

Article

Implementation of a Transportable Radar Mode S of Monopulse Secondary Surveillance (MSSR-S) for the Peruvian Civil Aviation Surveillance

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Abstract: This article describes the process of implementing a transportable radar MSSR-S for Peruvian civil aviation (ACP) to minimize the operational impact in emergencies that affects air traffic without causing structural damage and restore data from the radar in a short time. In recent years, ACP has shown constant falls in the radars, causing radar data to be lost for long periods of time and putting air safety at risk due to the lack of maintenance and overlapping radar coverage of more than three radars. The deployment of the transportable radar in Mode S of Monopulse Secondary Surveillance (MSSR-S) has allowed for work that involves the prolonged stoppage of the radar to be carried out and provided coverage to eight more radars during maintenance and modernization, covering the areas without coverage in the Peruvian air space (EAP). For the implementation, this was divided into three SPRINTs using the SCRUM methodology; the first sprint refers to the equipment and radar coverage study, the second the implementation and service test phase, and the third the operational analysis phase with the eight modernized radars. As a result of the implementation and integration with the other ACP radar systems, they were able to operate together, providing highly reliable radar data, performing a continuous analysis of radar performance through the PASS software, complying with the thresholds established by ICAO and EuroControl, and guaranteeing that the systems operate under perfect conditions and with full coverage at all time.

Keywords: civil aeronautics; MSSR-S radar; radar data; SCRUM; ICAO; PASS software



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1. Introduction

Surveillance and air navigation systems are fundamental for the surveillance of commercial air traffic within their radar coverage. Countries use these processes for the acquisition and implementation of their transportable radar systems.

In recent years, there has been an exponential increase in air traffic, generating congestion problems, areas without air surveillance, nearby obstacles that generate the duplication of aircraft runways, and a lack of replacement of radar equipment that leads to equipment degradation. This research work answers the following question: What will operational impact will be caused by the loss of stationary radar when an MSSR-S transportable radar is not implemented for Peruvian aeronautical surveillance?

The importance of implementing a transportable radar arises from the need to cover the gaps that exist in Peruvian air surveillance, which prevent 100% coverage of the airspace or the need for a backup system for Lima airport in emergencies. The Mode S radar system [1] offers high precision, low cost, and great flexibility to adapt to customer needs, complying with the international standards and requirements of a state-of-the-art technological surveillance radar station.

The implementation of the transportable radar consists of an LVA antenna, which is a fundamental part of the interrogation and acquisition of targets. Reference [2] evaluated the impact of the other determining factors, such as the reflection of the signal and the atmospheric refraction, on the coverage of the radar. Reference [3] found that each existing target will generate several responses from the position that will be obtained, similar to the final one; thus, the objects are called plots, which are displayed on the screen.

This implementation was executed using the Agile SCRUM methodological framework, ensuring compliance with the international standards for its operationalization and showing a configuration related to the modern architecture of an unmanned radar station, with easy-to-use interfaces that allow for local management and a fully remote nature, optimizing the balance between performance, rapid deployment, reliability, security, and cost-effectiveness.

The transportability of the elements is ensured to allow for their movement by different methods; therefore, the radar is ready to operate when integrated with the remote team for radar visualization, control, and monitoring functions [4], which must be carried out using the meeting coordination and Scrum team model according to the distribution of the cascading method through three iterations of SPRINT. The success of the project is based on the scope, time, and cost aspects during the execution of the transportable radar.

The goal of the study is as follows: the implementation of a transportable MSSR-S radar for Peruvian civil aeronautical surveillance to minimize the operational impact and improve air safety throughout the Peruvian territory.

2. Theoretical Foundation

2.1. Surveillance System

Reference [5] specifies the details of surveillance systems used to detect aircraft and send detailed information related to the air traffic control system. Air traffic control is not possible without surveillance systems, especially in areas with a high density of air traffic.

Surveillance is provided primarily by primary and secondary radars. In addition, according to [6], the “surveillance of air traffic has several applications, which have been growing over time. Each one of them pursues its own objectives and has particular needs, especially regarding the accuracy of the data”.

Likewise, [7] considers that “States have several radar installations, which have a high maintenance cost and limited benefits for achieving the requirements of the current operational concepts and the goals of the different aviation system improvement modules by blocks” (ASBU).

In many cases, they do not fully cover the flight information region (FIR) and they have cones of silence that affect the air traffic surveillance, so the implementation of new systems with lower installation and operating costs is inevitable but also brings considerable performance improvements. This means that the only issue is deciding which one to implement.

2.2. Radar System

For the detection and location of objects, according to [8], a radar operates as an electromagnetic system.

Radar systems can be classified according to a series of basic aspects such as the number of antennas, working frequency, and waveform.

Also, [9] gave details showing that this type of radar requires the aircraft to carry an on-board receiver–transmitter device called a transponder.

A Secondary Surveillance Radar (SSR) transmits pulses from an antenna, just like a primary radar.

When the transponder on-board the aircraft receives the radar pulse, it emits a response at a different frequency; this allows for differentiation of the echoes from Clutter.

Generally, the response from the transponder includes the height of the aircraft, in addition to its identification [5].

Indra's MSSR-S mode represents the next generation of radar systems in the secondary surveillance domain.

It is a fully digital version with a powerful and advanced set of functionalities, which ensure that any functional need will be covered at all times with a performance that is well above the defined requirements.

2.3. Radar Tracking Process

According to [9], a tracking system is used to observe moving objects and provide an ordered sequence of position data. This process involves estimating the state of a moving object from remote, indirect, and imprecise measurements. The measurements can originate from one or several sensors, including image and georeferenced tracking. In addition, uncertainties in the source of the measurement can also occur when multiple targets are closed, and even when the observed detections can be separated, they cannot be reliably associated with the targets.

A similar situation occurs in the track formation problem when there are multiple targets but their quantity is unknown and some of the measurements could be spurious; moreover, [10] indicates that the application related to the radar display translates the position of the echoes on the screen into a metric coordinate system based on the time and spatial position of the echoes and the software automatically calculates multiple flight parameters, such as the speed with respect to the ground, and the length and duration of the trajectory.

2.4. Radar Data Processing

In [11], networked radar systems receive a great deal of attention due to their higher probability of target detection, better target location and tracking performance compared to monostatic/bistatic radar systems.

According to the complexity and difficulty of practical application, network radar systems can be divided into simple network radar systems with decentralized processing, and traditional network radar systems with centralized data and information fusion processing. In addition, multiple flight parameters are automatically calculated, such as speed with respect to the ground, length and trajectory duration.

According to the General Direction from Civil Aviation, DGAC (2014), the processing of radar data is shown through a display that details the geolocation of the aircraft, where the radar parameters are defined during the preparation of the data and their corresponding display (position, elevation, refresh rate, and azimuth).

2.5. Diagram of the Transportable Radar

The transportable radar is built by two ISO₂₀ shelters. In the first one, the auxiliary equipment, such as UPS and generator sets, is located. In addition to the interrogator system, the second shelter is a deployable and retractable tower that contains the radiant system and the pedestal, which is responsible for the continuous rotation of the antenna, a photo of the system has been included in Figure 1.

The proposed deployable tower and antenna system for the transportable MSSR system are composed of the LVA antenna system and mechanical interface, antenna drive system, lighting system, deployable tower with antenna (11 m high) and lightning protection. The antenna drive system and antenna are integrated into the deployable tower; in the transport configuration, mechanical protection is provided during the pedestal and the antenna is transported. The electronics and power equipment for the transportable MSSR system are housed in a hardened shelter comprising the MSSR interrogator, which is made up of two identical channels. Each channel is connected to an RRF port; through this, the channel with an operational status is connected to the antenna. When the RRF is used to change the channel in operational or reserve status, the operational channel is connected to the ALV of the monopulse antenna, which is mounted on the deployable tower and is monitored by the UCS application installed in the control and monitoring

systems of the MSSR. This can be achieved both locally and remotely by developing the same orders, communication system and power elements. The Mode S transmitter receives the appropriate signals from the data extractor to modulate, amplify and develop the RF transmission of the interrogations for the SUMA channel and for the OMNI channel; the interrogation mode, interleaving, output power and other characteristics are sent from the control and management systems. It is worth noting that the MSSR Mode S system works at full capacity, with a high degree of security and confidence, in an autonomous way, and without the need for operator intervention; this is due to the fact that the system implements a BITE, which runs on real-time and is distributed among the different radar units of both channels. The information obtained from the BITE, as well as the possible alarms, are visualized in the UCS application in both the local and remote management systems. The receiver is divided into three different processing blocks to develop the functions of video processing, real-time channel control and link control. With this, the radar system will be able to detect and process targets ranging between 0.3 and 150 nautical miles, as well as SSR such as Mode S, and targets of more than 66,000 feet in height in the 360° azimuth when the transponders comply with ICAO annex 10, Volume IV.

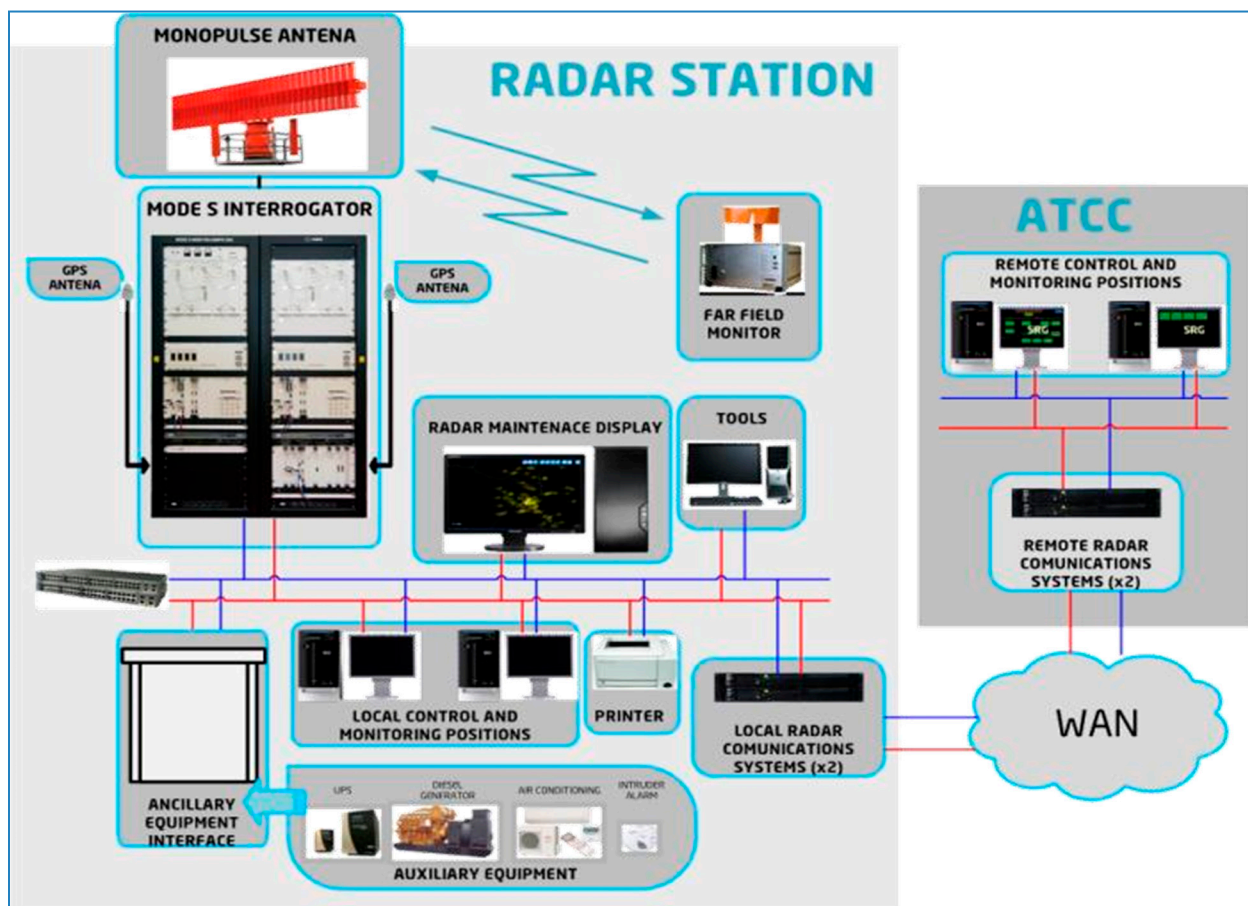


Figure 1. Architecture of an MSSR-S radar station.

3. Methods

The implementation process of the transportable radar MSSR-S followed the stages detailed in Table 1 according to the Agile SCRUM methodological framework (with three iterations of SPRINT), ensuring compliance with the international standards. The table shows a configuration of a modern architecture of an unmanned radar station, with easy-to-use interfaces which allow for complete local and remote management, optimizing the balance between the performance, rapid deployment, reliability and security.

Table 1. Stages of implementation of the transportable radar MSSR-S.

Phase	Activities	Objectives
Implementation preparatory	- Management process for the transportation from Spain to Perú. - Homologation of the radar; nationalization; whether radar could be transported within Peru.	- Description of the characteristics of each of the functionality's modules and equipment.
Site Analysis	- Study and evaluation of the site where it will be implemented, and its technical and operational feasibility from the perspective of radar coverage.	- Site report; simulation from radar data loss and its operational impact on coverage.
On-site Implementation	- Install all modules and check that none are damaged; turn radar power on. - Transportable radar architecture. - Functional description of MSSR-S.	- Installation Acceptance and Test (IAT) of the technical area, proving the conformity and operability.
Transportable Radar Deployment	- Start-up. - Deployment and retraction of the tower. - Video processing, responses, and blanks. - Fine-tuning. - Dry-run SAT	- Documentation of the operability of the radar and validation of its integration.
Integration of transportable radar	- The radar information will be sent by microwave to the radar technical room. - Acceptance test of the entire system.	- Radar data flow and management. Documentation.
System in service and performance analysis	- Incorporation into the air control center for the use of radar data. - MSSR-S radar performance.	- Documentation of the radar service.

Therefore, the implementation is completely ready to operate and integrated with the remote equipment for the visualization, control, and monitoring functions. Considering the deployment of the transportable radar in Mode S of Monopulse Secondary Surveillance (MSSR-S), covering each of the eight Peruvian Air Space (EAP) radars. Shown in Tables 1 and 2.

Table 2. Main technical characteristics of the mode S transportable radar.

Coverage radar	Scope: 256 NM. 66,000 ft altitude.
Probability of detection (Pd)	SSR: 397%. Mode S: 399%.
Probability of code validation	Mode: 3/A: $\geq 98\%$. Mode C: $\geq 96\%$. Mode S: $\geq 99\%$.
Detection of code	Mode: 3/A, C. Codes: 7500, 7600, 7700. Train of repetition from army emergency. Train of repetition from army identity. Detection and correction from mistakes for reply in S.
Validated false codes	Mode: 3/A: $< 0.1\%$. Mode C: $< 0.1\%$.
False blanks	$< 0.1\%$ lower to sweep like a medium.
Validated dates from false repetition Comm-B or Comm-D	No more than 1 segment in 107 messages.
Multiple blank process	Capacity for discrimination.
Asincrone environment support (fruit environment supported)	$\geq 11,000$ asincrones/seconds in the main haz from anthers.
Scope precision (systematic mistakes)	≤ 14 m.
Scope precision (aleatory mistakes)	Mode S: $10 \leq 15$ mt. SSR: $10 \leq 30$ mt.
Acimut precision (systematic mistakes)	$0 < OD < 6^\circ : 0.022^\circ$. $6 < OD < 10^\circ : 0.033^\circ$.
Acimut precision (aleatory mistakes)	Scope: $\leq 1/128$ NM. Acimut: $\leq 0.022^\circ$.
Global rate from jumps	$< 0.05\%$.
PROCESS FROM NEXT BLANKS (GARBLING)	
N° soften overlapping reply	Four SST, rejected from the ghost. Two-mode S.
Probability of detection of two blanks SSR	$\leq 60\%$ (< 0.05 NM, scope, $< 0.6^\circ$ acimut). $\leq 98\%$ ($0.5 < 2$ NM; scope, $\leq 0.6^\circ$ acimut). $\leq 98\%$ (2 NM; scope, $> 0.6^\circ$ y < 48 acimut).

Coverage of up to FL250 with the lower airspace chart and from FL300 with the upper airspace chart.

3.1. Sprint N° 1

In interaction 1, preparatory work was carried out for the implementation (acquisition of the deployable tower, antenna, pedestal, interrogator system and auxiliary equipment for operation) and transportable radar coverage analysis (coverage study regarding flight level, speed, azimuth and distance), complying with the standards for operation in adverse weather situations, optimizing performance with an analysis of the radar coverage that was implemented.

3.2. Sprint N° 2

After the acquisition of the equipment and analysis of radar coverage in the location was provided, the radar was implemented, following each of the established tasks to guarantee that all equipment was in perfect condition. The installation was inspected and operability test was carried out using measuring instruments, ending with the adjustment

of the radar in terms of either distance or azimuth. This means that the tower can be deployed in parallel mode, containing the radiating system, the RF, and the signal cables of each of the necessary sensors at all times. Figure 2 shows a transportable Radar ready.



Figure 2. Transportable radar system.

3.3. Sprint N° 3

In the final stage of the implementation of the transportable radar, it is necessary that all the radars are in operation and validation be carried out through opportunity flights to ensure a continuous analysis. For this, it is necessary to obtain data asterix recorder data that can be analyzed every 6 h due to the limited air traffic that occurs throughout the airspace. As shown in Figure 3.

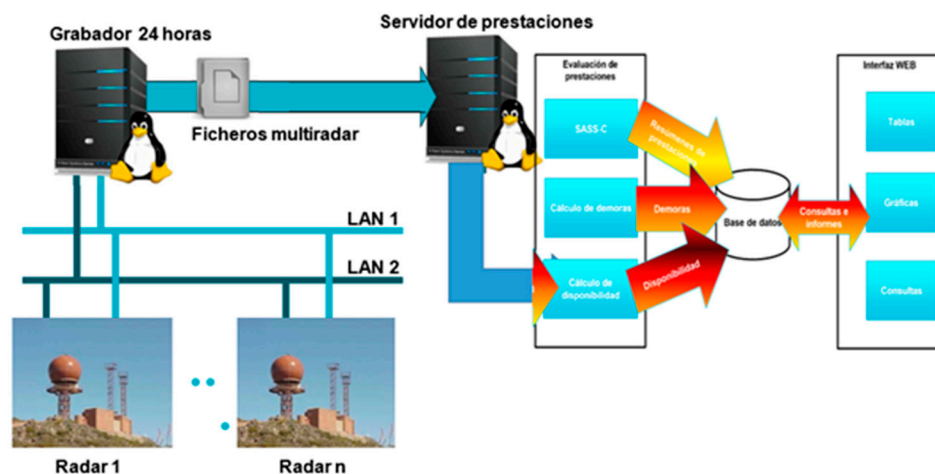


Figure 3. Diagram for performance analysis (SASS-C).

An analysis of the radar performance was carried out using the SASS-C software and, from there, the statistical data for the sample are extracted and displayed graphically using the PASS application with internet access. This allows for the status of the radars to be continuously monitored.

4. Result

It was found that the air surveillance systems did not have a backup radar system in the event of general failure, which directly affects the operation of air traffic. Therefore, the implementation of a transportable radar was necessary to minimize the operational impact

and ensure the highest performance, providing reliability and security, and requiring a short time to implement.

Subsequently, we carried out an analysis of the benefits before, during and after the start-up of the MSSR-S transportable radar, following the methodology established in Table 1.

During 2020, there was a worldwide event that affected the amount of opportunity traffic in the volume of radar coverage called the “SARS-CoV-2 coronavirus pandemic” which, due to the measures imposed by governments and the health agency (WHO-MINSA), decreased traffic. This was because of the measures proposed by governments, such as the beginning of confinement in different countries. This is illustrated in Figure 4.

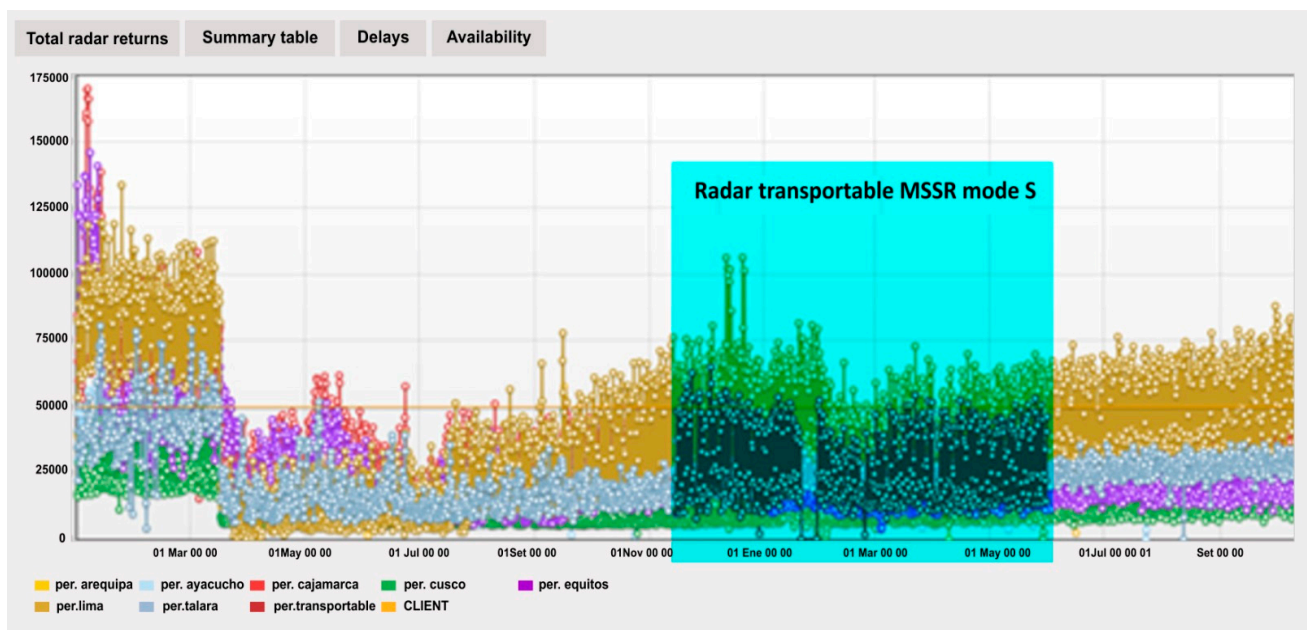


Figure 4. Target report number from 17 March 2020 through 2022.

After the start-up of the transportable radar, a comparative analysis was carried out comparing the performance of the radar from Lima and the MSSR-S transportable radar prior to the modernization stage, which means that the Lima radar moves out of operation. The transportable radar complies with all the established standards and the performance, as demonstrated in the detectability performance, which is higher than 99% on average. See image of Figure 5.

The evaluation of the false and multiple radar plots from Lima compared the MSSR-S transportable radar, prior to its commissioning as the main transportable radar, is presented as follows. As shown in Figure 6.

An analysis of the systematic and random errors in the range and azimuth of the radar from Lima versus the transportable radar MSSR mode S, prior to its commissioning as the main transportable radar, is presented as follows. As shown in Figure 7.

Figure 8 shows the loss area within the coverage of the transportable radar, both polar and vertical. Most of the Mode S losses are found in the northern areas of the radar, at 80 NM, due to the flight level of this aircraft and the presence of an obstacle in that area.

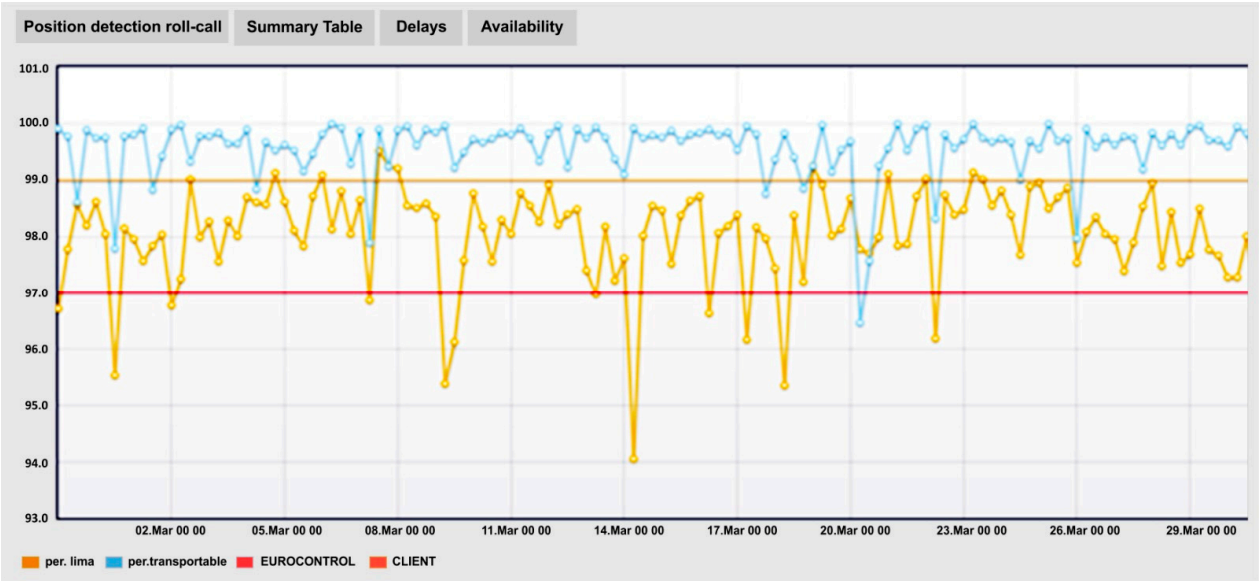


Figure 5. Performance of the radar from Lima versus the MSSR mode S transportable radar, before the maintenance stage radar from Lima.

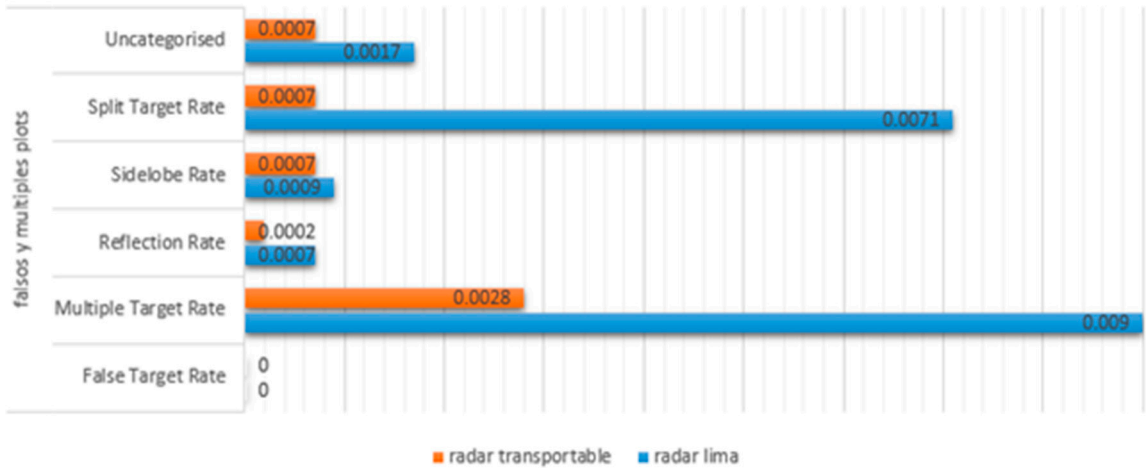


Figure 6. False and multiple plots: radar from Lima versus transportable radar.

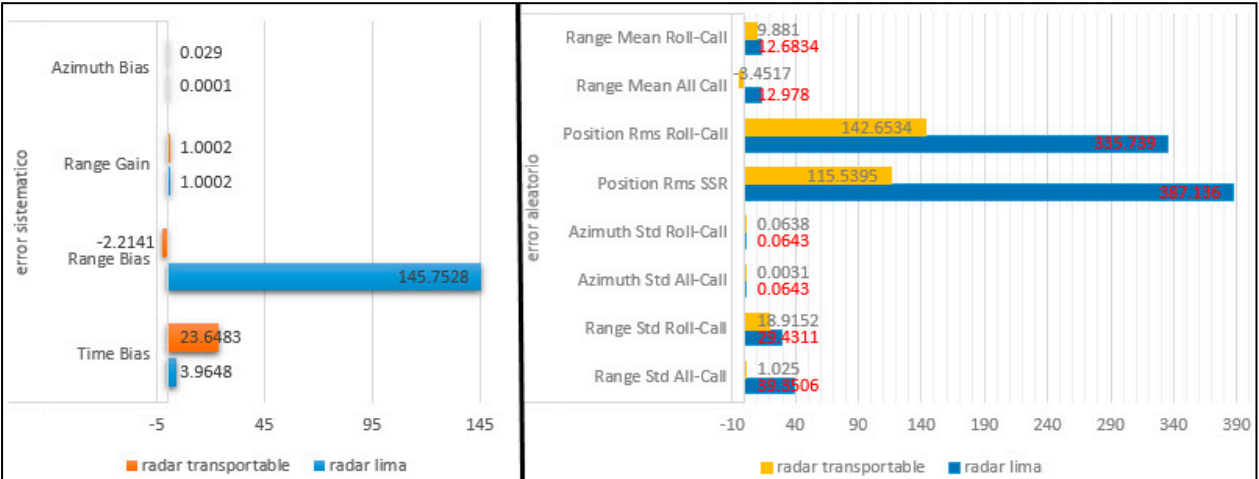


Figure 7. Systematic error and random error: radar from Lima versus transportable radar.

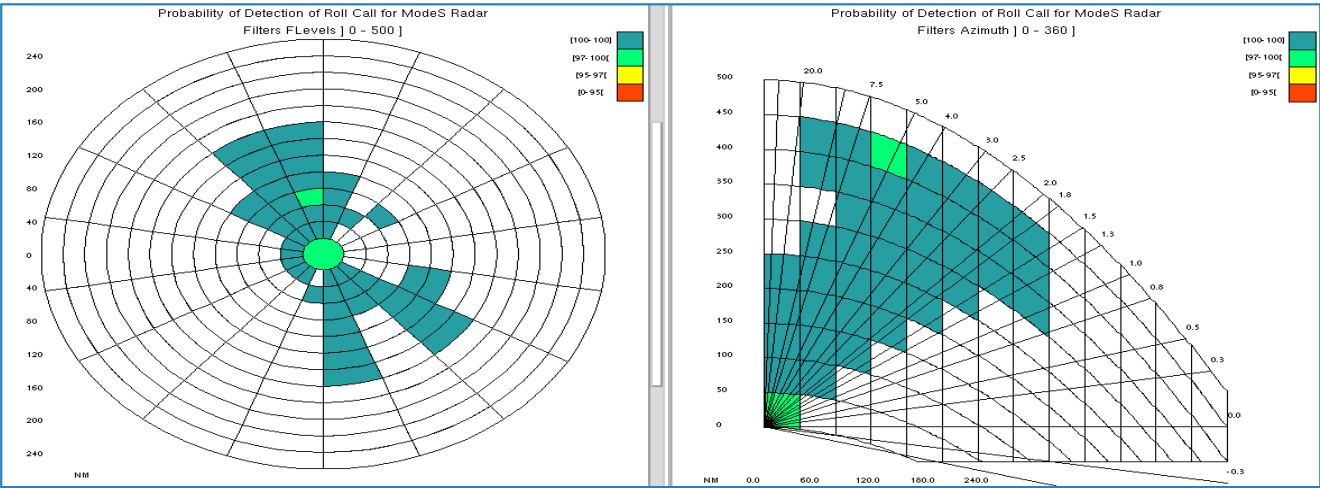


Figure 8. Detection probability of transportable radar Mode S, viewed in polar format.

The results obtained through the continuous evaluation of performance are shown below, where the general state of the Peruvian air surveillance system is detailed for the period of modernization of the radar from Lima, with the transportable radar remaining operational and used as the main radar.

The evaluation of the percentage of multiple targets that could be generated by different factors must be below 0.8% according to EuroControl. As shown in Figure 9.

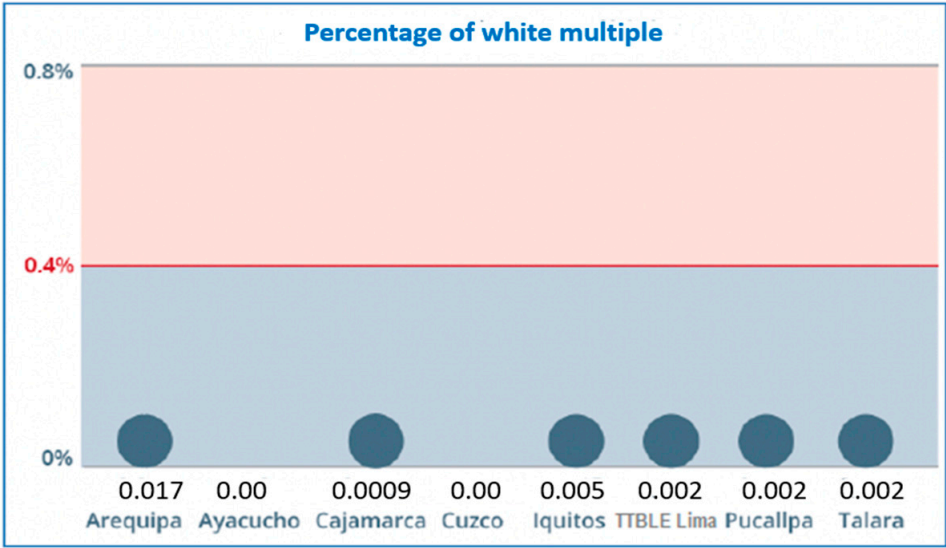


Figure 9. Percentage of multiple targets from CORPAC radars without the radar from Lima, including the transportable radar.

An evaluation of the systematic error in distance and azimuth, without the radar from Lima, is presented below. The systematic error is shown in the Figure 10.

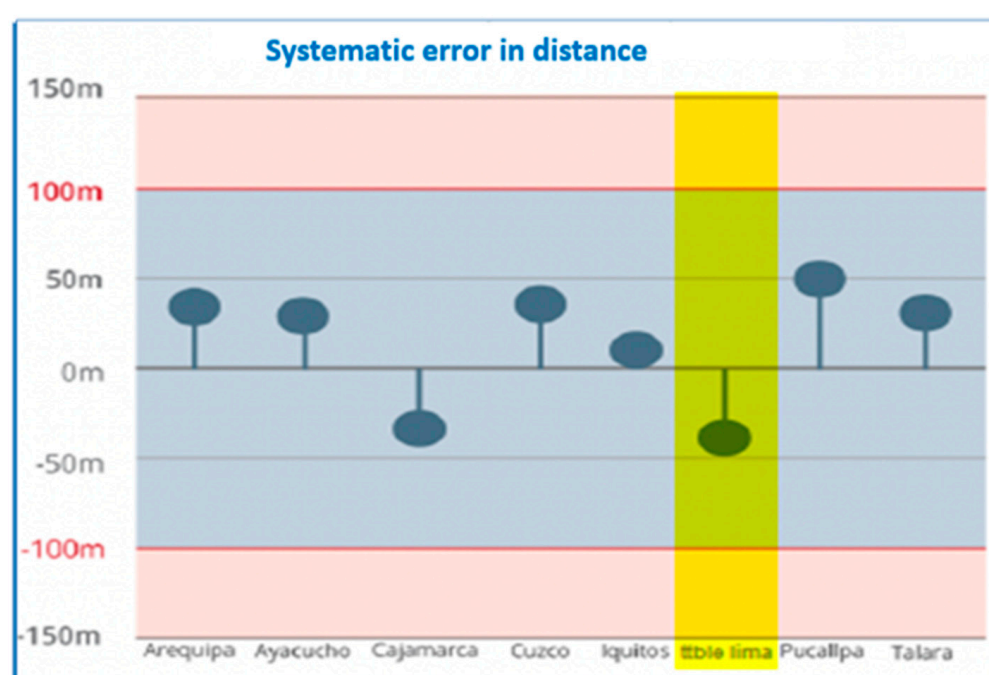


Figure 10. Systematic error in distance from the CORPAC radars without the radar from Lima, including the transportable radar. Note. The figure shows the systematic distance error in CORPAC radars without the Lima radar, including the transportable radar, which are within the limits established by EuroControl. The following Figure 11, shows the CORPAC azimuth error.

An evaluation of the azimuth precision of the radars, without the radar from Lima, is presented below. In Figure 12.

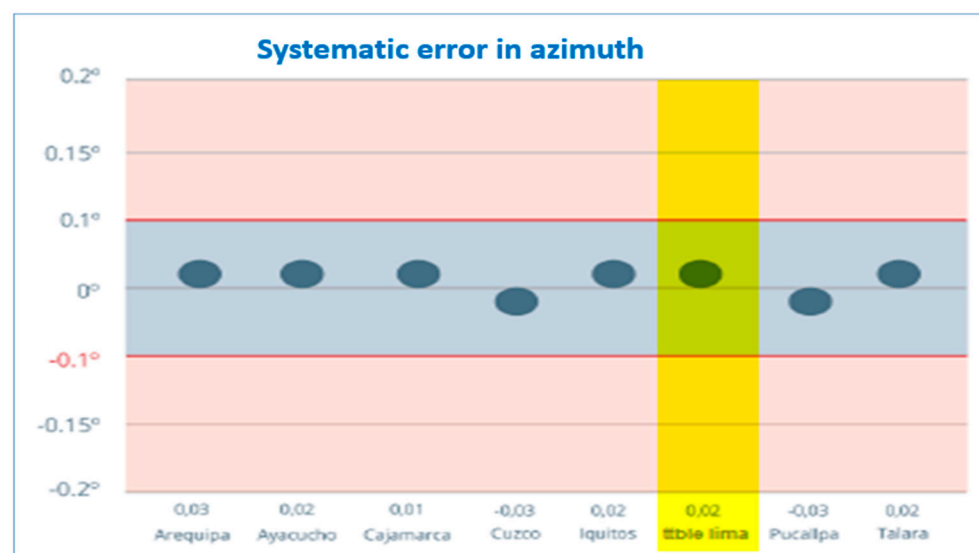


Figure 11. Systematic error in azimuth from the CORPAC radars without the radar from Lima, including the radar from Lima.

An evaluation of the distance precision of the radars in the maintenance period of the Lima radar shows that they were within the limit established by EuroControl. Shown in Figure 13.

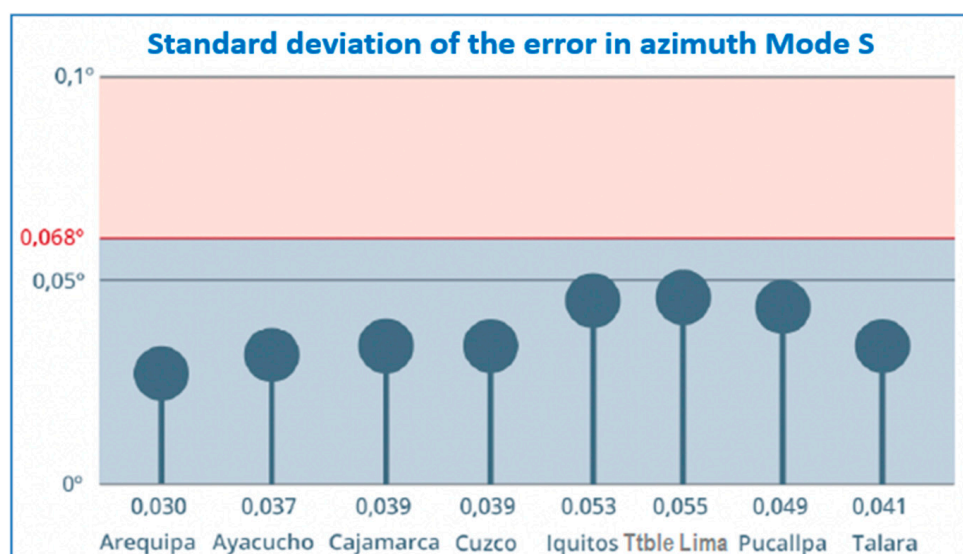


Figure 12. Standard deviation of error in mode S azimuth from the CORPAC radars without the radar from Lima, including the transportable radar.

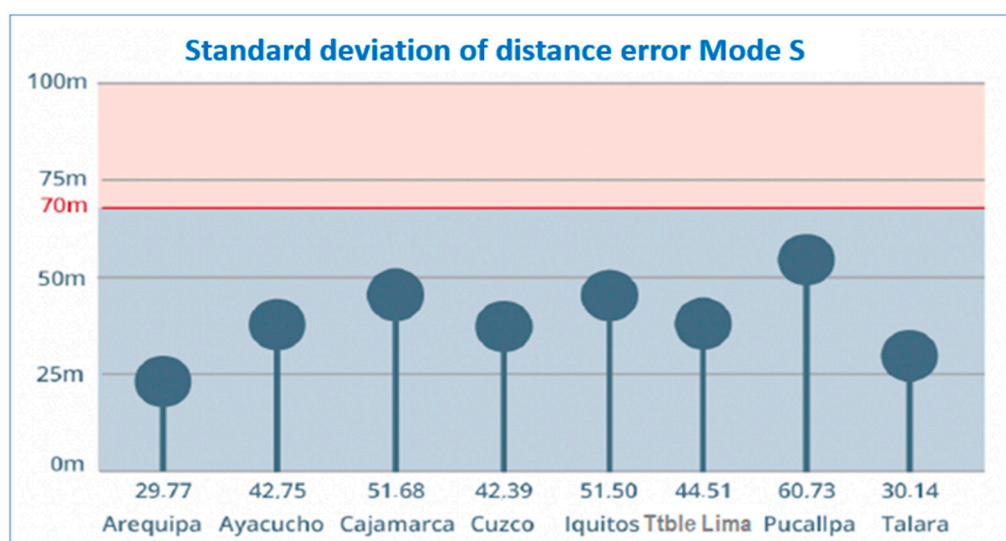


Figure 13. Standard deviation of errors in distance, mode S, from the CORPAC radars without the radar from Lima, including the transportable radar.

From these figures, it can be concluded that the transportable radar complies with the performance quality requirements, where the percentage of recordings obtained within in the detection probability range from all the analyzed radars is detailed.

Table 3 shows the probability of detection range (PD) during the period of modernization of the radar from Lima, which contained the radars from Peru. To ensure that the chaining is as precise as possible, it is convenient to correct the systematic errors in the eight radars.

Table 3. Detection probability range: multi-radar analysis.

Radar	Number of Evaluations	PD <90%	90% ≤ PD < 95%	95% ≤ PD < 97%	97% ≤ PD < 99%	PD ≥ 99%
Arequipa	120	0.83%	0.83%	0.00%	29.17%	69.17%
Ayacucho	120	0.00%	0.00%	0.00%	0.83%	99.17%
Cajamarca	120	0.00%	0.00%	0.00%	0.83%	99.17%
Cuzco	120	0.83%	0.83%	0.83%	7.50%	90.00%
Iquitos	120	0.83%	3.33%	12.50%	38.33%	45.00%
Ttble Lima	120	0.00%	0.00%	0.00%	0.83%	99.17%
Pucallpa	120	0.00%	0.83%	0.00%	35.00%	64.17%
Talara	120	1.67%	0.00%	0.83%	33.33%	64.17%

Table 4 shows the systematic error in the radars during the maintenance of the radar from Lima. This table shows that the eight radars from the CORPAC surveillance system have a precise performance in terms of both distance and azimuth, which is within the required limits.

Table 4. Analysis of the systematic error.

Radar	Systematic Error Distance	Correct	Systematic Azimuth	Correct
Arequipa	51.89 m	NO	0.0139°	NO
Ayacucho	6.34 m	NO	0.0152°	NO
Cajamarca	−47.21 m	NO	0.0126°	NO
Cuzco	72.14 m	NO	−0.0198°	NO
Iquitos	−50.70 m	NO	0.0122°	NO
Ttble Lima	−3.80 m	NO	0.0127°	NO
Pucallpa	21.67 m	NO	−0.0002°	NO
Talara	27.81,	NO	0.0059°	NO

Table 5 shows an evaluation of the accuracy of the radars, including the new transportable radar and the radar from Lima, during maintenance.

Table 5. Random error analysis.

Radar	Number of Evaluations	STD Error Acimut	% Evaluations STD > 0.068°	State
Arequipa	120	0.0289°	1.67%	Correcto
Ayacucho	120	0.0389°	5.83%	Correcto
Cajamarca	120	0.0423°	5.00%	Correcto
Cuzco	120	0.0367°	5.00%	Correcto
Iquitos	120	0.0545°	20.00%	Correcto
Ttble Lima	120	0.0544°	7.50%	Correcto
Pucallpa	120	0.0469°	1.67%	Correcto
Talara	120	0.0442°	4.17%	Correcto

5. Discussion

As Peru does not have an MSSR-S transportable radar for air surveillance that can minimize the operational impact of the restoration of radar data from operational radars in adverse situations, the transportable radar that we implemented was presented as a revolutionary system because it can be deployed in a short time and provide coverage for radars that are out of service. Therefore, the acquisition and implementation of a transportable radar MSSR-S can optimize the operational cost.

Figure 14 demonstrates that Jorge Chávez International Airport is the main airport in the country. This airport runs using of radar (right image), so when the transportable radar

is deployed, the coverage area (left image) reaches that of the radar from Lima in a very short time.

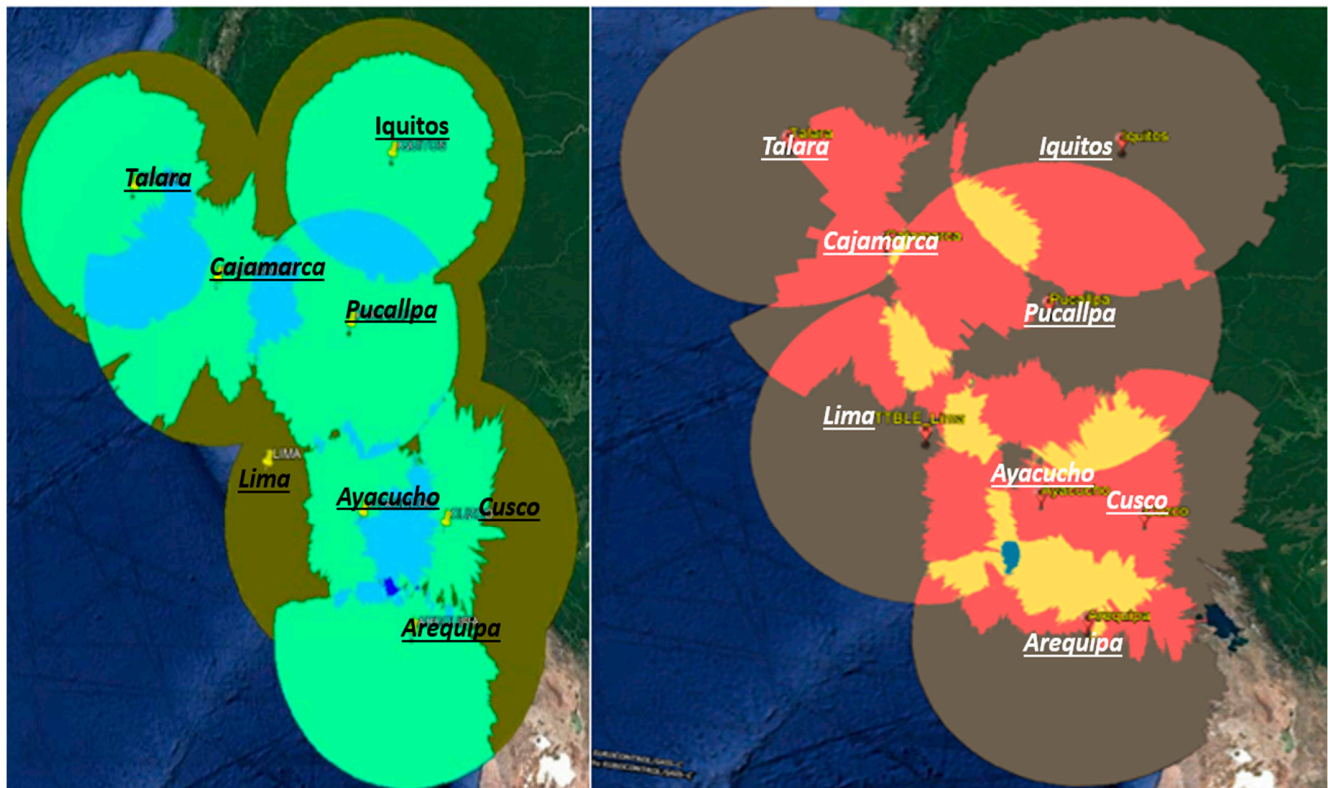


Figure 14. The figure shows the radar without coverage, then the radar's coverage when the transportable radar is in operation.

After implementation, it is necessary to carry out an analysis and optimize the radar systems' performance, as well as to predict degradations, using the PASS service. Adjustments in both azimuth and distance are of vital importance for all radars.

The air traffic system has been changing to adapt to the new social demands, mainly the safe growth in the global traffic capacity [12]. The use of MSSR-S radars to control air traffic surveillance will increase traffic safety and can cover the entire Peruvian airspace, as shown in Figure 8.

All simulations are based on modifications to the existing set of data, obtained from multi-recording radar sensors [13]. Data from real positioning measurements and coverage simulations were used to support and exemplify the theoretical findings [14]. Using these, an analysis was carried out to obtaining performance measures such as the precision in terms of distance and ensure that these were within the established thresholds (Table 3).

6. Conclusions

1. The implementation of the MSSR-S transportable radar for Peruvian aeronautical surveillance aims to minimize the operational impact of air traffic, and improve detection, tracking and operational safety features using the SCRUM framework.
2. As shown in Figure 14, the coverage of the transportable radar and the radar from Lima are very similar up to 150 NM (there is an instrument limitation of 150 nautical miles for the transportable radar). Starting at 150 NM and flight level 100, the radar from Lima has more coverage over some airways in the lower airspace than the transportable radar. This gap in the coverage of the transportable radar is covered from flight-level 250 by the radars from Cajamarca in the north (airway G675), and

- the radars from Ayacucho and Arequipa in the south (airways L525 and L302). In both the Lima TMA and the Pisco TMA, both radars have the same radar coverage.
3. Surveillance systems continue to constantly evolve with the use of new technologies, continuously improving the detection techniques and data communications, leading to a surveillance system characterized by its optimum coverage, maximum reliability and high availability, the high quality of the information provided, and the minimal cost of exploration.
 4. The information obtained from aircrafts by surveillance sensors can be essential and elementary (position, altitude and identification), or can involve more elaborate data communications (enhanced surveillance), in all phases of flight and on the ground. A continuous analysis of surveillance sensors is performed to meet the requirements established by ICAO for air surveillance systems. The eight radars, which are part of the surveillance system from CORPAC, are very good in terms of both position and detection. This is achieved through the PASS application.
 5. The preventive and corrective maintenance carried out by the radar sites has been optimized, minimizing the operational impact and covering the airspace while the radar is out of operation, as shown in the analysis of the results.

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