Study of ADS-B Data Evaluation

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Abstract

In western China, the terrain and meteorological conditions are so complex that it is not suitable to construct new radar stations. Automatic dependent surveillance-broadcast (ADS-B) is a totally new surveillance method, so before practically applied and operated in China, abundant tests and evaluations are necessary to validate the performance of ADS-B and guarantee the operational security. During the flight tests, we collect the data of radar, ADS-B and high accuracy position and compare the performance of ADS-B with radar based on high accuracy position. To solve the asynchronous problem among radar data, ADS-B data and real-time kinematic (RTK) data caused by different update rates, this article proposes the technique of synchronizing multi-surveillance data by extrapolating from the data of low update rate to high update rate according to velocity and heading. Meanwhile, because radar data, ADS-B data and RTK data are expressed in different coordinates and cannot be compared each other, this article provides a method to unifying the coordinates of multi-surveillance data. By the analysis and evaluation, we can conclude that the performance of ADS-B is better than radar.

Keywords: civil aviation; surveillance; ADS-B; accuracy; integrity; flight inspection; data evaluation

1. Introduction

Automatic dependent surveillance-broadcast (ADS-B) is a surveillance technology which allows aircraft to broadcast identification, state and position information to neighboring aircraft and nearby ground stations [1]. ADS-B is an important composition of CNS/ATM and the surveillance method recommended by the International Civil Aviation Organization (ICAO) in the next generation of air traffic management (ATM) [2]. ICAO has called the meeting of research and implementation working group to discuss the future application of ADS-B in the Asian-Pacific region and suggested mode S 1 090 MHz extended squitter (1090ES) be the recommended data link to provide radar-like services in the Asian-Pacific region. Many countries in the Asian-Pacific region have started test and evaluation about ADS-B providing radar-like services, and America and Australia have planned and deployed ADS-B stations in their countries.

The position information of ADS-B report is from the global navigation satellite system [3], so the safety and reliability of ADS-B technology will be affected by it. On the one hand, ADS-B technology selects 1090ES as the data link technology [4], on the other hand, the secondary surveillance radar also uses 1090ES as the data link technology, so the congestion of the 1090ES data link will be possible. For the purpose of applying the ADS-B technology in China, it is very necessary to evaluate the performance of ADS-B technology in China. In April 2007, Civil Aviation Administration of China (CAAC) installed 2 ADS-B stations in Chengdu and Jiuzhai, which are based on
1090ES, accomplishing the signal surveillance over Chengdu-Jiuzhai course. Till now, four flight tests have been made and the inspection aircraft has been equipped with real-time kinematic (RTK) equipment to collect high accuracy position as the baseline position data which is based on the carrier phase measurements of GPS signal and the real-time corrections provided by a single reference station, providing up to centimeter-level accuracy. In this paper, we will collect ADS-B, radar and baseline position data to evaluate the integrity, accuracy, altitude, velocity, etc. Meanwhile, we will compare ADS-B data with radar based on baseline data.

2. ADS-B Evaluation System

The framework of ADS-B evaluation system is shown in Fig. 1.

![Fig. 1 Framework of ADS-B evaluation system.](image)

Logically, the evaluation system can be divided into two parts, data acquisition (red part in Fig. 1) and data evaluation and display (blue part of Fig. 1).

2.1. Data acquisition

This part is to acquire and process all the test surveillance data for meeting the demands of data evaluation and display. The raw data of radar are from the radar ground station manufactured by Raytheon Corporation and the raw data of ADS-B are from the ADS-B ground station manufactured by Sensis Corporation. The true locations of the aircraft are obtained by onboard RTK receiver. The real-time kinematic (RTK) data are made up of raw observed data and accuracy difference data. The former is the raw GPS data collected from GPS receiver installed on the test aircraft. The latter is obtained from the internet and post-processed with the former data. For the radar data, the real-time information is needed, but the radar messages do not contain the real-time information, so the time stamp system is added to provide the time of radar data by getting the network time protocol (NTP) time and adding it to the radar messages. For the ADS-B data, we will get the formatted data by parsing the raw data of ADS-B according to the interface control document (ICD) of Sensis Corporation. For the RTK data, the GPS receiver interface language (GRIL) of Javad Navigation System is applied. We will extract the required data items and constitute the formatted data for data evaluation and display.

2.2. Data evaluation and display

This part is to evaluate the ADS-B data and display the results. The content of data evaluation is shown in Fig. 2. According to different data evaluation, the results would be intuitively displayed and analyzed.

The source data of ADS-B data evaluation system come from two aspects: the data of airplanes in certain airspace and the data of the inspected airplane. For the data of planes in air area, the system can evaluate the ADS-B support of planes in air area and carry out eight evaluation categories, namely evaluations of velocity, heading, integrity, altitude, position, distance between radar and ADS-B, range and reliability. For the data of the inspected airplane, the system can compare the performance of ADS-B with radar based on baseline data and carry out the above evaluations and other three evaluation categories, namely evaluations of accuracy, coordinate (Lat and Lon) error, and measure of dispersion.
3. Key Techniques

3.1. Technique of synchronizing multi-surveillance data

As we know, the update rate of radar data is one message for 4 s, that of ADS-B is 0.5 s and RTK is 0.2 s [7]. Therefore, during the same time interval, there are more RTK messages than radar and ADS-B, and the radar messages are the sparsest. We need the synchronous data to get the accuracy of radar and ADS-B, and compare the performance of radar and ADS-B, so the asynchronous multi-surveillance data should be extrapolated to be in step with each other. The progress of synchronizing ADS-B, radar and RTK data is shown in Fig. 3.

First, we will sign the data that the time is exactly the same among ADS-B data, radar data and the baseline data. Then we will deal with the rest of the ADS-B data, radar data and the baseline data to synchronize the ADS-B data, radar data and the baseline data. The steps are as follows:

1) For the radar data, extract the time message contained in the radar data and name the time \( T_1 \).

2) Extract the time message contained in baseline data that is the nearest from \( T_1 \) and name the time \( T_2 \).

3) Then we will get the position message (LA1, LO1), the velocity message \( (V_1) \) and the heading message \( (H_1) \) of radar data corresponding to \( T_1 \). The heading is defined as the angle between the airplane direction of advance and the true north, and \( H_1 \) comes from radar messages that the radar station outputs. It is originally achieved through calculating the angle between the target and the direction of antenna beam.

4) We can get the extrapolated position message (LA1E, LO1E) according to (LA1, LO1), \( V_1 \) and \( H_1 \). The expressions are as follows:

\[
\begin{align*}
\text{LA1E} &= \text{LA1} + (T_2 - T_1)V_1 \cos H_1 \\
\text{LO1E} &= \text{LO1} + (T_2 - T_1)V_1 \sin H_1
\end{align*}
\]

(1)

5) Extract the time message contained in ADS-B data that is the nearest from \( T_2 \) and name the time \( T_3 \).

6) Then we will get the position message (LA3, LO3), the velocity message \( (V_3) \) and the heading message \( (H_3) \) of ADS-B data corresponding to \( T_3 \). \( H_3 \) comes from ADS-B messages that the ADS-B station outputs. It is originally achieved from navigation data source and is more accurate than radar.

7) We can get the extrapolated position message (LA3E, LO3E) according to (LA3, LO3), \( V_3 \) and \( H_3 \). The expressions are as follows:

\[
\begin{align*}
\text{LA3E} &= \text{LA3} + (T_2 - T_1)V_3 \cos H_3 \\
\text{LO3E} &= \text{LO3} + (T_2 - T_1)V_3 \sin H_3
\end{align*}
\]

(2)

3.2. Conversion of polar coordinates into WGS-84 coordinates

In the radar data, the position message is expressed in polar coordinates and the position message of ADS-B data is expressed in WGS-84 coordinates [8-9]. To compare ADS-B data with radar data, it is necessary to converse polar coordinates into WGS-84 coor-
The conversion method is as follows: firstly, extract the slant range, the angle of deviation and the altitude from the radar data; secondly, compute the relative longitude and latitude to the radar station; finally, get the longitude and latitude by adding the relative longitude and latitude to the longitude and latitude of radar station.

Assume \((\phi, \eta)\) represents the longitude and latitude of the radar station, \((\text{Latitude}, \text{Longitude})\) the latitude and longitude of the plane, \((\alpha, \beta)\) the relative longitude and latitude to radar station, \(h\) the altitude of the plane, \(r\) the slant range, and \(T\) the angle of deviation.

The conversion expression of latitude is

\[
\text{Latitude} = \alpha + \phi
\]

The conversion expression of longitude is

\[
\text{Longitude} = \beta + \eta
\]

We find that the error between the position got by the above expressions and the real position is big, because the Earth is supposed to perfect sphere without considering the problem of eccentricity and the Earth is actually ellipse. So we improve the method: firstly, we converse the Earth coordinates of the radar station into Earth-centered, Earth-fixed (ECEF) coordinates; secondly, we extract the slant range, the angle of deviation and the altitude from the radar data to compute the Cartesian coordinates of the plane; thirdly, we converse the Cartesian coordinates of the plane into ECEF coordinates; finally, we will converse ECEF coordinates into WGS-84 coordinates. The expressions used for the conversion are as follows:

1) The expressions of the conversion of Earth coordinates into ECEF coordinates are

\[
\begin{align*}
x_r &= (c + H_r) \cos L_r \cos \lambda_r \\
y_r &= (c + H_r) \cos L_r \sin \lambda_r \\
z_r &= [c(1 - e^2) + H_r] \sin L_r
\end{align*}
\]

where \((L_r, \lambda_r, H_r)\) is the Earth coordinates of the radar station, \((x_r, y_r, z_r)\) the coordinates of ECEF and \(c\) the slant range.

\[
c = E_q / \sqrt{1 - e^2 \sin(2L)}
\]

where \(E_q\) is the radius of the Earth.

2) The expressions of the conversion of polar coordinates into Cartesian coordinates are

\[
\begin{align*}
x_n &= r \cos n \cos \theta \\
y_n &= r \cos n \sin \theta \\
z_n &= r \cos n
\end{align*}
\]

where \((r, \theta, n)\) is the polar coordinates of the plane and \((x_n, y_n, z_n)\) the Cartesian coordinates.

3) The expressions of the conversion of Cartesian coordinates into ECEF coordinates are

\[
\begin{align*}
X_e(k) &= X_t + RX_n(k) \\
R &= \begin{bmatrix}
-sin \lambda_t & -sin L_t \cos \lambda_t & \cos L_t \cos \lambda_t \\
\cos \lambda_t & -sin L_t \sin \lambda_t & \cos L_t \sin \lambda_t \\
0 & \cos L_t & \sin L_t
\end{bmatrix}
\]

\[
X_t = [x_t, y_t, z_t]^T
\]

where \(X_e(k)\) is the ECEF coordinates of the plane, \(X_t(k)\) the Cartesian coordinates of the plane; \(X_t\) the ECEF coordinates of the radar station; and \(L_t, \lambda_t\) are the longitude and latitude of the radar station.

4) The expressions of the ECEF coordinates into Earth coordinates are

\[
\begin{align*}
r &= \sqrt{x^2 + y^2} \\
a &= (r^2 + A^2 e^4)/(1 - e^2) \\
b &= (r^2 - A^2 e^4)/(1 - e^2) \\
g &= 1 + 13.5z^2(a^2 + b^2)/(z^2 + b)^2 \\
p &= 3\sqrt{q + \sqrt{q^2 - 1}} \\
t &= (z^2 + b)(p + p^{-1})/12 - b/6 + z^2/12 \\
L &= \text{arctan}[(z/2 + \sqrt{t} + \sqrt{z^2/4 - b/2 - t + \pi z/(4\sqrt{t})})/r] \\
\lambda &= 2\text{arctan}[(\sqrt{x^2 + y^2 - x}/y)]
\end{align*}
\]

where \((x, y, z)\) is the ECEF coordinate of the plane, \((L, \lambda, H)\) the Earth coordinate of the plane, and \(A\) the semimajor of Earth.

4. Results of Evaluation

4.1. ADS-B accuracy evaluation

For the accuracy evaluation, by comparing ADS-B, radar and baseline position data at the same time, we can get the distance between synchronized ADS-B and baseline position data, as well as the distance between synchronized radar and baseline position data. By the three flight tests, we can get the results shown in Fig. 4.
Fig. 4 ADS-B data accuracy evaluation results of three flight tests.

The x-coordinate is error burst and y-coordinate is report percentum. ADS-B data is shown in green and radar in blue. It is obvious that ADS-B messages are more than radar in the small error burst and less in the big error burst, so the accuracy of ADS-B data is better than radar data.

4.2. ADS-B integrity evaluation

Integrity of ADS-B reports is characterized by navigation uncertainty category (NUC), which ranges from the integers of 0 to 9 \cite{10}. According to relative ICAO standards, only if the NUC value of the ADS-B report is greater than 4, can the report meet the requirements of radar-like service. The number of ADS-B reports falling into different NUC values is counted to obtain the distribution of NUC. By collecting ADS-B reports from Chengdu ADS-B ground station for the flight tests, we can get the distribution of NUC as shown in Fig. 5.

Meanwhile, by collecting ADS-B reports from Chengdu ADS-B ground station for about 40 days, we can get the distribution of NUC as shown in Fig. 6. The number of the reports collected from Chengdu ADS-B ground station is 41,776,974. The x-coordinate is NUC value and y-coordinate is the report percentum. The red bar stands for the report that cannot meet the requirements of radar-like service and the green bar stands for the report that can meet the requirements of radar-like service.

From Fig. 5 and Fig. 6, we can see that a majority of reports with NUC greater than 4 can meet the requirement of radar-like service, and most of these reports with NUC equal to 6, 7 and 9 are high quality reports.

Fig. 5 ADS-B data integrity evaluation.

Fig. 6 ADS-B data integrity evaluation of Chengdu ADS-B ground station.

5. Conclusions

The method to evaluate integrity of ADS-B report is based on NUC value. By our counting, we find that almost all the reports with NUC less than 4 are the reports with NUC equal to 0 and the majority of reports of ADS-B can meet the requirements of radar-like service.

We count the data of 95% sample point during the accuracy evaluation and the best accuracy of ADS-B data is 33 m, compared with 200 m of radar data. Meanwhile, we count the distribution of accuracy and can get that the accuracy of ADS-B data is much better than radar.

References


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