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Correlation of Airborne Position Estimates to Ground Based Independent Estimates and Deviations from Flight-Planned Tracks

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This paper investigates the adherence to track of aircraft which are candidates for application of reduced horizontal separation minima in a portion of Pacific oceanic airspace. The goals of the analyses are to estimate and validate the distribution of lateral deviations from route centerline for aircraft equipped with Automatic Dependent Surveillance – Contract (ADS-C). The correlation of the ADS-C position reports with an independent source for aircraft position, en route radar, is presented. Radar coverage is not available in oceanic airspace, but aircraft are typically under radar coverage when entering and leaving oceanic airspace. In an effort to estimate the lateral deviations from track while in oceanic airspace, this study focuses on aircraft leaving oceanic airspace. The study makes comparisons between time-matched ADS-C positions, radar-estimated aircraft positions, and filed flight plans as aircraft leave the target portion of Pacific oceanic airspace after an extended period of travel in the airspace. The results of this study will be used to estimate an important parameter, the lateral overlap probability, needed to evaluate the horizontal collision risk for the airspace.

I. Introduction

Separation standards are the minimum distances required to be maintained between pairs of aircraft to limit the probability 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 Air Traffic Control (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 (ADS) into the procedural ATC environment allows for suitably equipped aircraft to provide ATC with frequent position updates as well as information on the future intent of the aircraft. In an ADS environment, where current position reports and information on the future intent of the aircraft 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. For changes in horizontal separation minima, the lateral navigation performance of the aircraft population is a primary influence on the collision risk. An important parameter in estimation of collision risk is the lateral overlap probability, which is determined by the lateral navigation performance of the aircraft population. Lateral overlap probability is defined as the likelihood that a pair of nominally separated aircraft are in lateral overlap. For a particular airspace, the lateral overlap probability can be estimated from the distribution of lateral deviations from route centerline.

This study will estimate the distribution of lateral deviations from route centerline for aircraft equipped with ADS operating in a portion of Pacific oceanic airspace. The correlation between the ADS-Contract (ADS-C) position reports with an independent source for aircraft position will be presented. The independent source for aircraft positions used in this study is 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 time-matched ADS-C positions and radar-estimated aircraft positions as aircraft leave the target portion of Pacific oceanic airspace after an extended period of travel in the airspace.

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Also, the adherence to track of aircraft which are candidates for application of the reduced horizontal-plane separation minimum is studied. The aircraft filed flight plans provide the planned track for each flight. The actual location of the aircraft is taken from the ADS-C position report and the available en route radar data. In an effort to estimate the lateral deviations from track while in oceanic airspace, this study focuses on aircraft leaving oceanic airspace. The aircraft positions at the time of the first radar contact are examined and compared to the filed flight plans and the available future intent information provided in the ADS-C position reports to estimate the lateral deviation from track. Aircraft with time-matched ADS-C positions and radar-estimated positions are investigated to observe the differences, between the estimated lateral deviations from track derived from the radar positions and from the aircrafts' own position estimate reported through ADS-C.

The results of this study will be used to estimate the lateral overlap probability needed to complete the evaluation of collision risk for recent changes to the horizontal-plane separation minima in the airspace.

II. Background

The International Civil Aviation Organization (ICAO) established a committee on Future Air Navigation Systems (FANS) to study and identify the concepts for enhancing communications, navigation, surveillance (CNS) and the technology related to the field of air navigation. In 1991, the FANS committee recommended that the future CNS systems should provide for (Ref. 2):

1) navigation enhanced or provided by Global Navigation Satellite System (GNSS)
2) satellite data and voice communication
3) surveillance enhanced by ADS.

In response to these recommendations, the Pacific planning groups, which included airspace users, aircraft manufacturers, communication providers, and ATS providers, developed plans to implement the ICAO FANS concepts in Pacific Ocean areas. The U.S. Federal Aviation Administration (FAA) and other ATS providers established plans to develop and deploy ground systems to support the CNS enhancements in Pacific airspace.

One result from the plans developed to support the CNS enhancements was the FAA's introduction of a new oceanic automation system, Ocean21. Ocean21 was introduced into full-time operation at the Oakland Oceanic Air Route Traffic Control Center (ARTCC) in October 2005. 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. This airspace contains diverse traffic flows, some of which are amongst the longest scheduled flights in the world. The portion of Pacific oceanic airspace of interest for this study is the Oakland Oceanic Airspace.

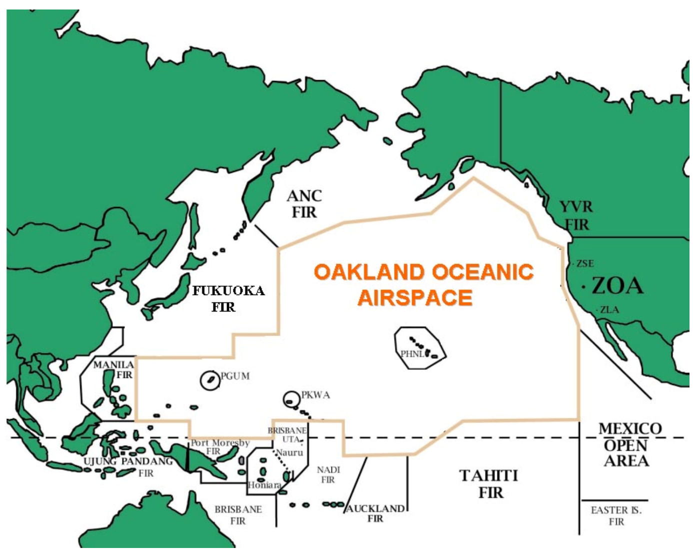

Figure 1. Oakland Oceanic Airspace

With the introduction of the decision-support tools provided by Ocean21 in Oakland Oceanic ARTCC and in conjunction with improvements in the CNS capabilities made by the user community, the FAA is able to reduce the horizontal separation standards for pairs of suitably equipped aircraft. Those airspace users meeting the requirements for reduced separation will achieve benefits including enhanced capacity and increased efficiency of operations. As mentioned earlier, one of the CNS requirements for reduction in lateral and longitudinal separation standards is ADS-C, [2-4]. Ref. 5 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 (Ref.5).

Aircraft which are eligible for reduced horizontal separation standards and which operate inside the Oakland Oceanic ARTCC's airspace, 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.

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 Oakland Oceanic airspace. There are three types of ADS-C position reports examined in this study. The three types are listed in Table 1 with a description of the position report. The generation of the ADS-C report types listed in Table 1 requires ATC to send an uplink ADS-C message to the aircraft containing the specific information related to 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. 5, 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 specified periodic contract, either 14 or 27 minutes under normal operation 2) Response to a request for position from ATC (Demand contract)	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) 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)
Lateral Deviation Report	1) Sent when the aircraft's actual position exceeds a lateral distance parameter from the aircraft's expected position on the active flight plan as stored on-board the aircraft	1) Current aircraft position (position, altitude, time) 2) Estimate of navigational accuracy

In Table 1, the report frequency for the Basic Periodic Report is given as either 14 or 27 minutes under normal operation. In determining the appropriate reporting frequency for the Basic Periodic Reports, the Ocean21 system examines the filed Required Navigation Performance (RNP) level contained in the flight plan, and specifies the appropriate reporting frequency in the ADS contract. Currently there are two RNP levels an aircraft can file for operations in Pacific airspace. The filed RNP level indicates certification for the 50-nm or the 30-nm lateral separation standard, and implies the report frequency for the Basic Periodic Reports: 27 or 14 minutes, respectively. Ref.2. provides the definition of RNP from the ICAO Manual on RNP as: a statement of the navigation performance accuracy necessary for operation within a defined airspace. Navigation performance accuracy is defined as: total navigation accuracy based on the combination of the navigation sensor error, airborne receiver error, display error and Flight Technical Error.

Common to all ADS-C report types listed in Table 1 is an estimate of navigational accuracy, or Figure of Merit (FOM). In Oakland oceanic airspace, the Ocean21 system uses the FOM value received in the ADS-C report for certain flights to determine whether reduced horizontal separation standards can be applied. Ref.6. provides a list of the possible FOM values along with a reason the specified FOM value was chosen. Portions of this list are presented in Table 2.

Table 2. Figure of Merit (FOM) Definitions for ADS-C Position Reports

Figure of Merit (FOM)	Accuracy of Position Determination (within 95% Probability)
0	Complete loss of navigational capabilities
1	< 30 nm
2	< 15 nm
3	< 8 nm
4	< 4 nm
5	< 1 nm
6	< 0.25 nm
7	< 0.05 nm

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 the Los Angeles and Oakland ARTCCs. The raw data are extracted to text files using software developed by the 84th Radar Evaluation Squadron (RADES) of the United States Air Force (USAF). The RADES software 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. Table 3 contains details for all the radars utilized in this study. The six radars listed in Table 3 are all Air Route Surveillance Radars (ARSR). A sample radar image taken with the RADES software is shown in Figure 2. The data displayed in Figure 2 represent three hours of flight data from the radars listed in Table 3.

Table 3. Los Angeles and Oakland ARTCC Radar Information

ARTCC	Radar ID	City, State
Los Angeles / Oakland	PRB	Paso Robles, CA
Oakland	QMV	Mill Valley, CA
Oakland	QZZ	Rainbow Bridge, CA
Oakland	RBL	Red Bluff, CA
Oakland	SAC	Sacramento, CA
Los Angeles / Oakland	VBG	Vandenberg, CA

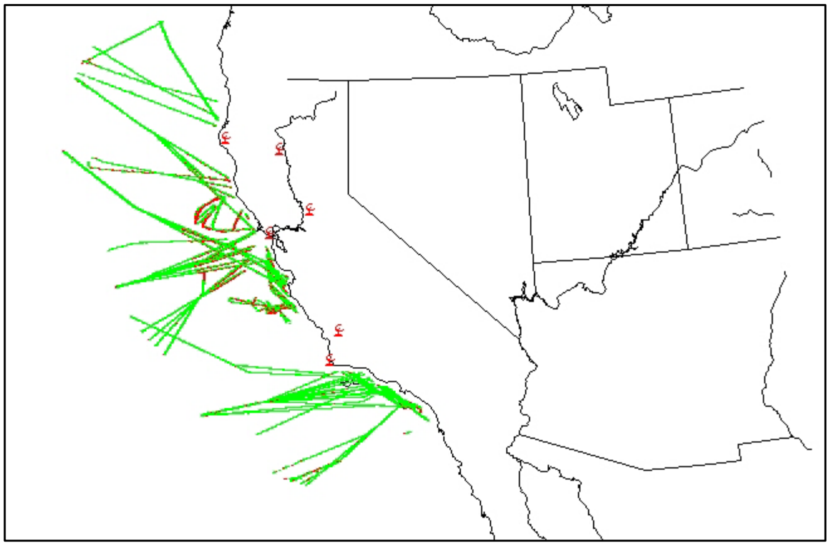

Figure 2. Sample Radar Image, Position Estimates Made by the Radars Listed in Table 3

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 Oakland oceanic airspace were available to provide flight-identification information not available in the en route radar data. These data were time-matched and appended to the en route radar data.

IV. Review of Related Studies

Previous studies have compared position estimates obtained from radar and ADS-Broadcast (ADS-B) reports. The study presented in Ref.7 compared ADS-B positions to position estimates obtained from a single radar. This study determined that the accuracy of the ADS-B versus radar-derived positions increased greatly as the distance from the radar location increased. The ADS-B positions were found to be 18 to 60 times more accurate than radar when aircraft were 40nm from the location of the radar. When aircraft were 200nm from radar, the ADS-B position was found to be 90 to almost 300 times more accurate than the radar-estimated position.

The study presented in Ref.8 provides a comparison on the position accuracy for multi-radar and ADS-B. The overlapping radar measurements from four radars were merged with the help of a Kalman filter. This study also found that the radar position error depends on the radar range. However, this study determined the position accuracy of ADS-B is not better than the position accuracy of a combined multi-radar measurement.

The study contained within this paper does not make use of ADS-B position data. It is highly possible the aircraft position information produced by ADS-B and ADS-C avionics would be the same for the trans-oceanic aircraft considered in this paper, because most of the ADS-C aircraft operating in this airspace have GPS navigation systems. Although ADS-B and ADS-C avionics produce estimates of aircraft position, the ADS-B avionics operates separately from ADS-C avionics. The important differences between ADS-B and ADS-C avionics are the reporting frequencies and the method of report transmission. An aircraft equipped with ADS-B broadcasts a position report every second. Because of the high reporting frequency, it is possible to apply a smoothing technique to the ADS-B data for interpolating aircraft position at times between the given ADS-B reports. Whereas, an aircraft utilizing ADS-C for position reporting downlinks a position report less frequently, every 14 or 27 minutes. Because of the differences in the operation of ADS-B and ADS-C avionics it is not possible to make any direct conclusions about the accuracy of ADS-C from the studies presented in Ref.7 and 8.

V. Methodology

This paper presents analyses of empirical data from trans-oceanic aircraft leaving the Oakland oceanic ARTCC and entering the west coast of the Continental United States (CONUS). The three empirical data sources include the radar-derived aircraft positions obtained from the major ARTCCs located along the 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 Ocean21 data archives contain the ADS-C position reports and aircraft-filed flight plans.

The sample period examined in this paper consisted of 105 days between January and early June 2007 for which en route radar and ETMS data were available from the Oakland and Los Angeles ARTCCs.

A. Assumptions

The main assumptions made in this analysis concern the intended route of flight for each aircraft. The intended route of flight is important since it is the route from which lateral deviations are measured. The available data provide two sources for the intended route of flight for an aircraft; 1) filed flight plan (FPL), and 2) future intent positions specified in the ADS-C position reports. The latter consists of the estimate of next position and the estimate of the next-plus-one-position; together these estimates of next position are referred to as the Predicted Route Group (PRG). The PRG contains an estimate of the arrival time at the next waypoint expected to be sequenced by the flight, as well as an estimate of the waypoint position that follows. In oceanic airspace, a waypoint is defined as a compulsory reporting point; all aircraft must provide a position report to ATC when operating over a waypoint. Each flight is required to file a flight plan with ATC specifying the intended route of flight. The intended route of flight contained in the FPL is defined by consecutive waypoints and/or established airways consisting of implied waypoints.

This analysis assumes aircraft follow great circle paths between consecutive waypoints. Since there are two sources available for the intended route of flight, the FPL and the PRG, there are two sources from which the lateral deviations can be computed. The flight segments examined in this paper are taken from eastbound oceanic flights ending their oceanic crossing and entering radar coverage along the west coast of the United States. During this time, there is a small period in which the ADS-C position reporting and radar position estimation overlap. It is this time period of overlapping ADS-C position reporting and radar position estimation that is examined in this paper. The data show most ADS contracts are terminated once ATC has acknowledged a radar position for the aircraft. As a result, it seems likely that the ADS-C positions are heavily influenced by GPS positioning accuracy or another aircraft navigational system and less so by onboard sensors updated by ground-based navigational aids. Since this is the navigational environment for trans-oceanic operations, the results contained in this paper are considered to be useful in gauging the accuracy of position reports provided for Oakland oceanic operations.

Once an aircraft is close or inside radar coverage, it highly possible that ATC would issue a clearance to proceed directly to a defined airspace position, even though the FPL may indicate another route was filed to arrive at the same location. In this case, an estimate of lateral deviation from track based on the FPL-defined track may lead to an erroneous conclusion. This is the reason the PRG was also included as a source for track position in estimating the lateral deviation. The next position estimates contained in the PRG usually match the waypoints specified in the FPL. However, when a flight receives clearance to deviate from track, the pilot will typically re-program the FMS to allow the automation systems on the aircraft to determine the appropriate path in following the clearance. In this case, the PRG would contain the re-programmed information. The assumed great circle path between consecutive waypoints applies to both the FPL and the PRG in this analysis.

B. Treatment of the Radar-derived Position Estimates

As mentioned earlier, radar-derived position estimates were made available for this study from the Los Angeles and Oakland ARTCCs. The intent of this paper is to use the radar position estimates as an independent source for aircraft position, not to measure the error in the radar position estimate. It is known, that radar position error depends on the distance between the radar location and the aircraft. Since this analysis is focused on aircraft positions estimated at the extremities of the radar range – where the ADS-C position reporting and radar position estimates overlap – radar position error is expected to be large.

Depending on 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, or more than one, of the available radar sources shown in Table 3. In an effort to reduce the known errors in the radar position estimates, the radar position estimates are smoothed according to the following steps:

1) All the radar position estimates available for each ADS-C flight are assembled

2) From these position estimates, any radar position estimates located within the PRG great circle segment are identified. The PRG great circle is defined by the endpoints provided in the PRG of the ADS-C position reports
3) Using the identified radar position estimates within the given PRG great circle segment, the latitude/longitude of each position are transformed to the stereographic plane
4) The method of least squares is used to fit a straight line to the stereographic coordinates, X/Y, resulting a smoothed linear fit to the radar position estimates
5) The smoothed stereographic coordinates, X/Y, are inversely transformed to latitude/longitude for use in the analysis.

The radar position estimates, occurring after the last available PRG great circle segment, were not smoothed. In other words, the radar positions given after the use of ADS-C was discontinued by the flight are unchanged in the analysis. The FPL is the only great circle route segment available once the ADS contract is terminated. The FPL is not used to smooth the radar position estimates because of the possibility of a flight receiving a clearance to proceed directly to a defined airspace fix, which could be a clearance to deviate from the FPL.

C. Estimates of Lateral Deviations from Track Using ADS-C Position Reports and Radar-Estimated Aircraft Positions

Since ADS-C position reports are important to ensure that the reduced horizontal separation minima are applied safely, the accuracy of the reports is also important. This analysis makes use of radar data collected from the Los Angeles and Oakland ARTCCs to study this accuracy. Radar-estimated aircraft positions are compared to the positions reported by ADS-C flights operating in Pacific airspace within coverage of FAA radars. Once in radar coverage, a radar-estimate of aircraft position is available approximately once every 12 seconds. The frequency between ADS-C position reports is much larger than 12 seconds as described in Table 1. The observed frequency for periodic ADS-C reports is roughly 14 or 27 minutes, depending on the filed RNP level of the aircraft. Because of the varied range in frequency for ADS-C position reporting, direct comparisons between ADS-C position reports and en route radar data are not possible without data manipulations. Instead of interpolating between ADS-C position reports, this analysis makes use of two sources of the intended route of flight for an aircraft, the FPL and the PRG. An estimate of lateral deviation from the intended route of flight is made using both the ADS-C position reports and the radar position estimates.

The method to estimate the lateral deviation from track is essentially the same regardless of the source for the intended route of flight and is summarized by the following steps:

1) The ADS-C position reports for a flight are assembled
2) The radar-derived position estimates which overlap the ADS-C position reports and continue beyond the last ADS-C position report are assembled for the same flight
3) For each position estimate, the appropriate great circle path defined by the consecutive waypoints in either the FPL or the PRG, is identified
4) If the source for the reference track is the PRG, the radar-estimated positions which overlap with the ADS-C reporting are smoothed
5) The latitude/longitude for the position estimate and great circle endpoints are converted to the rectangular coordinate system (X,Y,Z) using the World Geodetic System (WGS) 1984 Earth Model
6) The point lying on the great circle path which is directly abeam the position estimate is identified and converted to latitude/longitude
7) The great circle distance between the position estimate and the point on the intended route centerline directly abeam the position estimate is determined as the lateral deviation for the position estimate

The lateral distance between the reported position and the point abeam this position on the great circle gives the estimate of lateral deviation. Figure 3 illustrates an example of the great circle determined by the FPL and the PRG, along with the locations of the ADS-C position reports and the radar-derived position estimates for an eastbound flight.

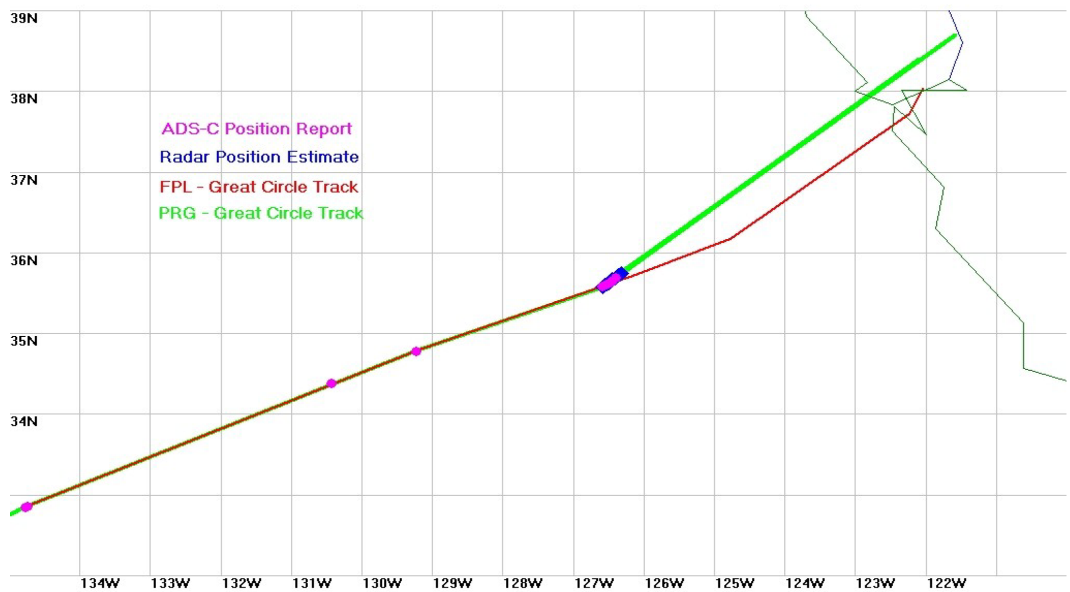

Figure 3. Example of the track determined by the FPL and the PRG, and locations of the ADS-C and radar-derived position reports

The red and green lines, which coincide with each other for most of the route segment displayed in Figure 3, represent a portion of the great circle route segments determined from the FPL and the PRG, respectively. The pink dots represent the ADS-C position reports and the blue dots represent the radar-derived position estimates. As shown in Figure 3, the great circle route segments from both the FPL and the PRG are identical until the flight enters radar coverage at approximately 35.5N/126.5W. Just after the first radar contact, a shift in the PRG great circle route (green line) can be seen in the figure. The split between the red and green lines in Figure 3 illustrate a situation in which ATC issued a clearance to deviate from the FPL. After acknowledging and accepting the clearance, the pilot reprogrammed the FMS for the new track and this information was relayed back to ATC through the ADS-C position report. The data illustrated in Figure 3 represent the typical behavior observed in the sample data for eastbound oceanic flights upon entering radar coverage.

D. Correlation between ADS-C Positions and Radar-Estimated Aircraft Positions

Comparisons among each set of lateral deviation estimates are made to draw conclusions regarding the adherence to track for aircraft which are candidates for application of reduced horizontal separation minima. These comparisons also provide the basis on which to estimate and validate the distribution of lateral deviations from route centerline for these aircraft.

VI. Analysis and Results

The sample period examined in this paper consisted of 105 days between January and early June 2007 for which en route radar and ETMS data were available from the either the Oakland or Los Angeles ARTCC. The ADS-C flights examined include eastbound flights exiting Pacific oceanic airspace. There were 4,076 unique flights examined in the data set. Summary statistics from each of the four analyses are presented in Table 4. The lateral deviation estimates were analyzed with the signed direction included, negative or positive values for deviations to the left or right, respectively, of the given route centerline.

As expected, a large number of radar position estimates were available for the analysis. A smaller number of radar position estimates were used in the PRG analysis than in the FPL analysis because in the PRG analysis the radar position estimates were truncated at the time the ADS contract was terminated. Fewer ADS-C position reports were used in the lateral deviation analysis that had the FPL as the route centerline, than in the analysis that had the PRG as the route centerline, because of the availability of the FPL for all flights in the data.

The lateral deviation estimates produced using the FPL as centerline show larger means and variances than those produced using the PRG as the route centerline. This result was due to the likelihood that an ATC clearance would be issued for a flight to proceed directly to a defined airspace fix once the aircraft was within radar coverage; these clearances authorize the flight to deviate from the FPL. Because of these known activities, which affect the lateral deviation estimates from the FPL, the remainder of the analyses will focus on the lateral deviation estimates, using the PRG as the route centerline only.

Table 4. Summary Statistics for the Lateral Deviation Estimates

Summary Statistics	Lateral Deviations Estimated from Radar Positions Vs. the FPL Track	Lateral Deviations Estimated from ADS-C Vs. the FPL Track	Lateral Deviations Estimated from Radar Positions Vs. the PRG Track	Lateral Deviations Estimated from ADS-C Vs. the PRG Track
Number of Position Estimates	421,199	32,112	78,998	39,012
1st Quantile	-0.568	-0.014	-0.286	-0.018
Median Value	0.127	0.005	-0.036	-0.002
3rd Quantile	2.140	0.980	0.169	0.007
Mean	0.716	0.301	-0.036	-0.001
Variance	11.841	0.626	0.219	0.034
Skewness	0.395	-3.947	-0.277	-1.374
Kurtosis	1.663	156.779	15.226	80.322

The skewness, which is a measure of the lack of symmetry in the data, is presented for each case in Table 4. The lateral deviation estimates produced using the PRG show the data to be slightly negatively skewed. The kurtosis, which is a measure of the tail-heaviness of the distribution, is also provided for each case presented in Table 4. The kurtosis values for the two cases in which the PRG is used in the lateral deviation estimation are large, indicating the distributions can be considered to have heavy tails. In the case of the ADS-C lateral deviations from the PRG, the kurtosis is much larger than that of the radar lateral deviations from the PRG, indicating the ADS-C data has a more acute peak in the center of the distribution and infrequent larger values in the tails of the distribution.

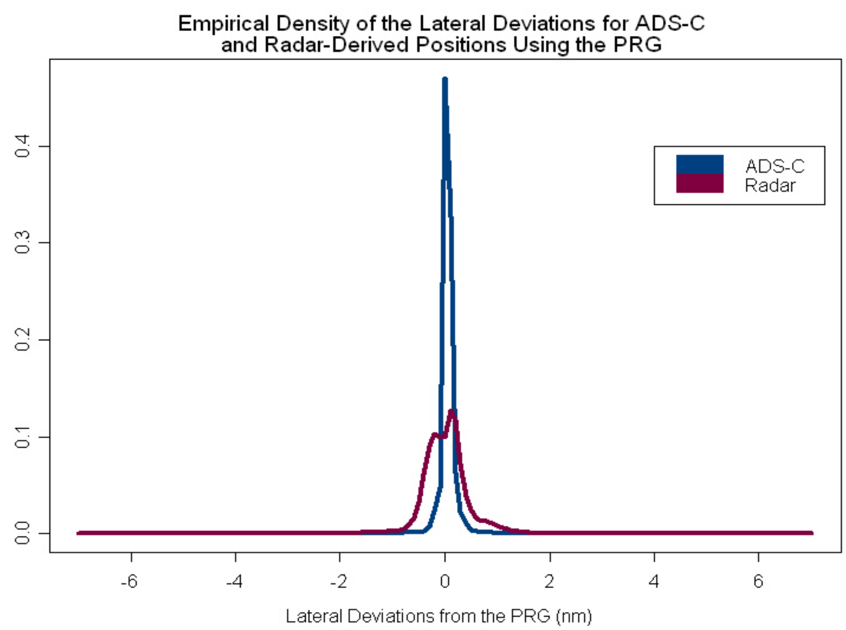

Figure 4. Empirical Densities of the Lateral Deviation Estimates of the Radar-Derived Position Estimates and the ADS-C Position Reports Using the PRG

The variance in the estimated lateral deviations from the ADS-C position reports is slightly smaller than the variance from the radar-derived position estimates. This result is evident in Figure 4, which presents the empirical densities of the lateral deviation estimates from the radar-derived position estimates and the ADS-C position reports using the PRG as the route centerline.

The results shown in Table 4 and Figure 4 show the comparisons between of the empirical data from two sources; ADS-C position reports and smoothed radar-derived position estimates. It is clear from these results the data do not follow the same distribution. To confirm this, a Kolmogorov-Smirnov goodness of fit was performed on the data; and the test result indicated the lateral deviations from the ADS-C data are not equivalent to the lateral deviations from the smoothed radar-derived positions. This result is not surprising, given the inherent error in the radar position estimates especially at the extremities of the radar coverage. However, the results do show that the ADS-C position reports produce a smaller estimate of the lateral deviation from route centerline, indicating the ADS-C position reports can be considered to be an accurate source for aircraft position in Oakland oceanic airspace.

The lateral deviations estimated from ADS-C position reports using the PRG as the intended track were further examined to determine which distributional form bests describes the data. Several distributional forms were tested, including the Gaussian, Double Exponential (DE), and a mixed distribution with a Gaussian core and a DE tail referred to as a Normal Double Exponential (NDE) distribution. In the past, aircraft lateral deviations have been modeled as Double Double Exponential (DDE) random variables (Ref.10). And in this case, the DDE provides the best fit to the empirical data. A probability density function for the DDE distribution is given in Eq. (1) as:

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

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.10). The weights are 1-α and α; the core density, $\frac{1}{2\lambda_1} e^{\frac{-|x|}{\lambda_1}}$, describes typical lateral deviations from the centerline of the aircraft's intended route; and the tail density, $\frac{1}{2\lambda_2} e^{\frac{-|x|}{\lambda_2}}$, describes atypical lateral deviations from the centerline of the intended route. The DDE distribution is a symmetric distribution. As shown in Table 4, the ADS-C lateral deviations from the PRG were found to be slightly negatively skewed. By fitting the data to a DDE distribution, it is assumed the directions of the lateral deviations are random and are equally likely to occur in either direction. Figure 5 presents the one-minus the cumulative density of the folded empirical data and the distributional forms considered.

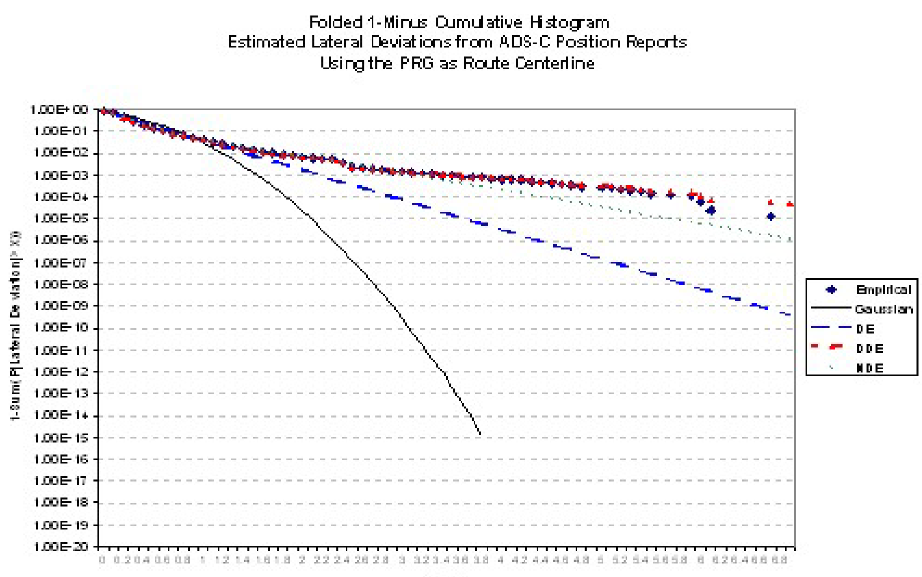

Figure 5. One-minus Cumulative Density of the Folded ADS-C Lateral Deviations from the PRG and Distributional Forms Considered in the Fitting Process

The results presented in Figure 5 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=0.0337, λ_1 =0.2946 nm, and λ_2 =1.0616 nm. 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 aircraft lateral errors as well. Some description of the distribution fitting process is contained in Ref.11. The resulting lateral overlap probability for a lateral separation standard of 30 nm is estimated as 1.526 x 10^{-15}. This lateral overlap probability estimate does not take into account any evidence of gross navigation errors in the airspace, and therefore is not the final probability value for use in the estimate of lateral collision risk for the airspace.

As mentioned earlier, each ADS-C position report contains a FOM value (Table 2). Over 98 percent of all the ADS-C position reports used in this analysis had a FOM value of six, which indicates the accuracy of the position determination by the aircraft avionics was within 0.25 nm of the true aircraft position. This result is a good indication that GPS is the navigation system utilized by most of the aircraft included in this study. The Ocean21 system examines the FOM value received in each ADS-C position report from aircraft eligible for the 30-nm lateral and longitudinal reduced horizontal separation standards. If the reported FOM is less than or equal to three, the aircraft is determined to be no longer eligible for the reduced horizontal separation standards. There were only five and two ADS-C position reports with FOM values equal to two and three, respectively, contained in the sample data.

VII. Conclusion

This paper provides an estimate of the distribution of lateral deviations from route centerline for aircraft equipped with ADS operating in the Oakland oceanic airspace. Comparisons were made between ADS-C position reports and smoothed radar-derived position estimates from eastbound trans-oceanic aircraft utilizing ADS-C for position reporting. The radar-derived position estimates were obtained from the available Los Angeles and Oakland ARTCCs ARSRs. The two sources of position estimates were taken during the small time period in which the ADS-C position reports and radar position estimates overlap, as the data show most operators discontinue the use of ADS-C once in radar coverage. The analysis results showed the lateral deviations from the ADS-C data were not equivalent to the lateral deviations from the radar-derived positions. This result was attributed to the inherent error in the radar position estimates used in the study. The comparison results show the ADS-C position reports produce a smaller mean and variance estimate of the lateral deviation from route centerline, indicating the ADS-C position reports can be considered to be an accurate source for aircraft position in Oakland oceanic airspace. Therefore, it is reasonable to assume that the accuracy of the ADS-C reported aircraft positions used by the Ocean21 system for controller decision support are expected to be good. This paper also determined that the DDE distribution provided the best fit for the ADS-C estimated lateral deviation data. The resulting estimate of the lateral overlap probability for a 30nm lateral separation standard is 1.526 x 10^{-15}. This estimate does not take into account any evidence of gross navigation errors in the airspace and is not the final probability value for use in the evaluation of lateral collision risk. The FAA Technical Center will use these data combined with any reports of gross navigation errors to estimate the lateral overlap probability needed to complete the evaluation of collision risk for recent changes to the horizontal-plane separation minima in the airspace.

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