Capstone ADS-B Evaluation Report

(Interim)

December 15, 2000

AUA-650

Table Of Contents

1 Introduction

This evaluation was performed to show that Automatic Dependent Surveillance – Broadcast (ADS-B) position data are equal to or better than radar data for use by air traffic controllers as aircraft surveillance information. The evaluation is intended for use by FAA Flight Standards officials to authorize application of current radar based rules to provide radar like services to aircraft equipped to provide ADS-B position data.

2 Background

The FAA Alaskan Region's Project Capstone was developed to provide three of nine high priority Free Flight Operational Enhancements requested by the Radio Telecommunications Conference of America (RTCA). The three enhancements are:

Cost Effective Controlled Flight Into Terrain (CFIT) Avoidance
Enhanced See and Avoid
Flight Information Service (FIS)

As a part of Project Capstone, several commercial, government, and other aircraft based in or near the Bethel area of Alaska have been equipped, on a voluntary basis, with government-furnished avionics. Services provided through the avionics suite improve the pilot's situational awareness and broadcast aircraft position and velocity data to FAA air traffic controllers. The avionics include:

An IFR-certified GPS navigation receiver
Automatic Dependent Surveillance-Broadcast (ADS-B) Transceiver
A moving map display with TIS-B traffic and terrain advisory services
A Flight Information Service graphical display

A datalink network provides two-way data transfer between the Capstone aircraft and FAA air traffic control, service provider, and operator base facilities. A communications gateway processor at the Anchorage Air Route Traffic Control Center (ARTCC) routes ADS-B messages to the Microprocessor Enroute Automated Radar Tracking System (Micro-EARTS). The Micro-EARTS fuses the ADS-B data with radar data and presents a composite air traffic display to the air traffic controllers. This is depicted in Figure 1.

GPS non-precision instrument approach procedures have been published for several urban and village airports in or near Bethel, Alaska. The ADS-B data provided to the Anchorage ARTCC air traffic controllers will allow monitoring of the GPS approaches.

A letter from the FAA Administrator on January 3, 2000 set a goal of January 1, 2001 for providing radar like service for Capstone equipped aircraft in and around the Bethel area. In order to provide this service, a determination must be made whether ADS-B data can be used as an acceptable surveillance information source.

In June, 2000 FAA Air Traffic Procedures personnel requested that FAA Flight Standards officials provide approval for the use of Capstone ADS-B position data as surveillance information. FAA Flight Standards officials requested that the FAA Micro-EARTS

Product Team (IPT) perform an assessment to determine whether Capstone ADS-B data are equal to or better than radar data for use as air traffic surveillance information.

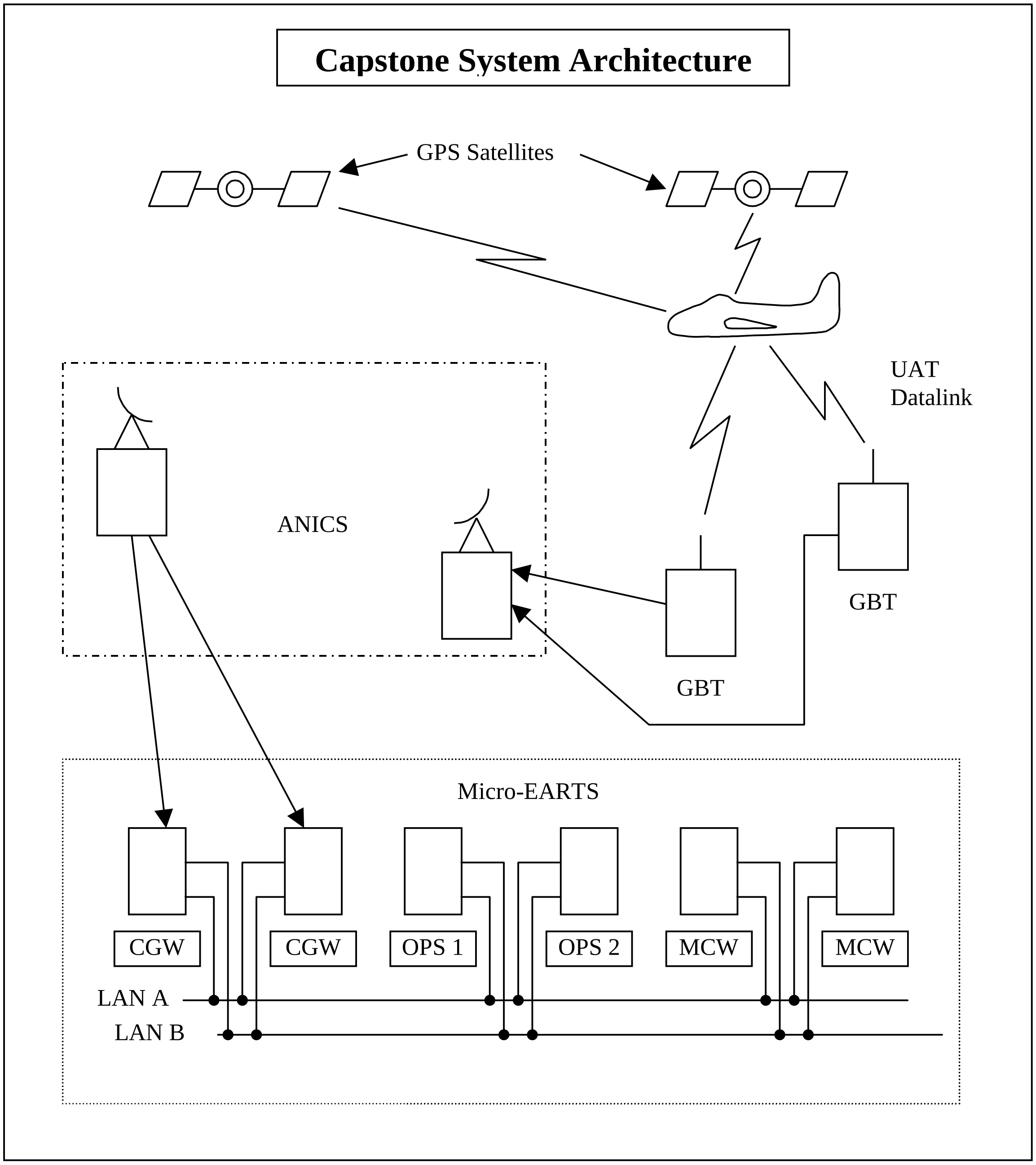


FIGURE 1

ANICS – Alaska NAS Interfacility Communications System
CGW – Capstone Gateway
GPS – Global Positioning System
GBT – Ground Based Transceiver
LAN – Local Area Network
OPS - Operational Processor
MCW – Micro-EARTS Controller Workstation
UAT – Universal Access Transceiver

3 Micro-EARTS Internal ADS-B Data Processing

The Micro-EARTS receives and processes ADS-B position reports in the same manner that it processes radar position reports. A separate track is initiated/maintained for each ADS-B aircraft from each ADS-B source. The Micro-EARTS bonds ADS-B tracks to system tracks that are also bonded to radar tracks for the same aircraft. A Kalman Filter is used to provide smoothed speed and heading data for the system track. This design permits quicker update of the system track data in response to aircraft maneuvers while maintaining the capability to prioritize surveillance source information for discreet geographical areas. Properly certified altitude information is obtained by digitizing barometric reference altimeter readings and is inserted in the ADS-B messages. Due to inherent inaccuracy in GPS derived altitude data, Capstone equipped aircraft do not transmit GPS height information and the Micro-EARTS will not use GPS height information if it is received.

An extremely small possibility exists that two Capstone ADS-B aircraft might briefly broadcast the same ICAO address in their ADS-B messages. If this should happen, the Micro-EARTS will maintain individual tracks for the two aircraft by using the same tracking algorithms that are used to maintain individual tracks for radar detected aircraft that use the same beacon code.

Controller display processing for aircraft tracks derived from ADS-B position data is the same as that used for tracks derived from radar data. This includes selection of display data for aircraft tracks supported by both radar and ADS-B surveillance. Coordinates used to display ADS-B data are the reported latitude/longitude converted to stereographic system coordinates. Data block symbology clearly indicates whether the aircraft is providing ADS-B position data. When both ADS-B data and certified radar data are received from a given aircraft, the track position displayed to the air traffic controller is the most recent radar reported position. The track display update interval used for aircraft reporting only ADS-B position data is adapted as appropriate to the controlling facility.

4 ADS-B Track Handoff Processing in Micro-EARTS

In order to prevent handoff of Capstone ADS-B aircraft surveillance data from ARTCC air traffic controllers to air traffic controllers at facilities that do not have the capability to process ADS-B data, automated interfacility handoff of ADS-B aircraft tracks not bonded to radar tracks is inhibited by the Micro-EARTS. Intrafacility handoff of ADS-B tracks between Micro-EARTS supported air traffic controllers has been fully implemented in the Micro-EARTS.

5 Micro-EARTS Safety Function Processing

The Micro-EARTS provides Minimum Safe Altitude Warning (MSAW), Conflict Alert (CA), Restricted Airspace Monitoring (RAM), and Mode C Intruder (MCI) service. Since safety function processing is applied to fused system tracks, addition of ADS-B track information to the system tracks will enhance the accuracy of the safety function information.

6 ADS-B and GPS monitoring in Micro-EARTS

GPS monitoring has been accomplished by installing GPS receivers called ADS-B Fixed Parrots at strategic locations in the areas designated for use of ADS-B surveillance data. Generally, these receivers are at the same location as the Ground Based Transceivers. Each of the ADS-B Fixed Parrots transmits its GPS derived position to the Micro-EARTS every five seconds. The independently surveyed geographical location of each of the ADS-B Fixed Parrots is stored within the Micro-EARTS database for comparison to the position transmitted in the periodic messages. When an indication is received that any of the GPS derived positions is inaccurate, the air traffic controllers are immediately alerted.

Avionics monitoring is accomplished within the airborne Capstone equipment through Receiver Autonomous Integrity Monitoring (RAIM). The ADS-B datalink network is monitored at several points along the transmission paths and losses are reported by the Micro-EARTS to FAA system monitoring personnel.

7 Micro-EARTS Tower Controller Workstation

A remote Micro-EARTS air traffic controller display has been installed in the Bethel, Alaska air traffic control tower to provide situational awareness support for the Bethel air traffic controllers.

8 Micro-EARTS ADS-B Data Recording

The Micro-EARTS Continuous Data Recording (CDR) function has been expanded to include recording of ADS-B messages, playback of ADS-B data for situation review, and plotting of ADS-B aircraft tracks in support of search and rescue activity.

9 Global Positioning System (GPS) Accuracy

The GPS is operated by the US Department of Defense (DoD) and maintained in accordance with DoD requirements. The DoD stated accuracy of the civil channel of the GPS is +/- 100 meters horizontal accuracy 95 percent of the time. The accuracy is further clarified that the 5 percent of the time in which horizontal position might exceed 100 meters is randomly distributed. These figures are given for times in which the Selective Acceptance (S/A) function of the GPS is active. The S/A function introduces controlled errors into the position calculation to degrade the system to hostile users. On May 2, 2000 the US President ordered cessation of the S/A function except when necessary for national security. This decision resulted in a substantial improvement in actual operational accuracy; +/- 6.3 meters vs. +/- 100 meters. However, since S/A can be reactivated without FAA knowledge, this evaluation assumes GPS accuracy with S/A.

10 FAA Air Traffic Control Radar Accuracy

Radar sensors used for air traffic control surveillance information at FAA air traffic control facilities are required to provide aircraft positions accurate to 1/8 nmi. in range from the sensor and 2 Azimuth Change Pulses (ACPs), or .022 degrees, in angular measure 85 percent of the time. Accuracy figures of +/- 1/4 nmi. in range and +/- 3 ACPS in azimuth are used to determine safe aircraft separation distance.

11 Accuracy Testing of Capstone GPS Receivers

In April, 2000 tests were performed at the FAA William J. Hughes Technical Center (WJHTC) in which simultaneous Capstone ADS-B data and very accurate Nike and laser ground radar data were collected. GPS position data were also collected using a special purpose on board GPS receiver and later corrected for ionospheric refraction and GPS satellite errors (S/A). All the data were later reduced and the Capstone ADS-B data were found to comply with the DoD stated GPS accuracy specification. A portion of the WJHTC data is attached as Appendix A.

12 Operational Data Collection and Reduction Methods

Operational Capstone ADS-B data were collected using the Micro-EARTS CDR capability and the Micro-EARTS CGW recording function. CDR data classes are specified in the Capstone ADS-B Evaluation Test Plan distributed on October 11, 2000. The test plan is attached as Appendix B.

Micro-EARTS data recordings were collected continuously on the ZAN Micro-EARTS Developmental System on magneto-optical media from 9/25/00 to 11/1/00. During this period one update to the Micro-EARTS Developmental System software was installed to correct radar site adaptation. A service level certification of the Developmental System was not performed. A representative 24 hour data sample was also taken from the Micro-EARTS CGW.

The recordings were stripped in 0.5 to 6.0 hour increments, depending on data quantities, and ADS-B messages were converted to MS Excel worksheets. Preliminary statistical quantities were extracted to verify data integrity and highlight possible anomalies. Points of interest were then evaluated as time permitted.

13 Analysis Methods

CDR data were analyzed by applying statistical theory to selected samples or by objective comparison of position data from independent sources – radar and ADS-B, for example. Since the radar data collected were from operational radars, the radar data were considered reliable. System performance was evaluated by reviewing controller comments, system maintenance logs, and performance data such as error listings and message rate statistics from the Micro-EARTS.

13.1 Capstone Avionics Performance Analysis

The Capstone avionics package consists primarily of a GPS receiver, a cockpit display processor and display, and a Universal Access Transceiver (UAT). As was mentioned above, the accuracy of position data provided by the GPS receiver was verified during Micro-EARTS ADS-B functionality acceptance tests in April, 2000. This subsequent evaluation, therefore, was concentrated on verifying that each aircraft using Capstone avionics provided credible periodic three dimensional position data. Credibility was judged by the content of the ADS-B message including the NUCp value, observation of an aircraft's track, comparison of the track with radar data when available, and review of controller comments.

13.2 GBT Performance Analysis

The Capstone GBTs are required to receive Capstone ADS-B messages in UAT format, add the proper time of day to the messages, and relay the messages to the ZAN Micro-EARTS via the Alaska National Air Space (NAS) Interface Communications System (ANICS). The normal reporting rate for Capstone equipped aircraft is once per second. The GBT also provides a periodic status message, normally every 30 seconds, indicating its GPS derived geographical position and its level of operability. An auxiliary function of the GBT is to provide ADS-B fixed parrot data by transmitting its GPS derived position via its UAT once every five seconds. GBT performance was analyzed by examining ADS-B and status message interval variations and by evaluating GPS derived position accuracy.

13.3 Analysis of GBT Status Message Content

Each Capstone GBT is programmed to transmit a status message to the Micro-EARTS every thirty seconds. Overall GBT workload and UAT and ground datalink load may occasionally prevent or delay transmission of the status message. GBT error indications were examined for effect on GBT performance and statistical data concerning both GBT performance and status message interval and/or loss were extracted from the MS Excel worksheets.

13.4 Analysis of GBT GPS Derived Position Message

The periodic GPS derived GBT position information is used similarly to that of an FAA radar parrot. It provides a crude but effective GPS monitor capability and is immediately shown on the air traffic controller's display if the GPS derived position is not within the limits adapted in the Micro-EARTS program. Approximately one percent of GPS derived geographical positions are expected to contain errors greater than 300 meters. Approximately 0.1 percent are expected to contain errors greater than one mile. The NUCp values transmitted with each GPS derived position report were analyzed for reliability and detection of expected periodic GPS satellite geometry variance or loss of RAIM.

13.5 Analysis of Micro-EARTS ADS-B Functionality

The Micro-EARTS receives, records, and processes all ADS-B messages. The processing includes bonding to radar data, linkage to flight plan data, and controller display update. The Micro-EARTS functionality was evaluated by statistically recurring CDR data, reviewing Program Trouble Reports (PTRs) and air traffic controller comments, and viewing controller and maintenance displays.

14 Data Chart and Report Explanation

All charts presented with this report were created using MS Excel. Each chart is annotated to indicate its applicability to the report and the data source from which the chart was created. Aircraft track plots are scattergram presentations with each aircraft or data source depicted by a unique symbol as necessary. Scattergrams are shown with a true aspect grid; i.e. north/south scale equal to east/west scale; except when purposely exaggerated to emphasize a point of interest. Charts with a distorted aspect ratio are identified by different X and Y axis scales.

15 Explanation of Anomalies

Table 1 contains a list of significant data anomalies observed, the method used to determine the cause, and corrective action taken or recommended

Table 1

Anomaly	Analysis Effort	Action/Recommendation
1. Numerous Unexpected ICAO addresses received. Addresses include FFXXXX, 000001	Receipt of address 000001 is the result of an incomplete avionics installation process. Other addresses will be referred to the avionics supplier for resolution.	The avionics installation procedure should include an operational verification prior to use of the Capstone equipment in flight. Operational procedures for each aircraft, such as initialization sequences, may also be needed.

Table 1		
Anomaly	**Analysis Effort**	**Action/Recommendation**
2. Some Capstone aircraft have been observed transmitting anonymous ICAO addresses without sending “VFR” in the A/C ID field or setting the address “T” bit	An explanation of the problem and supporting data will be forwarded to the avionics supplier.	Same as entry 1.
3. Some Capstone aircraft continuously transmit position reports with a NUCp value of zero	The problem will be forwarded with supporting data to the avionics supplier for resolution.	NUCp values should be set in accordance with avionics design criteria.
4. The frequency at which ADS-B messages with a NUCp value of zero are received is substantially higher than expected. High enough to exclude a significantly large percentage of aircraft from controller view at given times	The source of this problem is the same as item 3. The problem is stated in terms of controller visibility to stress the severity of inadequate NUCp values.	Due to the prevalence of aircraft transmitting constant zero NUCp values and the inadequacy of the NUCp value for ADS-B report discrimination, the Micro-EARTS software adaptation has been changed to accept all NUCp values.
5. The Micro-EARTS CDR Editor does not consider the “T” bit or 25th address bit when applying ICAO address filters.	The enhancement will be documented for consideration by software developers and configuration control personnel. This is a new requirement.	The ability to list only aircraft messages containing the “T” bit in the address would have been helpful for this evaluation.
6. The Micro-EARTS Editor will not permit filtering GBT status messages from the NonReport (NR) data class.	This new requirement was discussed briefly with Micro-EARTS software developers.	This capability was presented at the Capstone CDR and should be provided.
7. The Micro-EARTS CGW does not pass messages to the Micro-EARTS Operational Processors exactly as received when fields are not received in the message from the GBT. The method used to detect missing fields is not effective for loss of NUCp or GBT status bits and possibly for other fields.	The CGW functionality of inserting default values in missing message fields was discussed with the Micro-EARTS software developers.	The GBT messages should be preserved by the CGW and extracted to CDR as received. Loss of positive missing field indications prevent accurate analysis of system performance. The missing field rate is, by itself, a significant performance indicator, especially for GPS monitoring.

Table 1		
Anomaly	**Analysis Effort**	**Action/Recommendation**
8. The Micro-EARTS software is adapted to allow an error of 3 seconds in the latitude or longitude of the ADS-B fixed parrots before displaying the parrot.	No action taken yet	The tolerance should be corrected to +/- 0.2 seconds latitude, +/- 0.4 seconds longitude. All adapted positions should be to the nearest 0.01 second and all ADS-B fixed parrots should transmit positions to the nearest 0.1 second latitude and 0.2 second longitude.

16 Evaluation of Message Latency

ADS-B message latency is defined as the elapsed time from when the aircraft was at the reported geographical position until the message was processed by the Micro-EARTS. More specifically, the Micro-EARTS process time is the time at which the message was recorded to disk or the ADS-B track, flight data linkage, or other pertinent data were recorded to disk. The time source is clearly indicated on all data summaries or charts. Message latency is caused by avionics software and hardware design, GBT processing and workload, ANICS transmission time, and Micro-EARTS design and workload. The expected average message latency is 800 to 1000 milliseconds due primarily to ANICS transmission time of approximately 300 milliseconds and UAT transmission protocol.

17 Analysis of GBT Status Message Content

The GBT status message provides important information concerning the configuration and health of the GBT. Table 2 provides a brief explanation of the status message content. Not all status messages contain the same information. Two different length versions of the message are used. The shorter version contains the Discarded Report Count and not the GBT geographical position or the four GBT status items; the other contains the GBT position and status but not the Discarded Report Count.

Table 2	
Item Name	**Explanation**
GBT UAT RF receiver valid (RX)	Indicates status of the internal UAT RF receiver check for the last 30 seconds: No Failure (1) or Failed (0)
GBT internal UAT host interface valid (SR)	Indicates status of the UAT host interface check for the last 30 seconds: NoFailure(1) or Failed (0)
GBT UAT RF transmitter valid (TX)	Indicates status of the internal UAT RF transmitter check for the last 30 seconds: No Failure (1) or Failed (0)
GBT UAT 1 PPS valid (PP)	Indicates status of the UAT receiving valid 1 PPS (pulse per second) from the GBT's GPS for the last 30 seconds: No Failure (1) or Failed (0)

Table 2	
Item Name	**Explanation**
Role	Identification of the ROLE of a system: 01 Development. 10 Evaluation. 11 Operational.
Version	Identification of the VERSION of the Ground Based Transceiver (GBT)
GBT's latitude and longitude position	Either the surveyed or GPS derived geographical location of the GBT
Navigation Uncertainty Category (NUCp)	A number indicating the Horizontal Protection Limit Error for the GPS derived position. The Capstone equipment reports NUCp values of 0, 4, 5, 6 only
Discarded Report Count	Count of ADS-B Reports discarded during the most recent reporting period by the GBT due to inability to transmit via ANICS

18 Analysis of GBT ADS-B Reception Range

The Capstone GBTs and avionics equipment are designed to send and receive ADS-B messages over an effective line of sight range of 135 nmi. Micro-EARTS acceptance tests at the WJHTC verified that the Capstone equipment used during those tests provided the required range. Time did not permit evaluation of the effective limits of coverage for each GBT in the current Capstone environment.

19 Explanation of Micro-EARTS Stereographic Projection Accuracy

The Micro-EARTS presents air traffic situation pictures to the air traffic controllers using stereographic projection of the true earth model aircraft positions. The algorithms used to determine the projected position of earth oriented objects; aircraft, navigational fixes, and map features; are contained in NAS MD-676, Micro-EARTS Computer Program Functional Specification (CPFS). The accuracy of the display of aircraft and map features on the controller's display was tested and verified during acceptance tests of the EARTS (not Micro-EARTS) using Sperry Input/Output Processors, version B (IOPBs) and Plan View Displays (PVDs). The tests verified that the total worse case error due to all system inaccuracies and data resolutions was +/- 1/4 nmi.

Since the EARTS tests were performed, both the automation processors and the controller displays have improved to the point that the total system aircraft and map feature display errors have decreased significantly. The specified error limit has not, however, been changed. The Micro-EARTS has been tested to the same standards as the predecessor EARTS. Since the aircraft position errors of ADS-B surveillance sources are much less than the worse case radar reported position errors, and since the conversion of reported position from radar to geodetic coordinates is not necessary for ADS-B data, the worse case errors in ADS-B data display are much less than the worse case errors in radar data display.

20 Comparison of Radar and ADS-B Data

Appendix A contains data from extremely accurate tracking radars at the WJHTC and airborne Capstone GPS receivers. These data attest to the performance of the Capstone GPS receivers. Radar and ADS-B comparisons performed as part of the current evaluation were done to show whether current radar based separation services can be applied to aircraft whose surveillance source is ADS-B.

20.1 Comparison of Reported Aircraft Positions

A portion of the ADS-B and radar surveillance reports is the aircraft position. The evaluation approach was to produce visual presentations of radar and ADS-B aircraft tracks and provide statistical comparison values to indicate worse case and average relative radar and ADS-B position errors. The radar and ADS-B data collected for this comparison were provided from dedicated flights using a Boeing 727 equipped with Capstone avionics. The data are contained in Appendix C.

Time did not permit extraction of statistical comparison data from the 727 flights. The charts in Appendix C, however, indicate that the ADS-B reported positions are better than the ZAN MAR reported positions for presenting the location and heading of the aircraft.

20.2 Comparison of Reported Altitudes

Radar and ADS-B altitude reports were compared in the same way as radar and ADS-B aircraft position reports. Since both radar and ADS-B messages contain altitude data obtained from atmospheric pressure sensors, the differences between radar and ADS-B altitude reports are expected to be very small. The radar and ADS-B data collected for this comparison are contained in Appendix C. The maximum difference in reported altitude was 75 feet and was due to the difference in resolution of the two sources. ADS-B reports contain altitude to the nearest 25 feet and radar reports contain altitude to the nearest 100 feet.

21 ADS-B and Radar Data Fusion Evaluation

The algorithms used to bond data from multiple surveillance sources for a common aircraft are contained in NAS MD-677. These algorithms are the result of many years of processing radar data from radars having diverse characteristics. A simple process that accepts all reports from all sources and determines a current aircraft position through application of a generic Kalman filter would not meet FAA air traffic control data presentation requirements. The Micro-EARTS, therefore uses an alpha beta tracker to maintain individual surveillance track files and bonding algorithms to bond those files that apply to a common aircraft. A Kalman filter has been incorporated to maintain current speed and heading values for display of progress vectors and detection of safety function alarms.

Time did not permit a thorough analysis of the Micro-EARTS data fusion function. Data from the Boeing 727 flight indicate that the tracks created from individual sensor reports were properly bonded and did not produce false conflict alerts. Some false bonds between radar and ADS-B tracks in the Bethel area were observed by air traffic controllers, however, and changes to the Micro-EARTS bonding function have been developed. These changes will be implemented upon completion of testing.

22 Safety Function Evaluation

CDR data were collected to analyze minimum safe altitude violations, minimum safe aircraft spacing violations, uncontrolled aircraft intrusions, and military airspace incursions. The analysis performed to date indicates that the Micro-EARTS safety functions comply with the Capstone FDN and NAS-MD-672, titled “Conflict Alert Processing”, and NAS-MD-684, titled “Minimum Safe Altitude Warning”.

23 Evaluation Objectives

This section explains the results of each of the nine objectives of the Capstone ADS-B Evaluation Plan contained in Appendix B.

23.1 Objective 1: Evaluate ADS-B message content anomalies and transmission anomalies to determine error rates and origin of suspected data corruption and to identify necessary equipment and/or software corrections

Required Performance: All system components meet documented standards and tolerances as contained in applicable government and manufacturer specifications for the Capstone avionics and ground equipment, the ANICS, and the Cisco router.

Most of the anomalies found during this evaluation and the corrective action taken are listed in Section 15 above. Other anomalies included:

1. The ADS-B fixed parrot positions are reported to the nearest second instead of to the accuracy expected from other Capstone GPS receivers; +/- 0.1 second latitude, +/- 0.2 seconds longitude.

   This problem is expected to be corrected in future GBT software upgrades and is considered mandatory for proper GPS performance monitoring.

2. During periodic loss of optimum GPS performance, the ADS-B fixed parrot reported NUCp values required up to five 5-second intervals to reach zero. This indicates that the parrot position is not calculated each second. If so, the algorithms used for setting the NUCp value are not optimum for monitoring GPS performance.

   Although the NUCp values are delayed for up to five reporting intervals due to the NUCp derivation process (ref. Section 23.5), the parrot messages were analyzed to determine if the NUCp values might provide an indication of periodic changes in GPS satellite geometry that cause loss of RAIM and/or position accuracy. A cyclical pattern was found and is discussed in Section 23.5. This phenomenon will require further study and will be presented along with appropriate data to the GBT supplier and interested evaluators.

   A proposed method for using the ADS-B fixed parrots and published GPS performance charts to monitor GPS performance is presented in Section 23.5.

23.2 Objective 2. Evaluate all equipment outages and apparent equipment outages to determine cause, impact on service availability, and restoration time.

Required Performance: Service availability no less than 99.5 percent of the time during which data are collected. Availability will be based upon equipment and/or software failures and will not include scheduled outages or outages due to external causes.

The certification of the Bethel GBTs, BEA and BEP, was conducted on August 13, 2000. An AAL representative reported that no outages were experienced during the evaluation period.

23.3 Objective 3. Determination of ADS-B position latency when received at the MicroEARTS.

Required Performance: Minimum position latency not less than 350 ms, maximum position latency not more than 1.45 seconds, average position latency 800 to 1000 ms.

The Capstone Evaluation data show that the minimum and average latency criteria are always met when taken over a period of 30 minutes or more. The maximum latency indicated, however, is usually about one second too long. The cause of this indication has not yet been determined. Since the condition occurs in less than 0.01 percent of ADS-B messages, and since the Micro-EARTS, if properly adapted, will discard messages more than 1.8 seconds old, no operational impact is expected.

23.4 Objective 4. Evaluate MicroEARTS ADS-B functionality for compliance with the Capstone MicroEARTS NCP and FDNs.

Required Performance: The MicroEARTS meets all requirements specified in the Capstone NCP, all additional MicroEARTS enhancements required to meet the goals stated in the FAA Administrator's letter of 1/3/00 are scheduled to be completed by 1/1/01, all MicroEARTS enhancements required or desired subsequent to 1/1/01 are documented.

During the evaluation, several questions about the Micro-EARTS functionality were raised. Most of these are listed in Section 15. In almost all instances the Micro-EARTS was shown to function in accordance with the Capstone ADS-B Functional Description Narrative (FDN). In some instances, however, the functionality was not operational acceptable, and changes were made to the Micro-EARTS software. These changes were coordinated with all cognizant parties and thoroughly tested.
Some required functionality changes were not considered mandatory for initial operational use of the Capstone ADS-B data for air traffic control. These requirements are listed here:

1. ADS-B fixed parrot monitoring functions must be enhanced to provide a better and faster indication of degradation of GPS accuracy at the parrot locations.
2. Limited datablocks for radar tracks bonded to ADS-B tracks with altitude information should include the ADS-B reported altitude if radar altitude is not available.
3. Air traffic controllers expressed a desire to adapt ADS-B track data higher than radar data for display priority. i.e. Display ADS-B tracks in preference to radar tracks when aircraft are reported by both ADS-B and radar.
4. The Micro-EARTS has been modified to track ADS-B reports with any NUCp value, including zero. Exclusion of messages with zero NUCp values often results in loss of whole flights from the controller's display. As stated previously, the NUCp values are not suitable for determining acceptability of individual ADS-B reported positions.

23.5 Objective 5. Evaluate the performance of the Capstone ADS-B fixed parrots

Required Performance: Fewer than 0.5 percent of all received messages contain timestamps other than at zero seconds past a minute tick or a multiple of 5 seconds following a minute tick, an average of no less than 10 messages per minute when the Capstone ground equipment is fully operational.

One of the ADS-B fixed parrots, A/C ID “BEA”, was received every five seconds hour after hour. The other, A/C ID "BEP", was received at intervals that regularly varied from as low as three seconds to six seconds with a typical average of 4.8 seconds. This fact coupled with the fact that the status message intervals varied similarly from this GBT indicates that the two GBTs may not have had identical software installed.

Although the required performance was not met, the “BEA” parrot is operating almost as expected based upon performance information from the GBT supplier and is considered acceptable for initial operational use. Use of the “BEP” parrot, however, will require verification of proper software installation and an explanation from the GBT supplier of the difference in report periodicity.

Examination of the ADS-B fixed parrot reports included a detailed study of periodic changes in the NUCp values. Information from the GBT supplier suggested that the NUCp values transmitted with ADS-B messages, including the parrot messages, are derived from RAIM alarm indications in the GPS receiver status message. The first message transmitted after system activation is sent with a NUCp value of zero and the 1.0 mile RAIM alarm is enabled. If no RAIM alarm is received from the GPS receiver, the NUCp value is set to 4 and the 0.5 mile RAIM alarm is enabled. If no RAIM alarm is received, the NUCp value is set to 5 and the 0.25 mile RAIM alarm is enabled. If no RAIM alarm is received the NUCp values are set to 6 and the 0.25 RAIM alarm remains enabled. This results in NUCp values that do not apply to the position contained in the transmitted position because any RAIM alarm generated during the position calculation won’t be received by the message processing unit until the next status message is processed. A reverse logic, enabling progressively larger RAIM alarms and monitoring resulting status messages, is used to report periods of possibly less accurate position calculations.

Although the NUCp values are delayed for up to five seconds by the above process, the parrot messages were analyzed to determine if the NUCp values might provide an indication of periodic changes in GPS satellite geometry that cause loss of RAIM and/or position accuracy. A cyclical pattern was found in the NUCp values and may be useful along with published GPS performance charts for monitoring GPS performance.

Since the ADS-B message NUCp values cannot be used to indicate the acceptability of individual ADS-B positions, a method of monitoring the GPS performance must be established to assure that the air traffic controllers are alerted when questionable position accuracy is probable. The ADS-B fixed parrots and published GPS performance charts can be used for this purpose if appropriate procedures are implemented to assure response to deviations in the reported parrot position and degradation of parrot NUCp values. To this end, the Micro-EARTS ADS-B fixed parrot tolerance should be set to +/- 0.2 seconds latitude, +/- 0.4 seconds longitude and a critical alarm must be sent to the Micro-EARTS SMC and the ADS-B fixed parrot must be displayed at the controller’s display when this tolerance is exceeded. When no position is received in the ADS-B fixed parrot message the displayed position should be the last valid reported position. In addition, the parrot NUCp values should be monitored and similar alerts issued when the NUCp values drop to zero or are not reported in the parrot message for three consecutive reporting intervals. Both the controllers and maintenance personnel should be alert for erratic ADS-B aircraft tracks until the parrots return to normal. This procedure is similar to that used for radar parrots.

When the five-second parrot messages are not available due to failure of a receiving GBT, the position and NUCp values reported in the thirty second GBT status messages may be used to perform the GPS monitoring function.

23.6 Objective 6. Compare the displayed position of ADS-B aircraft with that of radar detected aircraft.

Required Performance: Computed average difference in the time corrected displayed position of aircraft reported by both ADS-B and radar not more than the applicable radar reporting error +/- 0.25 nmi after correcting for radar registration errors. No more than +/- 100 meter per second change in report to report position interval for ADS-B tracks.

Since time did not permit analysis of targets of opportunity, this objective was evaluated solely from the Boeing 727 data taken prior to Bethel GBT certification. Plots from the 727 flights are included in Appendix C. The required performance was exceeded by the 727 flights. The reader should note that the tracks indicated in the charts in Appendix C are not exactly as presented to the air traffic controllers since controller displays are not updated more often than every 4 seconds of flight.

23.7 Objective 7. Evaluate MicroEARTS ADS-B and radar data fusion

Required Performance: Same as Expected Results except that conflict alerts due to failure to bond track data from a common aircraft must not exceed 5 within any one hour period.

Several data fusion anomalies were observed by air traffic controllers during the evaluation and enhancements were made to the Micro-EARTS program. The enhancements included tighter tolerances for comparing radar and ADS-B aircraft speed, heading, and altitude and use of flight plan ADS-B address information to prevent inappropriate ADS-B and radar track bonds.

Observations by AAL-400 personnel during the early stages of data collection preparation indicated that the ZAN radar sites and radar parrots were adapted in the Micro-EARTS program to the nearest second in both latitude and longitude. Recordings of ZAN radar data showed that range corrections were being applied to several radars to correct registration problems. Since range corrections should never be necessary for radar data used by the FAA for air traffic control, the Micro-EARTS adaptation was changed to establish radar and parrot locations to the nearest 0.01 second and the range biases were removed. This change should be made for all ZAN radar sites and parrot locations. The resulting agreement between radar and ADS-B tracks for the Boeing 727 flights is readily apparent in the charts in Appendix C.

23.8 Objective 8. Evaluate the operation of the MicroEARTS Kalman Filter to assure no detrimental effect on MicroEARTS safety functions.

Required Performance: No false MSAWs for aircraft in radar coverage due to erroneous use of ADS-B information, no false conflict alerts between aircraft in radar coverage due to erroneous use of ADS-B information.

An analysis of Micro-EARTS MSAW and CA recordings and examination of Kalman filter performance was performed by the Micro-EARTS support contractor. The results showing that the Kalman Filter improves system track response to aircraft maneuvers are contained in Appendix C. Also, testing at the WJHTC indicates that the Kalman filter is acceptable for initial operational use and no data gathered during this evaluation period indicated otherwise.

Controller comments and Micro-EARTS program developer observations indicate a need to enhance the ability to adapt special areas around airports with published GPS approaches and ADS-B coverage for normal aircraft operations.

23.9 Objective 9. Evaluate operational GBT coverage to determine if significant holes exist in areas of frequent travel by Capstone equipped aircraft or along paths frequently used by air traffic controllers to vector aircraft.

Required Performance: Documentation and publication, if necessary, of all areas, if present, in the designed coverage boundaries of each FAA certified operational GBT in which ADS-B aircraft tracks are coasted by the MicroEARTS due to uncorrectable loss of messages from aircraft operating in those areas. i.e. Documentation of all uncorrectable holes in GBT coverage areas. Minimum documentation will be the report of the results of this test. Additional one time documentation of initial system performance may be required by the FAA for distribution to air traffic control personnel or maintenance personnel.

Time did not permit a thorough evaluation of gaps in GBT coverage using targets of opportunity. Gaps observed during the Boeing 727 flights were due to flight below line of sight and no other significant gaps were observed during preliminary evaluation of any of the Micro-EARTS recordings.

24 Evaluation Summary

This evaluation revealed the following facts concerning the acceptability of Capstone ADS-B data as an aircraft surveillance source.

1. The Capstone GPS receivers meet all established requirements for use as a source of aircraft position data.

2. The barometric altitude reported in ADS-B messages is better than that reported via radar beacon mode C messages in that the resolution is 25 feet versus 100 feet for mode C.

3. The NUCp values transmitted with each Capstone ADS-B aircraft message are of no value in determining the proper processing and display of reported aircraft positions and should not be used to prevent processing and display of ADS-B position reports.

4. The Capstone GPS monitoring capability provided by the ADS-B fixed parrots is adequate if used in conjunction with published GPS performance charts to provide early detection of localized significant GPS outages if proper monitoring procedures are implemented. The ADS-B fixed parrots operate similarly to radar parrots and are acceptable for use for periodic service certification.

25 Conclusions

The Capstone ADS-B data from Capstone equipped aircraft are as good or better than radar data for use as an aircraft surveillance source if properly processed and displayed. The Capstone ground support equipment must be maintained in accordance with published maintenance documents and the GPS performance must be monitored through use of published GPS performance charts and the ADS-B fixed parrots. In addition tight control must be maintained over the installation and operation of the Capstone avionics.

Appendix A
WJHTC Capstone GPS Receiver Accuracy Checks

MS Excel files of WJHTC test data available under separate cover.

Appendix B
Capstone ADS-B Acceptability Evaluation Plan

Capstone ADS-B Acceptability Evaluation Test Plan 10/11/00

The FAA Administrator has charged FAA Flight Standards with the task of approving "operational standards and associated operations specifications permitting use of radar-like services based on ADS-B equipment". AUA-600 has agreed to support Flight Standards in this task by collecting and analyzing Capstone ADS-B performance data.

The objective of this effort is to verify that the Capstone ADS-B ground system is acceptable for use in providing radar-like services and that the Capstone ADS-B ground system equipment performs in accordance with applicable specifications. The accuracy of the Capstone ADS-B Global Positioning System (GPS) receiver was tested at the WJHTC in April, 2000 and found to provide position information in accordance with the published GPS specification. ADS-B accuracy will therefore not be addressed in this task.

Since the ZAN Microprocessor Enroute Automated Radar Tracking System (Micro-EARTS) will be used to collect most of the data necessary for this evaluation and both ADS-B and radar data are needed, the data collection will not begin until at least one Capstone Ground Based Transceiver (GBT) has been certified in accordance with FAA certification procedures. Following this, ADS-B and radar data will be recorded via the Micro-EARTS Continuous Data Recording (CDR) function for a period of at least 30 days using targets of opportunity and dedicated test flights. The geographical test area is defined as that airspaceas defined in Airspace Docket 99-AAL-24. Each day's data will be reduced to Microsoft Excel format to facilitate analysis and charting.

The specific objectives, necessary data, expectations, and data collection methods to begin this evaluation are delineated below.

Objective 1. Evaluate ADS-B message content anomalies and transmission anomalies to determine error rates and origin of suspected data corruption and to identify necessary equipment and/or software corrections

Necessary Data: A 30 day collection of ADS-B messages and transmission error information

> Expected Results: Less than 0.1 percent of all messages contain detectable message content errors. Data transmission error rates due to all causes are less than 0.01 percent.
>
> Required Performance: All system components meet documented standards and tolerances as contained in applicable government and manufacturer specifications for the Capstone avionics and ground equipment, the ANICS, and the Cisco router.
>
> Data Source and Collection Method: Capstone equipped aircraft messages recorded by the Micro-EARTS.

Objective 2. Evaluate all equipment outages and apparent equipment outages to determine cause, impact on service availability, and restoration time.

> Necessary Data: A 30 day collection of FAA maintenance log entries, controller comments, and ADS-B messages.

Expected Results: No undetected ground equipment failures, no unscheduled equipment outages, no disruption of ADS-B service during the data collection period. An equipment failure is deemed to have been undetected if no FAA maintenance log entry is made to document the failure, no equipment or system status message is found that indicates the failure, and the applicable ADS-B fixed parrot, if any, is received periodically after the failure.

Required Performance: Service availability no less than 99.5 percent of the time during which data are collected. Availability will be based upon equipment and/or software failures and will not include scheduled outages or outages due to external causes.

Data Source and Collection Method: FAA Maintenance logs collected and compiled at least once per seven day data collection period, Controller comments collected and compiled weekly, and ADS-B messages recorded by the MicroEARTS.

Objective 3. Determination of ADS-B position latency when received at the MicroEARTS.

Necessary Data: A minimum of 3,000 Capstone ADS-B messages representing a random sampling from all Capstone equipped aircraft and Capstone ground system data transmission components. A 30 day collection of ADS-B messages received at the MicroEARTS is expected to fulfill this requirement.

Expected Results: Minimum position latency of no less than 475 ms, maximum position latency of not more than 1.35 seconds, average message latency of approximately 900 ms.

Required Performance: Minimum position latency not less than 350 ms, maximum position latency not more than 1.45 seconds, average position latency 800 to 1000 ms.

Data Source and Collection Method: ADS-B messages from Capstone equipped aircraft and Capstone GBTs recorded at the MicroEARTS.

Objective 4. Evaluate MicroEARTS ADS-B functionality for compliance with the Capstone MicroEARTS NCP and FDNs.

Necessary Data: MicroEARTS and airborne recorded data from controlled flight profiles flown between 8/21/00 and 8/24/00, a 30 day collection of ADS-B messages representing 30 days of system operation with equipment in a certified status, air traffic controller comments for a 30 day period, FAA maintenance logs

Expected Results: The MicroEARTS provides all functionality required by the Capstone NCP and FDNs.

Required Performance: The MicroEARTS meets all requirements specified in the Capstone NCP, all additional MicroEARTS enhancements required to meet the goals stated in the FAA Administrator's letter of 1/3/00 are scheduled to be completed by 1/1/01, all MicroEARTS enhancements required or desired subsequent to 1/1/01 are documented.

Data Source and Collection Methods: Air traffic controller comments compiled weekly, FAA maintenance log entries compiled weekly, internal MicroEARTS surveillance data and display data processing results as recorded by the MicroEARTS, controller keyboard entries recorded by the MicroEARTS, interfacility message data recorded by the MicroEARTS, MicroEARTS CGW recordings.

Objective 5. Evaluate the performance of the Capstone ADS-B fixed parrots

Necessary Data: ADS-B fixed parrot messages from all Capstone ADS-B fixed parrots for a minimum of 3 hours each day for a contiguous 30 day period. The messages must include a minimum of 600 messages from each GBT for every contiguous one hour time period in a 24 hour day; a total of no less than 14400 messages per parrot spread over the 30 day period.

Expected Results: Messages with time stamps at even 5 second intervals from the start of each minute, an average of no less than 10 messages per minute in any contiguous one hour period, average GPS position solution within 20 meters of surveyed position adapted in the MicroEARTS.

Required Performance: Fewer than 0.5 percent of all received messages contain timestamps other than at zero seconds past a minute tick or a multiple of 5 seconds following a minute tick, an average of no less than 10 messages per minute when the Capstone ground equipment is fully operational.

Data Source and Collection Methods: Capstone ADS-B fixed parrot messages from certified Capstone ADS-B fixed parrots as recorded by the MicroEARTS.

Objective 6. Compare the displayed position of ADS-B aircraft with that of radar detected aircraft.

Necessary Data: A minimum of three aircraft tracks from each overlapping radar and ADS-B coverage area each containing a minimum of 10 secondary radar detections and a minimum of 85 percent ADS-B position report rate within the 10 secondary radar detections. The tracks must not contain any coast intervals as defined by the MicroEARTS CPFS. If the overlapping radar is a MAR, the 10 radar detections must be primary radar reinforced.

Expected Results: Maximum time corrected difference between the displayed position of ADS-B and radar tracks not more than +/- 1.5 nmi for any track. No significant evidence of track stitching in ADS-B tracks.

Required Performance: Computed average difference in the time corrected displayed position of aircraft reported by both ADS-B and radar not more than the applicable radar reporting error +/- 0.25 nmi after correcting for radar registration errors. No more than +/- 100 meter per second change in report to report position interval for ADS-B tracks.

Data Source and Collection Methods: ADS-B messages from Capstone equipped aircraft operating in areas of radar coverage within 175 nmi of a Capstone GBT as recorded by the MicroEARTS.

Objective 7. Evaluate MicroEARTS ADS-B and radar data fusion

Necessary Data: A minimum of 200 hours of ADS-B and radar aircraft track data over a 30 day period for aircraft operating within 175 nmi of a Capstone GBT, a minimum of two hours of data from Capstone equipped aircraft flying defined paths within Capstone GBT coverage areas, and controller comments concerning displayed radar and ADS-B aircraft positions.

Expected Results: No false radar and ADS-B track bonds of more than 30 seconds duration, no controller detectable change in radar data display, fewer than 3 conflict alerts per hour due to unbonded radar and ADS-B tracks from common aircraft, no false MSAWs due to use of erroneous ADS-B altitude information, no false conflict alerts due to erroneous ADS-B position information, no failures to display radar detected aircraft position due to ADS-B track bonds

Required Performance: Same as Expected Results except that conflict alerts due to failure to bond track data from a common aircraft must not exceed 5 within any one hour period.

Data Source and Collection Methods: ADS-B messages from Capstone equipped aircraft and radar reports for all aircraft operating within 175 nmi of each certified Capstone GBT, ADS-B messages and radar reports from all aircraft flying defined paths in support of this evaluation as recorded by the MicroEARTS, air traffic controller logs compiled weekly, MicroEARTS SMC messages, and MicroEARTS CAs and MSAWs.

Objective 8. Evaluate the operation of the MicroEARTS Kalman Filter to assure no detrimental effect on MicroEARTS safety functions.

Necessary Data: A minimum of 200 hours of ADS-B and radar aircraft track data over a 30 day period for aircraft operating within 175 nmi of certified Capstone GBTs, a minimum of two hours of data from Capstone equipped aircraft flying defined paths within Capstone GBT coverage areas, and controller comments concerning CAs and MSAWs.

Expected Results: No false MSAWs for aircraft in radar coverage due to erroneous use of ADS-B information, no false conflict alerts between aircraft in radar coverage due to erroneous use of ADS-B information.

Required Performance: Same as Expected Results.

Data Source and Collection Methods: ADS-B messages from Capstone equipped aircraft and radar reports for all aircraft operating within 175 nmi of certified Capstone GBTs, air traffic controller logs compiled weekly, MicroEARTS SMC messages, and MicroEARTS CAs and MSAWs. All MicroEARTS data to be extracted from MicroEARTS recordings.

Objective 9. Evaluate operational GBT coverage to determine if significant holes exist in areas of frequent travel by Capstone equipped aircraft or along paths frequently used by air traffic controllers to vector aircraft.

Necessary Data: A minimum of 200 hours of ADS-B and radar position reports from Capstone equipped aircraft operating in and within 175 nmi of certified Capstone GBTs, a minimum of 2 hours of ADS-B and radar data from Capstone equipped aircraft flying defined paths in Capstone operational GBT coverage areas, and controller comments concerning loss of displayed position of Capstone equipped aircraft.

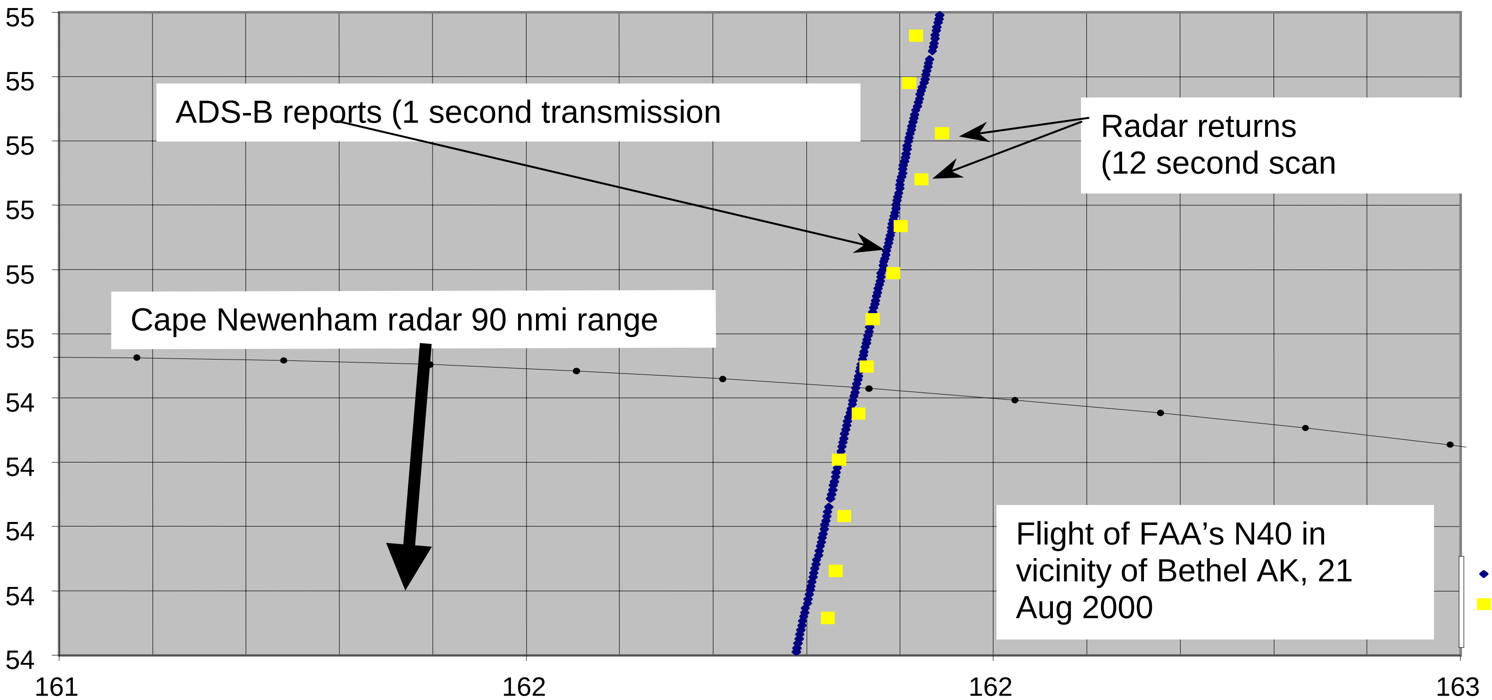
Expected Results: No significant gaps in aircraft tracks within the designed coverage area of any FAA certified Capstone GBT due to failure to receive ADS-B messages at the GBT.

Required Performance: Documentation and publication, if necessary, of all areas, if present, in the designed coverage boundaries of each FAA certified operational GBT in which ADS-B aircraft tracks are coasted by the MicroEARTS due to uncorrectable loss of messages from aircraft operating in those areas. i.e. Documentation of all uncorrectable holes in GBT coverage areas. Minimum documentation will be the report of the results of this test. Additional one time documentation of initial system performance may be required by the FAA for distribution to air traffic control personnel or maintenance personal.

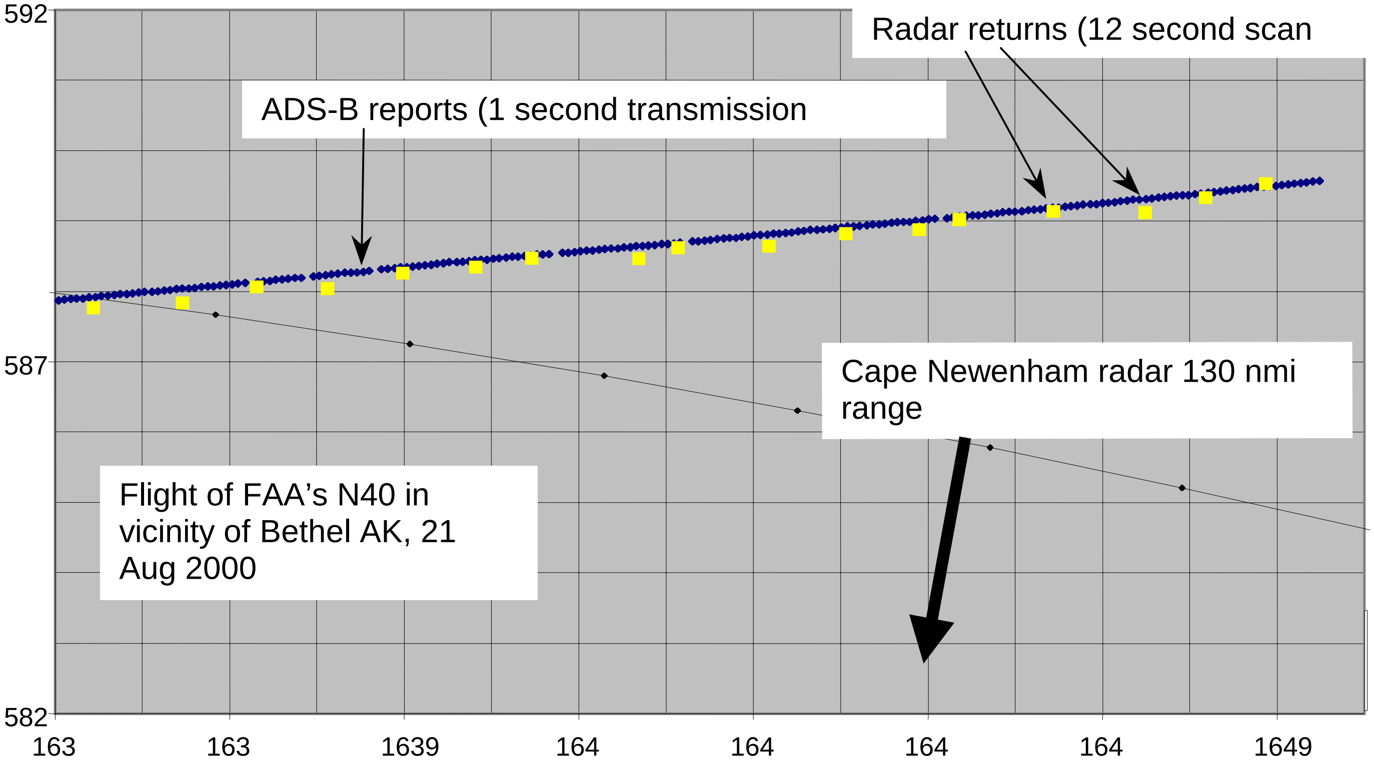
Data Source and Collection Methods: ADS-B messages and radar reports from Capstone equipped aircraft operating within 175 nmi of certified operational Capstone GBTs and ADS-B messages and radar reports from all aircraft flying defined paths in support of this evaluation, air traffic controller logs compiled weekly as recorded by the MicroEARTS.

Appendix C
Boeing 727 Test Flights, August, 2000

The following are MS Excel files of the Boeing 727 test flights conducted in August 2000.

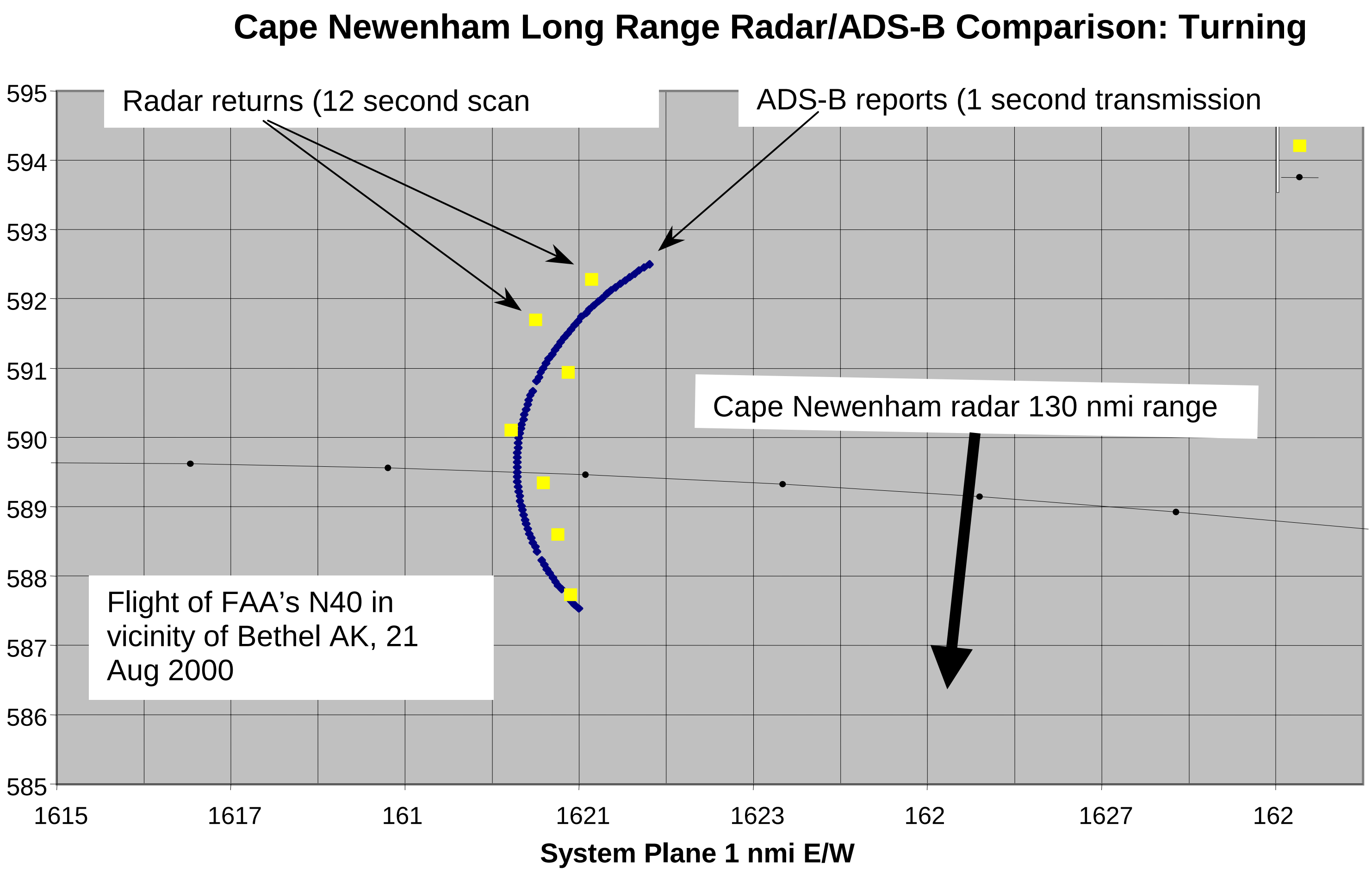


Cape Newenham Long Range Radar/ADS-B Comparison: Radial
System Plane 1 nmi E/W



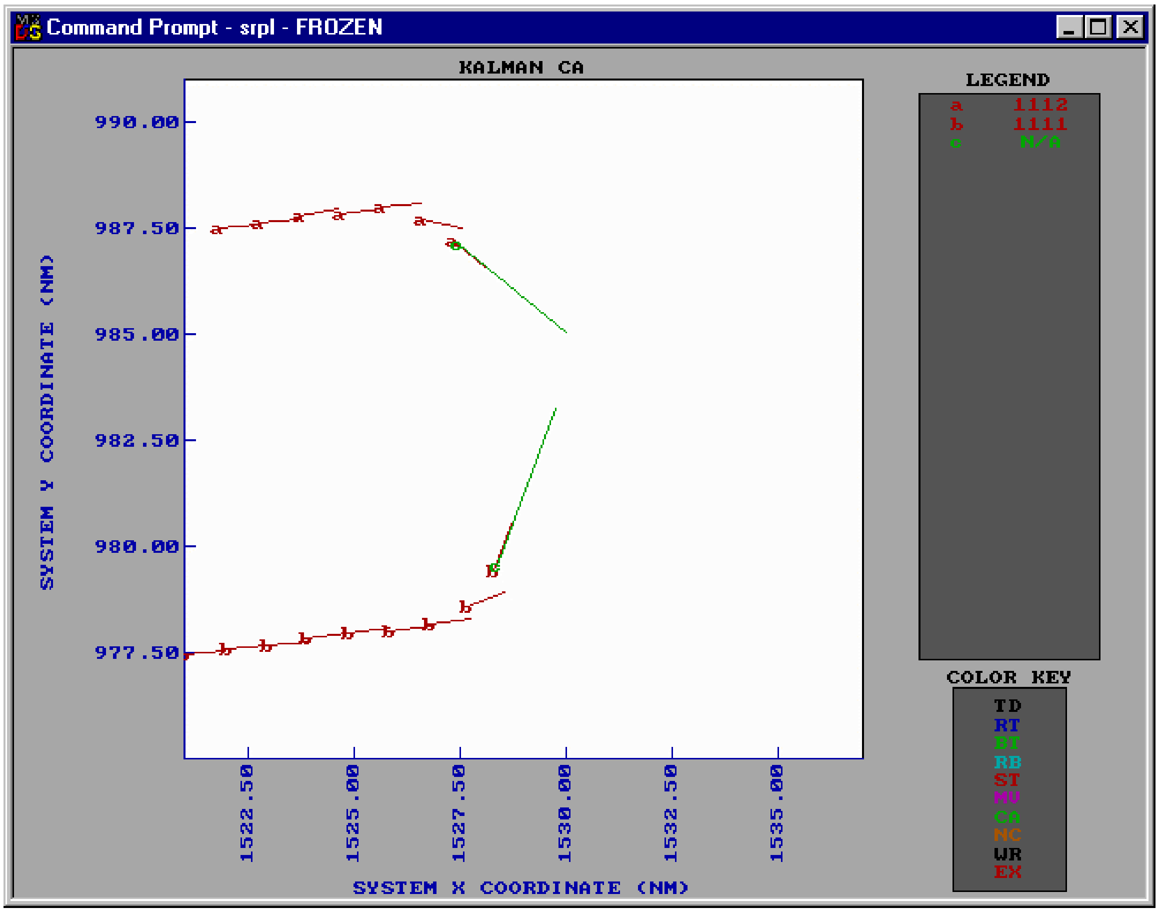
Cape Newenham Long Range Radar/ADS-B Comparison: Tangential

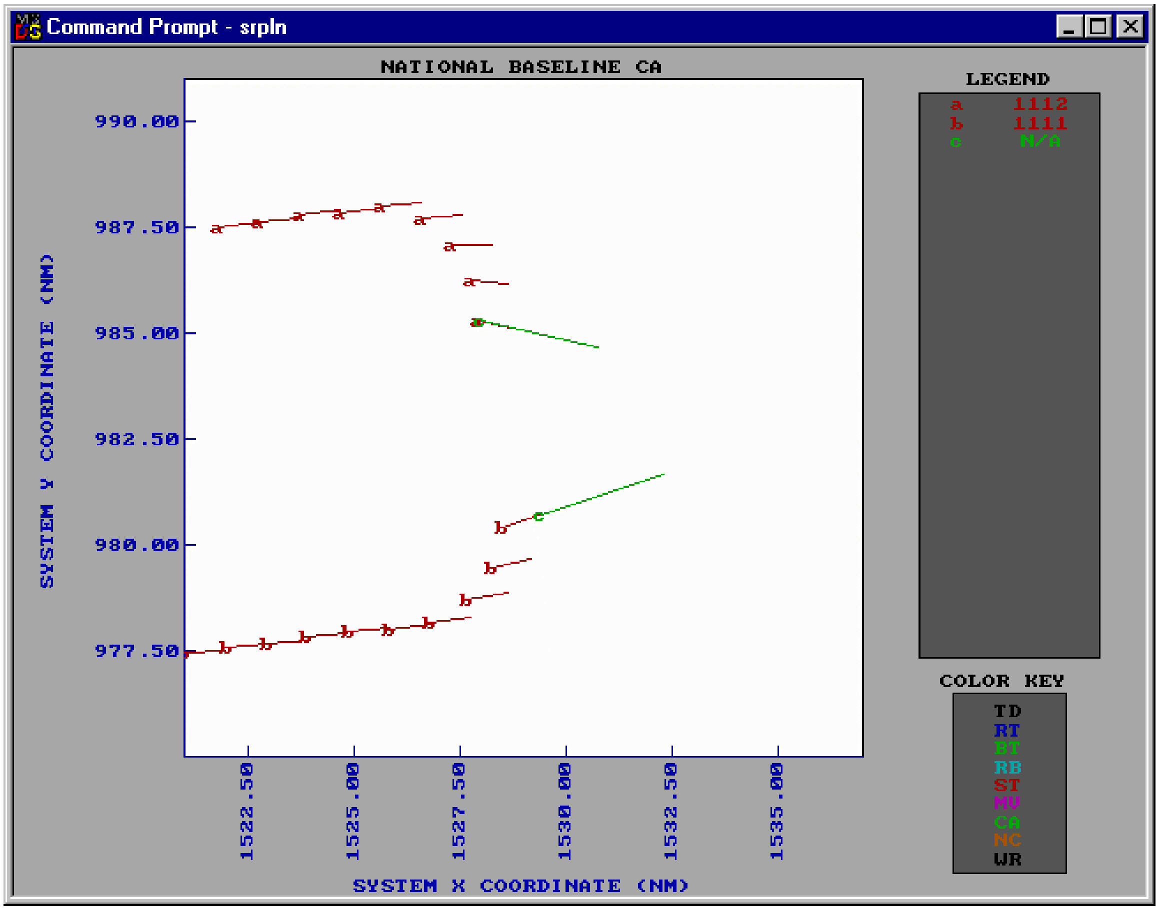
System Plane 1 nmi E/W

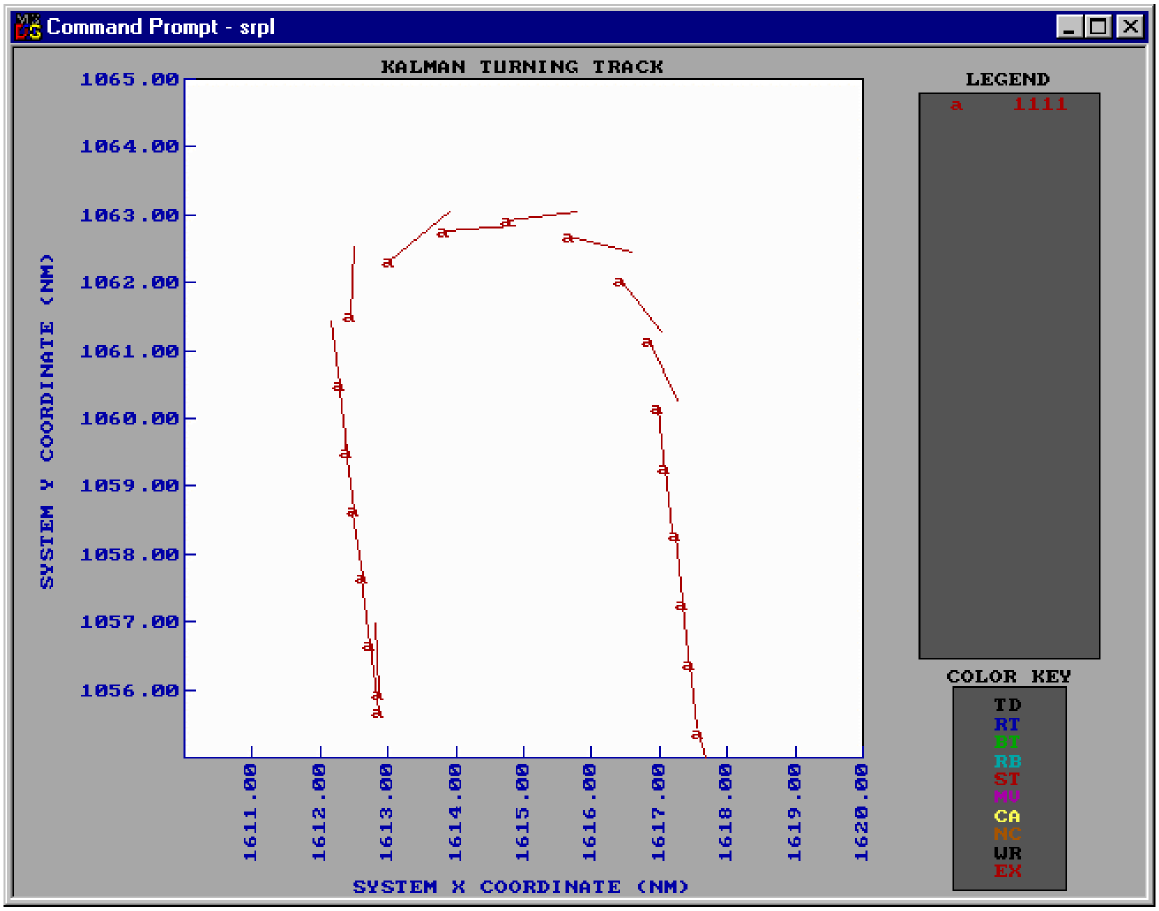

Cape Newenham Long Range Radar/ADS-B Comparison: Turning
Radar returns (12 second scan
ADS-B reports (1 second transmission
Cape Newenham radar 130 nmi range
Flight of FAA's N40 in vicinity of Bethel AK, 21 Aug 2000
595
594
593
592
591
590
589
588
587
586
585
1615
1617
161
1621
1623
162
1627
162
System Plane 1 nmi E/W

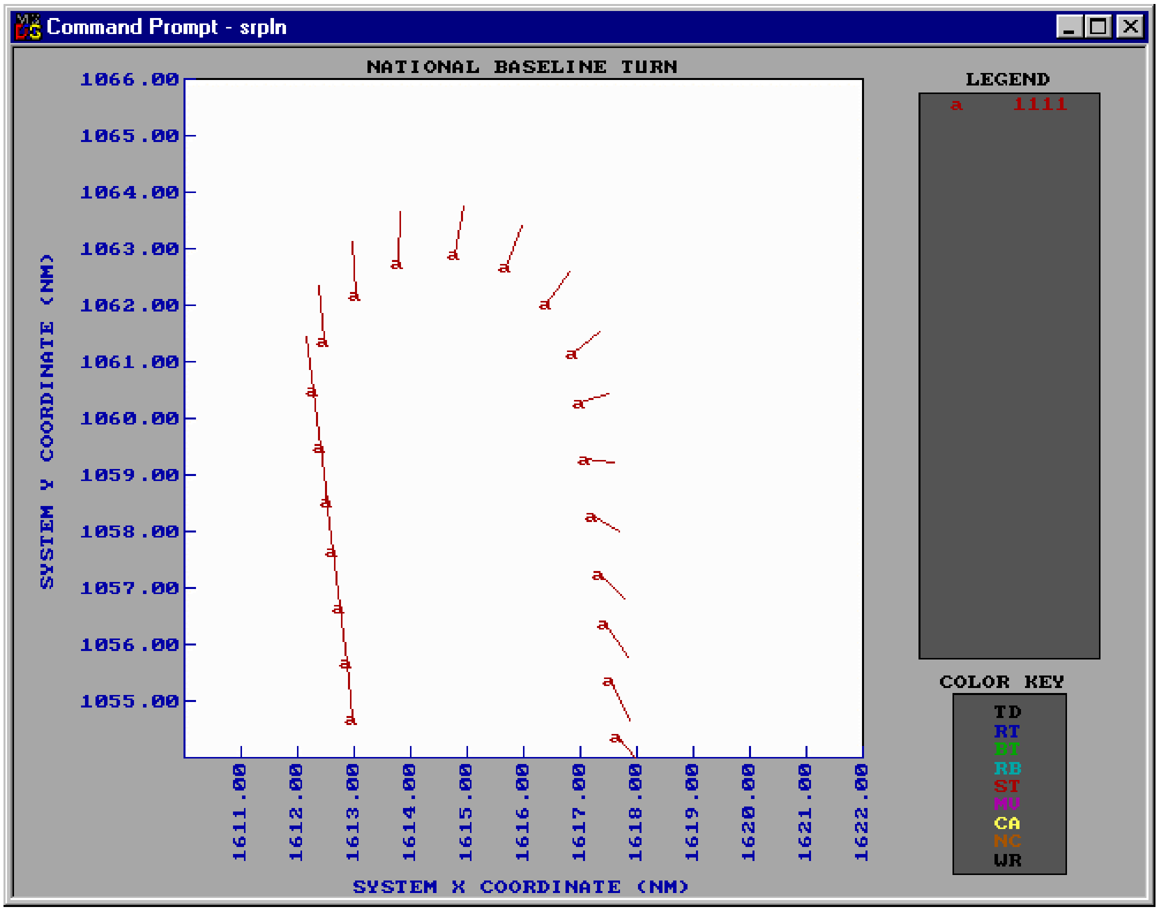
Appendix D
Kalman Filter Data

In response to Objective 8 of the report a comparison was made between the Micro-EARTS National Operational Baseline program and the Micro-EARTS ADS-B Capstone Operational Baseline program that incorporates the Kalman Filter. The comparison was conducted using Micro-EARTS Enhanced Target Generator with a scenario of two aircraft flying parallel then turning towards each other. A similar comparison was conducted with a single aircraft in a turning maneuver. The comparison clearly shows that application of the Kalman Filter as currently incorporated in the Capstone Baseline operational program significantly enhances the tracking of turning and maneuvering aircraft and is more responsive to safety applications such as conflict alert.




Command Prompt - srpln
NATIONAL BASELINE CA
LEGEND
a 1112
b 1111
c N/A
990.00
987.50
985.00
982.50
980.00
977.50
SYSTEM Y COORDINATE (NM)
1522.50
1525.00
1527.50
1530.00
1532.50
1535.00
SYSTEM X COORDINATE (NM)
COLOR KEY
TD
RT
BT
RB
ST
MV
CA
NC
WR


Command Prompt - srpl
KALMAN TURNING TRACK
1065.00
1064.00
1063.00
1062.00
1061.00
1060.00
1059.00
1058.00
1057.00
1056.00
SYSTEM Y COORDINATE (NM)
1611.00
1612.00
1613.00
1614.00
1615.00
1616.00
1617.00
1618.00
1619.00
1620.00
SYSTEM X COORDINATE (NM)
LEGEND
a 1111
COLOR KEY
TD
RT
BI
RB
ST
MU
CA
NC
WR
EX


Command Prompt - srpln
NATIONAL BASELINE TURN
SYSTEM Y COORDINATE (NM)
1066.00
1065.00
1064.00
1063.00
1062.00
1061.00
1060.00
1059.00
1058.00
1057.00
1056.00
1055.00
1611.00
1612.00
1613.00
1614.00
1615.00
1616.00
1617.00
1618.00
1619.00
1620.00
1621.00
1622.00
SYSTEM X COORDINATE (NM)
LEGEND
a 1111
COLOR KEY
TD
RT
BT
RB
ST
MU
CA
NC
WR