Integrity verification of ADS-B navigation data source

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Abstract. The importance of data source integrity to ADS-B monitoring performance is analyzed in this paper, and the corresponding monitoring algorithm is given. At present, ADS-B monitoring data mainly comes from GNSS, and GPS, as the main component of GNSS at this stage, its public data is relatively easy to obtain. Therefore, GPS is selected as ADS-B data source, the integrity of the navigation data source is analyzed and the data of an airport is verified by simulation in this paper.

1. Introduction
ADS-B can provide more accurate and real-time aircraft position monitoring information than radar monitoring system. ADS-B horizontal position data comes from the navigation system, and the airborne navigation source directly determines the monitoring performance of ADS-B. In order to characterize the quality characteristics of aircraft horizontal position, ADS-B system evaluates the accuracy and integrity of relevant position information. Ground equipment can monitor the accuracy and integrity of navigation data of each aerial device. When an aircraft gives an alarm on the accuracy or integrity of the navigation data source, the air traffic controller is required to increase the separation between the aircraft and others; if more aircrafts give alarm, the separation between all aircraft shall be increased. Therefore, the integrity of position information provides guarantee for the reliability of monitoring data and the safety of aircraft. As a new monitoring technology, ADS-B is still in the experimental stage in China, and the research on the integrity of navigation source is less. Therefore, it is necessary to study the ADS-B navigation data source and its integrity.

2. Integrity analysis
2.1 Integrity requirements
ADS-B navigation source availability is defined as the percentage of time that the system can be used for navigation in a certain period of time, which is based on providing reliable information to users. It is required to meet the requirements of accuracy and integrity at the same time. Integrity is judged by whether the protection level of user positioning error exceeds the standard. The integrity information is encoded by NIC (navigation integrity category) and SIL (source integrity level). In the actual monitoring process, the ground staff will judge the NIC and SIL of the received ADS-B message and analyze whether they meet the minimum monitoring requirements [1].
Integrity code is encoded by containment radius \((R_c)\), which is obtained by integrity monitoring algorithm according to satellite message. The coding rules are shown in table 1. When \(NIC\) is greater than 8, the determination of \(NIC\) value needs to be determined jointly by \(R_c\) and \(VPL\) (vertical protection limit) [1-2].

Table 1. Coding rules of \(NIC\).

| NIC Grade | Rc | NIC Grade | Rc |
|-----------|----|-----------|----|
| 0         | Rc Unknown | 6         | Rc<0.6NM (1111.2m) |
| 1         | Rc<20NM (37.04km) | 7         | Rc<0.2NM (370.4m) |
| 2         | Rc<8NM (14.81km) | 8         | Rc<0.1NM (185.2m) |
| 3         | Rc<4NM (7.408km) | 9         | Rc<75m and VPL<112m |
| 4         | Rc<2NM (3.704km) | 10        | Rc<25m and VPL<37.5m |
| 5         | Rc<1NM (1852m)  | 11        | Rc<7.5m and VPL<11m |

\(SIL\) (survey integrity level) is determined by the navigation data source[2]. It is defined as the probability of missed alarm when the requirements of \(NIC\) are not met. The coding rules are shown in table 2.

Table 2. Coding rules of \(SIL\).

| SIL Grade | Probability of Rc overrun |
|-----------|---------------------------|
| 0         | Unknown or greater than 10-3 per hour |
| 1         | \(\leq1\times10^{-3}\) per hour |
| 2         | \(\leq1\times10^{-5}\) per hour |
| 3         | \(\leq1\times10^{-7}\) per hour |

2.2 Integrity analysis based on RAIM algorithm

At present, there are three methods for GPS integrity monitoring: RAIM (Receiver Autonomous Integrity Monitoring), SBAS (GPS/Space-Based Augmentation System) and GBAS (GPS/Ground-Based Augmentation System). RAIM is a mature method in theory and practice. It is a kind of integrity monitoring technology which only uses the pseudo range measurement information of navigation satellite. RAIM algorithm is usually embedded in the receiver, which can make the receiver execute RAIM algorithm while receiving GPS measurement signal for positioning. The basic principle of algorithm is to detect the consistency between the measured values of each satellite, so redundant observation information is needed [3].

If the GPS receiver can receive \(N\) visible satellite signals at a certain time, i.e. generate \(N\) observations, then the GPS measurement equation [4] is:

\[
y = Hx + \varepsilon
\]  

(1)

Among them, \(y\) is \(N\times1\) dimensional observation vector and \(x\) is \(4\times1\) position state vector to be measured, including the real three-dimensional position coordinates of the user receiver itself and the clock deviation of the receiver; \(\varepsilon\) is \(N\times1\) dimension pseudo range error vector. When there is no satellite fault, all elements of pseudo range error \(\varepsilon\) vector obey \((0, \sigma^2)\) Gaussian distribution, \(H\) is \(N\times4\) dimensional observation matrix, shown as formula 2.

\[
H = \begin{bmatrix}
    a_{x1} & a_{y1} & a_{z1} & 1 \\
    a_{x2} & a_{y2} & a_{z2} & 1 \\
    \vdots & \vdots & \vdots & \vdots \\
    a_{xn} & a_{yn} & a_{zn} & 1 
\end{bmatrix}
\]  

(2)
The solution of user state vector $\hat{x}$ can be obtained by least square method:

$$\hat{x} = (H^T H)^{-1} H^T y$$

(3)

The calculated pseudo range vector $\hat{y}$ is compared with the actual one, and the pseudo range residual vector $w$ is obtained. The mathematical derivation relationship is as follows:

$$\hat{y} = H\hat{x}$$

(4)

$$w = y - \hat{y} = y - H(H'H)^{-1} H'y = [I_s - H(H'H)^{-1} H']\varepsilon$$

(5)

Matrix $S$ is defined as:

$$S = I_s - H(H'H)^{-1} H'$$

(6)

The sum of squares $F$ of the components of pseudo range residuals is:

$$F = D^T D = \nu^T S \nu$$

(7)

When there is no fault, the degree of freedom of the normalized variability $F/\sigma^2$ satisfying the $\chi^2(N-4)$ distribution is $N-4$. If there is a detection alarm, it is a false alarm. If $P_{FA}$ is the probability of false alarm, then:

$$\Pr(F/\sigma^2 < T^2) = \int_0^{T^2} f_{\chi^2(N-4)}(x)dx = 1 - P_{FA}$$

(8)

When the satellite fails, $F/\sigma^2$ obeys the non-central distribution $\chi^2(N-4, \lambda)$. Statistic $F/\sigma^2$ should be larger than $T^2$. Otherwise, it will be missed alarm. The missing probability $P_{MD}$ is given in the following formula:

$$P_{MD} = \Pr(SSE/\sigma^2 < T^2) = \int_0^{T^2} f_{\chi^2(N-4, \lambda)}(x)dx$$

(9)

The parameter $\lambda$ of the non-central distribution is obtained according to formula 8 and formula 9.

$$Rc = \delta HDOP_{max} \times \sigma \times \sqrt{\lambda}$$

(10)

Where $\delta HDOP_{max}$ is the maximum horizontal precision factor, It reflects the influence of geometry of observation satellite on horizontal positioning accuracy, and changes with the observation position and time. Its expression is:

$$\delta HDOP_{max} = \max\left(\frac{A_i^2 + A_{2i}^2}{S_i}\right)$$

(11)

Among them, $HDOP_i$ is the i-th failed satellite removed under $HDOP$. 

$$A = (G^T G)^{-1} G^T$$

(12)

The VPL expression is as follows:
\[ VPL = \delta VDOP_{\text{max}} \times \sigma \times \sqrt{\lambda} \] (13)

After the above methods, the \( R_c \) and \( VPL \) have been calculated, then the \( NIC \) can be determined.

3. Integrity simulation verification

The data of an airport in China is shown in Table 3. According to the data, simulation verification is carried out.

| Table 3. Basic information of airport during simulation |
|--------------------------------------------------------|
| Airport name | ×× |
| ARP latitude | N305657 |
| ARP longitude | E1041947 |
| Airport elevation (m) | 468 |
| Calendar weeks | 1020 |
| Ephemeris reference (m) | 589824 |
| Forecast start time | March 16, 2019 06:00:00 |
| Forecast end time | March 18, 2019 06:00:00 |
| Prediction interval (min) | 15 |
| Available elevation of satellite | 5° |

The simulation steps are as follows:

- Determine the position of the simulation point in the \( ECEF \) coordinate system, and convert the longitude and latitude points in the WGS-84 coordinate system of the airport point into the \( ECEF \) coordinate system[5-6] (In the \( ECEF \) coordinate system used in GPS, the \( XOY \) plane coincides with the equatorial plane of the earth, where the \( X \) axis points to the longitude \( 0^\circ \) direction and the \( Y \) axis points to the east longitude \( 90^\circ \) direction).

- Satellite position prediction, According to the United States website [7], the calendar parameters are updated every Saturday at 24:00, i.e. a new issue of the calendar is released. Reference provides the calculation method of GPS satellite position, and calculates the position coordinates of a satellite in the future \( t \) time. At present, there are 32 satellites in orbit in the GPS space segment, numbered from PRN01 to PRN32. The GPS almanac data of this period provides the orbit parameters of 30 satellites.

- Establishment of station-center coordinate system with current observation point. The three coordinate axes are perpendicular to each other and meet the right-hand rule. They point to the East, North and zenith directions respectively. In the station-center coordinate system, the position information of satellite is expressed by the elevation, azimuth and distance of satellite relative to aircraft.

- Without considering the terrain sheltering angle, the visible satellites are screened according to the sheltering angle of \( 5^\circ \).

- The observation matrix \( H \) is established according to the selected visible satellites.

- Calculate \( HDOP \) and \( R_c \) as above.

The results of this simulation are shown in Figure 1. Corresponding to the curve of \( R_c \) value change in the figure, we can see that it reaches \( 110m \leq 185.2m \) in 48 hours. Combined with the relationship between \( R_c \) and \( NIC \) listed in Table 1, it can be concluded that the airport meets the integrity accuracy category of \( NIC = 8 \) within 48h. In the simulation process, the probability of \( R_c \leq 185.2m \) is 100%, so the integrity level is to meet the requirements of \( SIL \geq 2 \).
Integrity is very important for satellite navigation, if the aircraft is sailing at high speed, it may deviate from the route in a short time if the integrity is unknown. Because GPS is the most commonly used navigation source at present, and if it is used as the main navigation system, the integrity function becomes more important. The results show that the integrity category of the airport meets the requirements.

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