ADS-B Collaboration with SSR

Oscar Bria[0000-0002-0001-4248] and Javier Giacomantone[0000-0001-9362-9323]

Research Institute in Computer Science (III-LIDI) - School of Computer Science
National University of La Plata - Argentina
onb@info.unlp.edu.ar

Abstract. In an air traffic surveillance station with SSR and ADS-B, the information generated by each sensor can be used to improve the performance of the other. In addition to improving the predictive performance required by Roll-Call interrogations, ADS-B can help to improve SSR performance in the vicinity of the cone of silence, allow passive acquisition and help to identify false SSR targets generated by reflection.

Keywords: ADS-B, SSR, Modo S, Collaboration among Sensors.

1. Introduction

Secondary Surveillance Radar (SSR) and Automatic Dependent Surveillance System by Broadcast (ADS-B) are two cooperative technologies for air traffic surveillance.

The SSR [1] independently determines the position of the aircraft which, in turn, is interrogated by the radar to gather complementary information. The SSR Mode S (Selective) [2] is the second generation of the SSR; allows selective interrogation, Roll-Call interrogations, using an exclusive 24-bit identification code for each aircraft [3,4]. SSRs typically have a position update rate between 4 and 10 seconds depending on the rotation speed of the antenna.

ADS-B [5] is dependent on Global Navigation Satellite Systems (e.g., GPS) for position determination, which is emitted along with other information spontaneously by the aircraft and received on the ground by a system simpler than a radar. ADS-Bs typically have a position update rate of around 1 second [6,7].

Nowadays it is common to find an SSR with Mode S and an ADS-B installed at the same site, therefore, with mostly overlapping coverage. In [8] a method of using the ADS-B tracker was presented to improve the prediction needed by SSR Mode S, when both sensors are located in the same place. One of the motivations for proposing this collaboration is that, as already shown, the ADS-B position update rate is significantly lower than that of SSR.

In the process of developing an integrated collaboration system between an ADS-B and a SSR, it is possible to include other improvements besides the correlation of the position of the aircraft reported by both sensors. The limitations imposed by the so-called cone of silence of the SSR coverage can be mitigated. The performance of the reflection detection and elimination system of the SSRs can also be improved.

2. Collaborative Trackers

In [8] a simple scheme of collaborative trackers [9,10] (see Figure 1) was presented for the prediction of the aircraft position, necessary for the timing of the SSR Roll-Call interrogation for the next antenna visit.

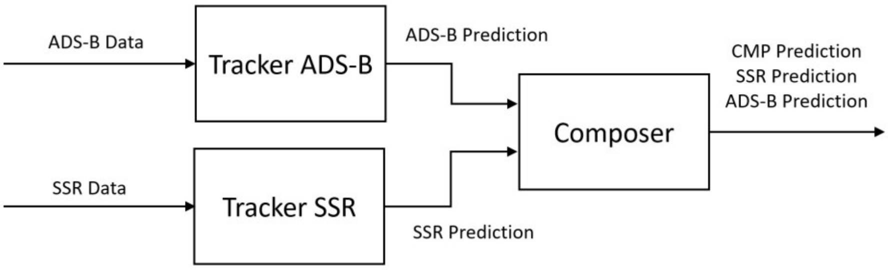

Fig.1: Block Diagram of the Collaboration between Trackers.

The block named Composer in Figure 1 calculates the average prediction weighted by the variances according to the following calculation [11]:

$$P = \left[P_1^{-1} + P_2^{-1}\right]^{-1} \quad (1)$$

$$\hat{x} = P\left[P_1^{-1}\hat{x}_1 + P_2^{-1}\hat{x}_2\right] \quad (2)$$

Where P_i are the individual covariances of each sensor prediction and $\hat{x}_i$ are their predictions. While P and $\hat{x}$ are the respective values of the composition.

The compose (CMP) prediction, given by the pair [$\hat{x}$,P], is statistically better[1], than the SSR prediction [12,13]. That contributes to better estimation, more efficient use of polling scheduling resources, and better performance of mode S in various respects [8].

3. Cone of Silence and Passive Acquisition

Radar coverage is the volume of airspace scanned by a radar or radar network [14]. The coverage volume of a surveillance radar is the volume generated by the revolution, around the antenna rotation axis, of the surface delimited by the following bounds (typical values are shown in brackets):

1. The minimum elevation angle from the horizon [0°].
2. The maximum elevation angle from the horizon [45°].
3. The minimum slant distance from the center of the antenna [0.5 NM].
4. The maximum slant distance from the center of the antenna [150 NM].
5. The maximum altitude with respect to the ground [FL 1000].

[1] The magnitude of the composition variance, P, is always less than the magnitude of any of the individual variances, P_i.

The solid generated by revolution includes a blind volume in the shape of an inverted cone contained between the maximum elevation angle and the axis of rotation of the antenna called the cone of silence (CoS)[2]. The CoS is produced by the effect of the shape of the irradiation pattern of the radar antenna, which in the case of SSRs has a square cosecant pattern [15]. Figure 2 shows the CoS in schematic form. For example, an aircraft flying at a cruising altitude of FL 300 (approx. 10 Km) will enter the CoS at 5.4 NM from the radar (approx. 10 Km) if the coverage reaches 45° in elevation. The SSR does not detect the aircraft while inside the cone, the track will be lost and it must be acquired again when the aircraft leaves the CoS, if at all. The re-acquisition process involves one or more All-Call queries.

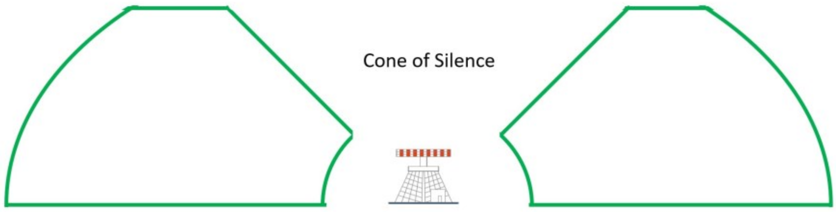

Fig.2: Vertical-Central Section of the Coverage Volume (not to scale).

The ADS-B collaboration function with the SSR improves the acquisition process of aircraft with squitter and mode S transponder at the exit of the cone of silence, avoiding the delay imposed by the exchange of interrogations and All-Call responses as usual in the active acquisition of the SSR.

With the help of the data supplied by ADS-B, the output of the SSR cone of silence is anticipated in such a way that a passive acquisition is carried out that allows the first interrogation of the SSR outside the cone of silence is directly a Roll-Call interrogation.

This function must include an active tracker based on ADS-B information for every possible aircraft that may exit the SSR's CoS and also must anticipate departure, early enough for the SSR to schedule a Roll-Call interrogation at the appropriate time.

Figure 3 is a diagram with details of the working environment of the collaboration within the CoS according to the following detail:

1. The dotted line above represents a trace of the responses or possible SSR responses given by an aircraft moving away from the radar heading East. The black dot corresponds to the situation where the radio range is not enough to process responses at that distance (which on the other hand may not be produced). The two blue dots correspond to responses not processed by the SSR because they are beyond its Surveillance Coverage (vertical green line farther to the right). The next two green dots correspond to responses processed by the SSR but not reported to the console, which correspond to All-Calls responses that are used to initialize the predictor for the next round. The two red dots correspond to responses processed and reported to the console, which are in correspondence with the responses to

[2] Another blind zone can also be generated if the angle of minimum elevation is above the horizon. This can occur in the azimuthal sectors including obstacles.

Roll-Call selective interrogations.

2. The central line represents the squitter emissions of the same aircraft moves away from the SSR moving from West to East, and which may or may not be processed. The key to colors is similar to the previous one.
3. The line below corresponds to the responses or possible responses of the aircraft to the SSR, when it works in a composite way with ADS-B. The color key is the same as before.

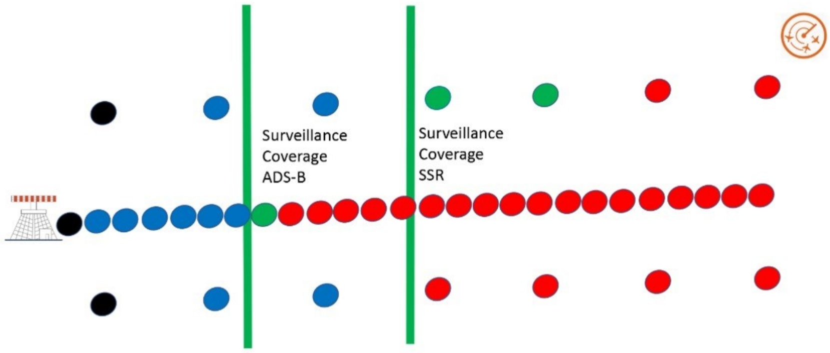

Fig.3: Detail of the Collaboration in the Cone of Silence.

For the third trace, it is observed that the two points immediately to the right of the second vertical green line are red. This is so because the SSR received information from ADS-B so that these points correspond to Roll-Call responses. This is possible if the ADS-B information arrives in a timely manner.

The details of how forecast anticipation is carried out will depend on how accurately the limits of the cone of silence overlapping with the minimum range are known or defined together with the presence or absence of a surveillance coverage map, and of the forward forecast accuracy that can be achieved with ADS-B data (see fixed point forecast at [11]). Due to the indeterminacy in the knowledge of the limits, superfluous or, on the contrary, few Roll-Call interrogations could be programmed.

The improvement of the order of two turns depends, in terms of distance, on the speed of the aircraft and the rate of rotation of the antenna. The improvement in the distance is of the order of 2 NM considering typical values of both speeds for an en-route traffic radar, as observed in Equation (3). The improvement does not depend on the altitude at which the aircraft leaves the CoS, but is still significant for the upper limit of typical coverage.

$$2\text{turns} \; \frac{450\text{Knots}}{1\text{turn}/8\text{seconds}} = 2\text{NM} \tag{3}$$

In practice, it is necessary to distinguish between the radio frequency range (distance up to which radio frequency signals can be processed) and the surveillance coverage which is set operationally for each sensor. Figure 4 shows the radio range and surveillance coverage for the SSR, further showing the flight situations that should be taken into account.

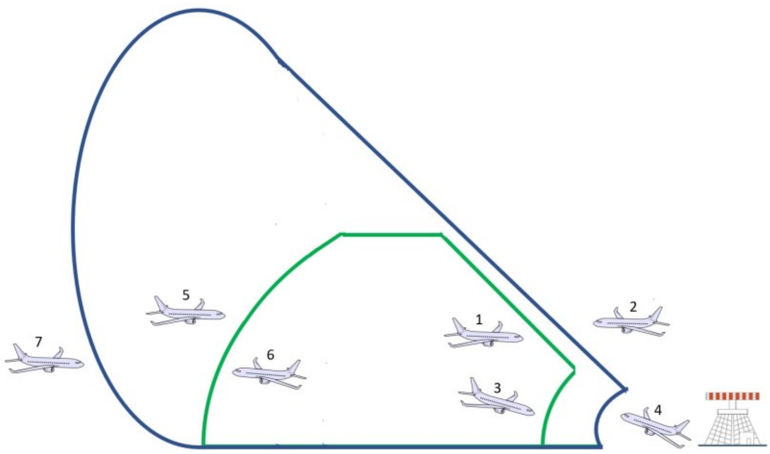

Fig.4: Radio Range and Surveillance Coverage.

1. Entering Cone of Silence.
2. Leaving Cone of Silence.
3. Landing in Blind Zone.
4. Taking off from Blind Zone.
5. Entering Surveillance Coverage.
6. Leaving Surveillance Coverage.
7. Entering Radio Range.

Case number 5 (Entering Surveillance Coverage) in Figure 4 can be treated as case number 2. (Leaving Cone of Silence) if there is ADS-B coverage beyond Surveillance Coverage. Also, in this case it is possible to acquire the trace through a passive acquisition using a technique similar to the one shown.

4. Reflections

Although SSR and ADS-B are both cooperative surveillance technologies, a very important distinction between them is that the former estimates the position (minus altitude) independently and the latter dependently [16]. Therefore, what in principle is a disadvantage for the latter can be helpful or essential to determine if a response is real or comes from a reflection, as shown below.

False detections occur due to reflection of electromagnetic waves by obstacles, both for interrogations and for responses from an SSR. Figure 5 shows the geometry of the reflections.

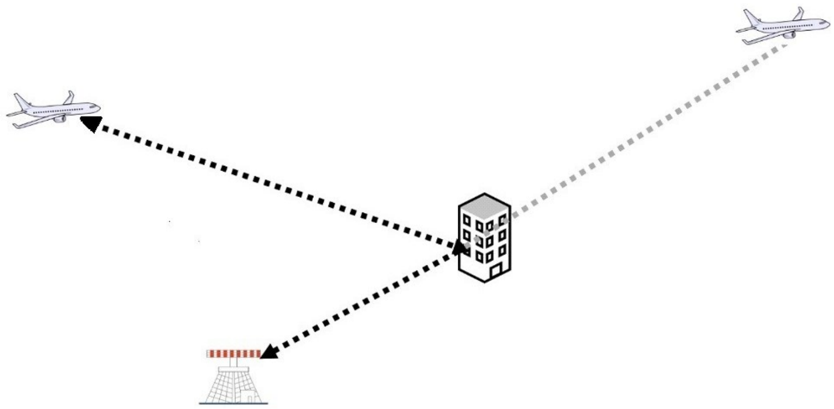

Fig.5: Geometry of Reflections

In Figure 5, the actual location of the aircraft is on the left, but when the radar has interrogated in the direction of the building it has generated a reflected interrogation which has also generated a reflected response which is received by radar. The SSR computes the position of the aircraft and places it in the position to the right.

Below are described several particular reflection situations in which ADS-B can contribute in varying depth.

1. When the interrogation mode is A/C the reflections can be identified through a well known procedure. If, for example, two aircraft with the same A code are detected in one turn of the antenna, it can be assumed that the aircraft that is at a greater distance from the radar is actually a reflection. In addition, the position of the reflector can be calculated, which is supposed to produce reflections for any other similar situation. Thus, it is convenient to survey a map of the reflectors present in the vicinity of the radar.

   Assuming v is the distance at which the real aircraft is above azimuth α and r is the distance at which its reflection is seen above azimuth β [3]. Then, the distance to the reflector R and the orientation of the normal vector to the reflecting plane $\perp$ can then be calculated. See Figure 6 in which the guidelines of geometric optics are followed and the small black segment represents the reflecting plane.

[3] α and β are measured with respect to the North turning to East.

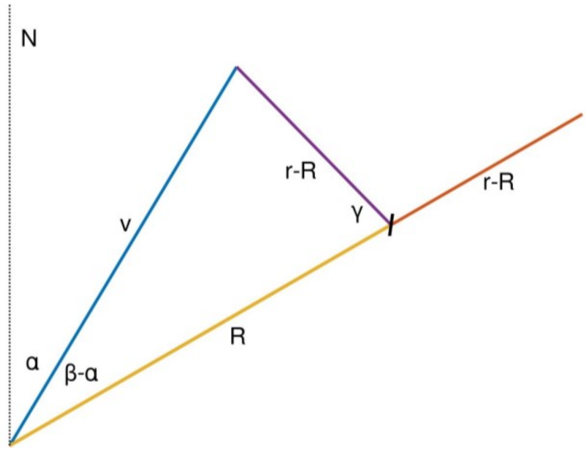

Fig.6: Geometry for calculating the Location of the Reflector.

Applying the laws of cosines and sines in the triangle of Figure 6,

$$R = \frac{1}{2}\frac{r^2 - v^2}{r - v\cos(\beta - \alpha)} \tag{4}$$

$$\perp = \frac{1}{2}\arcsin\frac{v\sin(\beta - \alpha)}{r - R} + \beta + \pi \tag{5}$$

The survey of the map of permanent reflectors for the airways of a radar site is part of the site study that must be carried out for each SSR installation [17]. In addition to the permanent reflectors, mobile reflectors that eventually appear should be temporarily included on the map. An obstacle can operate as a single or several reflectors in different planes. Relatively large obstacles, in addition to producing reflections, can produce blind zones at low altitudes as mentioned previously.

2. The S Roll-Call interrogation mode is, in principle, immune to reflections because interrogations are directed to a single aircraft known to be in the azimuthal direction towards the main beam of the radar antenna is pointing. What could happen is that through a reflector, during the All-Call interrogation period, the identifier S of an aircraft is acquired and, thus, it goes on to be interrogated Roll-Call through the reflector in the next few turns. Indeed, this condition could be detected, as for mode A/C, by the repetition of the identifier S and also the furthest detection is the false one[4].

[4] In this case, the reflection identification is more secure because it is known that the identifier S cannot be repeated.

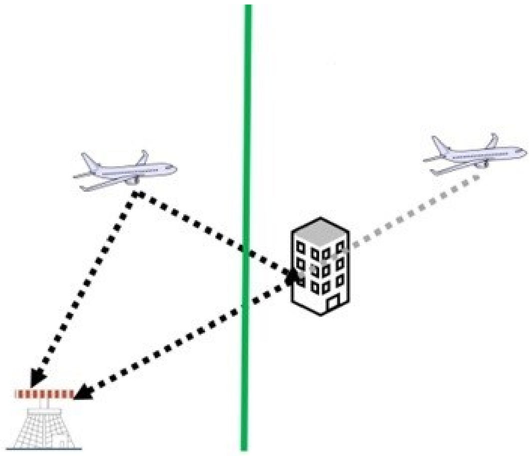

Fig.7: Singular Case of Geometry of Reflections.

3. Figure 7 shows a singular case of a mirroring situation. Here, the aircraft is within the CoS of the SSR and it is interrogated through a reflector that is outside the CoS. The aircraft responds for both a mode A/C interrogation and a mode S interrogation. In both situations there are no references to compare and determine that they are reflections. This is so because the same aircraft does not appear in any other azimuth of the turn. In both cases, the mistake is made by accepting the reflected aircraft on the right as existing. In other words, the traditional algorithm, only based on the SSR, does not distinguish the reflection as such for this geometry. The ADSB, which distinguishes the aircraft within the CoS, can contribute indicating that there is an aircraft that is responsible for a reflection and can contribute to the location of the reflector with a similar method to the one already explained.
4. ADS-B spontaneous emissions can also produce reflections similar to those of SSR radar, but are indistinguishable from direct emissions, except for arrival time, because ADS-B relies on the GNSS system for its location, and not on a measurement. Those refection situations must be solved by the ADS-B receptor itself or by post processing performed from the ground equipment.

5. Conclusions and Future Work

Additional features of ADS-B collaboration with SSR have been introduced when both sensors are at the same site. The contribution is significant for: ✓ Anticipate and simplify the acquisition of mode S tracks at the limits of the coverage.

✓ Allow and anticipate the acquisition of SSR tracks at the output of CoS.

✓ Reinforce and allow the identification of reflections that produce false targets in the SSR.

In those cases and in the case of the tracker, the integration of both sensors can be done by collecting data directly from the Asterix Cat.21 output of the ADS-B to help the Asterix Cat.48 generation processing of the SSR (see Figure 8).

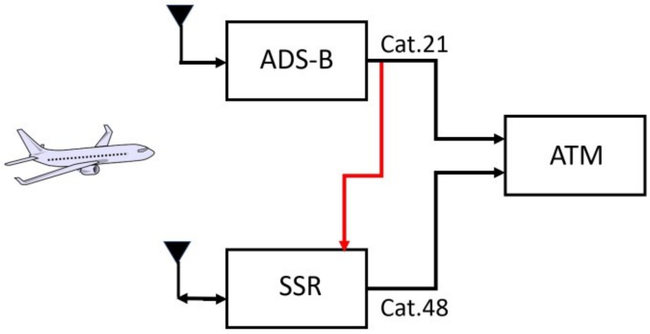

Fig.8: Asterix Collaboration Scheme.

The preliminary design must be finalized and its performance evaluated by simulating plausible scenarios, including simulated flights in holding patterns such as those existing in the vicinity of airports [18] and simulated flights within the SSR CoS [19].

In a detailed design, it is necessary to reconcile aspects of the protocol with the physical aspects, particularly in the areas close to the radar [20] and include functional aspects of the squitter as delayed transmission [21][5].

A posteriori, to the extent possible, tests should be implemented on the SSR and ADS-B installations of a real site [22], to collect statistics that can quantitatively verify the effective improvements provided by the functionalities

References

1. ICAO (International Civil Aviation Organization). Manual on the Secondary Surveillance Radar (SSR) Sytems. In: Doc 9684 AN/951 (2004)
2. Orlando, V., Drouilhet, P.: Functional Description of Mode S Beacon System. In: Project Report ATC-42 Revision B, Lincoln Laboratory, MIT (1982)
3. Stevens, M.: *Secondary Surveillance Radar.* Artech House (1988)
4. ICAO (International Civil Aviation Organization). *Annex 10, Third Edition of Volume IV.* (2014)
5. ICAO (International Civil Aviation Organization). Technical Provisions for Mode S Services and Extended Squitter. (2008)
6. RTCA: Minimum Operational Performance Standards for 1090 MHz Extended Squitter Automatic Dependent Surveillane - Broadcast (ADS-B) and Traffic Information Services (TIS-B). In: RTCA DO-260B (2011)

[5] As a consequence of delayed transmission, Figure 3 should be modified accordingly.

7. EUROCAE (The Europena Organisation for Civil Aviation Equipment): *Technical Specification for a 1090 MHz Extended Squitter ADS-B Ground System.* In: EUROCAE ED-129B. (2016)
8. Bria, O., Giacomantone, J.: *Colaboración ADS-B en la predicción SSR.* In: Libro de actas del XXVIII CACIC - Congreso Argentino de Ciencias de la Computación. (2022)
9. Sun, J.: The 1090 Megahertz Riddle: A Guide to Decoding Mode S and ADS-B Signals. 2nd Edition. TU Delft OPEN Publishing (2021)
10. McDewitt, A.J.: A Tracker for Monopulse SSR. In: IEE Colloquium on State Estimation in Aerospace And Tracking Applications (1989)
11. Bar-Shalom, Y., Rong Li, X., Kirubajaran, T.: *Estimation with Applications to Tracking and Navigation*, John Wiley & Sons, Inc. (2001)
12. Welch, G., Bishop, G.: An Introduction to the Kalman Filter. In: TR 95-041, Department of Computer Science, University of North Carolina at Chapel Hill (2006)
13. Broookner, E.: *Tracking and Kalman Filtering Made Easy*, Wiley-Interscience. (1998)
14. Radartutorial.eu: *Fundamentos Radar. Cobertura Radar*. In: https://www.radartutorial.eu/01.basics/rb21.es.html (2023)
15. Balanis, C.: *Antenna Theory: Analysis and Design*, John Wiley & Sons (2015)
16. Skybrary.aero: *Surveillance. definitions*. In: https://skybrary.aero/articles/surveillance (2023)
17. EUROCONTROL.: European Mode S Station Functional Specification (EMS), edition 4.0, EUROCONTROL-SPEC-189 (2021)
18. FAA, Aeronautical Information Services: Aeronautical Chart Users Guide. In: aernav.faa.gov/userguide/20220714/cug-complete.pdf (2022)
19. Mariano, P., De Marco, P., Giacomini, C.: *Data Integrity Augmentation by ADS-B SSR Hybrid Techniques*. In: Integrated Communications Navigation and Surveillance Conference (2018)
20. U.S. Department of Transportation, Federal Aviation Adminitration Specification: Mode Select Beacon System (Mode S) Sensor. In: FAA-E-2716 (1983)
21. EUROCAE (The Europena Organisation for Civil Aviation Equipment): Minimum Operational Performance Specification for Secondary Surveillance Radar Mode S Trasnsponders. In: EUROCAE ED-73B. (2003)
22. Addullah, A., Ismail, A., Badron, K., Rashid, N.: Improving Radar Detection by Adaptation of Automatic Dependent Surveillance-Broadcast (ADS-B) Technology, In: Advance d Science Letters, Vol. 22 (2016)