Scenarios and system configuration analyses of LDACS-SUR and DARN for validation campaign in the ASTONISH project

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***Abstract*—Nowadays, many countries are phasing out the only source of non-cooperative surveillance services - the primary surveillance radars. Moreover, the cooperative surveillance technologies, Secondary Surveillance Radar (SSR), Automatic Dependent Surveillance–Broadcast (ADS-B), and Traffic Collision Avoidance System (TCAS) all use the congested 1030 MHz and 1090 MHz frequency bands, making the secondary surveillance services vulnerable to outage and unavailability, in addition to the possible failures of the airborne transponders. To address these issues, two ground-based non-cooperative surveillance alternatives are considered: 1) a passive multistatic radar employing the L-Band Digital Aeronautical Communication System (LDACS) transmitters as illuminators of opportunity, and 2) a distributed active radar network. The scenarios considered for the validation of these approaches are presented in this work. Additionally, several analyses based on the numerical evaluation of the Cramer-Rao Bound and the signal coverage are conducted to define the ground system configurations to be considered in such validations.**

***Keywords*—Radar, Passive Radar, Civil Aviation, LDACS, Radar Network, CNS, Surveillance, Multistatic Radar**

I. INTRODUCTION

With aviation traffic reaching unprecedented levels, surveillance is a key air traffic management (ATM) service that ensures operational safety, improves airspace capacity, and provides the necessary resilience to accommodate the forecast increase in air traffic.

To this end, novel non-cooperative ground-based surveillance solutions for ATM operations are currently under investigation as part of the SESAR exploratory research project ASTONISH (Alternate Surveillance Technologies fOr iNnovatIve Solutions). These present an alternative for areas with no surveillance services but also serves as a backup solution in areas covered by traditional surveillance systems.

In particular, SESAR Solution 0516 “Alternate surveillance for ATM operations” aims at investigating a novel LDACS-based non-cooperative passive surveillance approach referred to as LDACS-SUR as well as a non-cooperative distributed active radar network approach referred to as DARN [1].

To begin with, LDACS (L-Band Digital Aeronautical Communication System) is the future air-to-ground (A/G) aeronautical communication link, currently undergoing the ICAO standardization [2]. In addition to the main aeronautical communication functionality, referred to as LDACS-COM, an LDACS-based backup/alternative navigation functionality, LDACS-NAV, is being pursued to provide alternative positioning, navigation, and timing (APNT) services. Similar to the LDACS-NAV functionality for APNT, LDACS-SUR aims to use the LDACS communication signals as signals of opportunity this time for setting up an LDACS-based non-cooperative passive multistatic radar system [3]. If proved feasible, this would enable a fully integrated LDACS-based CNS system to be put in place, simplifying deployment and reducing costs. Considering its technical characteristics, this solution would operate similar to passive surveillance radars which use terrestrial broadcasting station as sources of illumination [4], [5], [6]. The possible advantages of employing such technologies as multistatic primary surveillance radar for ATM where initially investigated in feasibility studies [7], which were further developed in dedicated research projects [8]. Recent assessment of such solutions have also been performed in real-world trials, jointly undertaken by industry and civil air-navigation-service-provider [9]. Efforts for standardization under the term Independent Non-Cooperative Surveillance (INCS) within the European Organisation for Civil Aviation Equipment defined expected data types [10] and performance levels [11] for INCS system types including bi-static, multi-static (active/ passive) radars.

While LDACS-COM and LDACS-NAV have already reached TRL 6 and TRL 4, respectively, LDACS-SUR is currently in its initial feasibility assessment, evaluated at TRL 1 and aiming to reach TRL 2 by the end of the ASTONISH project. LDACS-SUR is considered to be potentially valuable:

- where traditional surveillance services are not available. In these areas, LDACS-SUR can serve to provide surveillance coverage.
- where traditional surveillance services are available. In this case, LDACS-SUR is envisioned to provide an additional layer of surveillance to traditional surveillance services.

The second ground-based non-cooperative surveillance approach considered as part of the SESAR Solution 0516 targets a Distributed Active Radars Network (DARN) and concentrates on the use of compact distributed active radar systems. The intent is to employ a distributed radar system technology which is designed to actively scan and monitor the surrounding area, capable of detecting both static and dynamic objects and weather conditions. This approach also aims to reach TRL 2 by the end of the ASTONISH project.

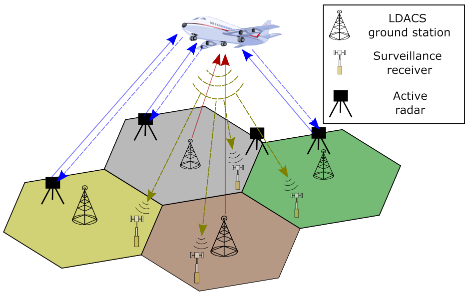


Figure 1. Concept overview for SESAR Solution 0516.

The remainder of this paper is organized as follows: Section II focuses on the preliminary validation exercise performed for LDACS-SUR while Section III on the preliminary validation for DARN. Both sections are similarly organized, presenting an overview of the system and the validation scenarios, explaining the system placement used in the validation, as well as describing the validation strategy and presenting the preliminary results in terms of system configuration. The paper is concluded in Section IV.

II. LDACS-SUR

A. System overview

LDACS-SUR uses the LDACS forward link communication signals, from the ground station (GS) to the airborne station (AS), as signals of opportunity for setting up an LDACS-based non-cooperative passive multistatic radar system, as depicted in Figure 1. The LDACS forward link signals are transmitted from the ground and inherently get reflected off the aircraft. Through the positioning of multiple spatially distributed surveillance receivers (Rx), the LDACS signal reflections can be received on the ground and used for aircraft localization purposes.

Given the very low transmit power of the LDACS transmit signals, it is expected that the reduced link budget of the signal reflections will make the radar signal processing very challenging in practice. In this respect, enabling the reception of the signal reflections at multiple widely distributed receivers as well as the use of a long integration time at each surveillance receiver are crucial steps for improving the detection performance by allowing for a spatial diversity gain and maximizing the signal processing gain.

B. Validation scenarios

Within the ASTONISH project it is considered relevant to assess simulations for LDACS-SUR in specific operational scenarios over the Italian airspace with different traffic characteristics to evaluate the technical performance:

- Milano Terminal Maneuvering Area (TMA) having surveillance services and high density airspace, and,
- Perugia Control zone (CTR) having low density airspace and no radar service.

As highlighted in Figure 2, Milan TMA consists of 8 zones. The total controlled area of this TMA extends about 200 km in east-to-west and 100 km in north-to-south direction, with the largest and central sector being Zone1_Lombardia. It encompasses the three major airports Milano Malpensa, Milano Linate and Bergamo and extends from 2000 ft AMSL up to FL 95. The seven directly adjacent zones have the same upper vertical limit (FL 95) but a different lower vertical limit (expressed in altitude if below the transition level or in-flight level if above the transition level) accommodate for the rising mountain slopes beneath of the Alps to the north and the Apennine mountain to the south of the TMA. Apart from this, the orography underneath is generally flat providing good radar line-of-sight conditions.

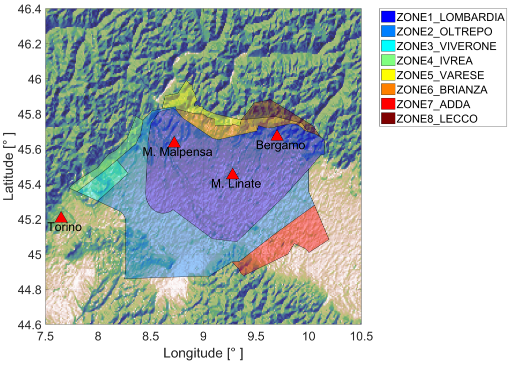


Figure 2. Validation scenario Milano TMA. The red triangle markers indicate locations of major airports.

The CTR of the Perugia airport has been selected as the second validation scenario for the study. As shown in Figure 3, the controlled area is divided into two zones stacked on top of each other. The lower Zone1 reaches from the ground level up to 2500 ft AMSL. It is directly followed by the larger upper Zone '2' which starts at 2500 ft AMSL and terminates at FL 115. It extends about 50 km in east-to-west and 80 km in north-to-south direction. The airport itself is situated in a valley of the Apennine with surrounding mountain tops rising up to 1290 m AMSL. Due to the relative steep slopes, parts of the orography protrudes into the lower volume of both control zones. As such communication and radar 'blind zones' had to be anticipated and accounted for in the simulated positioning of LDACS-COM transmit and LDACS-SUR Rx infrastructure.

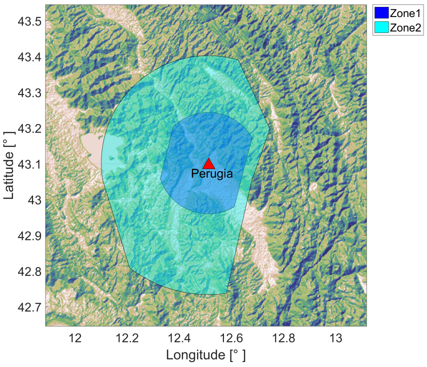


Figure 3. Validation scenario Perugia CTR. The red triangle marker indicates the airport's location.

For the efficient deployment of a LDACS-SUR passive radar, particular constraints such as illumination and interference caused by the available IoOs and other ATC equipment, their spatial distributions and different radiation pattern have to be accounted for. This is compounded further by the required low level surveillance task. Insights gathered from analysing the two described scenarios were used to inform the development of a dedicated LDACS-based passive radar positioning and modelling framework. It was developed with the primary function of providing specific deployment options for any scenario based on the given input data, rather than imprecise generalized model assumptions.

C. LDACS-SUR configuration definition

Tx specifications: For the LDACS-SUR performance analyses, LDACS-GS transmissions would be used opportunistically, meaning that their technical specifications would be implemented without any consideration regarding the objective of non-cooperative surveillance. Since the needs of LDACS-COM requirements are not currently known, specific assumptions regarding GS placement needed to be made. To keep in line with common passive radar naming conventions, LDACS-GS are from here on referred to as transmitters (Tx) when appropriate.

Assumptions regarding the Tx link budgets therefore were made in accordance with LDACS-COM specifications provided in the SESAR document [2]. The forward link propagation foresees a GS output power of up to 32 dBm (including 3 dB cable and duplexer losses) with an antenna gain of 12 dBi yielding an effective isotropic radiated power (EIRP) of up to 44 dBm. Link-budget calculations show that this enables the GS to establish an LDACS communication-link with an AS up to 200 NM.

Since exact specifications on the expected GS radiation characteristics have yet to be established in the LDACS-COM development cycle, the transmitting antenna pattern of the GS were modeled after commercially available L-band antennas [12], which already provide A/G radio navigation services. Such antennas consist of a stack of vertically polarized dipoles which are combined to form a linear broadside array with an omni-directional pattern in azimuth.

Figure 4 provides an example of a simulated GS radiation pattern in the vertical plane. It can be seen that the main beam is tilted upward with an angle of 3° to allow for optimal illumination of the air-volumes to be serviced. Together with the antenna's strong directivity, this enables long range communication, despite the low transmit power.

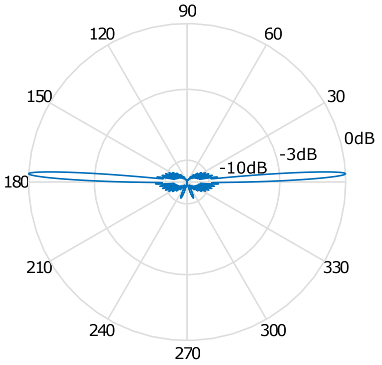


Figure 4. Tx antenna vertical radiation pattern at 1087.5 MHz.

Tx positioning: Considering a future development of the LDACS-GS infrastructure, it was assumed that initial Tx positions would exclusively be selected in accordance with the requirements of LDACS-COM, with no alterations made to accommodate the needs of the surveillance aspect. Considering the primary design goals for LDACS-COM to provide A/G communication in En-route and TMA airspaces, the placement of transmitters at locations close to the airport premises was used as an assumption within ASTONISH. Pre-existing communication and radionavigation installation could ease integration of the LDACS-GS infrastructure.

A dedictated compatibility study focused on identifying which locations could be used to operate a GS without disturbing any aeronautical radionavigation service (ARNS) including Distance Measuring Equipment/TACtical Air Navigation system (DME/TACAN). For the compatibility with the ARNS, the regulations according to the ITU Resolution 417 [13] were followed. This resolution limits the EIRP usable by an LDACS station in the higher part of the LDACS frequency band, reducing the maximum allowed EIRP as the frequency increases. In practice, it reduces the number of LDACS forward link channels that can be used at the maximum LDACS EIRP by a GS. For the compatibility with DME/TACAN, the compatibility criteria preliminary agreed with the German authorities in past LDACS flight campaigns, e.g., [14], were used. These criteria define a minimum desired-to-undesired signal power ratio at the DME/TACAN stations. This compatibility threshold depends on the frequency separation between the transmit LDACS frequency and the receive DME/TACAN frequency. Thus, a location was considered valid for the LDACS GS if at least one forward link channel could be used without disturbing ARNS and DME/TACAN functionalities.

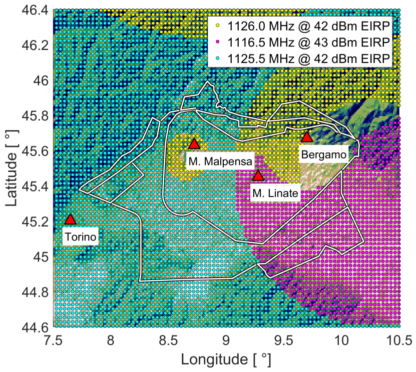


Figure 5. Areas in Milano TMA scenario compatible with LDACS Tx positioning.

TABLE I. LDACS TX ASSESMENT

Airport	f_{Tx}	P_{Tx}	Assessment
M. Linate	1116.5 MHz	31 dBm	RF compatible
M. Malpensa	1126.0 MHz	30 dBm	RF compatible
Torino	1125.5 MHz	30 dBm	RF compatible
Perugia	1115.0 MHz	32 dBm	RF compatible
Bergamo	NA	NA	RF incompatible

The study also revealed the impact of reducing the LDACS transmit power on the number of usable LDACS forward link frequencies and, therefore, on the number of valid locations for the GS. More information on the methodology for the LDACS frequency compatibility analyses with DME/TACAN and ARNS can be found in [15], [16].

The results of the analyses in terms of compatible Tx power and LDACS frequencies are shown in Figure 5 for the Milano TMA scenario. A similar study for the Perugia CTR scenario identified no compatibility issues. The results of this study are summarized in Table I. It provides a list of permissible LDACS-COM transmit frequencies f_{Tx} and the corresponding compatible transmit powers P_{Tx} at selected airports which could serve as possible LDACS-Tx locations. The table also contains a brief assessment of the suitability of such hypothetical Tx for the LDACS-SUR study.

Rx specifications: To keep the Rx concept in line with the general trends in passive radar development, the pattern characteristics for the surveillance antenna of the LDACS Rx was modeled as a uniform circular array of eight decoupled vertical polarized half-wave dipoles. The chosen antenna layout therefore aligns more closely with proven passive radar antenna designs proposed for ATC applications [5], [9]. This antenna layout permits the formation of beams with 11.9 dBi of gain as shown in Figure 6, which are steerable in azimuth and elevation. It was assumed, that using modern software defined receivers, each LDACS-SUR Rx can generate multiple beams simultaneously allowing for 360° coverage in azimuth, while its elements can cover 72° to 66° in elevation.

The system concept foresees that the reference signal required for local passive radar processing shall be provided over-the-air (OTA) via the direct path. As such the Rx can be positioned with greater flexibility under the condition that a radar line of sight to the Tx is available.

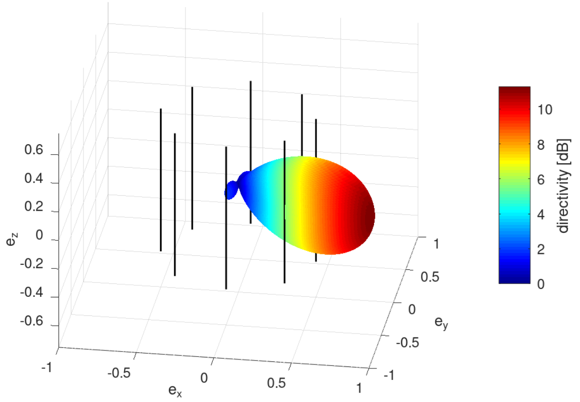


Figure 6. Modeled pattern of a single Rx surveillance beam in an eighth element circular array at 1087.5 MHz.

TABLE II. LDACS A/G LINK-BUDGET PARAMETER UNDER THE PRESENCE OF INTERFERENCES ACCORDING TO [2]

Rx parameter	Value
Safety margins	6 dB
Cable loss	3 dB
Dublexer loss	0 dB*
Bandwidth	498050 Hz
Total Noise Power	-107 dBm
Receiver Noise Figure	6 dB
Required C/(N+I) @ BER=10^{-6}	3 dB
LDACS-bit rate	291200
Ref. channel sensitivity (S1)	-98.03 dBm

*modified from [2]

The relevant requirements for LDACS-COM signals reception were adopted from the recommendation in [2], which derive a minimum Rx sensitivity $S1$ (including safety margins) using the parameters listed in Table II. To account for higher possible gain and the lack of a duplexer with respect to the reference design intended for airborne stations, some minor modifications where made as indicated. Where applicable, these link budget values were carried over to also characterize the sensitivity in the Rx surveillance channels.

Rx positioning: For the LDACS-SUR system to operate optimally as passive bistatic radar, the following boundary conditions have to be considered for the development of its receiving nodes:

- Performance in terms of probability of detection $P_{d,i}$ is determined by the Rx position in relation to the Tx and the surveilled airspace volume (dictated by bistatic radar equation). Processing parameters considered a coherent processing interval (CPI) of 5 seconds and a false-alarm rate P_{fa} of 10^{-6}.
- Pattern propagation factors (also called F-factors) affecting the FL signal's propagation path. These were calculated based on the specific orography of the scenario and include both surface reflections and diffraction of signal paths that graze the terrain surface.
- Reference channel receive power P_{ref} needs to exceed

$S1$ to decode the LDACS-signal with bit-error rates (BER) better than 10^{-6}. Reference signal power P_{ref} at location needs to exceed the sensor sensitivity $S1$, to allow for the OTA reception of the LDACS-COM signal close to ground-level.
- Direct signal interference (DSI) caused by the forward link reception in the surveillance channels via the direct path, reduces the sensitivity and thus Rx performance. Its tolerance to DSI depends on its dynamic range (DR), which is determined by the effective ADC (Analog to Digital Converter) sampling depth. For the analysis $DR = 88.5\,\mathrm{dB}$ was assumed which can be accomplished with 15-bit sampling depth.
- Cross and co-channel interference with other radio navigation equipment has to be accounted for. Due to the prior compatibility analyses, interference was considered to be negligible.
- Lower elevation positions are generally favored to retain economic viability.

Further requirements have to be considered to ensure that the distributed Rx perform properly as a passive radar network:

- Multilateration approaches, based on bistatic range measurements of aircraft, were identified as the primary means for localization in LDACS-SUR. To predict achievable position estimation errors for a given spatial Rx distribution, Cramer-Rao Bounds (CRB) were analyzed.
- Total number m of distributed Rx should be limited to ensure economical viability.
- The multilateration approach requires the coverage volume of a number of Rx-Tx bistatic pairs k out of m to overlap. From this, the local decision rule ot type "k out of m (AND)" for the probability of target location P_d is derived as:

$$P_d = \prod_{i=1}^{k} P_{d,i} \tag{1}$$

  In this system concept study $k = 3$ was considered as being sufficient to fix the location of targets in the air-volume.

D. Validation strategy

Numerical simulations were carried out to determine the appropriate Rx number and geometric distribution for the LDACS-SUR network in an iterative process under the constrains discussed in the previous subsections. This positioning analysis involved testing a set of initial candidate distributions against a lower resolution representation of each operational scenario. A network's performance with respect to coverage in the given air-volume was then tested against two different key requirement thresholds, stipulated in EUROCONTROL guidance documentation [17]:

- "Horizontal position error, including measurement error and error due to information latency, shall be equal to or less than 300 m RMS global [3N_C-R4]." It should be noted, that information latencies were not considered in this study.
- "The probability of position detection within the defined update interval shall be greater than or equal to 97% ($P_d \geq 0.97$) for any target [3N_C-R2]."

The best performing distribution was then selected and tested against a higher fidelity scenario representation. This process was repeated, while progressively adjusting the Rx technical specification and candidate locations until a adequate network distribution could be identified.

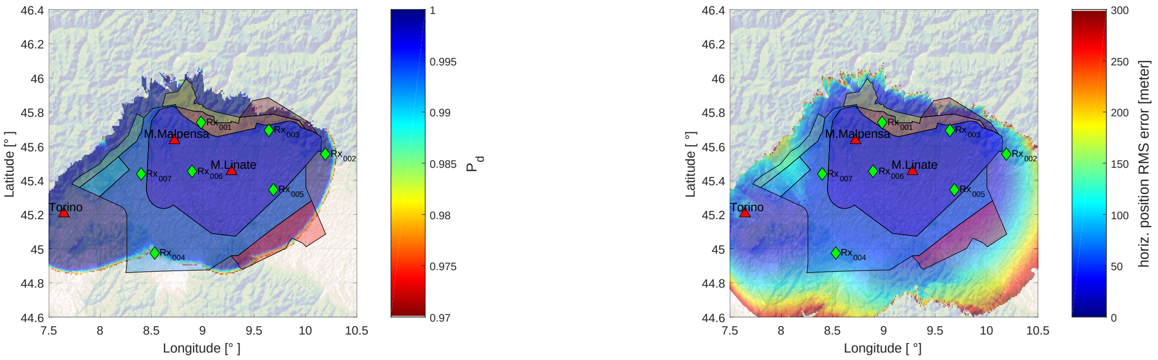
E. Preliminary results on LDACS-SUR configuration

Milano TMA: The larger control area necessitates the placement of seven Rx to achieve coverage. Figure7a shows the identified Rx distribution marked with green labels. The overlay highlights the achievable coverage at 4500 ft AMSL in terms of P_d, as defined in Eq. 3, when all three LDACS-Tx are exploited as illuminators simultaneously. It can be seen that full coverage is achieved for all but three TMA Sectors. The lack of illumination becomes the limiting factor for the sectors Zone7_ADDA and Zone2_OLTREPO which extend furthest to the south (compare Fig. 2). To the north, coverage of Zone6_BRIANZA is partially affected by the orography of the mountain slopes of the Alps. The corresponding estimates of the horizontal RMS error in Figure 7b show sufficient coverage throughout the TMA, except for a minor gap in Zone6.

These findings provide an insight into the number of Rx for an LDACS-SUR servicing a larger TMA. It shows that a placement at such scale requires a distributed network of LDACS-Tx to be present to provide sufficient illumination. On the LDACS-SUR side this necessitates its Rx to be capable of processing multiple LDACS-bands simultaneously. Full coverage could also be achieved with the positioning of more Rx serving as gap-fillers. Alternatively, the Rx performance could be improved with direction finding capabilities at the node level at the cost of higher Rx complexity.

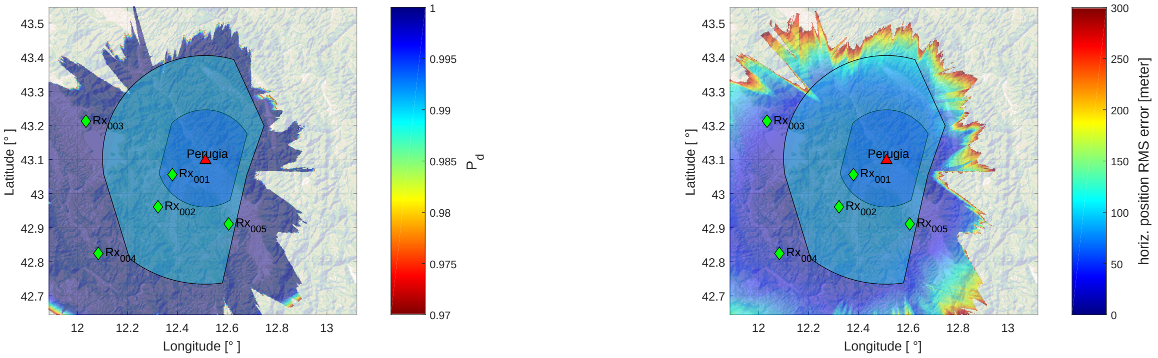
Perugia CTR: A placement of five LDACS-SUR Rx seems to be sufficient to meet the initial performance requirement. Figure 7c shows the locations of the receivers labeled Rx_{001} to Rx_{005} indicated by the green markers. The network distribution is skewed to the south-west due to the specific line-of-sight conditions. The overlay shows the coverage in terms of P_d at 4500 ft AMSL for the network. It can be seen that the requirement threshold can be met for the larger CTR Zone2 for this altitude. It should be noted, that the orography below induces particularly strong radar shadowing to the northeast and to the west of the CTR. Figure 7d shows the corresponding analysis of the horizontal position error expected for 4500 ft AMSL derived from a CRB analysis. The requirement thresholds for this performance parameter are met as well for CTR Zone2.

These results indicate that the relevant requirement thresholds can be met by LDACS-SUR for airspaces with volumes comparable in size to the Perugia CTR if LDACS-COM illumination can be provided from within the control zone.



(a) Probability of detection P_d for Milano TMA.

(b) Horizontal position RMS error for Milano TMA.



(c) Probability of detection P_d for Perugia CTR.

(d) Horizontal position RMS error for Perugia CTR.

Figure 7. Preliminary coverage results on LDACS-SUR configuration at 4500 ft AMSL .

The specific orography has a crucial impact on the network distribution since multiple RF line-of-sight condition have to be met.

III. DARN

A. System overview

In civil aviation, airspace surveillance is traditionally based on the use of Primary Surveillance Radars (PSRs), a well-established technology that provides distance and azimuth measurements through active signal reflection. PSRs are characterized by a very high detection range (in the order of hundreds of kilometers) and do not require any on-board equipment to locate aircraft. However, these systems present some critical limitations such as low accuracy and update rate, expensive installation and maintenance, high-power requirements, and lack of redundancy. The increasing density of air traffic is putting pressure on traditional surveillance capabilities based on PSRs. A valuable solution to overcome these limitations can be represented by using a Distributed Active Radar Network (DARN). Netted radar systems are able to provide higher target detection and tracking capabilities, more accurate measurements, better multi-target tracking performance, and redundancy in case of single system failure [18]-[19].

In this work, we propose the use of a phased-array radar network as an alternative solution for airspace surveillance around airports. How candidate locations where to place the radars of the network have been extracted is shown, together with the positioning technique. Finally, results showing the network topology and the achieved performance are reported, so to validate the effectiveness of the approach.

B. Validation scenario

Shannon airport, in Ireland has been chosen as scenario for the DARN validation. This location presents an actual operational radar deployment, which makes it a suitable site for conducting the validation. Furthermore, as for Perugia's airport, the Shannon one does not have a PSR. The area considered has an extension of 30×20 km and it is mostly planar. This allows the radars signals propagation to be not obstructed, facilitating the positioning of the network. The only limitation is the presence of the sea, which the airport overlooks, and which limits the choice of certain locations for the radars. Figure 8 depicts the area of interest around Shannon airport. The red rectangle represents the airport position while the blue region is the controlled area that the network has to survey. This area extends in altitude from 300 ft AMSL up to FL100, therefore defining a volume. The definition of this surveillance volume has been determined by considering the usual landing trajectories of airliners approaching the airport. The objective of deploying the DARN is to ensure coverage across the entire area of interest, while meeting performance requirements for aircraft detection and tracking.

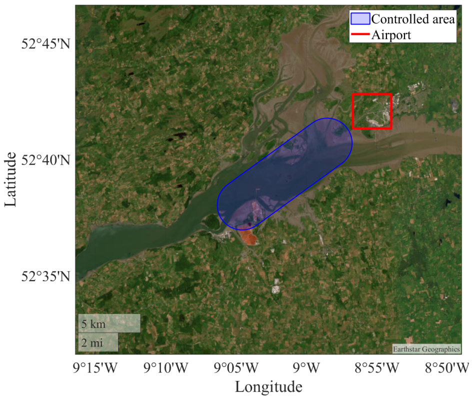


Figure 8. Shannon airport scenario

C. *DARN configuration definition*

The radar system considered for simulations is a low to medium power radar for airspace surveillance and weather observation [20]. Differently from traditional PSRs, it is characterized by an high update rate and resolution, which guarantees better tracking performance. Table III lists the parameters of the sensor.

The positioning of the radars network is carried out through the optimization framework described in [21]. The use of this procedure is based on the idea that the topology of the DARN highly influence the overall network performance, therefore the position of each sensor must be carefully chosen. Since multiple positions can represent a suitable location for the radars of the network, the cited optimization algorithm is used in order to find the best location for each sensor. The procedure is divided in two main steps:

1) Extraction of candidate radar locations:
   First of all, some suitable locations where the radars can be placed should be extracted. In order to do that, a 3D surface map model of the scenario is used. They are extracted by dividing the area in sub-cells, using a rectangular grid. In each one of these cells, the point characterized by the highest altitude is selected as suitable location. Furthermore, radar minimum and maximum detection range, R_{min} and R_{max} respectively, are considered. In fact, points within a distance from the controlled area higher than R_{max} and lower than R_{min} are not considered as candidates, since from that positions part or all of the controlled area is out of the radars field-of-view (FOV). A total of 99 candidate locations have been extracted for the Shannon scenario and they are depicted in Figure 9.
2) Search for optimal positions:
   Once the candidate locations are extracted, they are used as input to the optimization algorithm. The algorithm is a customized version of the Particle Swarm Optimizer (PSO), tailored for dealing with combinatorial optimization problems in high-dimensional search spaces. It takes into account some predefined surveillance performance requirements (explained more in detail in the next paragraph) and it searches for the best network topology able to satisfy them.

TABLE III. RADAR PARAMETERS

Parameter	Variable	Value
Trasmitted Power	P_T	25 W
Frequency	F	9.6 GHz
Beamwidth	Δ	$\sim 2° \times 2°$
Bandwidth	B	6 MHz
Wavelength	λ	3.22 cm
Antenna Gain	G	37 dB
Range Limits	R	[1 30] km
Range Resolution	ΔR	25 m
Pulse duration	τ	6.7 μs
Number of pulses	N	8

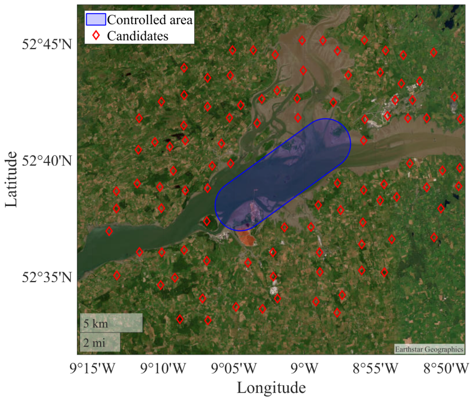


Figure 9. Extracted candidate locations

D. *Validation strategy*

The positioning of the radars in the network is based on two main criteria, which are the Cramer-Rao Bound (CRB) and the joint probability of detection (PD). The CRB is a lower bound that quantifies the target tracking performance of the radar network and it is defined as:

$$CRB = \sqrt{trace(cov(\mathbf{x}))} \tag{2}$$

where $\mathrm{cov}(\mathbf{x})$ is the covariance associated with the target position $\mathbf{x}$, and $\mathrm{trace}(\cdot)$ is the operator calculating the trace of the matrix contained in the brackets. As regards to P_d, it represents the overall probability of the network of detecting a target and can be obtained under the assumption that the single radar measurements are independent, thus having:

$$P_d = 1 - \prod_{i=1}^{k} (1 - P_{d,i}) \tag{3}$$

Where $P_{d,i}$ is the detection probability associated to the i-th radar and k is the total number of radar composing the network. Basically, the algorithm runs up to a maximum number of iterations, trying to maximize the coverage over the controlled area, while optimizing at the same time CRB and PD.

E. *Preliminary Results on DARN configuration*

The performance of the network has been validated by varying the number of radars composing the network from 2 to 7. Figures 10-12 show the optimized network topology for 2, 4 and 6 radars. The CRB is also reported, estimated considering for each point over the horizontal axes all the overlying cells along the vertical axis and averaging their CRB values. In all the configurations showed, the network is able to cover the whole controlled area, while the CRB varies. As it could be expected, higher is the number of radars composing the network, lower are the CRB values. We can consider as benchmark the required tracking accuracy for Ground-Based Surveillance Systems (GBSS) reported in the document DO-381 from the Radio Technical Commission for Aeronautics (RTCA) [22]. Except for the case of 2 radars, where the mean CRB of a portion of the controlled area reach the value of 180 m, for the other cases it is very low, being below 40 m for almost all the area in the case of 4 radars and below 10 m in case of 6 radars. These results show the effectiveness of the radar network in reaching highly promising values of detection and tracking accuracy, extremely better than the ones of a single high-power radar. Therefore, the DARN could represent a valid and efficient alternative to classic surveillance systems and, depending on the number of radars required, the cost-effectiveness of this solution could be significantly high.

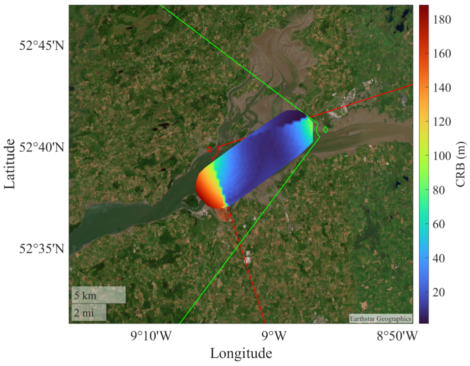


Figure 10. CRB with 2 radars

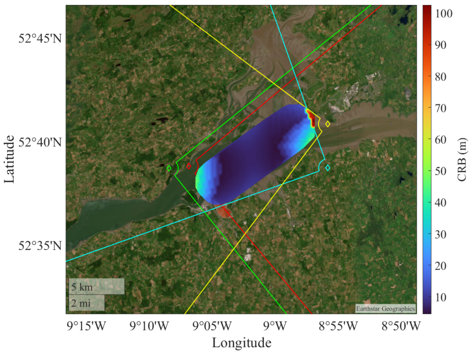


Figure 11. CRB with 4 radars

IV. CONCLUSION

Based on the preliminary results for the ground positioning presented in this work, both LDACS-SUR and DARN seem to be promising technologies. Detailed validation activities will be performed within the ASTONISH project in the next months taking into account the scenarios displayed in this work and with the ground configuration defined here. Nevertheless, further investigation in terms of configuration might occur taking into account the stakeholders' feedback or additional technical details that could be refined during the ASTONISH lifecycle.

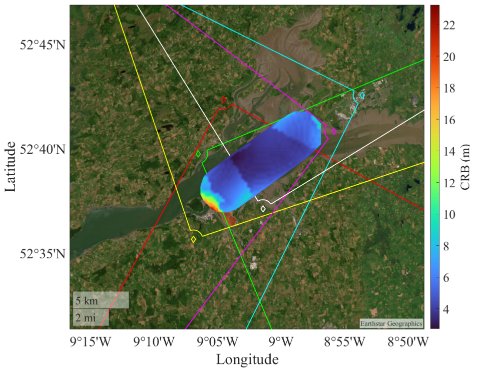


Figure 12. CRB with 6 radars

Prototyping such a receiver and performing lab tests, as well as executing an experimental campaign for proof of concept are potential future lines of work that would bring this solution beyond TRL2. However, these activities would need to be performed in a potential future project beyond ASTONISH.

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