AERONAUTICAL SURVEILLANCE SYSTEMS: HISTORICAL AND FUTURE PERSPECTIVES

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ABSTRACT

The determination of aircraft position is an essential activity in air traffic control. The systems that perform this function have been evolving continuously over the years, as problems were identified and new technologies developed. Today, some of them are being used in parallel, mainly due to the transition period existing before the full adoption of new technologies. It is expected that this situation may cause some confusion on the characteristics, objectives and limitations of each system among aviation professionals. Given that context, this article aims to summarize features of the main surveillance systems used for aeronautical purposes, in order to allow a better understanding on the current scenario and the tendencies for the future. The analysis of the systems characteristics allow to conclude that a combination of ADS-B and Multilateration systems will possibly be the basis for the future civil aviation surveillance schemes, due to its complementary characteristics.

Keywords: Surveillance systems, transponders, Modes A/C/S, ADS-B, Multilateration.

1. INTRODUCTION

e history of aviation, several types of radar systems were used to determine the position of aircraft and thus enable the air traffic control. The steady growth of global aviation led to the need for changes in these surveillance systems. The objective of this work is to show the different characteristics of these systems, their advantages and disadvantages and describe its historical evolution in general. For that, the following systems will be discussed:

- PSR (Primary Surveillance Radar)
    - SSR (Secondary Surveillance Radar), in its various forms (Modes A,C and S)
- ADS-B systems
- Multilateration

2. PRIMARY SURVEILLANCE RADAR (PSR)

The PSR (Primary Surveillance Radar) is an aircraft positioning system based on the emission of electromagnetic waves by a ground radar and subsequent capture of the reflection of these waves caused by aircraft.

The PSR radar antenna directs the electromagnetic energy in a very narrow lobe in the horizontal plane, but broad in the vertical plane. In addition to the main emission lobe, there are also sidelobes which direct signals in other directions, with smaller amplitude than of the main lobe. This antenna is kept in constant rotation, with the objective of sending the electromagnetic waves in all directions. This description can be better observed in Figure 1 .

When the electromagnetic wave reaches an object, part of it is reflected back to the antenna. This reflected signal is captured and processed in order to determine the position of the aircraft with respect to the antenna.

The PSR is a surveillance system that does not depend on target cooperation, meaning that no equipment is necessary onboard aircraft to support its operation. This characteristic makes the PSR use generally required for security reasons (Eurocontrol, 2009).

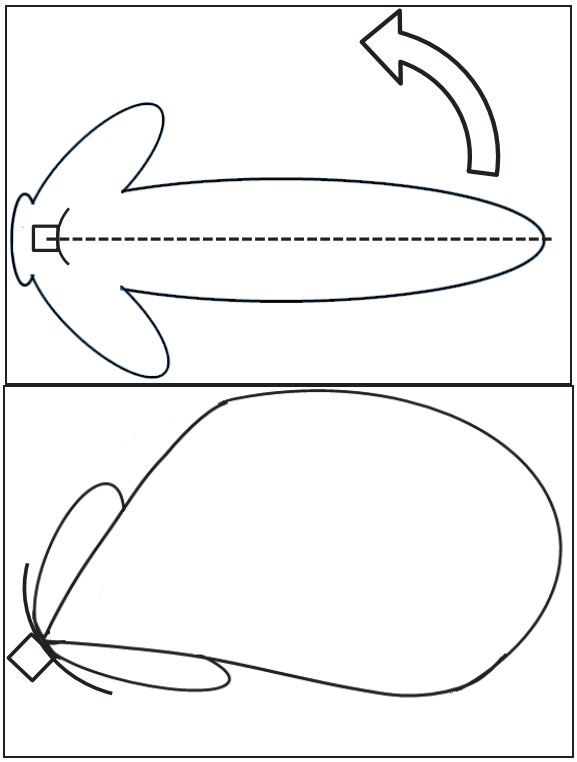


Figure 1 Standard horizontal and vertical emission of radar antennas (adapted from Ferrara, 1989)

However, the PSR system has some disadvantages, summarized below (Powell, 1981):

- It requires high energy of the radiated signal, so that the reflected signal has enough energy to be detected. Even so, the range of the radar is still dependent on the size and reflective characteristics of the aircraft.
- Aircraft identification can only be done by executing maneuvers that differentiate the aircraft on the radar screen, which is impractical in a congested airspace;
- There is interference from other elements in addition to aircraft, such as clouds or precipitation.
- The system does not determine the altitude of the aircraft, due to the beam width in the vertical plane.
- If the aircraft is very close to the radar, it can reflect the energy from the side lobes of the antenna, resulting in spurious receptions on the radar screen.

3. SECONDARY SURVEILLANCE RADAR (SSR)

3.1. Basic Description

The disadvantages of the PSR, in particular the difficulty associated with identification, led to the development of the Secondary Surveillance Radar (SSR - Secondary Surveillance Radar), initially focused on military applications to identify enemy aircraft on radar during World War II (IFF - Identification Friend or Foe).

The SSR system is based on the transponder, equipment installed onboard the aircraft that operates in conjunction with radar systems on the ground. After receiving an interrogation signal emitted by these ground radars, the transponder replies with a signal which is later received and processed by the interrogator radar, which uses the received information as needed.

The SSR antennas are generally mounted together with the PSR ones, and the information from the two systems are shown to the controller on the same display. The emission characteristics of the SSR antenna are also similar to those of PSR antenna, as shown previously in Figure 1. Figure 2 illustrates the antennas of the two systems.



Figure 2 - PSR and SSR antennas (adapted from http://www.eldis.cz/)

The main types of SSR systems in use will be described in the following sections:

3.2. SSR Modes A/C

3.2.1. Modes A/C interrogations

The first transponders widely used in the aerospace sector were Mode A/C transponders. Mode A is used to identify aircraft, and Mode C to determine its altitude.

The SSR interrogation radiated by the ground antenna is encoded into two radio frequency pulses (designated P1 and P3) with duration of 0.8 microseconds (μs) and 1030 MHz frequency. The spacing between these pulses determines the type of interrogation being transmitted (A or C). In addition to the modes A/C, the modes B/D were also defined, although they have not been widely used in practice. The basic types of interrogation intended for civilian use are described in Table 1 (Powell, 1981).

Table 1 - SSR modes A/C interrogations

Interrogation mode	Use	Pulse Spacing
Mode A	Identification	8 μs
Mode C	Altitude	21 μs

The emission characteristics of SSR antennas also includes sidelobes, as shown in Figure 1, so it is possible that aircraft capture interrogations coming from these spurious sidelobes. In order to avoid this possibility, current systems use one additional pulse, called SLS - Sidelobe Suppression Pulse. This pulse is transmitted 2 μs after pulse P1, from a stationary and non-directional antenna. That is, this pulse is transmitted in all directions simultaneously, so that the aircraft's transponder will receive it regardless of the position of the SSR antenna. The SLS pulse amplitude is calculated to be greater than the amplitude of emission sidelobes, but smaller than the main lobe. This allows the aircraft transponder to compare the amplitudes of the pulses P1 and SLS: if P1 is less than the SLS means that the aircraft is receiving an interrogation originated from a side lobe, thus it is rejected by the system.

Figure 3 illustrates the spacing between the pulses described, as well as the operational logic behind SLS (Ferrara, 1989).

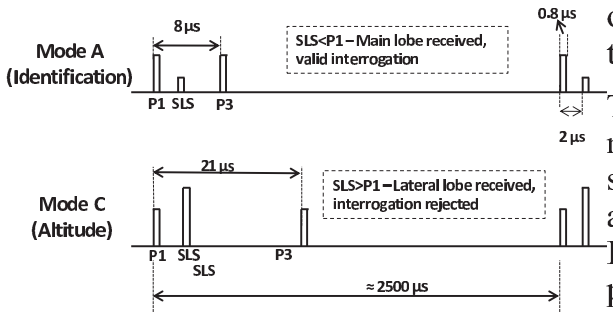


Figure 3 - Modes A and C interrogation pulses

Typically, SSR interrogations are sent at a rate of 400 Hz (that is, a time of 2500µs between interrogations). However this rate may vary: the ideal is to keep it as small as possible in order to avoid false detections. In general, the system is assembled so as to obtain from 20 to 40 replies per revolution of the antenna. This number of replies is caused by the width of the beam transmitted by the interrogator antenna, which causes the transponder to receive multiple interrogations during each antenna revolution. The direction of the aircraft with respect to the antenna is then determined by the several replies triggered on each antenna revolution. This azimuth determination technique, called "Sliding Window", is illustrated in Figure 4.

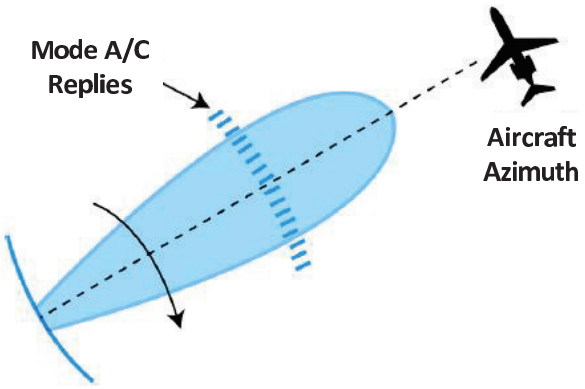


Figure 4 - Mode A/C azimuth determination (adapted from Paydar, 2010)

3.2.2. Mode A/C general reply format

Mode A/C replies are also encoded in radio frequency pulses, however with duration of 0.45 µs and a frequency of 1090 MHz. Every reply contains two pulses F1 and F2, separated by 20.3 µs, which delimit the information being transmitted. Between them, there are 12 other pulses that encode the information to be transmitted (identification or altitude).

There is provision for a 13th pulse (X), which may be used in a possible expansion of the system. It can also be transmitted another pulse after F2, called SPI (Special Position Indicator). This pulse, used to highlight a particular aircraft on the radar display, is transmitted from a pilot command (IDENT), and is kept on the replies for about 20 seconds after the command.

In total, there are 16 bits transmitted in a Mode A/C reply (2 delimiter bits F1/F2, 12 information bits, SPI and X bit).

3.2.3. Mode A reply

In the Mode A reply, the aircraft identification is encrypted by grouping the 12 data pulses into 4 blocks, designated as A, B, C and D. Each block has three pulses (designated by suffixes 1, 2 and 4) and may represent the values 0 through 7 in binary coding. Thus, the transponder system transmits 8^4=4096 different codes, ranging from 0000 to 7777. Figure 5 illustrates the pulse positioning on a Mode A reply (Ferrara, 1989):

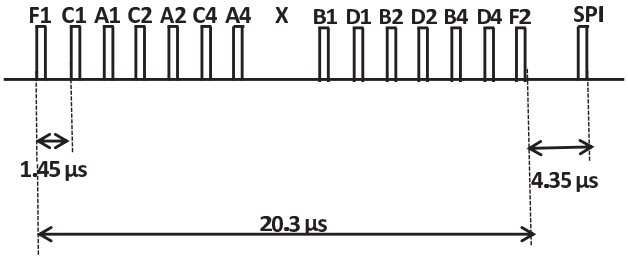


Figure 5 - Modes A reply pulses

Figure 6 and Table 2 give an example of a possible Mode A reply, and its corresponding decodification:



Figure 6 – Example of Mode A reply

Table 2 - Example of Mode A reply decodification

Group	4	2	1	Decodification	Ident.
A	1	0	1	$(A_4 \cdot 4)+(A_2 \cdot 2)+(A_1 \cdot 1) = (1 \cdot 4)+(0 \cdot 2)+(1 \cdot 1)$	**5**
B	0	0	1	$(B_4 \cdot 4)+(B_2 \cdot 2)+(B_1 \cdot 1) =$	**1**

				(0·4)+(0·2)+(1·1)	
C	0	0	0	(C_4·4)+ (C_2·2)+(C_1·1) = (0·4)+(0·2)+(0·1)	**0**
D	0	1	0	(D_4·4)+ (D_2·2)+(D_1·1) = (0·4)+(1·2)+(0·1)	**2**

The identification code is entered by the pilot in the transponder after designation defined by traffic control on the ground. The term "squawk" is used by controllers to make this designation: for example, the phrase "Cessna 123AB, squawk 1234" means that the controller requires the aircraft to select the transponder code 1234.

Certain codes are internationally standardized by ICAO (International Civil Aviation Organization) for specific uses, as described in Table 3 (ICAO, 2007a):

Table 3 - Examples of standard transponder codes

Code	Use
7700	Aircraft in emergency
7600	Aircraft with radio communication failure
7500	Hijacked aircraft
2000	Aircraft with no transponder code assigned by traffic control.

3.2.4. Mode C reply

In the Mode C reply, the encoding of aircraft altitude was standardized by the ICAO in increments of 100 feet, ranging from -1000 to 126,700 feet, totaling 1278 codes needed to represent this altitude range (Powell, 1981).

The altitude value is provided by an altimeter that generates the code to be transmitted by the transponder. As there are 4096 possible codes, there is some redundancy in this encoding.

To address this redundancy, the Mode C Coding is made in a more complex manner than Mode A: the pulse D1 is not used and, additionally, at least one pulse C is transmitted, but never pulses C1 and C4 together. Thus, Mode C encoding has 8 possible values for group A, 8 from group B, 5 for group C and 4 for Group D, totaling 8 8 5 4 = 1280 possible altitude codes, only two more than the necessary.

3.3. SSR Mode S

3.3.1. Mode S basic description

Transponders Mode A/C increased the amount of information provided to air traffic controllers, and addressed some problems associated with the PSR, as listed below:

- Identification of the aircraft, using 4096 different codes.
- Determination of aircraft altitude.
- Greater range, because the transponder sends a much stronger signal than the PSR signal reflection.
- Less interference, since the signal is stronger and has distinguishable features.
- Ability to highlight aircraft on the radar screen, with the IDENT command.

Nevertheless, with the increase in global air traffic, the number of Mode A codes started to become insufficient. Moreover, the frequency of 1090 MHz started to get saturated, causing two kinds of problems: interference between pulses of different aircraft replies and spurious replies coming from transponders interrogated by different radars on the ground.

As a result, the Mode S transponder (Selective) was developed to address the problems associated with the modes A/C and to support the automation of air traffic control in heavy traffic areas. The fundamental difference between Mode S and Mode A/C is the way to select which aircraft will be interrogated. In Mode A/C, this selection is done spatially, that is, all aircraft that capture the signal from the interrogator will emit a reply. In the Mode S, each aircraft has a unique identifier code, so that the selection of which aircraft must reply to an interrogation is achieved by including the address of the aircraft in the interrogation message. This use of discrete addresses presents two main advantages:

1) Enables the interrogator to limit the interrogations only for aircraft under its responsibility, rather than continually interrogate all aircraft that are within the range of the system.

2) Allows for an ordering of interrogations, so that the replies of different aircraft are not mixed when received.

For backward compatibility, Mode S uses signal formats already used by Mode A/C (interrogation in 1010 MHz and replies in 1090 MHz), and adds to these signals the messages needed to address aircraft equipped with Mode-S transponders.

3.3.2. Mode S interrogations

The Mode S interrogator radar uses three types of interrogations, as described below (Orlando et al, 1986):

a) Interrogation All-Call Mode A/C/S - Triggers replies of all aircraft equipped with transponders Mode A, C or S.

b) Interrogation All-Call Mode A/C - Triggers replies of all aircraft equipped with Mode A and C transponders, that is, do not trigger Mode S transponders.

c) Interrogation Mode S - Trigger replies only from a specific aircraft equipped with Mode S transponder. This aircraft is defined inside the interrogation message. This prevents multiple aircraft to reply to the interrogation at the same time.

The interrogations All-Call Mode A/C/S and All-Call mode A/C are quite similar to Mode A/C, but with the inclusion of a pulse P4 after pulse P3. The type of interrogation is defined by the duration of this pulse P4: if it is 1.6 μs long, the interrogation is an All-Call Mode A/C/S, and if it is 0.8 μs long, the interrogations is an All-Call Mode A/C that inhibits the reply of Mode S transponders. These two interrogations are depicted in Figure 7:

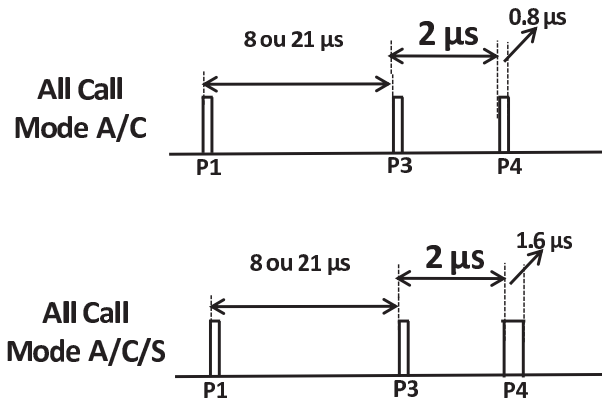


Figure 7- All call interrogations (adapted from Orlando et al, 1986)

The Mode S interrogation is formed by three pulses, P1, P2 and P6. The pulses P1 and P2 are separated from 2 μs. Transponders Mode A/C interpret this as a Sidelobe suppression command (SLS) and thus do not send a reply. Without this, the subsequent pulse P6 would trigger the transponder Mode A/C, causing a spurious reply.

The pulse P6 is 16.25 or 30.25 μs long and contains information modulated with Differential Phase Shift Keying (DPSK), which has better immunity to interference than the Pulse Amplitude Modulation Pulse (PAM) used by Modes A/C. This format allows the transmission of 56 or 112 bits in the interrogation.

The basic format of Mode S interrogation is depicted in Figure 8 (Orlando et al, 1986):

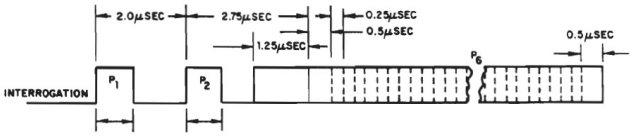


Figure 8 - Mode S interrogation

The bits contained in pulse P6 are encoded in fields that allow the implementation of several functionalities by the system. There are 25 interrogation formats (Uplink Formats - UF) standardized by ICAO. Only eight are currently used, as described in Table 4 (ICAO, 2007c):

Table 4 – Standardized uplink formats

Uplink Format	Use
UF0	Short air-air surveillance (ACAS - Aircraft Collision Avoidance System)
UF4	Surveillance, altitude request
UF5	Surveillance, identify request
UF11	Mode S only all-call
UF16	Long air-air surveillance (ACAS)
UF20	Comm-A, altitude request
UF21	Comm-A, identify request
UF24	Comm-C (ELM – Extended Length Message)

One of the features enabled by Mode S Transponder is the unique addressing of the aircraft, with 24 bits, which reduces the interference and spurious replies found in transponders Mode A/C. This addressing comprise 2^{24}=16,777,216 different codes, thus enable worldwide unique identification of aircraft (Eurocontrol, 2003). The distribution of address codes is done by the civil aviation authorities of each country, following allocation rules defined by ICAO. For example, codes starting with the sequence 111001 are allocated to Brazilian registered aircraft, which yields 262,144 available addresses (ICAO, 2007a). For the sake of comparison, there were 19,401 aircraft registered in Brazil in 01/10/2012 (ANAC, 2013).

Figure 9 illustrates the use of Mode S addresses in Brazil:

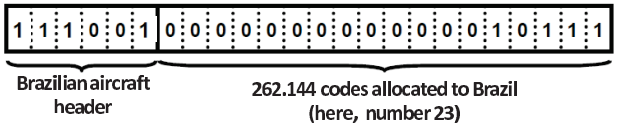


Figure 9 - Example of Brazilian aircraft Mode S address code

In order to facilitate handling, the 24 bit addresses are often expressed in hexadecimal format, which reduces its representation to a series of 6 digits, each one ranging from 0-9/A-F.

3.3.3. Mode S replies

The Mode S reply has two formats, which also use the frequency of 1090 MHz. The first format is identical to the transponder Mode A/C reply described before and is used to reply to Mode A/C interrogations (Orlando et al, 1986).

The second reply format is the Mode S reply per se, used to reply to interrogations Mode S and All-Call Mode A/C/S. This reply is composed of a preamble and a data block containing 56 or 112 bits, as in the Mode S interrogation. The address code of the aircraft (24 bits) is included in this data block.

The preamble consists of a series of 4 pulses of 0.5 μs, designed to be easily distinguishable from Mode A/C replies. This allows simple separation between Mode A/C replies that may be received together with the Mode S reply. The data block begins 8.0 μs after the start of the first pulse of the preamble.

The binary information is transmitted using Pulse Position Modulation (PPM), which works as follows: each data bit has 1.0 μs duration; if a pulse of 0.5 μs is transmitted in the first half of the 1.0 μs interval, the value of the data bit is 1; and if a 0.5 μs pulse is transmitted in the second half of the 1.0 μs interval, the value of the data bit is 0. This kind of modulation allows greater detection of bits even with interference caused by Mode A/C replies.

Figure 10 depicts the Mode S reply format.

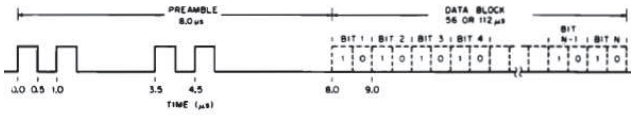


Figure 10 - Mode S reply format (Orlando, 2013)

Another advantage of the PPM modulation is the fixed number of pulses in each reply, independently of its content, which ensures enough power for monopulse direction estimates. This technique is used by Mode S systems to obtain the direction of the aircraft given only one reply. It consists in the emission of two additional signals together with the main lobe of the antenna, called "sum" and "difference" signals. Their emission is made such that a reply captured perpendicularly to the antenna produces a maximum sum signal output, but a zero output from the difference signal. If the reply is captured in different angles, the sum signal will be smaller and the difference signal bigger. Thus, the angle of arrival of the reply may be determined by the ratio of the sum and difference signals, given a single reply (Orlando et al, 1986). This technique is illustrated in Figure 11:

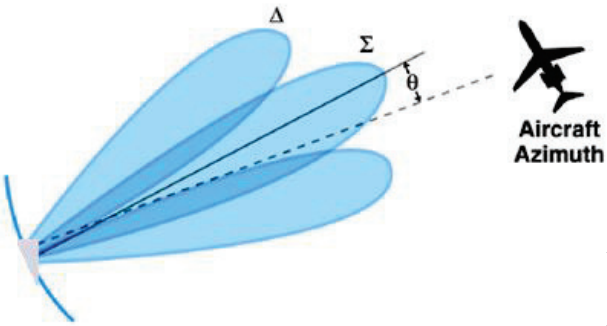


Figure 11 - Monopulse azimuth determination (adapted from Paydar, 2010)

In addition to the replies, the Mode S transponder also transmits an unsolicited message called "squitter". This message is transmitted every second, regardless of the reception of an interrogation. This message type is used by ACAS systems (Airborne Collision Avoidance Systems) to prevent collisions between aircraft.

As with the interrogation, the Mode S reply also has 25 formats standardized by ICAO (downlink formats – DF), and 10 of these formats are currently used (ICAO, 2007b). Table 5 lists these formats:

Table 5 - Downlink formats standardized by ICAO

Downlink Format	**Use**
DF0	Short air-air surveillance (ACAS)
DF4	Surveillance, altitude reply
DF5	Surveillance, identify reply
DF11	All-call reply
DF16	Long air-air surveillance (ACAS)
DF17	Extended squitter
DF18	Extended squitter/non transponder
DF20	Comm-B, altitude reply
DF21	Comm-B, identify reply
DF24	Comm-D (ELM)

4. ADS-B SYSTEM

4.1. Basic Description

SSR systems, despite being a great evolution compared to PSR, present a major drawback: its functioning is also based on the rotation of the radar antenna, which limits the refresh rate of aircraft position to the rotation frequency of the antenna. Moreover, the moving parts involved in SSR makes the system more complicated to install and costly to maintain (Creativerge, 2013).

Given those SSR disadvantages, the ADS-B (Automatic Dependent Surveillance-Broadcast) is a system where aircraft automatically and continuously transmit navigational information, in such a way that it can be received by other aircraft or ground receivers within transmission range. This information includes position, altitude, speed, aircraft identification and category.

The ADS-B is divided into two service types: ADS-B In and ADS-B Out. The ADS-B Out is the transmission of information by each aircraft, which provides air traffic controllers with aircraft real-time position, often with greater accuracy than current SSR systems. ADS-B In refers to the ability of aircraft to receive ADS-B information transmitted by other aircraft and ground traffic control. This improves flight safety by increasing the situational awareness of pilots, who can view in the electronic displays the position of other aircraft, as well as updated weather information.

With this operation, the determination of the position of the aircraft will no longer be made through interrogations to transponders: traffic control will permanently receive the position of the aircraft, while transmitting meteorological information and other important data for the flight, such as NOTAMs and areas restricted to flight.

The implementation of ADS-B basically depends on the existence of two certified equipment onboard: a high-integrity GNSS (Global Navigation Satellite System), which determines the position of the aircraft, and a datalink provider, which transmits and receives

ADS-B information. The ADS-B datalink may use the 1090 MHz frequency (already used by the transponder Mode A/C and S) or 978 MHz.

At this point it is possible to understand the terms of the ADS-B acronym, as follows:

- *Automatic* - There is no need of an interrogation to trigger the data transmission by the aircraft, so it is automatic.
- *Dependent* - The system depends on special equipment installed onboard, for position determination and transmission of data.
- *Surveillance* - The system provides a means for automatic coordination and monitoring of traffic.

This philosophy of functioning allow for the elimination of moving parts present in SSR systems, which make ADS-B stations smaller and easier to maintain, thus reducing the overall operational cost of the system compared with SSR (Eurocontrol, 2009). It also enables the update of aircraft position every second, as well as the transmission of several other data, yielding better situation awareness for the air traffic control and the pilots.

4.2. ADS-B transponder

As seen before, Mode S transponders transmit the "squitter" message in every second, regardless of reception of an interrogation. Thus, Mode S transponders can be used to provide the ADS-B Out datalink after being modified to transmit ADS-B information continuously, together with the "Squitter" message already transmitted by these transponders. This functionality is called “Extended Squitter” (1090ES), and uses the standard DF17 downlink format. Figure 12 illustrates the contents of these messages:

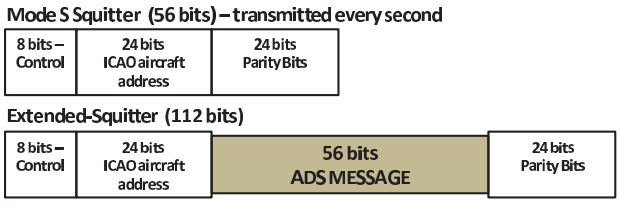


Figure 12 – Format of Squitter and Extended Squitter messages (adapted from Orlando, 2013)

Despite the existence of ADS-B transponders with a frequency of 978 MHz (called UAT - Universal Access Transceiver), the Extended Squitter was the standard for ADS-B datalink chosen for use on an international scale and high altitudes. With that, UAT systems will be used for regional aircraft in general aviation (FAA, 2010).

5. MULTILATERATION

5.1. Basic Description

The Multilateration positioning scheme is based on a method known as Time Difference of Arrival (TDOA). It uses information received by a number of ground stations that capture SSR replies and ADS-B data. At the time of transmission of these data, the aircraft will be at different distances from each of these stations, so the data will be received by each station at slightly different times due to different propagation times for each station. From the processing of these reception times it is possible to accurately determine the position of the aircraft. Figure 13 illustrates the process of position determination by Multilateration.

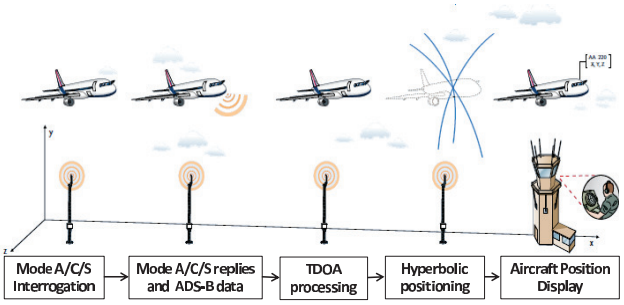


Figure 13 - Position determination with Multilateration technique (Creativerge, 2013)

The position calculation algorithm is called Hyperbolic Positioning. In general it may be described in the following steps:

- The TDOA calculated with information from two stations determines a hyperboloid surface where the aircraft can be located.
- With the addition of a third station, it is obtained two further TDOA hyperboloid surfaces, relative to the difference of arrival from the third station to the first and second ones, so that the intersection of

the three hyperboloids defines a single point in space.

Figure 14 illustrates the hyperboloids involved in Multilateration position determination:

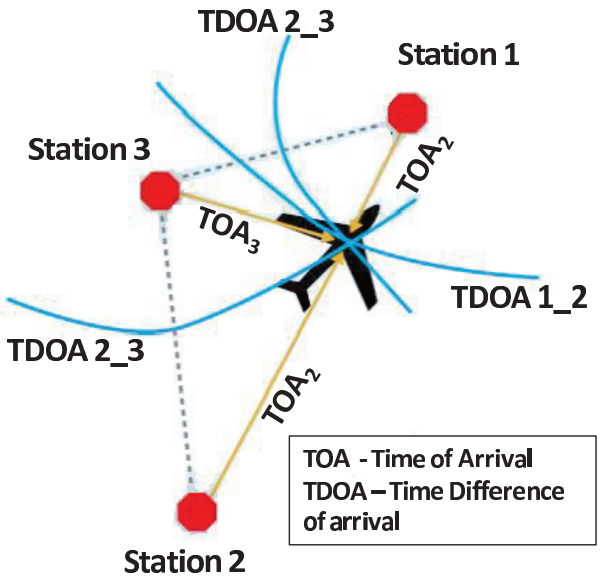


Figure 14 - Hyperboloids used for Multilateration position determination (adapted from Turner, 2013)

In theory, information received by three ground stations would be enough to determine the position of the aircraft. However, a fourth station is also needed to determine the emission time for the transponder data. In practical operation, even more information is used in order to provide redundancy to the system (Gaviria, 2012).

5.2. Comparison with other systems

Due to its presented advantages, ADS-B systems will be an important part of future air traffic management system. However, the cost of installation of ADS-B equipment in current aircraft fleet will limit its widespread use in the short term.

Additionally, the ADS-B aircraft positioning scheme is "single-failure mode", meaning that if only one element fails (such as the GNSS or the transponder), the ADS-B information will not be available for that aircraft. Therefore, it is foreseen that ADS-B alone will not meet safety requirements in high density TMA operations. In those cases, another surveillance system will be needed to provide the necessary redundancy (Eurocontrol, 2009). In the United States, it is being proposed to maintain part of the current SSR network even after the widespread implementation of ADS-B, in order to provide this backup for the ADS-B system (FAA, 2010).

Despite the possibility of using SSR as a backup for ADS-B, the Multilateration technology is also emerging as a possible backup technology, since it presents many advantages over SSR, as follows:

- It enables the benefits of improved surveillance provided by ADS-B even before 100% of the fleet is ADS-B equipped, since it uses information of both ADS-B and SSR systems to determine the position of aircraft (Eurocontrol, 2009).
- Multilateration positioning can be performed at rates comparable to ADS-B (up to 1 update/second), as compared with the 4-12 seconds interval of SSR (ICAO 2007c).
- ADS-B and Multilateration capabilities can be easily combined into a single station, yielding cost benefit in terms of installation and maintenance. This might take advantage of the ADS-B infrastructure installation without additional costs, and also provide an improved transition to ADS-B. (Creativerge, 2013).
- Multilateration stations are simpler and smaller than SSR, due to the absence of rotating parts, which facilitates installation and maintenance (James, 2007).
- The network of Multilateration stations can be tailored to create coverage performance according to specific needs. Also, the network improves lower altitude coverage and prevents line-of-sight issues that are present in SSR, thus it can be used as a "gap-filler" solution. (Abu-Taieh, 2011 and SAAB, 2013a).
- Overall life-cycle cost of Multilateration are expected to be between 20 to 35% lower than SSR (Eurocontrol, 2005).
- Even when ADS-B is fully implemented, the Multilateration network can perform both essential ADS-B backup and validation functions, as well as to track eventual non-ADS-B traffic even beyond the transition period. (Creativerge, 2013).

- The concept of a network of stations involved with Multilateration gives it the capability of withstanding the loss of one or more sensors, characteristic that would only be equaled by SSR with the installation of several radar stations, at a much higher cost. This redundancy effect is depicted in Figure 15.

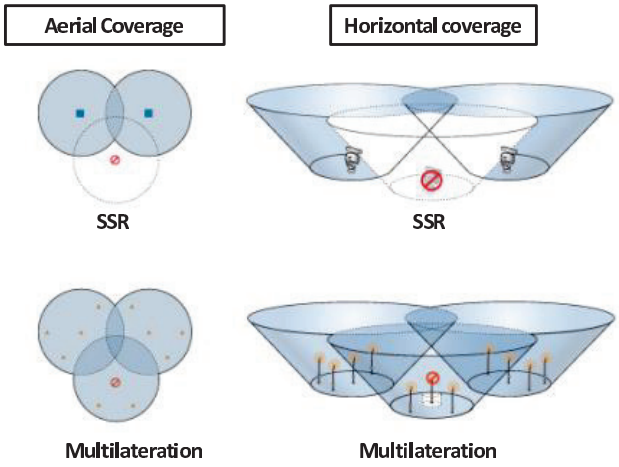


Figure 15 - Redundancy found in Multilateration systems (Creativerge, 2013)

Figure 16 depicts a Multilateration station, which shows that it can be installed in already existing communication towers and terminals (Saab, 2013a).



Figure 16 - Multilateration station (taken from http://era.aero/)

5.3. Multilateration Applications

In general, Multilateration applications in the air traffic control are as follows (ICAO 2007c):

- Surface surveillance at airports - aircraft and ground support equipment;
- Traffic surveillance in airspace (with or without radar coverage);
- Performance monitoring and validation of ADS-B and RVSM systems (Reduced Vertical Separation Minima).

The Multilateration systems may, therefore, be used in conjunction with ADS-B because they have characteristics that complement each other (ICAO, 2007c):

- It increases surveillance coverage at lower altitudes (below the radar coverage) and in areas without radar coverage at all.

- It enables local and airport surface surveillance, increasing airport safety especially in low visibility conditions and at the same time protecting against vehicle runway incursions;
- Due to its greater flexibility of use, it can be used in any infrastructure scenarios, types of airspace, flight phases and fleet situation fleet in terms of surveillance equipment.
- It may be used in the future for validation and backup for ADS-B systems

In practical terms, Multilateration systems are currently being used where the use of radar may be unfeasible or where an improved surveillance may be needed before wide adoption of the ADS-B system. Some situations where these conditions are met include:

- Airports located in mountainous regions, which would demand several radars to adequately cover its terminal areas, due to line-of-sight constraints. The high number of radars needed on these situations may justify the use of the lower cost Multilateration stations. This solution is currently being used in several airports around the world (Saab 2013 b, c, e).
- Busy airports demanding improved efficiency and safety levels before ADS-B full implementation (Saab 2013 d).
- Sea oil rigs, where installing radar is cost-inefficient compared to the Multilateration receivers, due to sizing constraints (Eurocontrol, 2009).
- Airports where improved surface surveillance is required, which cannot be performed adequately by SSR due to line-of-sight issues caused by airport terminals, hangars and other constructions (Creativerge, 2013).

6. CONCLUSIONS

This article described the major systems currently in use for aircraft surveillance. From the historical development depicted, the advantages associated with ADS-B system can be clearly seen, justifying why its large scale use is being fostered by the civil aviation authorities.

However, even the ADS-B has some limitations that may be addressed with SSR or Multilateration systems. Given the advantages of the combined ADS-B/Multilateration systems presented in this work, it is possible that the future air traffic control system will be based on these two types of technology together.

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