogator, effectively at the Peak Power meter position as shown in Figure 1.

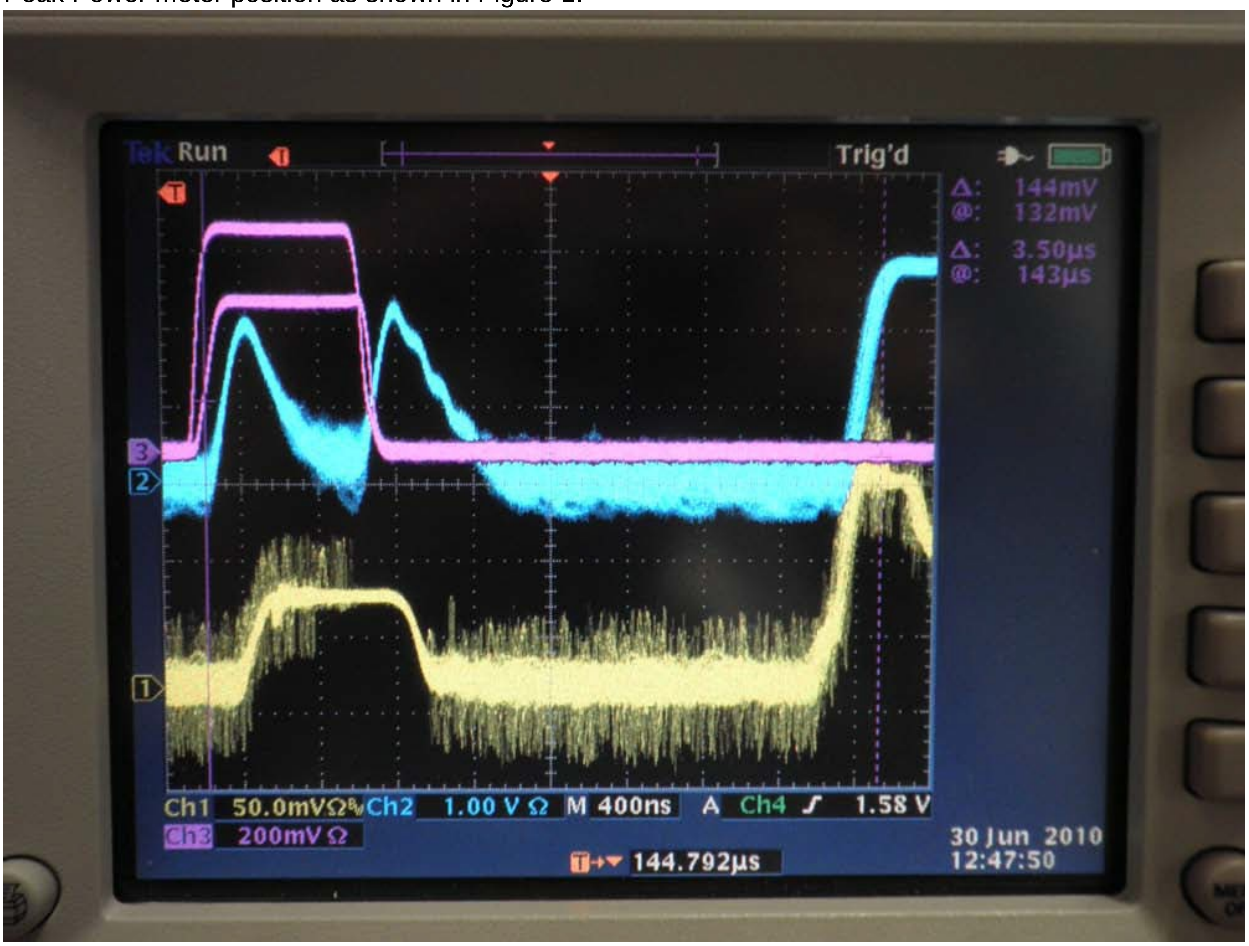

Figure 2 – P3 time to F1 with MRSM delayed to zero offset.

The output from the TX I/F Unit monitor was fed to a multi-beam oscilloscope as shown in Figure 2. By adjusting the loads between the TX I/F Unit and the MRSM, the pulses could be triggered from the system trigger and measured with the MRSM delay set to Zero NM again. The timing at the MRSM Transponder monitor point was fed to the oscilloscope. The delay was set to zero and the timing from the detected video of P3 to F1 was 3.06 µsec, but the time since P3 was sent was an extra 0.5 µsec, depending on timing of rising edges. It was realised that the missing 0.0243 NMile, was due to the 0.2 μsec delay between the transmission of P3 at the Interrogator and the time that it was detected at the MRSM transponder. The delay is due to the Transponder Receiver response and is comparable to the Interrogator Receiver response that was previously allowed for.


Run
Trig'd
Δ: 264mV
@: 388mV
Δ: 220ns
@: 143µs
Ch1 50.0mV
Ch2 1.00 V Ω
M 200ns
A Ch4 1.58 V
Ch3 200mV Ω
143.016µs
30 Jun 2010
12:47:03

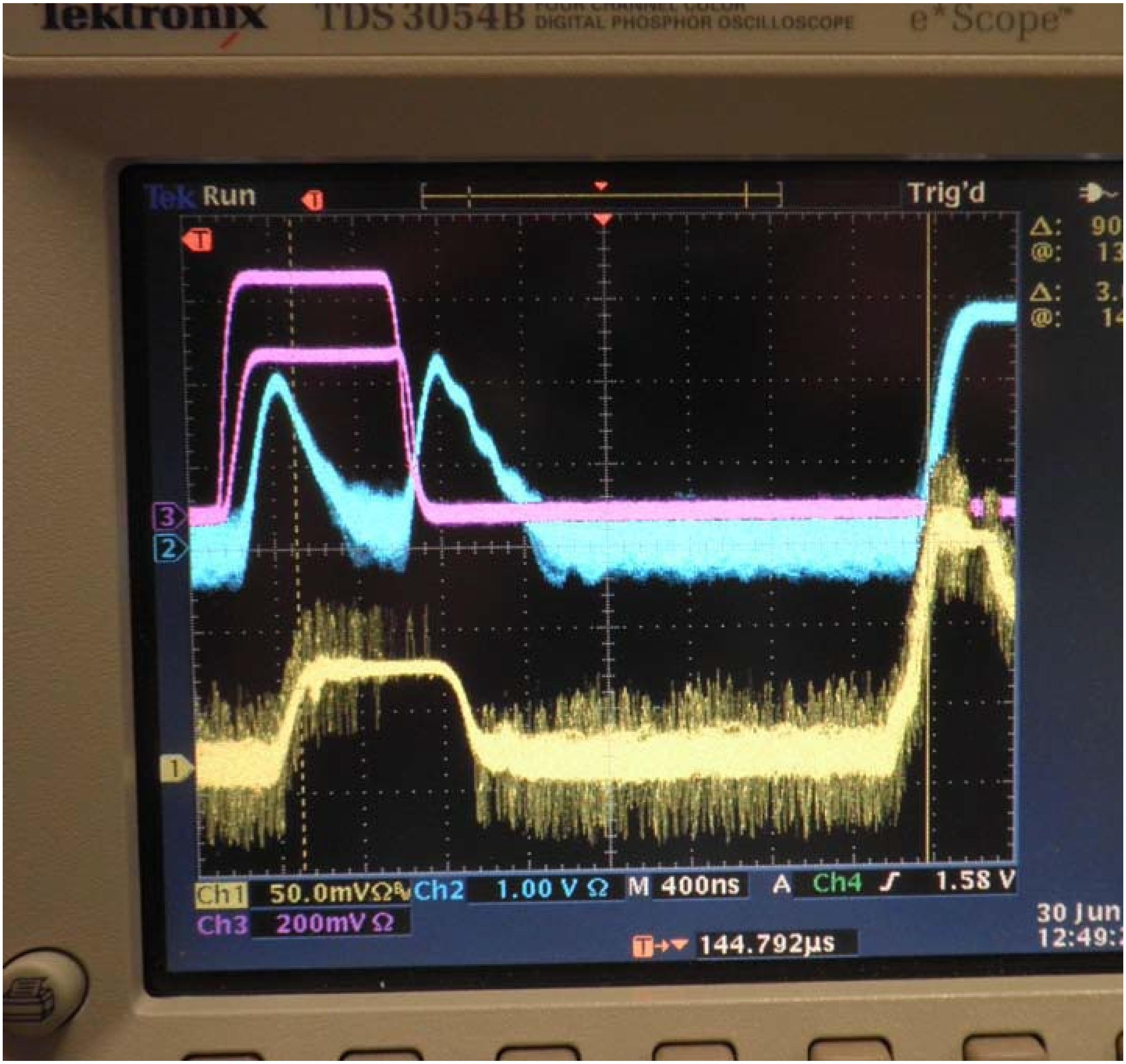
Tektronix TDS 3054B FOUR CHANNEL COLOR DIGITAL PHOSPHOR OSCILLOSCOPE e*Scope
Tek Run
Trig'd
Ch1 50.0mVΩ
Ch2 1.00 V Ω
M 400ns
A Ch4 1.58 V
Ch3 200mV Ω
144.792μs

Figure 3 – MRSM delayed to zero offset.Page 6 of 7

If the timing for the Transponder Receiver response is added to the range offset of the Interrogator, the position of the Transponder report is closer to the GPS position, and seems to be the correct thing to do. It still does not allow for the cabling in the airframe, but if this bias offset is added to the Range Zero calibration process, then the radar has better absolute range accuracy for the majority of targets.

2.2.3 Investigate rising edge due to Amplitude of detected Signal.

A brief investigation in to the possibility of the Amplitude of detected signals affecting the range was carried out. No detectable change in the reported range of the replies was seen when the MRSM was attenuated over a range of 40dB. The error contribution was therefore dismissed.

3 Future Work

The possibility of using ADS-B targets was discussed, but this is not a simple task and would need the TMD to be operating properly.

It may be possible to check the range of a target from one radar and check position of supported tracks at another. If the SCN could be set up between neighbouring radars, a target flying low between the radars may display the range error as Cat.17 reports from one radar.

The alternative is to study the display system for a range error. If it is not detectable at the display, then the error may not significant enough to merit further investigations.

A question as to why the MRSM transponder had been marked up with a TAD of 3.3 μsec needs to be answered by checks at the RSL Harlow Factory.Page 7 of 7

4 Appendix A - Range Conversion and Timing Calculations

The following is an extract from an Excell spreadsheet used to re-check the calculations. 1852	m equivalent of 1NM	6076	feet in 1NM
1.23552E-05	Cell A2=A1/F3*2	0.3048058	1 foot in metres
12.3552	µsec equiv of 1NM in Vacuum	299792548	m/s speed of light in Vacuum
12.3587	µsec equiv of 1NM in Air.	1.000282	Refractive Index of Air
1.23587E-05		Cell A2=A2*F4	
275		Range limit required of DASR System.	
0.026		Mean SSR to GPS Bias Error (NM) reported in DR033	
157.976		Mean SSR to GPS Bias Error (feet) reported in DR033	
0.0625	µsec equiv of 1RU in Air.	197.739113	RUs in 1NM
9.365871815		metre equiv of 1RU in Air.	
30.72734187		feet equiv of 1RU in Air.	
122.9093675		Limit of Range check (4*RU) in feet.	
0.25		Limit of Range check (4*RU) in µsec.	
0.2		µsec variation of TAD.	
98.32749399		feet equiv of 0.2usec TAD.	
5.1412192		Mean SSR to GPS Bias Error (RU) reported in DR033	
30.6		µsec timing from P3 of ACES target.	
441.6		RU timing from P3 of ACES target, (subtracted 3 µsec).	
2.233245582		NM timing from P3 of ACES target, (subtracted 3 µsec).	
55		NM delay added to MRSM	
679.536		µsec equiv of 55NM in Vacuum	
54.98442393		55NM in Air as timed by Software	
0.015576072		NM error due to MRSM offset.	
0.3		µsec Labelled MRSM effective TAD.	
0.024274398		NM equivalent of Labelled MRSM effective TAD.	
234		RUs reported at M2D with SMON delayed to 0NM. Effective physical + Cable delay.	
1.183377415		NMs reported at M2D with SMON delayed to 0NM. Effective physical + Cable delay.	
1.1591		NMs predicted from the Physical and the TAD and Cables.	
0.024277415			
1.52		µsec range equivalent of MRSM at 0.1NM when connected to Mk2D.	
0.122990282		NM range equivalent of MRSM at 0.1NM when connected to Mk2D.	
24.31998927		RU range equivalent of MRSM at 0.1NM when connected to Mk2D.	

Appendix ?: ASR-11 MSSR Standalone OT Results Memo – ASR-11 Program Office

ASR-11 MSSR Standalone OT Results Memo.pdf
Forwarded by Preston
SRTQC Placement
16_1_6Thompson
Final OT report 31oct03.pdf
Maybe the history, edited, if we need to create hierarchy for brevity…

Appendix C: Post-Run Questionnaire

Post-Run Questionnaire

1. In general, compare this approach to other, straight-in, ILS, approaches that you perform.

Easy			Moderate			Difficult		
1	2	3	4	5	6	7	8	9

2. Rate your level of comfort at the point of breaking out and transitioning from IMC to Visual conditions

Very Comfortable			Moderately Comfortable			Uncomfortable		
1	2	3	4	5	6	7	8	9