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Examination of Airborne Position-Time Estimates From Enroute Automatic Dependent Surveillance

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This paper examines the aircraft provided estimates of future position from flight operations utilizing Automatic Dependent Surveillance – Contract (ADS-C). The goals of the analyses are to estimate and validate the distribution of longitudinal speed errors for these aircraft. This study also presents the development of a tool used to monitor the difference between the aircraft master clock and the Air Route Traffic Control Center (ARTCC) time. This comparison is made using an independent source for aircraft position, en route radar. Radar coverage is not available in oceanic airspace, but aircraft are typically under radar coverage when entering and leaving oceanic airspace. The study makes comparisons between position-matched ADS-C positions, radar-estimated aircraft positions, and filed flight plans. This monitoring activity is critical to airspace safety because air traffic control (ATC) relies heavily on the accuracy of the ADS-C position reports to safely maintain horizontal separation.

I. Introduction

The introduction of advanced aircraft navigation systems and modern Air Traffic Control (ATC) ground systems has allowed for reduced separation standards for suitably equipped aircraft. Separation standards are the minimum distances required between pairs of aircraft to limit the rate of collision. Air traffic services (ATS) apply the separation standards between pairs of aircraft either horizontally or vertically. In non-radar airspace, such as oceanic airspace, ATS use procedural control to ensure the separation standards are in place. Ref. 1 describes procedural ATC as the application of aircraft separation based solely on position information received from aircraft via air-ground communications. The introduction of Automatic Dependent Surveillance-Contract (ADS-C) into the procedural ATC environment allows for suitably equipped aircraft to provide ATC with frequent current position information as well as estimated updates of future aircraft positions. In an ADS-C environment, where current position reports and information on the future positions are communicated directly from the aircraft to ATC, significant reductions in separation minima between suitably equipped aircraft are possible.

Ref. 1 also calls for an evaluation of collision risk when changes to separation minima are considered. Before changes are made to a separation minimum, collision risk analyses are conducted to ensure the proposed changes will meet the safety goals. The lateral navigational performance of the aircraft population is a primary influence on the estimate of collision risk. In addition, the accuracy of the estimates of next position provided by the aircraft influence the collision risk estimates for the longitudinal dimension. An important parameter in estimation of collision risk is the longitudinal overlap probability, which can be determined using traffic data collected from the affected airspace. Longitudinal overlap probability is defined as the likelihood that a pair of nominally separated aircraft are in longitudinal overlap.

This study will examine aircraft-provided estimates of future position and time obtained from enroute ADS-C aircraft. The Ocean21 system, the United States (US) provided ground ATC automation system, uses these estimates of arrival time at the next waypoint along with weather data models to ensure the required separation minima between aircraft is not violated. The results of this study will be used to estimate the longitudinal speed prediction error distribution, used in the collision risk model to evaluate the collision risk associated with reduced longitudinal separation standards.

In addition, this study will develop a means to observe the clock setting accuracy for aircraft utilizing ADS-C with an independent source for aircraft position. The independent source for aircraft positions used in this study is

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en route radar data. Radar coverage is not available in oceanic airspace, but aircraft are typically under radar coverage when entering and leaving oceanic airspace. This study makes comparisons between ADS-C positions and radar-estimated aircraft positions for ADS-C aircraft operating within radar coverage to observe the clock setting accuracy the aircraft utilizing ADS-C.

The general guidance provided by the International Civil Aviation Organization (ICAO) is provided in Ref. 2. Aircraft are to use Coordinated Universal Time (UTC) for flight operations and are required to obtain a time check prior to operating a controlled flight[2]. For flight operations in North Atlantic airspace, the ICAO and regional groups provide guidance for setting the aircraft master clock specific to aircraft utilizing ADS-C. This guidance is contained in Ref. 3. The guidance states that it is important for the time-keeping device used to indicate waypoint passing, the aircraft Master Clock, to be accurate. The aircraft Master Clock should be synchronized to an acceptable UTC signal prior to take-off[3]. For enroute aircraft using ADS-C, it is often assumed that the aircraft clock is synchronized to GPS time. However, this practice is not monitored and ATC is left to trust the position-time information provided by the airborne systems.

This paper contains comparisons between the time-stamps obtained from ADS-C positions and radar-estimated aircraft positions as aircraft enter and leave the New York and Oakland Oceanic Flight Information Regions (FIRs). The very accurate current position information, latitude and longitude, provided by GPS-based ADS-C aircraft were examined in Ref 4. The intention of this exercise is to develop a tool to regularly monitor the time-keeping accuracy of ADS-C aircraft in oceanic airspace and to notify the ATS providers and airspace users if results suggest there is evidence of clock setting discrepancies. This monitoring activity is critical to airspace safety because ATC and the Ocean21 system rely heavily on the accuracy of the ADS-C position reports to safely maintain horizontal separation.

II. Background

The reduced separation standards applied in oceanic airspace rely on the use of ADS-C, satellite data communication, and Global Navigation Satellite Systems (GNSS) for the essential communication, navigation and surveillance (CNS) functions. The development of the initial plan to utilize these advanced CNS systems is described in Ref 4. As a consequence of this plan, the US Federal Aviation Administration (FAA) introduced a new oceanic ATC automation system, Ocean21. Ocean21 was introduced into full-time operation at the Oakland Oceanic Air Route Traffic Control Center (ARTCC) in October 2005, and into the New York Oceanic ARTCC in June 2006 for controlling flight operations in the Oakland and New York oceanic FIRs, respectively.

The Oakland Oceanic ARTCC is an ATS provider, responsible for roughly 18 million square miles of airspace over the Pacific Ocean. Figure 1 is a graphical representation of the portion of Pacific oceanic airspace controlled by the Oakland Oceanic ARTCC, referred to as the Oakland Oceanic FIR. This airspace contains diverse traffic flows, some of which are amongst the longest scheduled flights in the world.

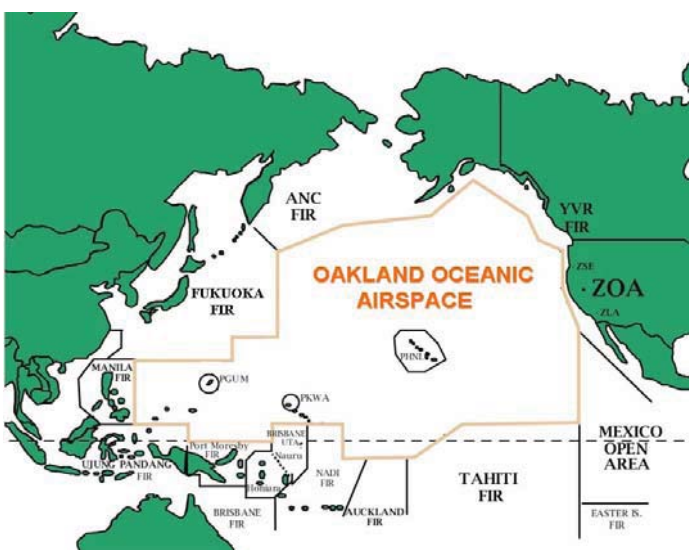

Figure 1. Oakland Oceanic FIR

The New York Oceanic ARTCC is an ATS provider responsible for a portion of the North Atlantic Traffic Flow, which contains air traffic operating primarily between North American and European regions. The New York Oceanic ARTCC is also responsible for the majority of the Western Atlantic Route System (WATRS). The WATRS route network is composed of two principal flows: north-south connecting the East Coast of the United States and eastern Canada with the Caribbean-South American region, and southwest-northeast connecting Europe with the southeastern United States and the Caribbean, with ancillary traffic flow between the southern United States and the Caribbean-South American region. Figure 2 is a graphical representation of the airspace controlled by the New York Oceanic ARTCC, referred to as the New York Oceanic FIR.

The introduction of the decision-support tools provided by Ocean21 in the Oakland Oceanic FIR and in conjunction with improvements in the CNS capabilities made by the user community, has allowed the FAA to reduce the horizontal separation standards for pairs of suitably equipped aircraft. Similar reductions in lateral and longitudinal separation standards have not been introduced into the New York Oceanic FIR due to the low proportions of suitably equipped aircraft and limitations in the existing ground systems of the ATS providers surrounding the New York Oceanic FIR.

In Pacific airspace, those airspace users meeting the requirements for reduced separation will experience benefits including enhanced capacity and increased efficiency of operations. One of the CNS requirements for reduction in the longitudinal separation standard is ADS-C[5-6]. Ref. 7 describes the details of the ADS-C communication contracts which are established between ATC ground systems and an aircraft's avionics system. The use of ADS-C is intended to replace controller-pilot data link communications (CPDLC) and verbal position reporting in oceanic and other airspace where procedural separation is currently applied[7].

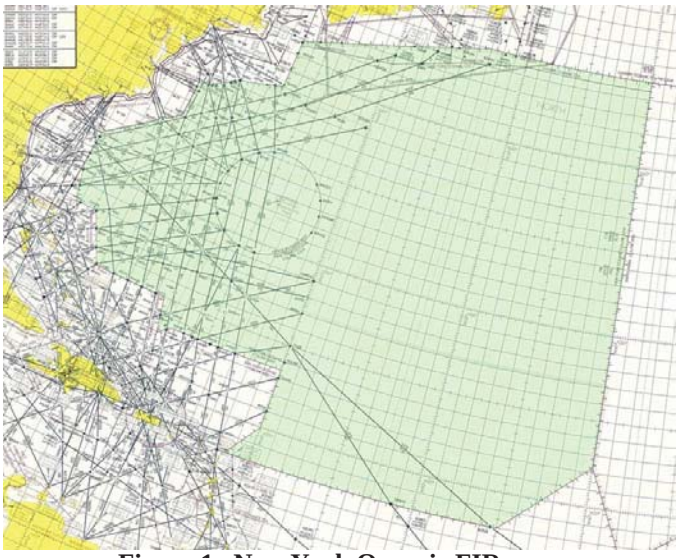

Figure 1. New York Oceanic FIR

Aircraft eligible for reduced horizontal separation standards and which operate inside the Oakland Oceanic FIR, utilize ADS-C for position reporting. The ADS-C position report contains aircraft position estimated by the aircraft's navigation system. For these aircraft, the ADS-C position report is informed by highly accurate position determination accomplished in the aircraft navigation system. The ADS-C position data are obtained from the aircraft Flight Management System (FMS) which chooses from amongst the navigation sensors available (for example, Global Positioning System (GPS), Distance Measuring Equipment (DME), and Inertial Navigation System (INS)) to obtain the best possible position solution. In oceanic operation, the best possible position solution typically comes from GPS, given that enough GPS satellites are available. Frequent reporting of the aircraft's accurate position is important in the assurance that the reduced separation minima are applied safely. In addition, certain ADS-C position reports contain estimated time of arrival (ETA) at the next sequenced compulsory reporting point, or waypoint. Due to the frequency of the ADS-C reports, it is possible for ATC to receive several updated estimates of aircraft position for the same future waypoint prior to the aircraft reaching the waypoint.

III. Data Sources and Descriptions

Historical data obtained from the Ocean21 system has been made available for this study. The data from the Ocean21 system contains the ADS-C position reports and the filed flight plans for flights operating within the New York and Oakland Oceanic FIRs. There are two types of ADS-C position reports examined in this study. Table 1 contains descriptions of these position report types. The generation of the ADS-C position reports listed in Table 1 requires ATC to send an uplink ADS-C message to the aircraft. These uplink messages specify the information requested for each message type. If the uplink ADS-C message is missing or not specified correctly, the aircraft avionics will not generate the ADS-C position reports. Ref. 7, section 6.2 contains a description of the required uplink ADS-C messages for each of the ADS-C position reports listed in Table 1.

Table 1. ADS-C Position Report Types Examined

ADS-C Report Type	Report Frequency	Description of Contents
Basic Periodic Report	1) Depends on a variable periodic contract, either 14, 20, or 27 minutes under normal operation 2) Response to a request for position	1) Current aircraft position (position, altitude, time) 2) Estimate of navigational accuracy 3) Estimate of next position (position, altitude,

ADS-C Report Type	Report Frequency	Description of Contents
	from ATC (Demand contract) 3) Reporting frequency if 5 minutes if reduced separations are applied and a weather deviation clearance is given	estimated time of arrival (ETA)) 4) Estimate of next-plus-one position (position and altitude) 5) Information including current heading, aircraft speed, wind direction/magnitude, and temperature
Waypoint Change Report	1) Under normal operation, report is sent during routine waypoint sequencing 2) Any change to next or next-plus-one waypoints, such as a change to a non-ATS waypoint entered by pilot, or execution of a new route	1) Current aircraft position (position, altitude, time) 2) Estimate of navigational accuracy 3) Estimate of next position (position, altitude, estimated time of arrival (ETA)) 4) Estimate of next-plus-one position (position and altitude)

In Table 1, the report frequency for the Basic Periodic Report is given as 14, 20 or 27 minutes as a means to support variable separation minima. The Ocean21 system assigns the appropriate reporting frequency for the Basic Periodic Reports using the filed Required Navigation Performance (RNP) level contained in the flight plan. In Oakland Oceanic airspace, there are two RNP levels an aircraft can file for operations in Pacific airspace. The filed RNP level indicates the navigational accuracy that supports the 50nm or the 30nm lateral separation standard, and implies the report frequency for the Basic Periodic Reports will be 27 or 14 minutes, respectively. In New York Oceanic airspace, aircraft equipped with ADS-C are given a periodic reporting frequency of 14 minutes if the filed RNP level is given as RNP 4, and a 20 minute periodic reporting frequency is assigned to the remaining ADS-C equipped aircraft.

En route radar data are obtained from the FAA's PC-based continuous radar data recorder system, the Enhanced - Radar Intelligent Tool (E-RIT). E-RIT is designed to provide ARTCCs with PC-based radar data recording and analysis tools. These data are made available to the FAA Technical Center. This study makes use of E-RIT recorded data from both the east and west coast of the US. The New York Oceanic FIR overlaps with airspace covered by radars used by the Boston, New York, Washington DC, and Jacksonville ARTCCs, this group is referred to as the East Coast ARTCCs in the paper. The Oakland Oceanic FIR overlaps with airspace covered by radars used by the Seattle, Oakland and Los Angeles ARTCCs, this group is referred to as the West Coast ARTCCs in the paper. The raw data are recorded and extracted to text files using software developed by the 84th Radar Evaluation Squadron (RADES) of the United States Air Force (USAF) which allows for data filtering. Filters are set to extract the following from the raw data; beacon reinforced messages, Mode C values between FL200 and FL430, and traffic within preset geographic boundaries. All radar-derived positions available for the ADS-C aircraft are used in this analysis. The RADES software contains a graphical viewer with an option to output the data in ASCII format. The output file contains a version of the original data reduced according to the filters selected before running the software. Data from sixty-three Air Route Surveillance Radars (ARSR) were available for this study. Sample radar images taken with the RADES software are shown in Figures 3 and 4. The data displayed in Figure 3 represent two hours of flight data from the radars located on the west coast of the US. Figure 4 displays two hours of flight data from the radars located on the east coast of the US.

The time source for the radar data made available for the study is the same time kept by the ARTCC utilizing the radar for obtaining aircraft position estimates. This paper refers to the time kept at the ARTCC as the ARTCC Time. The FAA requires that Coordinated Universal Time (UTC) be used in all operating facilities. The time keeping requirements for each FAA facility is described in Ref 8. Specifically, Ref 8, paragraph 205.c states:

> "The External Communications Server (ECS) also handles the interface to an external Coded Time Source (CTS), and is responsible for using the standard Network Time Protocol (NTP) to synchronize other processors in the system. Two Global Positioning System (GPS) time receivers are present at each facility and each of the two ECSs on either channel are attached to different receivers for availability purposes."[8]

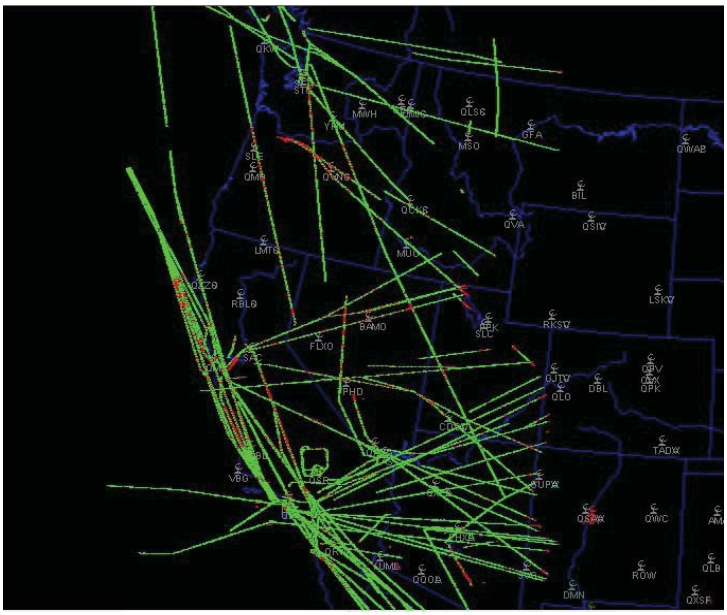

Figure 3. Sample Radar Image, Aircraft Positions from the West Coast ARTCCs

The FAA's Enhanced Traffic Management System (ETMS) provides the means of applying air traffic management principles to traffic movements in the U.S. National Airspace System, as well as in oceanic airspace delegated to the FAA. The ETMS records pertaining to operations in New York and Oakland oceanic airspace were available to provide flight-identification information not available in the en route radar data. These data were position and time-matched, then appended to the en route radar data.

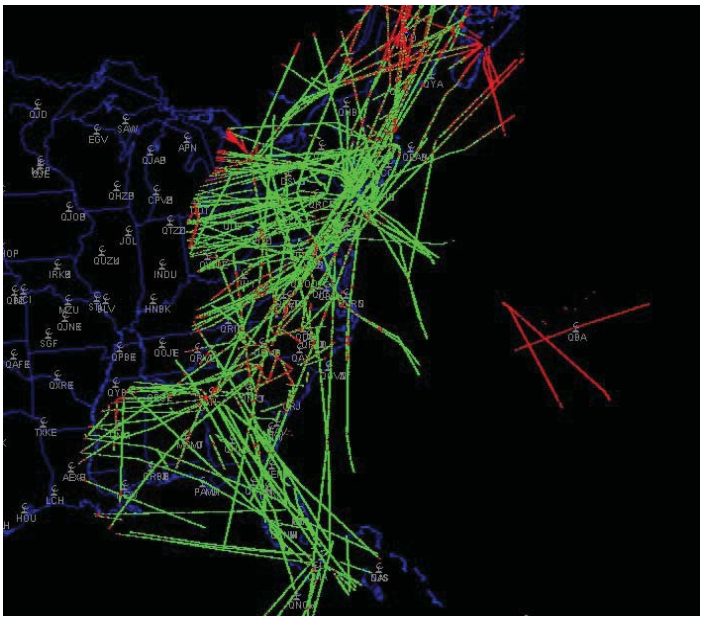

Figure 4. Sample Radar Image, Aircraft Positions from the East Coast ARTCCs

IV. Review of Related Studies

A study which examined the distribution of the longitudinal speed prediction error in a similar airspace is presented in Ref 9. Ref 9 evaluates ADS-C data received in a portion of North Pacific Oceanic airspace, whose air

traffic services are provided by the Japan Civil Aviation Bureau (JCAB). There are differences in the ground systems used by the FAA and JCAB. One difference relevant to this study are the options selected for the ADS-C Basic Periodic Report. The JCAB ATC-systems utilize additional information in the Basic Periodic Report, this additional information is called the intent data. The intent data provides a prediction for aircraft position at the expected time of the next Basic Periodic Report. Therefore, in addition to the position prediction at the next sequenced waypoint, the study presented in Ref. 9 accessed position predictions for the expected aircraft position at the time the next Basic Periodic Report was expected. The aircraft operating in the New York and Oakland Oceanic FIRs do not provide position estimates for the time the next expected Basic Periodic Report is due, position estimates are provided for the next sequenced waypoint only. The ATC automation for the New York and Oakland Oceanic FIRs do not request intent data when the ADS-C contracts are established.

In addition, the study presented in Ref. 9 evaluates the longitudinal speed prediction error for a parallel route system. The New York and Oakland Oceanic FIRs consists of various traffic flows – some of which occur within the inter-tropical convergence zone (Ref. 10). The inter-tropical convergence zone is a region of clouds and occasional thunderstorms that encircle the earth near the equator. It is not unusual for aircraft operating in this region to require a change of planned course due to weather. Each change in course affects the aircraft-provided estimates of future positions.

V. Methodology

This paper presents analyses of empirical data from trans-oceanic aircraft operating within the New York and Oakland Oceanic FIRs. The Ocean21 data archives contain the ADS-C position reports and aircraft-filed flight plans. The ADS-C position reports provide the aircraft estimates of current and next position. These position reports were matched to the filed flight plan to identify the aircraft type for each flight.

In addition, a portion of the study concentrates on operations transferring between oceanic airspace and the airspace over the Continental United States (CONUS). The independent data source needed to examine aspects of these operations includes the radar-derived aircraft positions obtained from the major ARTCCs located along the east and west coast of the CONUS. These data are matched to the ETMS data containing flight identification information. The RADES software provides the radar-derived aircraft positions, the latitude and longitude, from the given slant range and azimuth contained in the raw en route radar data.

The data period examined was February through May 2009 for the analysis of the airborne position time estimates. The sample period over which the clock setting accuracy study was conducted was 53 days between March and April 2009 for which en route radar and ETMS data were available from the East and West Coast ARTCCs.

A. Assumptions

This analysis assumes aircraft follow great circle paths between consecutive waypoints. The flight segments examined in this paper are taken from oceanic operations in both Pacific and North Atlantic airspace. The time period between consecutive position reports can be as much as 27 minutes. Therefore, interpolation of the aircraft actual position using the reported position locations is sometimes needed to properly examine the difference between the aircraft estimate of position and the actual position. The assumption that aircraft follow great circle paths between consecutive waypoints is heavily used in the interpolation process.

B. Treatment of the Aircraft Estimates of Future Position

Since ADS-C position reports are important to ensure that the reduced horizontal separation minima are applied safely, the accuracy of the reports and estimates of future positions are also important. The aircraft provide two ADS-C message types which contain estimates of next position, Waypoint Change Report and Basic Periodic Report (see table 1). The reported positions for all aircraft utilizing ADS-C were assembled and organized by message time. The ADS-C messages containing estimates of next position were examined. For each estimate of next position, an attempt to find the matching Waypoint Change Report was made. As exact matches of estimated and actual position were rare, most estimates required interpolation of the next position. An exact match was determined if the estimated great circle distance between the aircraft-provided estimate of position and the actual Waypoint Change Report was less than 2.5nm. This criterion was used due to the possibility of an aircraft applying the strategic lateral offset procedure. The actual reported ADS-C positions were used to perform the interpolation, Ref 4. provides details on the accuracy of these position reports. The interpolation to determine the actual position and time of the aircraft was performed according to the following steps:

1) The direction of the flight was determined to be either north, south, east or west.

2) A search for two position reports which "straddle" the aircraft-provided estimate of position was performed. The criterion used in the search was aircraft location – not time. The key was to find one position report whose location along the flight path was just before the aircraft-provided estimate of position and another position report whose location along the flight path was just after the aircraft-provided estimate of position rather than finding the two reported positions whose reported time straddled the estimated time over position.
3) If the direction of the flight was determined to be north or south – the latitude of the aircraft-provided estimate of position was used to interpolate for the longitude and the time over the interpolated position. If the direction of the flight was determined to be east or west – the longitude of the aircraft-provided estimate of position was used to interpolate for the latitude and the time over the interpolated position.
4) Let the latitude and longitude for the two positions which "straddle" the unknown position be represented as (φ_1,θ_1) and (φ_2,θ_2). If flight is traveling east or west, the interpolated longitude, θ_i, is taken from the aircraft-provided estimate of position. If the flight is traveling north or south, the interpolated latitude, φ_i, is taken from the aircraft-provided estimate of position.
5) The plane which intersects the sphere has equation $Ax+By+Cz=0$. The coefficients for the plane, A, B and C, which intersects the sphere at the points (φ_1,θ_1), (φ_2,θ_2) and the origin are determined from the following:

$$A = \cos(\varphi_1)\cos(\theta_1)\sin(\varphi_2)-\cos(\varphi_2)\cos(\theta_2)\sin(\varphi_1)$$

$$B = \sin(\varphi_1)\cos(\varphi_2)\sin(\theta_2)-\sin(\varphi_2)\cos(\varphi_1)\sin(\theta_1)$$

$$C = \cos(\varphi_1)\sin(\theta_1)\cos(\varphi_2)\cos(\theta_2)-\cos(\varphi_2)\sin(\theta_2)\cos(\varphi_1)\cos(\theta_1)$$

6) Using this plane, the unknown latitude, φ_i, is found by solving:

$$\varphi_i = -\arctan((A\sin(\theta_i)+B\cos(\theta_i))/C)$$

7) There are two solutions for the interpolated longitude, θ_i, the solution is the longitude which is between (φ_1,θ_1) and (φ_2,θ_2). The solutions for θ_i, are found by solving:

$$\sin(\theta_{i1}) = \frac{(-AC\tan(\phi_i) + B\sqrt{A^2 + B^2 - C^2\tan^2(\phi_i)}}{A^2 + B^2}$$

$$\cos(\theta_{i1}) = \frac{(-BC\tan(\phi_i) - A\sqrt{A^2 + B^2 - C^2\tan^2(\phi_i)}}{A^2 + B^2}$$

$$\sin(\theta_{i2}) = \frac{(-AC\tan(\phi_i) - B\sqrt{A^2 + B^2 - C^2\tan^2(\phi_i)}}{A^2 + B^2}$$

$$\cos(\theta_{i2}) = \frac{(-BC\tan(\phi_i) + A\sqrt{A^2 + B^2 - C^2\tan^2(\phi_i)}}{A^2 + B^2}$$

The two solutions for the interpolated longitude, θ_{i1} and θ_{i2}, are found by:

$$if\ \sin(\theta_{i1}) \geq 0, \quad \theta_{i1} = a\cos(\cos(\theta_{i1});$$

$$\sin(\theta_{i1}) < 0, \quad \theta_{i1} = -a\cos(\cos(\theta_{i1})$$

$$if\ \sin(\theta_{i2}) \geq 0, \quad \theta_{i2} = a\cos(\cos(\theta_{i2});$$

$$\sin(\theta_{i2}) < 0, \quad \theta_{i2} = -a\cos(\cos(\theta_{i2})$$

8) Assuming constant speed between consecutive position reports, the speed between the points (φ_1,θ_1), (φ_2,θ_2) is determined using the travel time and great circle distance between the points (φ_1,θ_1) and (φ_2,θ_2). The time at the interpolated position, T_i, is determined using the assumed aircraft constant speed and the great circle distance between the points (φ_1,θ_1) and (φ_i,θ_i).

9) The measurement of error is examined in terms of both time, E_t, and speed, E_s. The time error is computed as the difference of the actual or interpolated time at the estimated location from the aircraft-provided estimate of time, T_e, at next waypoint. The speed error, E_s, is computed as the difference of the actual or interpolated speed, S_i, from the speed computed given the aircraft-provided estimate, S_e, of next waypoint.

$$E_t = T_e - T_i \tag{1}$$

$$E_s = S_e - S_i \tag{2}$$

Interpolation was needed when a matching Waypoint Change Report was not found for the aircraft-provided estimate of position. There were several different cases in which a matching Waypoint Change Report was not found. One frequently occurring case was when the pilot made changes to the next sequenced waypoint(s) in the Flight Management System (FMS) prior to the aircraft reaching the previously reported next waypoint. These changes to the FMS are sometimes made when severe weather is encountered and a change of course is needed. Figure 5 provides an example of a case in which the ADS-C messages received indicated that a change to the next waypoint was made in the FMS and illustrates the corresponding interpolation results. The flight path pictured in Figure 5 is from a southbound flight operating in Oakland oceanic airspace. The portion of the flight shown is between 10°N latitude and 10°S latitude. The blue line represents the reported flight path. The red triangles are the locations of the aircraft-provided estimated future waypoints. The green circles are the actual and/or interpolated waypoint locations used to compare the aircraft-estimated versus the actual waypoint positions. The example in Figure 5 shows the location of the aircraft-provided estimate of the next waypoint to be slightly west of the flight path. Prior to reaching the first waypoint pictured, an adjustment was made to the FMS indicating a slight change of course. Other data sources available indicate that this flight requested and was cleared for a weather deviation.

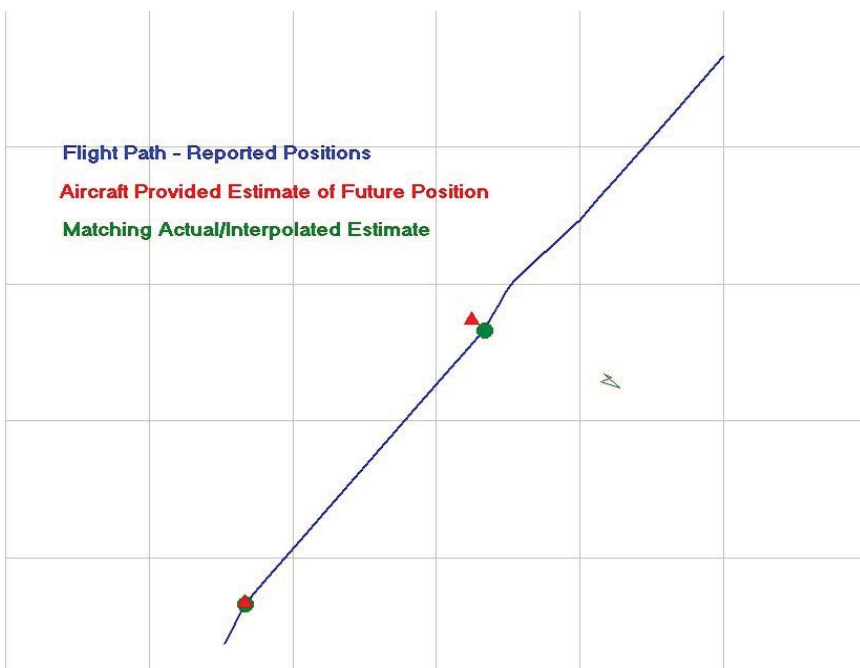

Figure 5. Example of Interpolation for the location of the actual aircraft position to match the aircraft estimated position

C. Correlation between Aircraft-Provided Estimate of Position and Time at Next Waypoint and Actual Waypoint Position and Time

Comparisons among each set of aircraft-provided estimate of next waypoint and actual or interpolated waypoint are made to draw conclusions regarding the longitudinal prediction error for aircraft which are candidates for application of reduced horizontal separation minima. The comparisons are made using equations (1) and (2). These comparisons also provide the basis on which to estimate and validate the distribution of longitudinal prediction errors for these aircraft.

D. Treatment of the Radar-derived Position Estimates

As mentioned earlier, radar-derived position estimates were made available for this study from the East and West Coast ARTCCs. The intent of this paper is to use the radar position estimates as an independent source of time for comparison with the aircraft master clock, not to measure the error in the radar position estimate. It is known, that radar position error increases as the distance between the radar location and the aircraft increases. Thus, the examination of the aircraft clock setting accuracy used radar-derived position estimates which were within 75nm of the radar location. This restriction was imposed to reduce the contribution of errors in the radar position estimates.

Depending upon the location of the aircraft considered in this study, the data show it is possible for multiple radars to provide a position estimate for the aircraft. Because of different rotation rates among the individual radars, and the location of the aircraft, these position estimates do not occur at the same time. The radar position estimates come from any one of the available radar sources. For each individual comparison of time, radar data from only one source is used to limit any errors introduced from using multiple radars at different distances from the aircraft. Due to the infrequent ADS-C position reports, in some cases it was necessary to interpolate between consecutive radar-derived aircraft positions to obtain a match for comparison. The interpolation on the radar position estimate was performed according to the following steps:

1) All the radar position estimates available for each ADS-C flight were assembled
2) From these position estimates, any radar position estimates located within 75nm of the radar location were examined. The resulting radar estimates were further examined for potential matches with ADS-C position reports. Any exact matches in position location were identified.
3) If an exact match was not found, the two closest, in terms of distance, radar-estimated positions which "straddled" each ADS-C position report were found and used in the interpolation.
4) Assuming a constant speed between the consecutive radar-estimated positions, the "radar" time for the matching ADS-C position report was determined. To minimize any error in the radar-estimated position of the aircraft, the estimated radar time at the ADS-C position was taken as the average time calculated in reference to both of the given radar-estimated position times.

VI. Analysis and Results

A. Aircraft Estimate of Future Waypoint Position and Time and the Actual Waypoint Position and Time

The sample period examined in this paper consisted of a four month interval from February 2009 through May 2009, inclusive. ADS-C position reports from both the New York and Oakland Oceanic FIRs were examined. There were 65,449 and 63,703 unique ADS-C flights examined in the New York and Oakland Oceanic FIR data sets, respectively. All of the Basic Periodic Reports and Waypoint Change Reports from these unique flights were considered. The number of Basic Periodic Reports and Waypoint Change Reports received during the sample period at the New York and Oakland ARTCCs were 242,206 and 695,456, respectively. The flying time for operations conducted in the Oakland Oceanic FIR is much longer than those conducted in New York Oceanic FIR resulting in many more messages received by the Oakland ARTCC than by the New York ARTCC.

All of the Basic Periodic Reports and Waypoint Change Reports received were examined. Some of these messages contained estimates of future position which resulted in abnormally large values for E_t and E_s. In an attempt to assess the cause of these large values and further quantify the results, an additional parameter was introduced to the analysis. The total time for which the current estimate of future position was used in the Ocean21 system was considered. This time was calculated as the time between consecutive ADS-C messages, Basic Periodic Reports and/or Waypoint Change Reports, providing estimates of future position from the same aircraft. This time is referred to as the time until the next update. In some instances the aircraft-provided estimates of next position which resulted in abnormally large values for E_t and E_s were quickly replaced with more accurate estimates, likely due to action taken by ATC to request a replacement ADS-C message from the aircraft. The quick replacement of the future position estimate was observed through the examination of the time until the next update. The aircraft-

provided estimates of future position with abnormally large values for E_t and E_s and less than two minutes until the next update were excluded from this analysis.

Table 2 provides a listing of the categories created to assess the cause of the observed large values for E_t and E_s. The first category listed in Table 2, describes the ADS-C messages for which the aircraft-provided estimate of future position was located in adjacent airspace. The ADS-C reports meeting this description were excluded from the analysis because a matching actual position would not be found in the available data once the aircraft left either the New York or Oakland Oceanic FIR. The second category listed in Table 2 addresses the problems related to the datalink transit time and connectivity; these messages were also removed from the analysis. Categories 3 through 5 are related to observed errors in the ADS-C messages. All of the aircraft-provided estimates of future position which match the description of categories 3 and 4 were removed from the analysis, but the estimates of future position matching category 5 were further examined. If the time until the next update for the estimates of future position corresponding to category 5 was less than 2 minutes, the estimate was removed from the analysis. Category 6 deals with aircraft-provided future positions undergoing multiple observed changes prior to the aircraft crossing over any of the future positions. It was not possible to locate a matching actual position report or perform interpolation for all of these cases, thus the estimate of future position was removed from the analysis.

Table 2. Categories for Frequently Observed Errors in Aircraft-Provided Estimate of Position

Category	Description
1	Aircraft does not cross over the estimated future position in New York or Oakland oceanic airspace because the future position is located within adjacent airspace. This it is not possible to obtain an actual position report for the aircraft over the estimated future position
2	ADS-C position reports were unavailable for the estimated future position due to problems with ADS/datalink connection. This problem can cause the ADS-C report to arrive much later than expected. It can also require a change in the medium used for position reporting to High Frequency (HF) radio.
3	The ADS-C message is incomplete. The estimated time and/or position of the next waypoint are missing from the message.
4	Error in the aircraft-provided estimate of future position. The aircraft had already crossed over the estimated future position prior to transmitting the current ADS-C report.
5	Error in the aircraft-provided estimate of time at future position. In some cases, the aircraft-provided time estimate at future position was equivalent to the current message time. In other cases, the provided time estimate at future position resulted in an abnormally low speed.
6	Multiple changes made to aircraft-provided future positions were observed in data. Matching actual position not found or interpolation not possible for all of the adjusted estimates of future position. Some of these instances were combined with lateral deviation reports, indicating a possible change in course.

Summary statistics from the New York and Oakland Oceanic FIRs are presented in Table 3. The time error, E_t, and speed error, E_s, are computed using equations (1) and (2), respectively. The negative values for the time error indicate that the actual time was later than that estimated by the aircraft. The positive values for the speed error indicate that the aircraft estimated speed is faster than the actual speed.

The mean estimates of Time Error, E_t, for both New York and Oakland airspace are slightly negative, while the mean estimates of speed error, E_s, are positive. This result makes sense intuitively since a negative estimate for E_t means the aircraft crossed over the waypoint later than expected, which also means that the expected speed of the aircraft was faster than what was actually observed resulting in a positive estimate for E_s.

Table 3. Summary Statistics for the Time and Speed Errors

Summary Statistics	Speed Error, E_s, for New York Oceanic Airspace (knots)	Time Error, E_t, for New York Oceanic Airspace (min)	Speed Error, E_s, for Oakland Oceanic Airspace (knots)	Time Error, E_t, for Oakland Oceanic Airspace (min)
Number of Position Estimates	105,758	105,758	396,654	396,654
1st Quantile	-4.229	-0.350	-2.640	-0.450

Summary Statistics	Speed Error, E_s, for New York Oceanic Airspace (knots)	Time Error, E_t, for New York Oceanic Airspace (min)	Speed Error, E_s, for Oakland Oceanic Airspace (knots)	Time Error, E_t, for Oakland Oceanic Airspace (min)
Median Value	0.518	-0.050	1.975	-0.100
3rd Quantile	5.402	0.150	6.995	0.100
Mean	0.601	-0.267	2.364	-0.203
Variance	98.353	10.938	96.638	0.802
Skewness	-0.205	-22.174	0.825	-0.308
Kurtosis	14.134	591.146	34.317	75.291

A large number of aircraft-provided estimates of future position were observed in the New York data matching the description in category 5 of Table 2 having relatively long time durations for the time until the next update. These estimates remain in the analysis for now; however, future plans include an evaluation of these data by a group of operational experts. Following this review, the analysis will be revised accordingly.

The skewness, which is a measure of the lack of symmetry in the data, is presented for each error type listed in Table 3. The time error estimates for both the New York and Oakland Oceanic FIRs show the data to be negatively skewed. The kurtosis, which is a measure of the tail-heaviness of the distribution, is also provided for each case presented in Table 3. The kurtosis values are large, indicating the distributions can be considered to have heavy tails. The kurtosis is much larger for the E_t than that of the E_s, indicating the E_t has a more acute peak in the center of the distribution and infrequent larger values in the tails of the distribution. This result is likely due to the smaller magnitudes of the values for E_t comparison to the larger magnitudes for the E_s values. The high number of estimates matching the description in category 5 of Table 2 is likely the cause of the higher variance, skewness and kurtosis for E_t in New York airspace compared to Oakland airspace. Further investigation into these data by operational experts is needed to confirm this result.

Figures 6 and 7 present the histograms of the time error, E_t, for the New York and Oakland data sets, respectively. Figures 8 and 9 present the histograms for the speed error, E_s, for the New York and Oakland data sets, respectively.

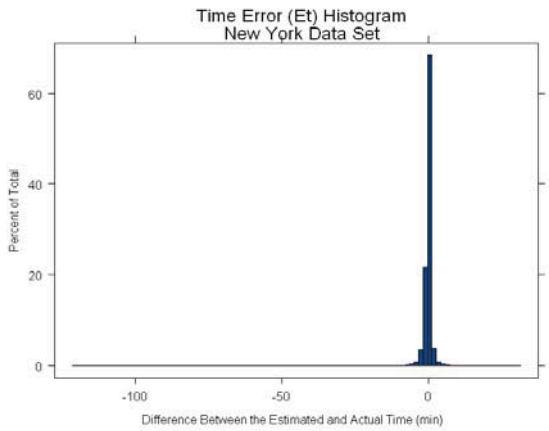

Figure 6. Empirical Histogram of the Time Error, E_t, New York Data Set

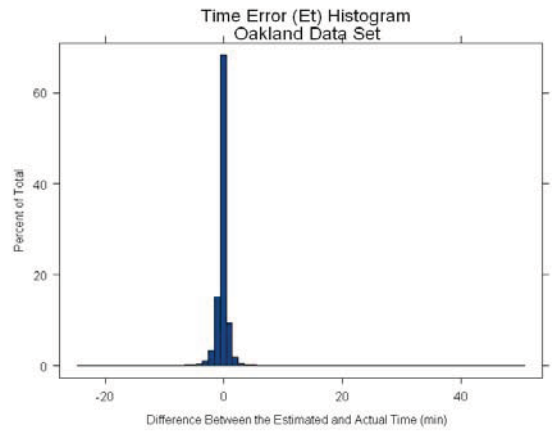

Figure 7. Empirical Histogram of the Time Error, E_t, Oakland Data Set

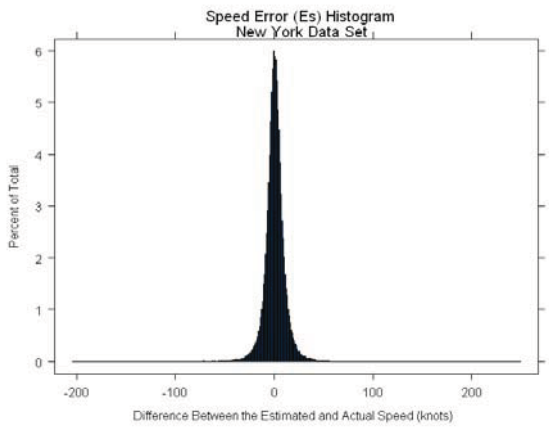

Figure 8. Empirical Histogram of the Speed Error, E_s, New York Data Set

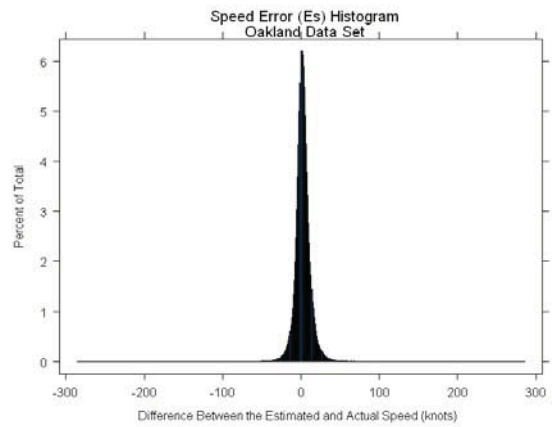

Figure 9. Empirical Histogram of the Speed Error, E_s, Oakland Data Set

The range in the time error, E_t, from the New York data set is slightly larger than range in the time error from the Oakland data set. This result is visible in comparing Figures 6 and 7 which presents the empirical histograms of the time error from both data sets. The larger variance for the time error data from New York shown in Table 3 provides further evidence that there are observed differences in the two data sets.

The results shown in Table 3 and Figures 6 through 9 show the comparisons between of the empirical data from the New York and Oakland data sets. It is clear from these results the data do not follow the same distribution. To confirm this, a Kolmogorov-Smirnov goodness of fit at a 95% confidence level was performed on the data. The test result indicated to reject the null hypothesis, that the time and speed error data from the New York Oceanic FIR are not drawn from the same distribution as the time and speed error data from the Oakland Oceanic FIR. This result is not surprising, given the observed differences in the estimates of position due to a variety of reasons such as dissimilar weather conditions, periodic reporting times for ADS-C aircraft, mixture of aircraft types utilizing the airspace, and frequency of errors observed in the messages containing estimates of future position. However, the results do show that the time and speed error distributions are of similar shape and non-normal in both New York and Oakland data.

The time and speed error values with large magnitudes and with corresponding large values for the time until the next update appear in the tails of the data. As mentioned earlier, future plans include assembling a group of operational experts to review these events. The purpose of the operational expert review is to obtain information related to the effect these events may have on both ATC and aircrew operations, with the possibility for corrective action to be implemented if necessary. More detailed information will be presented to the group of operational experts, such as the Box and Whisker plots contained in Figures 10 and 11. The data presented in Figure 10 and 11

contain the time error data by aircraft group from New York and Oakland airspace, respectively. The names of the aircraft groups have been de-identified in the figures.

Although the names of the aircraft groups have been de-identified, the time error data from the New York data set show clear differences between the aircraft groups. Most of the extreme data shown in Figure 10 for aircraft groups "Y" and "Z" meet the criteria for at least one of the categories presented in Table 2. However these data had relatively long durations for the time until the next update, and therefore remain in the data set.

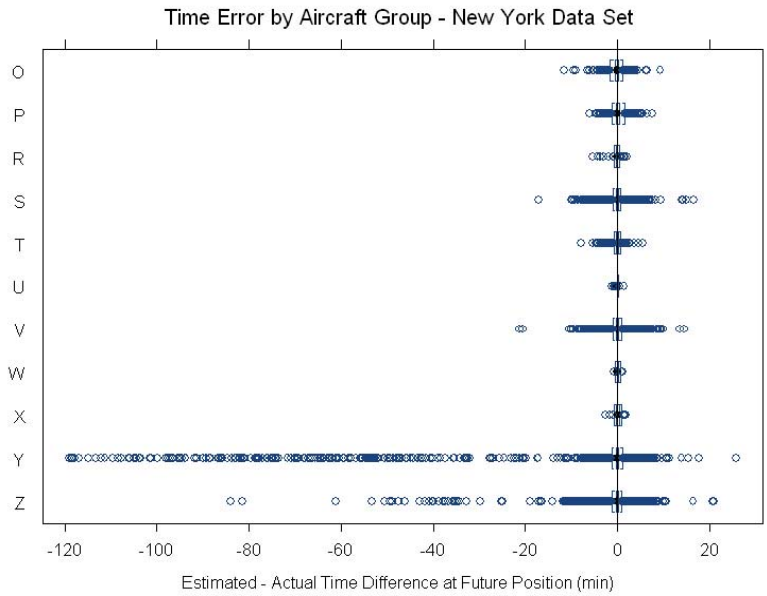

Figure 10. Time Error, E_t, by Aircraft Group – New York Data

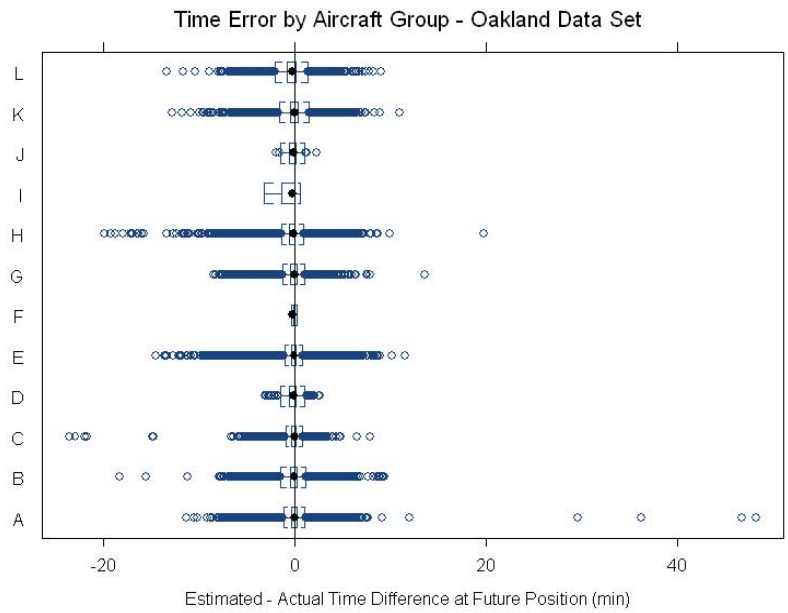

Figure 11. Time Error, E_t, by Aircraft Group – Oakland Data

The speed error data estimated from ADS-C position reports for Oakland airspace were further examined to determine which distributional form bests describes the data. Several distributional forms were tested, including the Gaussian, Double Exponential (DE), a mixed distribution with a Gaussian core and a DE tail referred to as a Normal

Double Exponential (NDE) distribution, and a mixed distribution with a DE core and a DE tail referred to as a Double Double Exponential (DDE) distribution. In this case, using the maximum likelihood technique, the DDE provides the best fit to the empirical data. A probability density function for the DDE distribution is given in Eq. (3) as:

$$f(x;\alpha,\lambda_1,\lambda_2)=\frac{1-\alpha}{2\lambda_1}e^{\frac{-|x|}{\lambda_1}}+\frac{\alpha}{2\lambda_2}e^{\frac{-|x|}{\lambda_2}} \qquad \text{where } 0<\alpha<1, \text{ and } 0<\lambda_1<\lambda_2 \tag{3}$$

The DDE density is a weighted sum of two DE densities, one often called the "core" density, and the other known as the "tail" density (Ref.11). The weights are 1-α and α; the core density, $\frac{1}{2\lambda_1}e^{\frac{-|x|}{\lambda_1}}$, describes typical longitudinal speed errors; and the tail density, $\frac{1}{2\lambda_2}e^{\frac{-|x|}{\lambda_2}}$, describes atypical longitudinal speed errors. The DDE distribution is a symmetric distribution. As shown in Table 3, the speed errors from Oakland airspace were ADS-C found to be slightly positively skewed. By fitting the data to a DDE distribution of the form described above, it is assumed the speed errors are random and are equally likely to be negative or positive. Figure 12 presents the one-minus the cumulative density of the folded empirical data and the distributional forms considered.

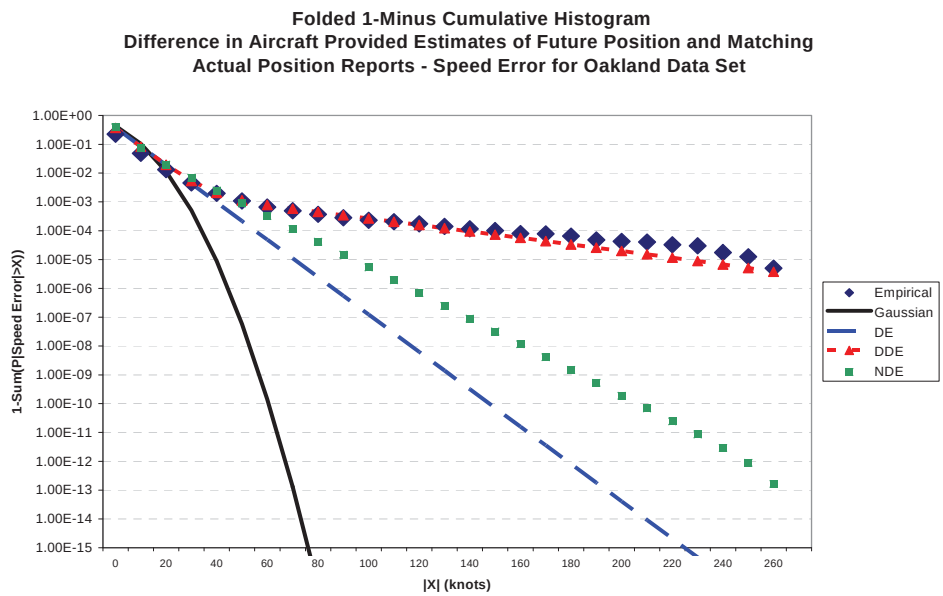

Figure 12. One-minus Cumulative Density of the Folded Speed Error Data Fitting Process – Oakland Data Set

The results presented in Figure 12 indicate that the DDE density provides the best fit to the empirical data. The maximum likelihood procedure was used to determine the parameters of the fitted distributional forms. The parameters for the resulting DDE distribution are the following; α =0.0044, λ_1 =6.536 knots, and λ_2 =38.902 knots. The same distribution fitting process was applied to the New York data set. The DDE density provides the best fit to the empirical data as well. The parameters for the resulting DDE distribution for the New York data are the following: α =0.0252, λ_1 =6.371 knots, and λ_2 =18.848 knots. The distribution fitting software used in this analysis was developed by the FAA Technical Center for modeling aircraft altitude-keeping errors, but is applicable for any set of data whose probability density function is considered to be symmetric about one maximum, monotonically increasing for values less than the maximum and monotonically decreasing for values greater than the maximum. Some description of the distribution fitting process is contained in Ref. 12. As mentioned earlier, further examination will be completed on the data by a group of operational experts. Pending the results of this

examination, the analysis presented in this paper may be revised. The group of operational experts will closely examine the most extreme values for speed and time error in both New York and Oakland airspace.

B. Time Comparisons between ADS-C Position Reports and an Independent Source of Aircraft Position to Examine the Clock Setting Accuracy of ADS-C Aircraft

The available radar data was compiled for the time period March 6 through April 27, 2009 and merged with the ETMS data. By using the time and position information in each data source, it is possible to match the ETMS flights to the radar traces. This combination creates a data source with highly accurate position information along with identifying information about each flight allowing for comparisons with the ADS-C position reports contained in the Ocean21 data. Figure 13 presents the locations of the ADS-C positions (blue) compared with the radar positions (green) for March 6, 2009.

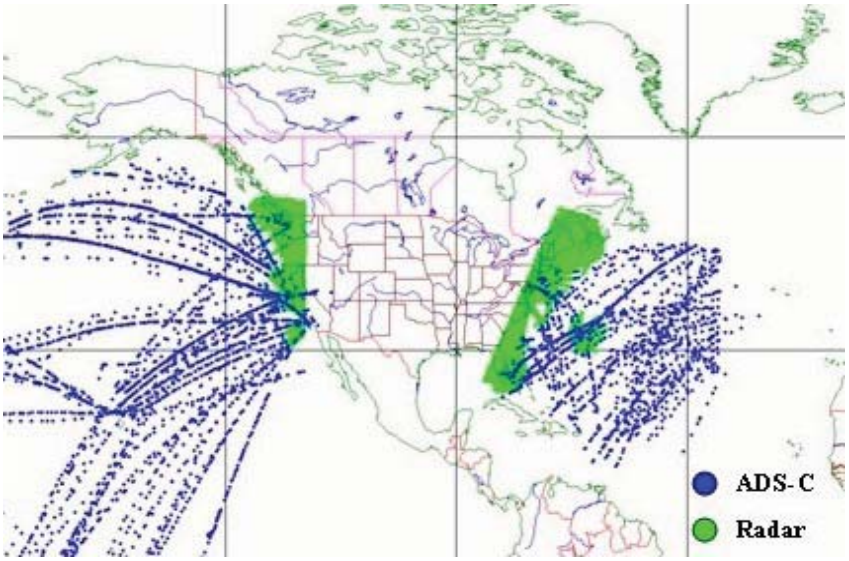

Figure 13. Overlap of Radar-Estimated Aircraft Positions and ADS-C Position Reports in New York and Oakland Oceanic Airspace

To determine the aircraft clock-setting accuracy, radar-derived positions and ADS-C position reports are needed. The ADS-C position reports were matched to all corresponding radar-derived positions by calendar date, position location and flight-identifying information. Due to the coverage area of the radar, the region of overlap of data from the two sources is small as shown in Figure 13. The accuracy of the radar-estimated position is considered to improve as the aircraft travels closer to the radar site location. Therefore, only the radar-estimated positions which were within 75nm of the radar site were utilized in this study. The total ADS-C positions with matches to radar-estimated positions in New York and Oakland oceanic airspace were 60 and 578, respectively.

The comparison of the radar-estimated time, which is equivalent to the ARTCC clock, with the aircraft master clock was done by subtraction. The position time contained in the ADS-C position report was subtracted from the estimated radar time at the location of the ADS-C position. Therefore, negative differences indicate that the master clock is set ahead of the ARTCC Time clock.

The mean estimate of clock accuracy error was 2.39 seconds. The maximum and minimum clock accuracy error values observed were 6.67 and -0.50 seconds, respectively. Figure 14 contains the empirical histogram of the clock accuracy data from the combined New York and Oakland data sets.

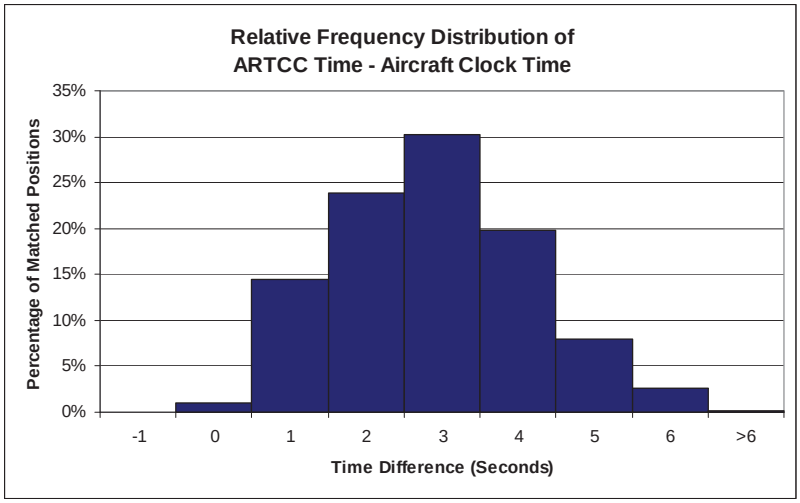

Figure 14. Empirical Histogram of the Difference in the Position Time Contained in the Radar Position Estimate and the Matching ADS-C Position Report

VII. Conclusion

This paper examined the aircraft-provided estimates of position and time at future waypoints obtained from enroute ADS-C aircraft. Comparisons were made in terms of estimated and actual aircraft speed and the estimated and actual time of arrival at the future waypoint. The ADS-C operations in both New York and Oakland oceanic airspace were examined in this study. The Ocean21 system uses these estimates of future position along with weather data models to ensure the required separation between aircraft is maintained. There were aircraft provided estimates of position which resulted in large speed and time errors. An additional parameter was introduced to the data analysis to filter some of the large errors and provide a measure of time for which the estimate of future position was used by the Ocean21 system before an updated estimate was received by the aircraft. Some of the aircraft-provided position estimates with large errors were quickly replaced with an updated and more accurate estimate of future position. This time interval, referred to as the time until the next update, was used to remove some of the large speed and time errors from the data set. However, large speed and time errors remain in the data. There are near term plans to present these data to a group of operational experts for further evaluation. The results of this evaluation may require adjustments to this analysis.

The analysis results showed the speed and time error data from New York and Oakland airspace follow similar forms but, were not equivalent. The results of this study estimated the distribution of the longitudinal speed prediction error for use in the collision risk modeling for evaluating the collision risk associated with reduced longitudinal separation standards. The speed error data from the Oakland Oceanic FIR was modeled to fit a DDE distribution with parameters α =0.0044, λ_1 =6.536 knots, and λ_2 =38.902 knots. The speed error data from the New York Oceanic FIR was also modeled to fit a DDE distribution with parameters α =0.0252, λ_1 =6.371 knots, and λ_2 =18.848 knots.

In addition, this study developed a tool to monitor the clock setting accuracy for aircraft utilizing ADS-C with an independent source for aircraft position. The independent source for aircraft positions used in this study was en route radar data. Radar coverage is not available in oceanic airspace, but aircraft are typically under radar coverage when entering and leaving oceanic airspace. This study made comparisons between position-matched ADS-C positions and radar-estimated aircraft positions as ADS-C aircraft operate within radar coverage to observe the clock setting accuracy of aircraft using ADS-C. The data examined in this paper show no significant differences between the ARTCC time clock and any of the master clocks on the aircraft in the data set. This tool will be exercised periodically to monitor the clock setting of aircraft utilizing ADS-C in oceanic airspace. The accuracy of the aircraft master clock is critical to safe operations and application of reduced longitudinal separation standards.

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