



# Improvement in RSSI-Based Distance Estimation for Aircraft ADS-B Signal by Antenna Diversity

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**Abstract.** Automatic Dependent Surveillance—Broadcast (ADS-B) is an emerging means of aeronautical surveillance for air traffic control, in which aircraft periodically broadcast positional updates to ground stations. ADS-B is high performance, but anomaly positions should be detected and removed for safety and security. A possible method is estimating the receiver-aircraft distance based on received signal strength (RSS) and compare it with the reported position. For this, an improvement in distance estimation is proposed in this paper, where antenna diversity is exploited. ADS-B signals are transmitted from two antennas, installed on bottom and top of the aircraft body, respectively. By combining estimation results for the two antenna, estimation error caused by noise and fading can be mitigated. The proposed method was evaluated by measurement. The error was mitigated to a standard deviation of 12.2 km from 17.2 km (top antenna only) and 17.3 km (bottom antenna only).

**Keywords:** ADS-B · Received Signal Strength · Position Verification

## 1 Introduction

Automatic Dependent Surveillance—Broadcast (ADS-B) is an emerging means of aeronautical surveillance for air traffic control. Aircraft periodically broadcast positional updates to ground stations, and reported positions can be provided to air traffic controllers. ADS-B is high performance, but anomaly positions should be detected and removed [1–3]. Anomaly positions may be generated by illegal transmission (spoofing) because ADS-B does not have an authentication and encryption scheme. Failure in avionics can also be a source of anomaly.

Among various methods proposed so far, exploitation of received signal strength (RSS) [4–6] has the following advantages. First, it does not require replacement of traditional receivers, unlike array signal processing [5, 7]. Second, it does not require multiple receivers, unlike time-difference-of-arrival (TDOA) methods or multilateration [5, 8–13]. Third, it does not require modification on the message format or protocol.

However, it has been known that RSS is difficult to be exploited due to signal fluctuation caused by fading. Another difficulty is that exact transmit power is unknown.

Therefore, there are only few successful cases. In [4], RSS-distance correlation and auto-correlation of RSS were used instead of estimating the distance. The statistical properties were used to overcome the difficulties, which enabled an intrusion detection method. Because of the use of the statistical properties, however, signal-by-signal decision is not possible. In [6], RSS-based distancing was achieved by employing two steps; calibration and estimation. However, the measurement error is still large with a standard deviation of 18.6 km. Therefore, effort for error reduction is needed.

In order to improve the RSS-based distance estimation, antenna diversity was exploited in this work. ADS-B signals are transmitted from two antennas, installed on bottom and top of the aircraft body, respectively. By combining estimation results for the two antenna, estimation error caused by fading can be mitigated.

This paper is organized as follows. In Sect. 2, the proposed method is described. In Sect. 3, evaluation by measurement is presented. In Sect. 4, this paper is concluded.

## 2 Proposed Method

### 2.1 Antenna Diversity

The proposed method is explained by an example. Figure 1 (a) and (b) show the track of the measured aircraft and measured RSS, respectively. A typical airliner has two transponder antennas: one on the top surface of the fuselage and the other on the bottom surface of the fuselage. The ADS-B signals are transmitted alternately by the bottom and top antennas. As seen in the Fig. 1, RSS differs depending on the antenna type. Therefore, the main idea is to estimate the distance separately for the two antennas, then combine the estimation results. By doing so, reduction of error is expected because 1) the number of available measurements is increased, thereby mitigating a white noise, and 2) effect of fading is cancelled each other (for uncorrelated part). The detail of the distance estimation applied each antenna is described as follows.

### 2.2 Distance Estimation

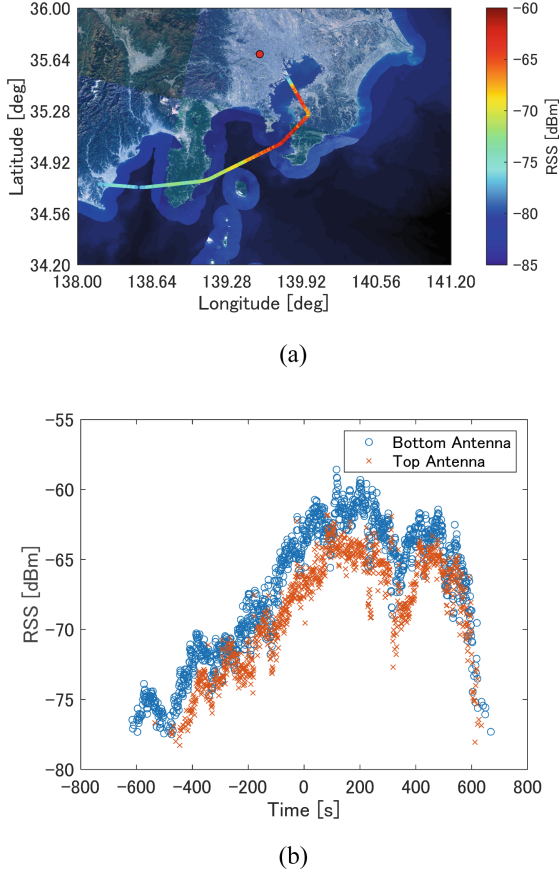
The proposed method consists of two steps: calibration and estimation [6]. Each step is conducted for different flight of same aircraft. Because an aircraft of scheduled flight is expected to fly the same route repeatedly.

#### 2.2.1 Step I: Calibration

The purpose of the calibration step (Step I) is to create a database of transmit power of each aircraft. This step is necessary because the international standard allows a deviation of up to 6 dB. To estimate the transmit power, the nominal RSS,  $\hat{P}_r$ , is calculated as follows:

$$\hat{P}_r = P_{t,0} + G_{t,0} - L_{\text{atm}} - L_{\text{fs}} + G_r \quad (1)$$

where  $P_{t,0} = 51$  dBm is the nominal transmission power,  $G_{t,0} = 0$  dB is the nominal transmission antenna gain,  $L_{\text{atm}}$  is the atmospheric attenuation (0.0090 dB per 1 NM



**Fig. 1.** RSS measurement example: (a) track of the measured aircraft and (b) measured RSS, where the two series due to different antennas are clearly observed. For the map data, GSI tile was used [14].

$= 1.852 \text{ km}$ ),  $L_{\text{fs}} = \left(\frac{4\pi d}{\lambda}\right)$  is the free-space path loss for the distance  $d$ ,  $G_r$  is the receiver antenna gain. Then, the difference between the measurement,  $\tilde{P}_r$ , and nominal is calculated by

$$\Delta = \tilde{P}_r - \hat{P}_r \quad (2)$$

Assuming that the average in difference is mainly caused by the transmit power deviation, it is estimated by taking a median (as a robust estimation of the average) as follows:

$$B = \text{median}(\Delta) \quad (3)$$

$B$  is stored in the database as the transmit power parameter associated to each aircraft. Note that association with the aircraft can be achieved by the unique number assigned to each aircraft (called the ICAO address).

### 2.2.2 Step II: Estimation

In the estimation step (Step II), the distance is estimated using the transmit power parameter,  $B$ , stored in the database. To derive the estimation, the measured RSS is modelled as follows:

$$\tilde{P}_r = P_{t,0} + G_{t,0} + B - L_{\text{atm}} - L_{\text{fs}} + G_r + X \quad (4)$$

where  $X$  is a fading and stochastic. The difference from (1) is that the RSS is not nominal anymore but realistic by introducing  $B$  and  $X$ . This equation is, however, difficult to solve for distance for nonlinearity. Then,  $L_{\text{atm}}$  is omitted at this moment, and solve the equation for the free-space path loss:

$$L_{\text{fs}} = (P_{t,0} + G_{t,0} + G_r + B + X) - \tilde{P}_r \quad (5)$$

Assuming  $X \sim N(0, \sigma_x^2)$ , an estimate of  $L_{\text{fs}}$  is given as follows:

$$\tilde{L}_{\text{fs}} = (P_{t,0} + G_{t,0} + G_r + B) - \tilde{P}_r \quad (6)$$

Further, solving  $L_{\text{fs}}$  for  $d$  and substituting  $\tilde{L}_{\text{fs}}$ , an estimate of  $d$  is obtained as follows:

$$\tilde{d} = \frac{\lambda}{4\pi} 10^{\left(\frac{\tilde{L}_{\text{fs}}}{20}\right)} \quad (7)$$

As mentioned, this estimate does not consider the effect of atmospheric attenuation. To consider that, an iterative solution is available in [6] but omitted for brevity in this paper.

### 2.3 Combining and Smoothing

Applying the above method to the two antennas, the two time-series of  $d$  is obtained. To combine the two series, they are merged and sorted in time. Then, a moving average of past  $N$  signals can be taken as follows:

$$\tilde{d}_s(i) = \frac{1}{N} \sum_{j=i-N+1}^i \tilde{d}(j) \quad (8)$$

where  $\tilde{d}_s(i)$  is the output of the moving average at the sampling index  $i$  and  $\tilde{d}(j)$  is the merged estimate with the sampling index  $j$ . Because the two series are transmitted alternatively, this process basically combines  $\frac{N}{2}$  signals from top antenna and  $\frac{N}{2}$  signals from bottom antenna, although some missed reception may cause small unbalance. Moreover, this process can also provide effect of smoothing, which further suppress a noise.  $N$  is a parameter to be decided. For a larger value, suppression of noise and fading will be stronger, but response to changing distance will be slow, which may lead a biased estimation. In this paper,  $N = 10$  was selected empirically, as a value that a tangible suppression was observed.

### 3 Evaluation

#### 3.1 Measurement

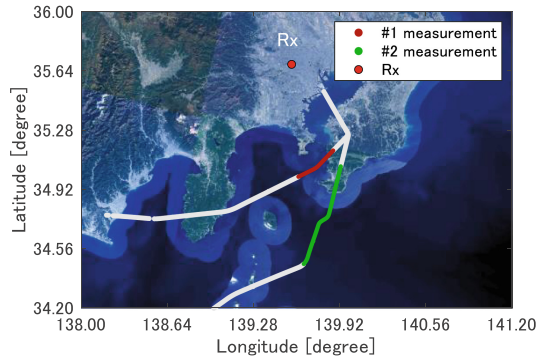
To evaluate the proposed method, measurement was conducted on 8, 9, 14, and 16 February 2022. The receiver was located in Chofu City, Tokyo, Japan. Opportunistic flights were measured, including arrivals and departures to/from Tokyo International Airport. The duration is 24 h each day, resulted in 96 h in total. The measurement system was developed by a laptop computer, a software defined radio (SDR) transceiver USRP 2901, and a custom-built antenna. The SDR transceiver down-converted and digitized RF signals. The laptop run a program written in C++ that detected and recorded ADS-B signals based on the RF signals. The recorded signals were analysed by MATLAB after the measurement.

#### 3.2 Result for Example Aircraft

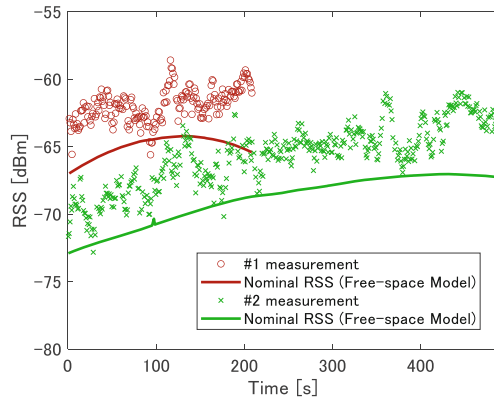
Figure 2 shows the result for an example aircraft, which is the same as Fig. 1. This aircraft was measured two times (#1 and #2). The both flights were arrivals to Tokyo International Airport. #1 measurement was used for the calibration step (Step I), whereas #2 measurement was used for the estimation step (Step II). Also, because the ground (receiver) antenna was directional, only the signals captured within the main-beam were analysed, which correspond to the coloured lines in Fig. 2 (a). Figure 2 (b) shows the RSS in that area. From #1 measurement,  $B = 3.1\text{dB}$  for the bottom antenna, and  $B = 0.1\text{dB}$  for the top antenna, were obtained. Then, distance estimation was applied to #2 measurement. The result is shown in Fig. 2(c), where the rough estimations of distance were successfully obtained for each antenna (the red and blue crosses). Fluctuation and the resulting error were, however, observed due to noise and fading. The error had a standard deviation of 14.5 km and 19.8 km for the bottom antenna and top antenna, respectively. By combining the two antennas and smoothing, the error was mitigated (the black circles in Fig. 2(c)) to a standard deviation of 12.3 km. The fluctuation was suppressed. Correlated part of fading still remained, which resulted in a significant error. However, considering that the maximum coverage of ADS-B can reach to 463 km (250 NM), rough positional verification may be possible with the observed accuracy.

#### 3.3 Result for Multiple Aircraft

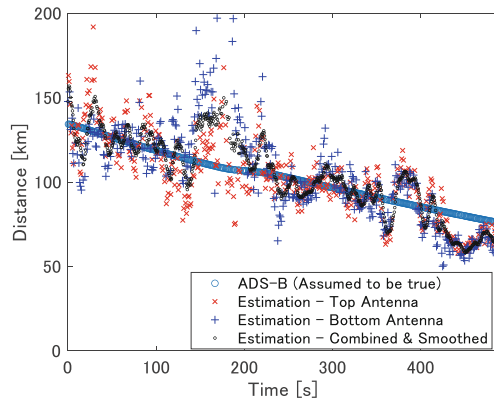
Evaluation was conducted for 266 flights with 106 selected aircraft. 66 aircraft, 28 aircraft, 10 aircraft, 2 aircraft were measured 2, 3, 4, and 5 times. Figure 3(a) shows their tracks. They are all arrivals that took a similar route. The first measurement for each aircraft was used for calibration, and the rest was used for estimation. The number of the estimations were 36473 (bottom antenna), 35878 (top antenna), and 72351 (combined). Figure 3 (b) shows error distributions of distance estimation, where cumulative distribution functions (CDF) were plotted. Most of the error ranged from -40 km to 40 km with a standard deviation of 17.3 km and 17.2 km for the bottom and top antennas, respectively (the blue and red lines in Fig. 3 (b)). By combining the two antennas and smoothing, the error was mitigated (the black line in Fig. 3 (b)). The standard deviation was improved to 12.2 km.



(a)

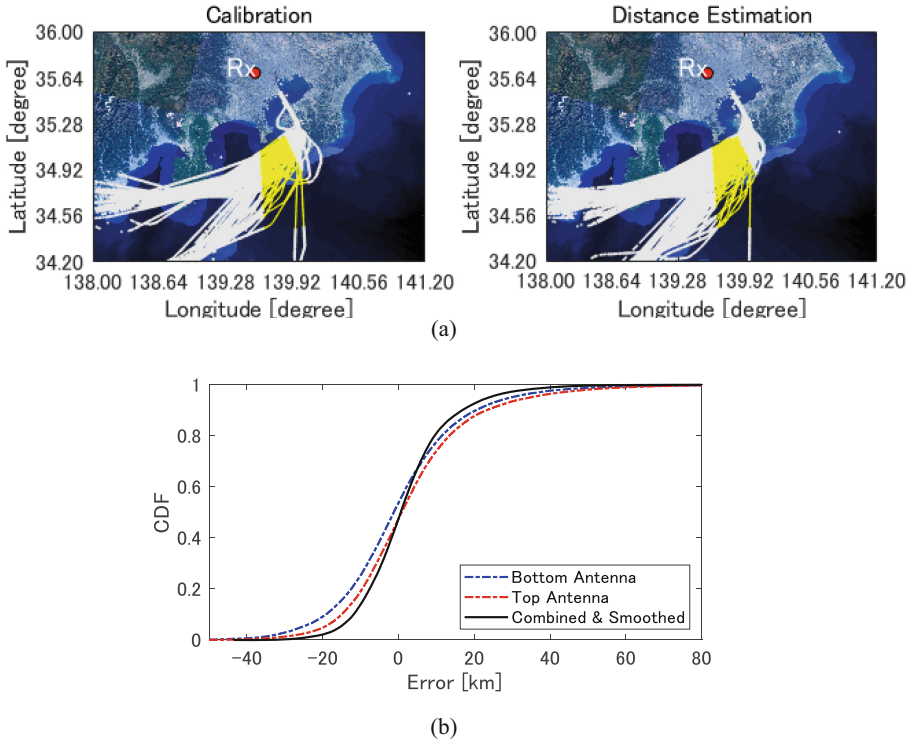


(b)



(c)

**Fig. 2.** Evaluation result for the example aircraft: (a) track, (b) measured RSS and the nominal RSS, (c) distance estimation. For the map data, GSI tile was used [14].



**Fig. 3.** Evaluation result for selected multiple aircraft: (a) tracks, (b) error distribution. For the map data, GSI tile was used.

## 4 Conclusion

This paper proposed an improvement in RSS-based estimation of aircraft distance by exploiting antenna diversity. By combining and smoothing two series of estimation, error was mitigated to a standard deviation of 12.2 km from 17.2 km (top antenna only) and 17.3 km (bottom antenna only). This will enable rough verification of reported positions, although further improvement is desirable. Therefore, future work will be parameter optimization and applying a more advanced scheme of smoothing such as a Kalman filter.

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