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EVALUATION OF GARBLED REPLIES FOR AIRCRAFTS INTERROGATED BY SSR SYSTEM

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Abstract. *In aviation, an undesirable phenomenon that can occur with increased airport traffic is garbling. The main problem is that if two aircraft are within a short critical distance to each other, the replay messages (response signals) can overlap. To better understand the garbling phenomenon by aviation students and engineers and to prevent the occurrence of this undesirable phenomenon that can lead to tragic events, we have modelled and simulated this phenomenon using an algorithm that statistically estimates the number of garbled replies (erroneous replay messages/ response signals) for several aircraft interrogated by a secondary surveillance radar.*

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1. Introduction

Secondary Surveillance Radar (SSR) helps identifying aircrafts and often works in conjunction with the *Primary Surveillance Radar* (PSR) for better target awareness, as illustrated in Figure 1.

Figure 1. Airport antennae for SSR (left side top) and PSR (left side down). The whole antennae system (right side).

The PSR radiates an electro-magnetic wave and receives the echo reflected from any objects (targets) detecting their presence, range (distance from PSR to target) and azimuth, but not their identity. In PSR system, energy is radiated via a

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rotating radar antenna to *illuminate* (find) a target. The target can be an aircraft, the ground or a cloud. Some of this energy is reflected from the target and is collected in the same antenna, as depicted in Figure 2.

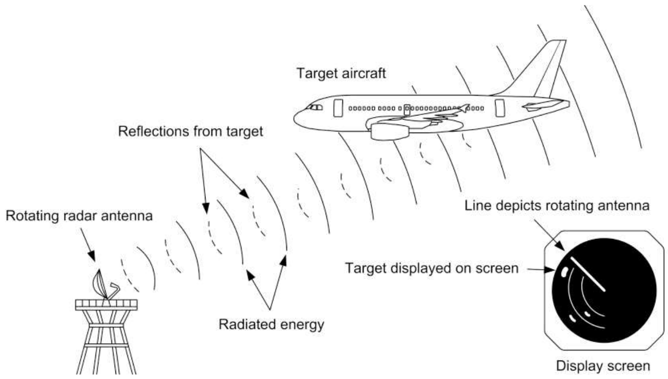

Figure 2. Functional principle of PSR system.

The strength of the returned energy is measured and used to determine the range of the target. A rotating antenna provides the directional information (the azimuth) such that the target can be displayed on a screen [1], [4], [5], [6].

The PSR has its disadvantages, one of which is that the amount of energy being transmitted is very large compared with the amount of energy reflected from the target. An alternative method is to employ a SSR that casts a specific low-energy signal (the interrogation/query signal) to a known target (*e.g.* aircraft). This signal is analyzed by aircraft equipment (a transponder) and a new (or secondary) signal, i.e. not a reflected signal, is sent back to the origin (the reply signal), as summarized in Figure 3.

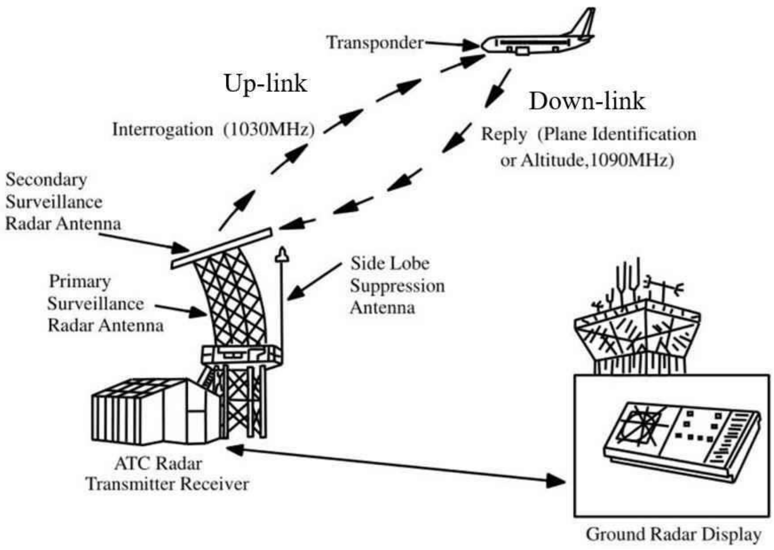

Figure 3. Functional principle of SSR system.

The SSR system was developed during the Second World War, to discriminate between friendly and enemy aircrafts and/or ships. The procedure is referred to as *Identification Friend or Foe* [IFF] [8], [9].

The air traffic control is of great importance in aviation. Ground controllers need to frequently talk to the pilots flying in the controlled area. They communicate to each other by using (very) high frequency communication systems. At the same time, the controllers also need to monitor the positions and trajectories of airplanes flying within the controlled area. This is realized by mixing PSR and SSR systems.

For civilian aircrafts, the current SSR protocol derived from the early military IFF and is known as *Air Traffic Control Radar Beacon System* (ATCRBS). The ATCRBS system is an interrogation-based system that includes a ground-based interrogator and an on-plane transponder. On the ground, an ATCRBS sensor sends out an interrogation (*up-link*) signal, by using the 1030 MHz frequency band, from a rotating antenna to all aircrafts flying in its sector. Aircrafts that are equipped with transponders receive the up-link signal and send back a **reply** (*down-link*) signal, within the 1090 MHz frequency band [1], [7].

The SSR interrogation consists of three rectangular pulses (at 1030 MHz) of 0.8 µs duration each, as shown in Figure 4.

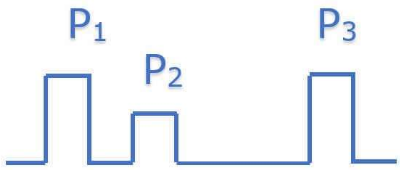

Figure 4. SSR interrogation pulses.

In the figure, P1 and P3 constitute actual interrogation pulses, while P2 stands for a *Side Lobe Suppression* (SLS) pulse. The pulse P2 is added after 2 µs from the pulse P1, to prevent the transponder from replying to the side of the interrogator antenna from one of the side lobes. In Figure 5, one can see that replies from the antenna side lobes can be eliminated by omni-directionally transmitting P2, as a reference level.

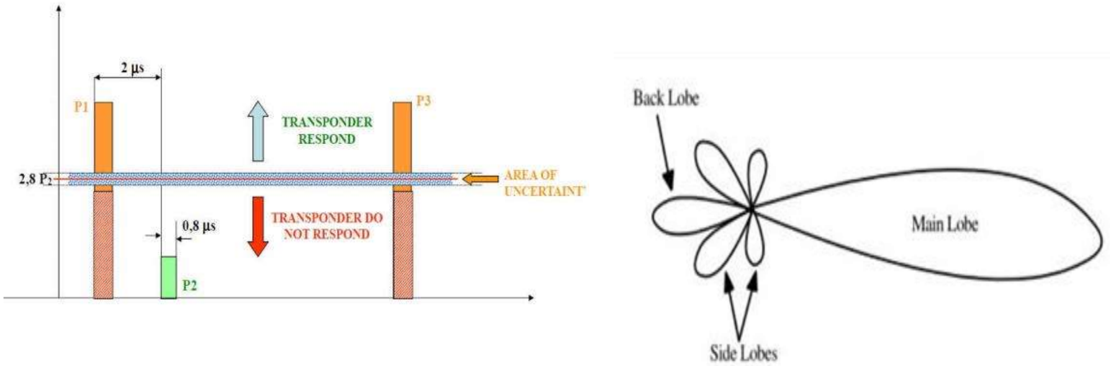

Figure 5. The role of SLS pulse P2 (left side) and the radiation lobes of antenna (right side).

The radiated signal strength SLS pulse is greater than the radiated signal strength from any side lobe. Since the interrogation pulses are stronger than the SLS pulse (the amplitude of P1 and P3 are more than 2.8 times of P2 amplitude), the interrogation came from the main lobe of the antenna and the transponder replies to the interrogation (the secondary lobes level are at most 1/16 of main lobe level). If the interrogation pulse is weaker than the SLS pulse, the interrogation was received from a side lobe and the transponder is prevented to reply.

The duration between P1 and P3 determines the interrogation mode. Four modes are considered: Mode A (8 µs), Mode B (17 µs), Mode C (21 µs), Mode D (25 µs). Two of interrogation (queries) are considered as primary: Mode A, to perform aircraft identification and monitoring and Mode C, to estimate the aircraft altitude. In Figure 6, one can see a schematic of the two primary modes.

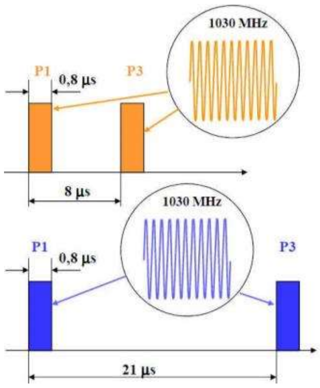

Figure 6. Mode A (8 µs) (up) and Mode C (21 µs) (down) interrogations.

Aircraft transponder replies usually consist of a stream including 14 rectangular pulses (at 1090 MHz), each of which lasting for 0.45 µs. The whole reply signal has a constant duration of 20.3 µs and is used to provide aircraft identity or altitude. Figure 7 shows the format of a reply signal. The pulses are sided by two frame pulses playing the role of brackets (namely, F1 and F2).

Between the frame pulses there is space for 12 additional pulses, known as *the 12 bit code*. The pulse train effectively is a binary code in which maximum 2^{12}=4096 possible combinations can be sent. There is a maximum of 15 pulses/bit (the duration between A_4 and B_1 is unused), with each data bit having its own time slot. The leading edge of F1 (the first pulse being transmitted) is used for timing. The first data bit, C1, is transmitted 1.45 μs after F1. The second data bit, A1, is transmitted 2.9 μs after F1, and so on, in increments of 1.45 μs. The answer to interrogation in Mode A is an *ID Code* or *squawk code* (for aircraft identification). The answer to interrogation in Mode C is an *Altitude Code*. An additional pulse, referred to as *Special Pulse Identity*, is employed for identification purpose. This bit can be activated by the aircrew by pressing a front-panel switch as directed by the air traffic controller. This pulse causes the display of the aircraft transmitting it to brighten on the radar display as mark of aircraft identification.

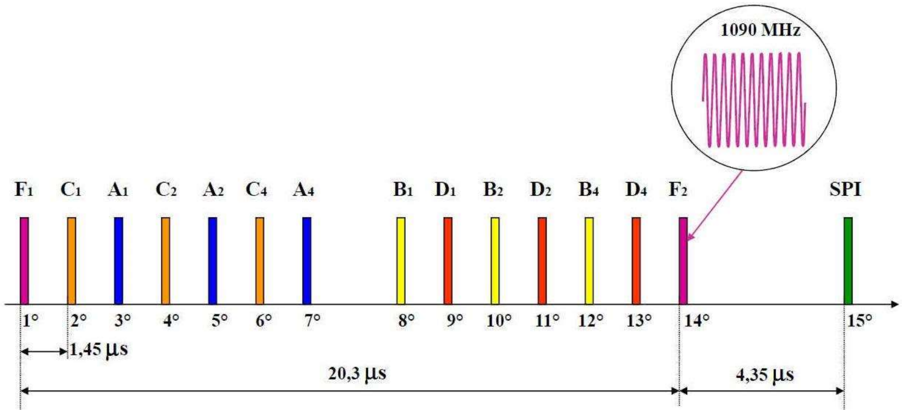

Figure 7. Reply signal format.

The remaining of article is structured as follows. The next section is devoted to garbling phenomenon. In section 3, one shows how the garbling can be statistical modeled. In section 4, some simulation results are presented and analyzed. The article completes with concluding remarks and a references list.

2. Garbling

An important module of the SSR system is the reply signal processor unit. One of the major issues in reply processing is the occurrence of garbled replies, due to the overlapping of reply signals. *Garbling* is the term used in surveillance radar (especially in air traffic control using SSR) to describe an echo fusion phenomenon caused by the overlapping responses of two or more targets in proximity, within the same radar beam.

In practical scenarios, SSR replies are often garbled (*e.g.* for formation flights). If two aircrafts are on the same bearing from the ground station and closer to each other, they may produce overlapping replies to the ground SSR interrogator. This is referred to as *garbling* or *garble phenomenon* [1], [5], [13], [14], [15].

Overlapping occurs when slant range difference between the two targets is less than *de-garble resolution*, computed as follows [2], [3]:

$$G_r = \frac{c \cdot T_{SSR}}{2}, \tag{1}$$

where: c is the speed of light (300,000 km/s), while T_{SSR} is the reply signal duration (20.3 μs). Thus, according to (1), $G_r = 3045$ m.

Dealing with garbling is a fundamental problem in the design of the classical SSR system, especially in case of increased traffic. Aircraft are often closely spaced in range and azimuth but at different heights. Replies from two aircraft will overlap if their range separation is within the equivalent of the 20.3 μs reply duration or 3.045 km distance range. The most serious garbling situations occur when the difference between azimuths is very small, such that replies from both aircrafts are received from all interrogations across the beam.

Two types of the overlapping are possible, as illustrated in Figure 8: asynchronous or synchronous.

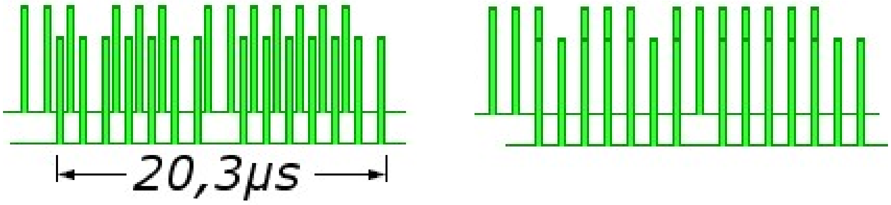

Figure 8. Asynchronous Garbling (left side) and Synchronous Garbling (right side).

In the left side of figure, two replies overlap in time in away that their time grids are not congruent, so one speaks about *Asynchronous Garbling*. This type of garbling occurs when the distance between any two aircrafts is less than de-garble resolution but not a multiple of 217.5 m. Such replies can be separated and one by one correctly decoded. However, if two or more replies overlap in time such that their time grids are congruent, one speaks about *Synchronous Garbling*. For example, in case of 15 aircrafts, such a garbling occurs when the targets are at the same azimuth or if the distance between any two targets is expressed in multiples of 217.5 m:

$$\frac{c}{2} \cdot \frac{n \cdot T_{SSR}}{14} = \frac{n \cdot G_r}{14} = \frac{3045}{14} \cdot n = 217.5 \cdot n, \quad \forall n \in \overline{1,15}. \tag{2}$$

In this case, one cannot decide whether a certain impulse belongs to one reply or another; very likely, decoding of wrong replies often occurs. Such replies must therefore be disabled.

The replies that the SSR receives (after its own interrogation) are said to be *garbled* if any of the following conditions occur:

a. the reply duration at the input of receiver is greater than the standard frame duration of 20.3 μs;
b. the amplitudes of pulses within the standard frame length are different;
c. the current pulse width is greater than the standard pulse width.

3. Statistical modeling of garbling

To better understand the garbling phenomenon by aviation students and engineers and to prevent the occurrence of this undesirable phenomenon, an algorithm to statistically estimate the number of garbled replies (erroneous replay messages / response signals) for a number of aircrafts interrogated by a SSR has been designed, implemented and run (in simulation). Therefore, to allow implementation of the algorithm, the following strategy was adopted [10], [11], [12].

Step 1: Setting limits and initializations

As Figure 9 shows, the SSR is placed into the origin of coordinates system, while the aircraft is reduced to a point in space.

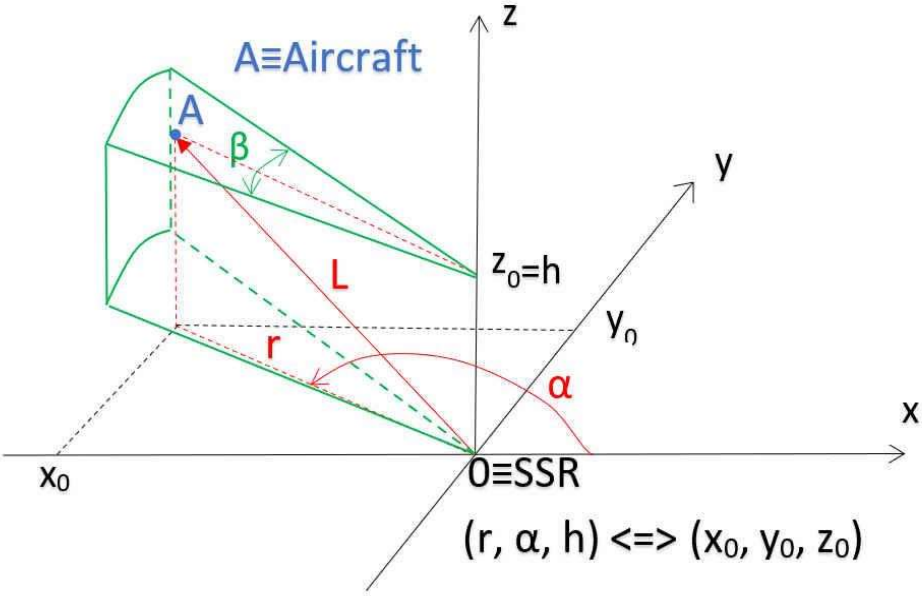

Figure 9. Aircraft representation in polar and cartesian coordinates, with SSR as the coordinates origin.

In this framework, the following parameters are set:

- the number of aircrafts for simulation: $N \in \{10, 20, 50, 100, 200, 500, 1000\}$ (7 scenarios);
- the azimuth angle (α) is the angular polar coordinate of aircraft in the horizontal plane (variable);
- the angular SSR beam width: $\beta = 2° \cong 0.035\ \text{rad}$;
- the SSR maximum radius: $R_{max} = 360\ \text{km}$ (this also is the maximum range of absolute values along the axes Ox and Oy);
- the airport safety radius: $R_{min} = 3\ \text{km}$;
- the aircraft radius ($r \in [R_{min}, R_{max}]$) is the metric polar coordinate of aircraft in the horizontal plane (variable);
- the SSR maximum altitude: $H_{max} = 30\ \text{km}$ (this also is the maximum range of altitude values along the axis Oz);
- the SSR minimum altitude: $H_{min} = 50\ \text{m}$ (this also is the minimum range of altitude values along the axis Oz);
- the aircraft altitude ($h \in [H_{min}, H_{max}]$) is the height of aircraft (variable).

On the radar screen, the aircrafts appear as spots (blips), such as i and j in Figure 10. The radius and azimuth are easily computed from the screen locations. Nevertheless, the altitude cannot be computed, being displayed. In modern avionics, beside the altitude, the aircraft identifier also is displayed.

Figure 10. Aircrafts localization on the radar screen.

Step 2: Generating Cartesian coordinates at random

A set of coordinates are generated at random for each aircraft considered for simulation: $\left\{(x_n, y_n, z_n)\right\}_{n\in\overline{1,N}}$. Obviously, the following constraints have to be fulfilled:

$$\begin{cases} |x_n|, |y_n| \in [R_{\min}, R_{\max}] \\ R_{\min} \le \sqrt{x_n^2 + y_n^2} \le R_{\max}, \quad \forall\, n \in \overline{1,N}. \\ z_n \in [H_{\min}, H_{\max}] \end{cases} \tag{3}$$

A pseudo-random numbers generator, with uniform distribution, can be employed to complete this step. For example, in MATLAB programming environment, the function **`rand`** can generate uniformly distributed pseudo-random numbers in range $[0,1]$. Bijective mappings between the interval $[0,1]$ and intervals $[R_{\min}, R_{\max}]$ or $[H_{\min}, H_{\max}]$ are easy to define. The sign of coordinates along Ox and Oy axes can be generated by using the function **`rand`** as well. (For example, if the generated number is less than 0.5, then the coordinate becomes negative; if exactly 0.5, the coordinate becomes null; otherwise, the coordinate remains unchanged.)

The only problem is to fulfil the second constraint in (3). Assume that, for some $n \in \overline{1,N}$, $\sqrt{x_n^2 + y_n^2} \notin [R_{\min}, R_{\max}]$. Then, use the function **rand** to generate a new number $r_n \in [R_{\min}, R_{\max}]$ and reset the two coordinates to:

$$x_n \leftarrow \frac{r_n}{\sqrt{x_n^2 + y_n^2}} x_n \quad \& \quad y_n \leftarrow \frac{r_n}{\sqrt{x_n^2 + y_n^2}} y_n . \tag{4}$$

Consequently, the new coordinates (4) verify the property:

$$\sqrt{x_n^2 + y_n^2} = r_n \in [R_{\min}, R_{\max}] . \tag{5}$$

Step 3: Computing the polar coordinates and distance to SSR

From the (pseudo-)randomly generated Cartesian coordinates: $\left\{(x_n, y_n, z_n)\right\}_{n \in \overline{1,N}}$, compute first the polar coordinates of all aircrafts:

$$\begin{cases} r_n = \sqrt{x_n^2 + y_n^2} \\ \alpha_n \in \arctan\left(\dfrac{y_n}{x_n}\right) \end{cases}, \quad \forall\, n \in \overline{1,N} . \tag{6}$$

In (6), the arctan function is computed by considering the coordinates signs, to place the aircrafts in all 4 quadrants. Second, compute the distance from each aircraft to the SSR system:

$$L_n = \sqrt{r_n^2 + z_n^2} , \quad \forall\, n \in \overline{1,N} . \tag{7}$$

Step 4: Counting the possibly wrong reply messages

Let $i, j \in \overline{1,N}$ be two different aircrafts (with $i \neq j$). Then they in the range of garbling phenomenon if:

$$|L_i - L_j| \le G_r = 3045\ \text{m} \quad \& \quad |\alpha_i - \alpha_j| \le \beta = 0.035\ \text{rad} . \tag{8}$$

In this case, add the couple $\{i, j\}$ to the set of aircrafts that possibly are able to produce garbling, $\mathbf{G}$.

To build this set, all couples of aircrafts have to be tested, which means a number of $\binom{N}{2} = \dfrac{N(N-1)}{2}$ tests to perform. This also is the maximum length of set $\mathbf{G}$, denoted by $L_{\mathbf{G}}^{N,\max}$. However, this length is very unlikely to obtain, especially when the number of aircrafts, N, is big. Let $L_{\mathbf{G}}$ be the length of set $\mathbf{G}$.

Step 5: Building elementary statistics of garbling

Set $M = 10,000$ as the number of simulations to perform. Then, build the set $\mathbf{G}^N$ and compute its length $L_{\mathbf{G}}^N$ in each of the M simulations, for the same number of aircrafts, N, like in **Steps 2–4** above. Thus, a column vector of length M, including all $L_{\mathbf{G}}^N$, numbers will be available in the end: $\mathbf{L}^N = \left[L_{\mathbf{G},m}^N \right]_{m\in\overline{1,M}}$. According to settings in the first step, 7 simulation scenarios are considered, depending on the number of aircrafts. Hence, a matrix of $L_{\mathbf{G}}$-like numbers can be built, by concatenating all column vectors $\mathbf{L}^N$. Denote the matrix by $\mathbf{L}$. Then: $\mathbf{L} \in \mathbf{N}^{M\times 7} = \mathbf{N}^{10,000\times 7}$.

Three statistical parameters can be derived from matrix $\mathbf{L}$:

a. average of garbling replies number for the same number of aircrafts, $\langle L^N \rangle$; this can be computed on columns of matrix $\mathbf{L}$ and a row vector of averages is obtained, say $\langle \mathbf{L} \rangle$;

b. rate of garbling replies for the same number of aircrafts, with respect to the maximum number of garbling replies:

$$R_{\mathbf{G}}^{N,\max} = 100 \frac{\langle L^N \rangle}{L_{\mathbf{G}}^{N,\max}} [\%]; \tag{9}$$

a row vector of rates (9) can be built while dividing each element of vector $\langle \mathbf{L} \rangle$ by the corresponding maximum number of garbling replies, $L_{\mathbf{G}}^{N,\max}$; denote this vector by $\mathbf{R}_{\mathbf{G}}^{\max}$;

c. rate of garbling replies for the same number of aircrafts, with respect to the number of aircrafts (NA):

$$R_{\mathrm{NA}}^{N} = 100 \frac{\langle L^N \rangle}{N} [\%]; \tag{10}$$

similarly, a row vector of rates (10) can be built while dividing each element of vector $\langle \mathbf{L} \rangle$ by the corresponding number of aircrafts, N; denote this vector by $\mathbf{R}_{\mathrm{NA}}^{N}$;

Step 6: Displaying variations of average and rates row vectors from Step 5.

4. Simulation results and discussion

The algorithm above has been implemented into MATLAB programming environment. The procedure was initiated to run according to the settings defined in **Step 1**. After running the algorithm, the obtained results are displayed in the following figures.

Figure 11 shows the detected aircrafts by the SSR in one simulation, for $N = 10$ (on the left side) and $N = 20$ (on the right side). Recall, however, that 10,000 such simulations have been performed for each N.

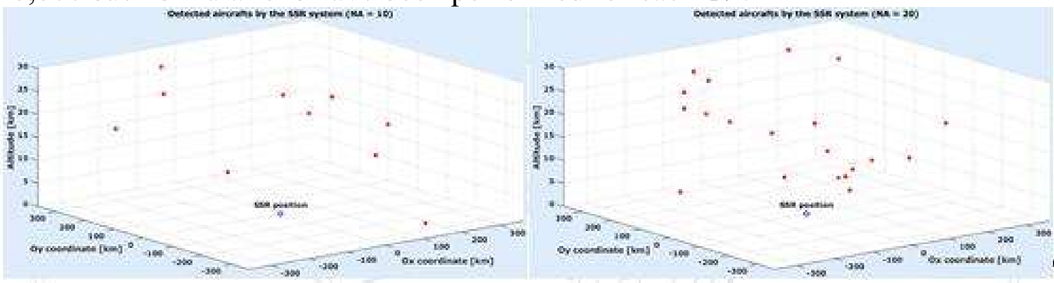

Figure 11. Detected aircrafts by the SSR in one simulation, for: $N = 10$ (left side) and $N = 20$ (right side).

The average number of garbling replies, $\langle \mathbf{L} \rangle$, is depicted in Figure 12.

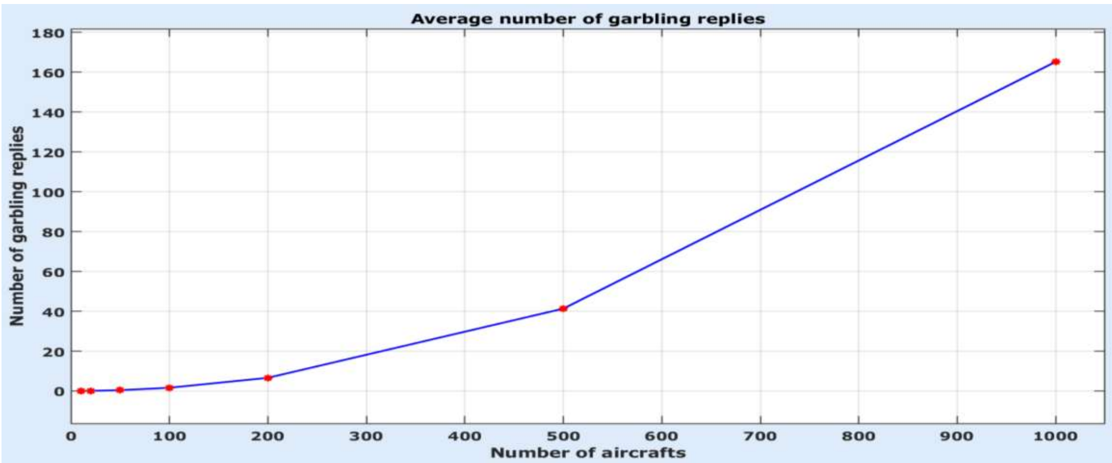

Figure 12. Average number of garbling replies.

The average number of wrong replies increases with the number of aircrafts gravitating around the airport, as expected. Moreover, this number seems to increase following a polynomial variation (very likely, according to a parabolic rule).

The variation of rates $\mathbf{R}_{\mathbf{G}}^{\max}$ and $\mathbf{R}_{\mathrm{NA}}^{N}$ are illustrated in Figures 13 and 14, respectively.

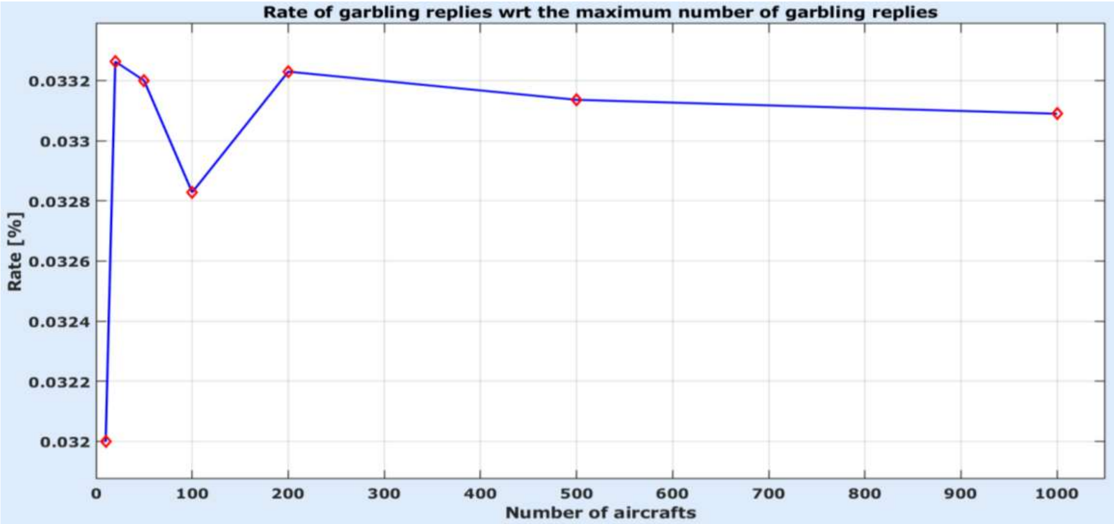

Figure 13. Rate of garbling replies with respect to the maximum number of garbling replies.

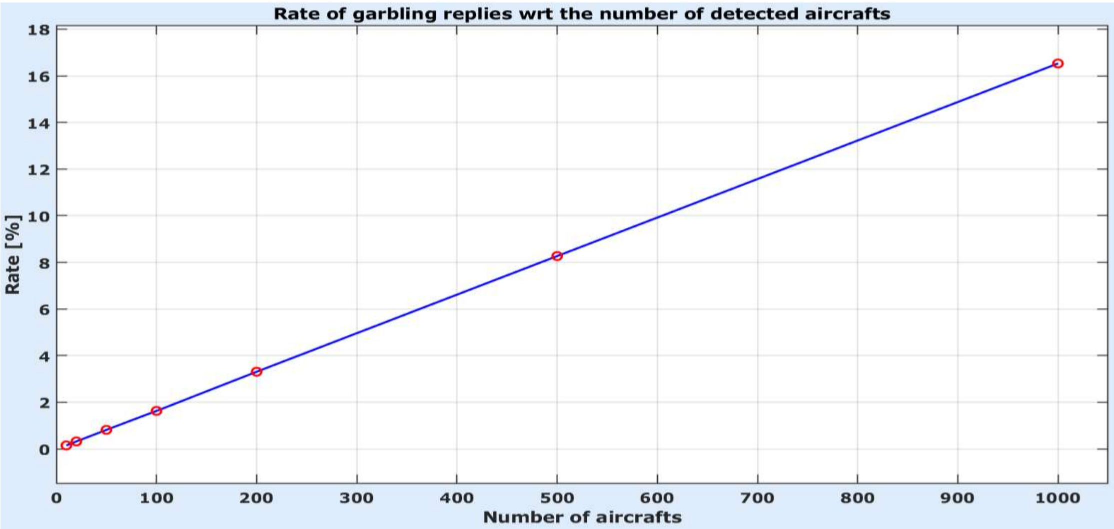

Figure 14. Rate of garbling replies with respect to the number of detected aircrafts.

At a first sight, the variation in Figure 13 is surprising. It suggests that the rate of wrong answers asymptotically stabilizes when the number of detected aircrafts increases. This effect is due to the fact the maximum number of garbling replies, $L_{\mathbf{G}}^{N,\max}$, increases like a parabola. When dividing the parabola-like variation of average number of garbling replies (see Figure 12 again) by the parabolic variation of $L_{\mathbf{G}}^{N,\max}$, a stabilization of garbling rate is obtained. Thus, this type of rate reveals that big number of detected aircrafts does not necessarily involves significant increase of garbling rate, since the number of all combinations between couples of aircrafts is big enough.

More natural is the variation of garbling rate in Figure 14. This time, the parabolic variation of Figure 12 was divided by a linear variation, which resulted in another linear variation as well. In this case, for a large number of aircrafts gravitating around an airport, at a given time, the probability of false replies (affected by garbling) increases, as expected. Hopefully, the increase seems to follow a linear variation.

5. Concluding remarks and future developments

The problem of wrong answers mixed with the correct ones, during aviation monitoring, is important in flights management. This article stated the problem and offered a statistical characterization of garbling phenomenon. At the same time, the article outlined that the design and implementation of a SSR beside the PSR is fully justified, in order to avoid aviation hazards.

To reduce garbling replies, as future developments, advanced signal processing techniques and algorithms (hardware and software) can be employed [16], to extract all replies from the received signal (in the case of asynchronous garbling) or at least some of such replies (in the case of synchronous garbling).

R E F E R E N C E S

[1] Stevens, M.C., Secondary Surveillance Radar; Artech House, Inc.: Norwood, MA, USA, 1988; ISBN 0-89006-292-7.

[2] Stevens, M.C., "Monopulse Secondary Surveillance Radar – Principles and performance of a new generation SSR system", Proceedings of the international conference, pp.208-214, Radar-82.

[3] Gupta R., Valarmathi J., Rajesh R., Sharma R., T Balakrishnan, A., Monopulse Based Correlation Technique for De-Garble Processing of SSR Replies, 2006/10/16 CIE International Conference on Radar, pp. 1501-1505. Publisher IEEE.

[4] Peebles, Peyton Z., Radar Principles, John Wiley & Sons, 1998.

[5] Barton, D.K.; Leonov, S.A., Radar Technology Encyclopedia; Artech House, Inc.: Norwood, MA, USA, 1998; ISBN 0-89006-893-3.

[6] Skolnik M.I., Introduction to Radar Systems, 3rd ed.; The McGraw-Hill Book Co.: Singapore, 1981.

[7] International Civil Aviation Organization (ICAO), Surveillance and Collision Avoidance Systems. Annex 10, 4th ed.; International Civil Aviation Organization: Montréal, QC, Canada, 2007; Volume 4, ISBN 92-9194-952-3.

[8] Skolnik Merrill I., Radar Handbook, McGraw-Hill Companies, 2008.

[9] Lenov A.I., Fomichev K.I., Monopulse Radar, Artech House, Norwood, MA, 1995.

[10] Söderström T., Stoica P., System Identification, Prentice Hall, London, U.K., 1989.

[11] Stefanoiu D., Culita J., Stoica P., A Foundation to System Modeling and Identification, PRINTECH Press, Bucharest, Romania, 2005.

[12] Stefanoiu D., Matei I., Stoica P., Practical Approaches to System Modeling and Identification, PRINTECH Press, Bucharest, Romania, 2004.

[13] Scanlan, A., Modern Radar Techniques, Artech House, Norwood, MA, 1988.

[14] URL: https://www.radartutorial.eu/13.ssr/sr15.en.html (accessed on December 27, 2022).

[15] URL: https://de.wikipedia.org/wiki/Garbling (accessed on December 27, 2022).

[16] Petrochilos, N., Algorithms for separation of SSR replies, Ph.D. thesis, Delft University of Technology, Delft, Netherlands, 2002.