NATO SSA/SST Capability Provision or Improvement by Means of DADR/FADR Type Radar Networking

José Luis Bárcena Humanes
INDRA
Torrejón de Ardoz, Madrid
SPAIN

jlbarcena@indra.es

Carlos F. Castillo-Rubio
INDRA
Torrejón de Ardoz, Madrid
SPAIN

cfcastillo@indra.es

Francisco M. Almerich Simó
INDRA
Torrejón de Ardoz, Madrid
SPAIN

fmalmerich@eservicios.indra.es

ABSTRACT

Deployable Air Defence Radar (DADR) and Fixed Air Defence radar (FADR) systems provide early warning of air and missile threats or incursions. Although the Air Surveillance modes (AS) of these kind of systems are optimized to cover heights primarily associated with ABTs (Air Breathing Targets), their beam-centred design and the flexibility that digital beamforming provides allow them to incorporate other secondary operative modes. For example, by adding TBM (Tactical Ballistic Missile) dedicated beams to the air-surveillance beam sequence, an increased elevation coverage is achieved enabling the simultaneous detection and tracking of TBM targets.

Through the design of special beams and/or operative modes that achieve longer in range and higher in elevation coverages, Space Situation Awareness (SSA) / Space Surveillance and Tracking (SST) capabilities at Low Earth Orbit (LEO) levels can be considered for these radars. Using the same operative mode design approach based on the adaptation of the beam sequence, these functionalities could be obtained with only software or minor hardware modifications.

The switching of the radar to such working modes compatible with LEO surveillance actions could be internally triggered by the operator (using a previously loaded space object catalogue), or externally cued through the reception of a previously defined functionality activation request. The obtained SST capabilities, either operating individually at each radar or linked in a multiradar network, could complement and enhance SSA capability provided by existing SST dedicated radar systems.

1.0 INTRODUCTION

The main mission of DADR/FADR 3D radar systems is to provide Early Warning Surveillance to exercise the Air Sovereignty of continental territory or over deployed forces. These radar types also contribute to the NATO Integrated Air and Missile Defense (NATINAMDS), safeguarding and protecting Alliance territory, populations and forces against any air and missile threat and attack.

Beam Template of its fundamental Air Surveillance (AS) mode is optimized to cover a volume with a long instrumented range, 360º in azimuth and heights up to 100 Kfeet. Triggered by own radar search algorithms or by an external cue, radar beam management techniques applied allow for adding beams to the normal beam sequence, enabling an increased coverage in elevation for the detection and tracking of various TBM-like targets at same azimuth sector, with minimal degradation in the ABT surveillance performance at that azimuth.

Digital beamforming techniques introduce an exceptional flexibility in the programming and configuration by the operator of such kind of special dedicated modes in terms of energy, illumination time, beam steering and waveforms management. Consequently, based on the same principle, additional modes with longer detection ranges and/or higher elevation coverages can be incorporated into such type of existing

DADR/FADR radar systems for SSA/SST at LEO levels, with no or minor hardware modifications. The SST capability could be internally or externally operated:

- The radar system SW module in charge of the LEO task scheduling, could carry out the orbital propagation of objects whose TLE parameters have been previously loaded. Then, the system could determine which of them, where and when they would be within the coverage of the radar (taking into account LEO extended range and coverage in elevation). For those trajectories that meet the above conditions, surveillance actions may be scheduled upon operator request: the system will use the dedicated LEO beams to try to illuminate targets of interest along the programmed paths. If there is illumination of the programmed target, depending on the echo's detection and track initiation process and criteria, a LEO event could be then started.
- This functionality can be enhanced with a communication interface so that the necessary information to activate the functionality (external CUE requests) can be received, including the search activation request and the parameters necessary for the system to determine the trajectories of the objects to be analysed and to program the surveillance attempts.

In addition, a specific LEO Mode of operation could be established making not mandatory to maintain the simultaneous ABT surveillance activities within the margins of the instrumental coverage. This will clearly provide a greater flexibility and performance since more system resources could be dedicated to the LEO Mode.

The capabilities obtained at a sensor level (DADR/FADR sensors operating individually) can also be used to significantly improve NATO SSA and the Common Recognized Space Picture by means of the integration of the object detections received from the radar systems deployed in different nations, giving rise to a sensor network. Such network could complement and enhance an SSA backbone capability provided by existing radar systems, such as the S3TSR already in operation in Spanish Air Force Moron air base and/or other types of optical/EO/range finding sensors.

In order to develop this concept, the rest of the document is organized as follows: in section 2, a brief introduction to the beam template adaptation capabilities of DADR/FADR systems and how they are used to provide specific tracking capabilities is presented. In section 3, SSA/SST functionality provision is presented focussed on a single radar. Radar network operative concept will be then described in section 4. Finally, main conclusions will be summarized in section 5.

2.0 DADR/FADR BEAM TEMPLATE ADAPTIVE CAPABILITIES

DADR/FADR radars focus on early warning air surveillance tasks. Therefore, their instrumental coverages are configured to cover typical ABT flying altitudes up to the maximum instrumented range in 360 degrees around the Radar Position.

Air Surveillance radars based on Pencil-beams radar designs explore their coverage volume through mechanical azimuth scanning using programmable beams electronically steered in elevation.

Taking advantage of the flexibility of digital beam steering capabilities, different and complementary beams in elevation are designed in order to provide the optimum performance at different sets of ranges/elevations working conditions, in terms of energy, illumination time, waveform management, etc. The scheduled sequence of the designed pencil-beams defines the coverage and performance characteristics of the radar sensor, a set of pencil-beams programmed to cover the whole elevation instrumented volume is called beam template. Hence, the basic beam template for a DADR/FADR systems will be mainly established by the air surveillance main mission and its established requirements. The configuration of the beam template must leverage the radar resources (mainly dwell time and energy) and overall system performance achieved.

Digital beam steering technique allows including special beams for specific missions different from ABT detection. Particularly, DADR/FADR radars also contribute to the NATO antimissile effort through NATO Integrated Air and Missile Defense (NATINAMDS); TBM (Tactical Ballistic Missile) are one of the threats that must be considered to fulfil that task. These kind of targets diverges to the usually considered ABTs (Air Breathing Targets) in terms of physical characteristics, speed, manoeuvrability, flight dynamics, and flight altitude.

In terms of system coverage, TBM surveillance and tracking tasks require the system the capability to cover higher elevations than conventional air surveillance does: flight altitudes of one order of magnitude higher could be considered when the missile focused task is approached. This is achievable taking advantage of the pencil-beam design, adding to the basic beam template TBM dedicated beams that can be specifically designed for TBM targets, directed to higher elevations and longer ranges.

Special TBM beams can be triggered by the own radar TBM search algorithms or by an external TBM cue. The radar processor is able to select one of the aforementioned TBM beams to be added to the base beam template, enabling an increased coverage in elevation and range. In Figure 2-1 an example for TBM extension coverage beams are depicted: one providing extra range coverage at low elevation and the other one pointing to an elevation not achieved by the conventional beams.

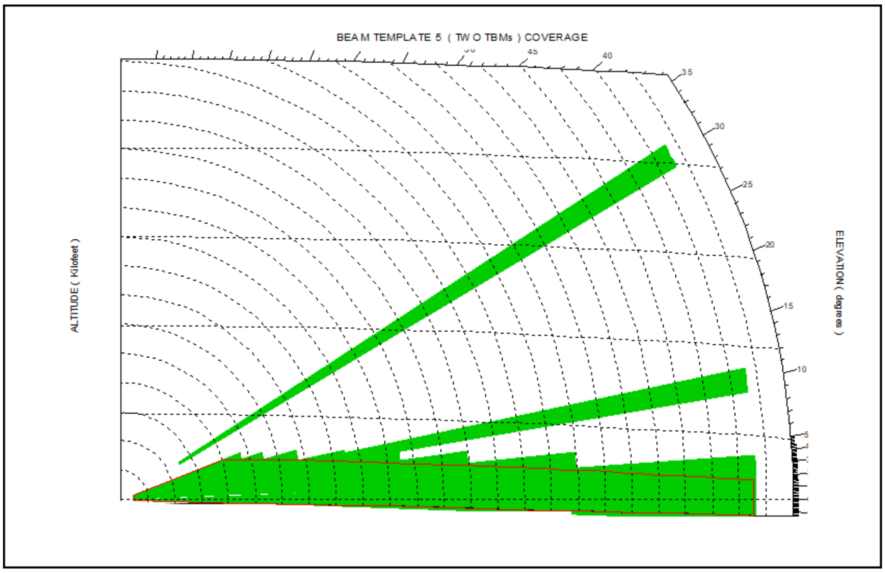


Figure 2-1: Example of two TBM extension coverage beams.

Simultaneous ABT and TBM track capability is achieved through the modification of the beam sequence, making the last to diverge from the optimum for ABTs surveillance duties. Keeping this into consideration, an air surveillance operative mode is selected, designed primary for ABTs surveillance, but also allowing certain number of beam sequence modification through the inclusion of TBM beams, enough to enable TBM capabilities, but not to degrade surveillance task performance.

A similar strategy is proposed in this paper for LEO object detection, described in the next section.

3.0 SSA/SST CAPABILITY PROVISION

Low Earth Orbit region define an area of space surrounding Earth, below an altitude 2000km, where most of the artificial objects in space are located [1]: low mass/energy cost ratio and other communication system advantages (latency, bandwidth, etc.) make it a very advantageous region for manmade objects. In addition, ballistic missiles, with very high altitude profiles, trespass this area in their apogee. These objects make this a crucial crowded area and remark the relevance of its surveillance: object in this area must be carefully track, if they are on a LEO orbit itself or are sub-orbital and only surpass its limits before returning Earth surface.

3.1 Functionality description

Through the pencil-beam design schema, with a similar strategy commented in the previous section, a LEO object detection functionality can be included. Three elements must be considered to achieve this goal:

- A LEO dedicated beams, specifically designed to provide:
  - Longer ranges coverage of around a value of 1500km.
  - An extended elevation coverage: the higher the elevation system is able to consistently cover, the smaller the shadow cone within the FOR, and hence, the higher and longer the number of object the system will be able to illuminate.
  - The number of LEO extension beams included in the beam template must be kept below a certain threshold in order to avoid degradation on conventional air surveillance capabilities.
- Beam sequence scheduler mechanism, that analyse the LEO illumination request in order to adaptively configure a beam sequence, in the corresponding azimuth sector, that includes LEO dedicated beams, taking into consideration the currently active operative mode and the performance and resource restrictions that derive from it. Outside of the specific azimuth sector where special LEO beams are inserted, the normal ABT coverage will be kept unaltered.
- A SW module that allows the operator to ask for, configure and schedule functional requests for LEO object detection. When a locally operated LEO detection task request is set, the process is defined as follow:
  - The system SW module in charge of the LEO task scheduling select one or a set of elements of a LEO object database (previously loaded), defined by the TLE parameters describing their orbits.
  - Based on the information the database provides, the sensor site location, its FOR (assuming the extended range and elevation coverage conditions achieved by the LEO beams) and the radar performance characteristics, the SW module determines if the analysed objects will be within the system coverage, and also estimates at what moment this is going to happen.
  - Through an automatic mechanism, for those trajectories that meet the above conditions, surveillance actions are scheduled, trying to obtain detections during the calculated orbital passes. For those scheduled requests, the system will select the best-fitted dedicated LEO beams to be scheduled into the beam sequence in order to illuminate the expected location of the targets of interest.
  - If the backscatter from the illuminated target meets the SNR requirements, a detection of the LEO object will be obtained. Sequential detections will generate a confirmed LOE-object to be delivered through specific data messages. Three detections are required to confirm a LEO event as minimum.

The LEO detection capability is activated by the radar operator in the Local or Remote Control Console or by from the C2 centre. A communication interface is required so that the necessary information to activate the functionality can be received and update the radar LEO object database can be transmitted, including the search activation request and the parameters necessary for the system to determine the passes of the objects to be analysed and to program the surveillance attempts. The radar will transmit back to the C2 the LEO event data.

3.2 Monoradar LEO functionality performance

The FADR/DADR LEO detection capability performance is limited by the radar location (latitude) and instrumented range & elevation for the specific LEO detection beams. A generic LEO elliptic orbit can be, basically, defined by its Height at the perigee and apogee, Eccentricity and Inclination, as well as the Longitude of Ascending Node (RAAN) [2]. For the object to be detected, it is necessary that its orbit crosses the radar LEO instrumented coverage in, at least one of its orbits. This can only happen if its Inclination is above a minimum Tangential Inclination defined as:

$$\lambda_{tg} = asin[sin(\lambda) * cos(rng) - cos(\lambda) * sin(rng)]$$

With

$$rng = \frac{d}{R_E * (1 - e_E^2)} \left(1 - e_E^2 sin^2(\lambda)\right)^{3/2}$$

With λ the radar latitude, d the radar maximum instrumented range, R_E and e_E the Earth mean Radius and eccentricity respectively. This formula considers a minimum elevation coverage up to 0 deg (horizon).

As a minimum number of detections are required in order to generate a LEO event (at least 3 detections), this implies a practical minimum Inclination (I_{min}) of the LEO object, thus $I_{min} > \lambda_{tg}$

In the following figure, a minimum trajectory is represented for a radar located in 40 deg. Lat and maximum instrumented range of 1500 km.

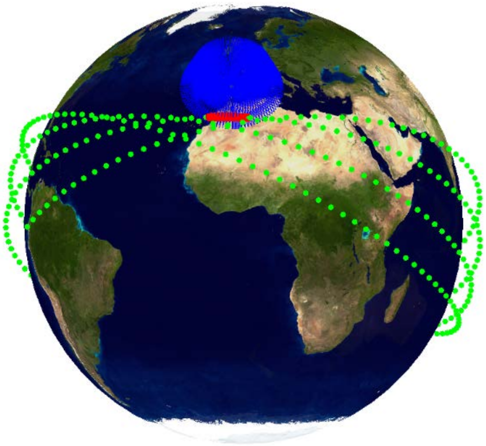


Figure 3-1: Example of LEO orbit with an Inclination 28.5 deg., Eccentricity 1 and RAAN 293.5 deg. The radar is located in Lat 40 deg and Lon -5 deg. In green dots the LEO orbit is shown, in blue, the radar instrumented coverage and red dots the radar detections.

In the previous figure, it can be seen that, depending on the orbit, it is not necessary to select the LEO coverage extension for the full 360° azimuth. Typically, 180 degrees in azimuth is enough for all possible trajectories to be tracked. Nevertheless, an increase up to 360º will provide more detections to generate an event in some trajectories (see next figure for a polar LEO orbit example).

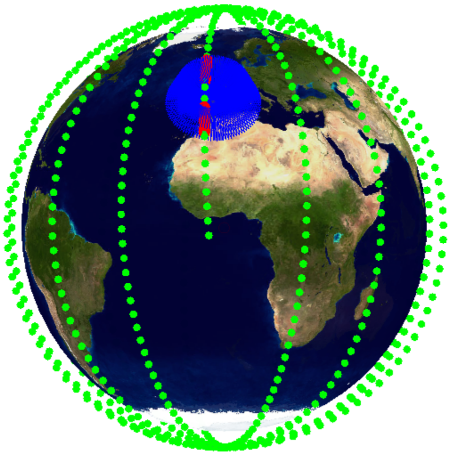


Figure 3-2: Example of LEO orbit with an Inclination 90 deg (polar orbit). Red dots represent the radar detections when a 360º LEO detection sector (full coverage) is configured.

Regarding the recommended elevation coverage, this is dependent on the LEO orbit Inclination and Height. A minimum 40 deg coverage in elevation is required for most of the typical orbits and a recommended 60 deg. will be required for orbits as high as 1200 Km.

In the following example, a practical scenario is proposed based on TerraSAR-X satellite with a polar orbit of 97.44 deg of Inclination, eccentricity close to 0 and 514km of altitude. In the following figure, the orbit is shown for 24h, obtaining two passes through the radar coverage area (360º azimuth LEO sector, 40 deg elevation and 1500km maximum range).

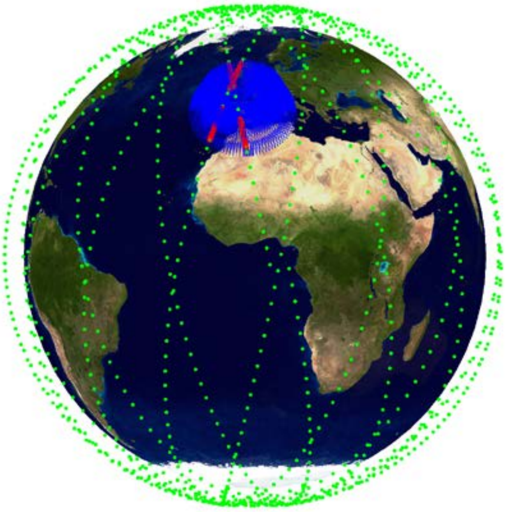
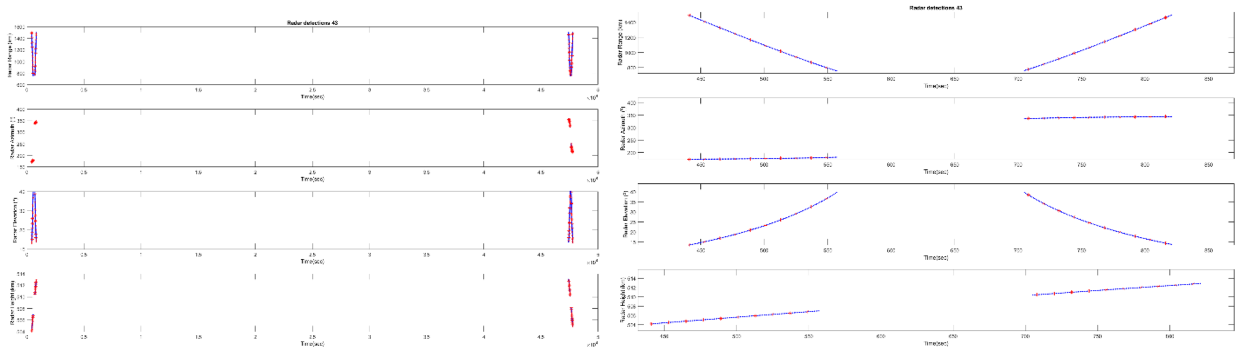


Figure 3-3: Example of LEO orbit based on TerraSAR satellite. Red dots represent the radar detections.

In the radar coordinates, the following detection can be obtained, assuming a scan period of 12 seconds.



(a) (b)

Figure 3-4: Satellite trajectory (blue dots) and radar detections with scan periods 12 sec. (red dots). (a) shows detections in 24h and (b) one pass detections.

As a polar trajectory is considered, two sets of detections are possible per satellite pass, each one with 10 detections in 120 sec., which is enough to generate a LEO-event. The assumed RCS of the target is above 10m^2, as the object presents a cylindrical shape with diameter of 1.2m and length 5.4m. The FADR/DADR detection capability is enough to detect this target with more than 80% detection probability.

As was previously stated, the beam sequence modification allows the sensor to achieve LEO detection capabilities by adding specific beams to the ABT detection beam template. As this makes the sequence to diverge from the one optimally designed for air-surveillance performance, a trade off must be stablished to maintain the latter fulfilling operative requirements. Considering one LEO-beam per beam template, in the azimuth region where this function is operating, the reduction can be seen in the following figure to be below a 5% of detection range reduction in the ABT capability.

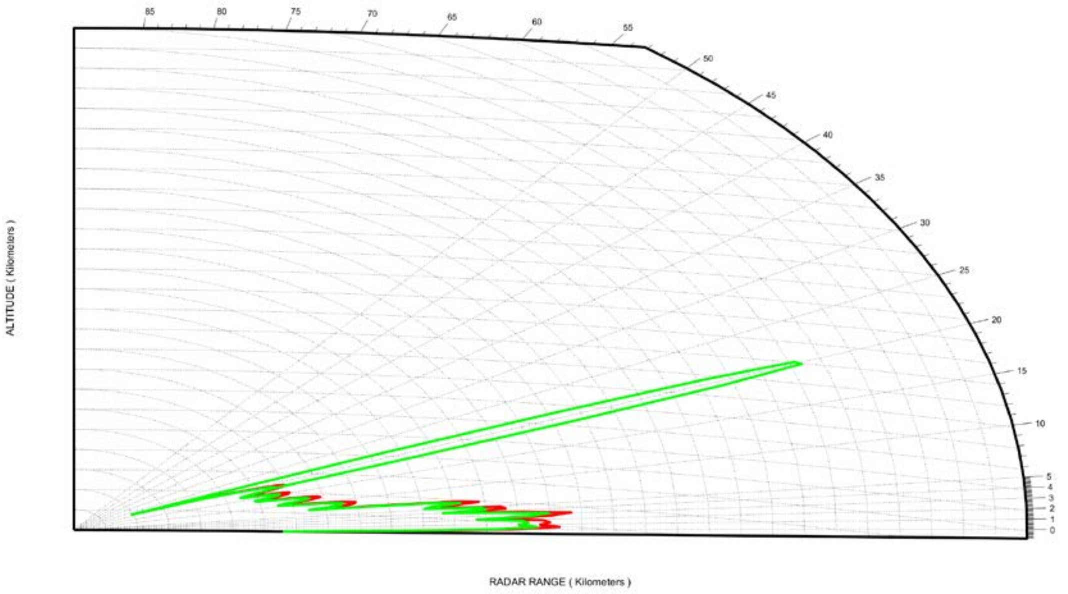


Figure 3-5: Coverage chart for a normal ABT beam template (red line) and a combined LEO

detection + ABT beam template (green line).

In order to optimize this effect, the LEO beam template programming will be only performed in the time and azimuth sectors where a detectable orbit is foreseen based on the available database. This allows the system to balance the resources management to prioritize LEOs, ABT and TBMs capabilities.

4.0 RADAR NETWORK OPERATIVE CONCEPT

NATO Integrated Air and Missile Defence (NATINAMDS) has dozens of early warning radars integrated, some of which have or could have the functionality to detect tactical ballistic missiles and, therefore, are candidates to also implement the SST capability.

The command and control for SST capability is assigned to the NATO Air Command Structure and within this structure, in the NATO Space Center, created in 2020 and located at Allied Air command in Ramstein. The responsibility of this new NATO entity is to coordinate Allied space activities and provide support to NATO operations from space. NSC is working closely with Allies' national space agencies and organizations and the NATO Command Structure to fuse data, products, and services (DPS) provided by nations. According to NATO, by strengthening the links between NATO Command Structure and national space entities, the Centre will increase space domain awareness at all levels.

NATO Integrated Air and Missile Defence (NATINAMDS) is an essential continuous mission in peacetime, crisis and conflict, safeguarding and protecting Alliance territory, populations and forces against any air and missile threat and attack. To accomplish its mission, as one of the ASAC assets, it has air surveillance early warning systems, such as FADR and DADR, sensors considered in this capability.

Taking into account the dual use of sensors (NATINAMDS + SST) and the fact that the tactical command and tactical control of the NATINAMDS sensors falls respectively on the CAOCs and ARS entities, aiming to avoid any conflict, it will be necessary to guarantee the required coordination between the NATO Space Center and the Air C2 entities involved (mainly the ARS).

The figure below, shows the possibility on how to integrate and coordinate the new capability in the NATO Air Command Structure/NATO Force Structure. In addition, the figure also differentiates (blue and yellow colours) the entities that contribute to NATINAMDS from the NATO Air Command Structure and from the NATO Force Structure.

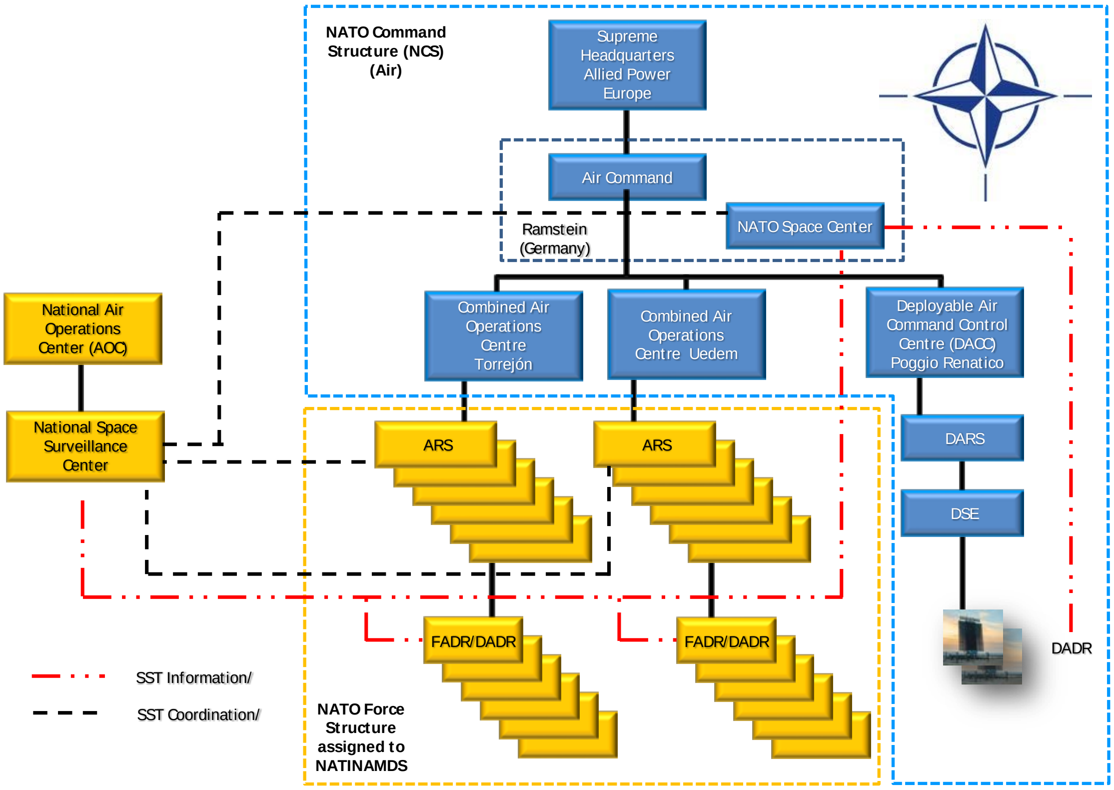


Figure 4-1: SST functionality integration.

The exploitation of this distributed network of early warning sensors with low orbit object detection capabilities has a multiplicative effect in the global surveillance coverage. A simple example can be found in Table 4-1, considering only three sensors and the catalogue [3], which contains a comparison of estimation of space target visibility:

- Cat_{ill}(TIME): % of the targets listed in the catalogue that are expected to be illuminated for a sensor given its characteristics (range and elevation coverage, site location, etc.) in a time less than the threshold provided by “TIME” parameter.

Table 4-1: LEO capabilities estimated metric: target visibility.

	Sensor FoR	**Location**	**Cat_{ill}** (12H)	**Cat_{ill}** (1D)	**Cat_{ill}** (5D)
TEST1	Inst. range = 1500Km Elevation =40º	27ºN, 15ºO	69,05 %	78,9 %	82,73 %
TEST2	Inst. range = 1500Km Elevation =40º	40ºN, 3ºO	70,35 %	79,7 %	82,14 %
TEST3	Inst. range = 1500Km Elevation =40º	35ºN, 25ºE	70,25 %	79,8 %	82.53 %

Network	Sensors working cooperatively	N/A	78,12 %	82,07 %	83.53 %

Simulations have been carried out assuming three radar locations, working independently, and also the radar network composed by multiple sensors (locations are depicted in Figure 4-2). As is seen, when network cooperative mode is assume, the target visibility increases. This improvement depends on the time threshold considered for the visibility. As this parameter is more restrictive with the system, higher is the visibility profit obtained from the sensor cooperation: an improvement around the 8% of the catalogue objects is obtained when visibility is restrained to the first 12 hours.

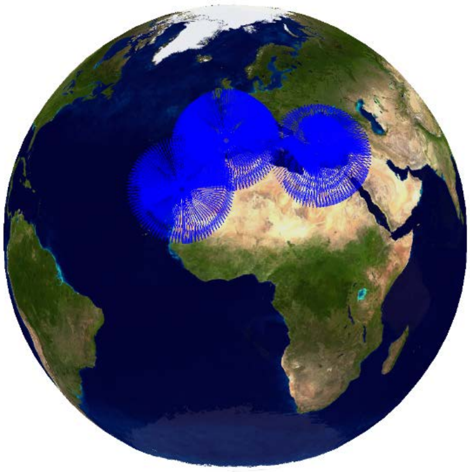


Figure 4-2: Geographical location for the considered sensor network example.

At the location considered for TEST1, another analysis has been carried out in order to represent possible differences of the selected sensors in terms of system models, or of the capability of using or not using dedicated LEO mode of operation. An additional sensor was considered which differs on the maximum available elevation coverage that was set to 60º giving rise to $\mathbf{Cat_{ill}}$(12H) = 77,67 %, obtaining an improvement close to an 8 % respect of using a sensor with elevation up to 40º.

The analysis have been performed using more than 19.000 objects obtained from [3] for catalogued LEO objects (LEO: Mean Motion > 11.25 and Eccentricity < 0.25).

In addition to an improvement in the LEO objects visibility, the exploitation of a distributed 3D radar network also provides a reduction in the wait time until the objects are reachable by the sensors: for the network case of study, this time will be the minimum time obtained for any of the individual sensors.

In Figure 4-3 the Cumulative Distribution Function (CDF) for the first observation time, and for the average re-observation time are depicted for the individual sensor used on TEST2 and for the aforementioned network. In table 4-2 values obtained from those functions are presented providing:

- $\mathbf{F_{obser}}$(TIME) = % of the targets listed in the catalogue whose first observation time is less than the provided threshold.
- $\mathbf{Avg_{ReObs}}$ (TIME) = % of the targets listed in the catalogue whose average re-observation time is less than the provided threshold.

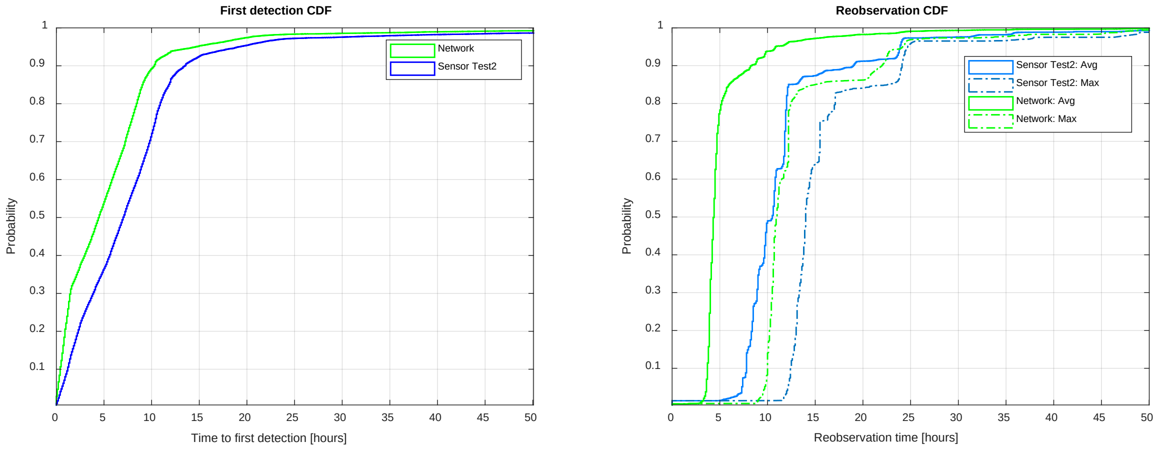


Figure 4-3: CDF comparison between Test2 sensor and the considered Network: first detection (left) and re-observation time (right).

As the first observation time and re-observation time are strongly depending on the sensor site location, a strong improvement is obtained due to the geographical diversity when the sensor network is considered: up to the 34,66 % of the considered objects are expected to be illuminated twice in less than 9 hours when only a sensor is used, but close to the 92% when the network approach is considered.

Table 4-2: LEO capabilities estimated metric: first observation and re-observation times.

	F_{obser}(6H)	F_{obser}(12H)	Avg_{ReObs} (9H)	Avg_{ReObs} (12H)	Avg_{ReObs} (24H)
TEST1	41,38	84,03	7,043	68,25	93,93
TEST2	43,17	86,54	34,66	82,1	96,27
TEST3	43,5	85,66	20,55	77,08	95,47
Network	61,34	93,81	91,89	95,91	98,88

5.0 CONCLUSIONS

This study shows the potential of FADR and DADR systems to provide Space Situation Awareness (SSA) / Space Surveillance and Tracking (SST) capabilities at LEO level. The technical capabilities that these radars must fulfil have been analysed to conclude that SST can be implemented in a similar way as TBM capability already does, extending coverage in Elevation and Range for specific azimuth sectors.

Performance for SST has been studied, and limitations to the coverage have been stated, depending on the location of a single radar. A network configuration with multiple radars in different locations shows a multiplicative effect that allows obtaining a greater coverage and mostly an improvement in terms of first observation time and re-observation time.

INDRA has confirmed this capability in a real DADR, upgraded with an updated SW including the SST function, which demonstrates the capability to detect LEO object from a TLE database.

This upgraded SST functionality would allow FADR and DADR NATINAMDS sensors to support and enhance Space Surveillance at NATO Space Center, while continue performing Air & Missile Defence simultaneously.

6.0 REFERENCES

[1] B. Emery and A. Camps, "Introduction to Satellite Remote Sensing", Ed. 1, Aug. 2017.

[2] Parameters Describing Elliptical Orbits, web page: https://www.classe.cornell.edu/~seb/celestia/orbital-parameters.html, accessed Aug. 20, 2022.

[3] SATCAT, Space-Track.org in https://www.space-track.org/auth/login