On the Design of a Planar Phased Array Radar Antenna Architecture for Space Debris Situational Awareness

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ABSTRACT

The Space Situational Awareness (SSA) program from the European Space Agency (ESA) protects Europe's citizens and their satellite-based services by detecting space hazards. ESA Ground Systems (GS) division is currently designing a phased array radar composed of thousands of radiating elements for future stages of the SSA program [1]. The radar shall guarantee the detection of most of the Low Earth Orbit (LEO) space debris, providing a general map of space junk. While range accuracy is mainly dictated by the radar waveform, the detection and tracking of small objects in LEO regimes is highly dependent on the angular accuracy achieved by the smart phased array antenna, demonstrating the important of the performance of this architecture.

To predict the performance of the whole system, ESA has developed a completed SSA radar simulator tool. This Matlab simulator is capable of analyzing all related mechanisms involved in radar operation, from the external environment modeling to the data processing, extracting plots and tracks. It supports, among others, several radar architectures (monostatic, close monostatic and bistatic), different kind of waveforms (pulsed and continuous wave), various array topologies (radiofrequency and digital beamforming), two tracking methodologies (track while scan and active tracking), and distinct radar processes (coherent and non-coherent).

In Section I, a state of art will be shortly presented, [2,3]. The architecture under study is a monopulse radar working at 1.25 GHz. Equipped with six square transmission and three circular receiving phased array planar antennas with circular polarization arranged in three tuples of two transmission and one receiving antenna, it must be able to detect targets under specification in order to avoid catastrophic collisions during satellite launches. It will be used LFM pulses with 1kW peak power per transmitter element. Main objectives of this paper will be also depicted, which are:

- Study and design of the phased array antenna. In order to reduce the high cost, number of transmitters/receivers must be minimized. Most important variables in this issue are the Field of Regard (FoR, determining maximum distance between array elements to avoid grating lobes), pulse width waveform per elevation angle (setting blind range per elevation angle) and available peak power (related to number of elements per array).
- Radar performance simulation (with Matlab-based tools available in ESA) of the primary phased array antenna radar, in order to assess the achievable accuracy of the proposed structure.

Combining both tasks it is possible to obtain a balance between system cost and technical performance skills, which will set the optimum architecture.

Section II will show an ingenious design method to obtain optimum single arrays composing future SSA Radar at 1.25 GHz. By considering common pulse radar equation and taking into account the FoR under study, each array will be optimized in size, number of elements and transmitted power. In order to obtain a probability of detection of 98% of the total targets, the required signal to noise ratio derived from the radar equation must be 18.45 dB. Radar equation (1) shows its relation with variables related to the sacan angle.

$$SNR = \frac{P_{peak} t_{pulse} G_t G_r \lambda^2 \sigma}{(4\pi)^3 k T_S R^4 L} = \frac{P_{peak} G_t G_r \lambda^2}{(4\pi)^3 k T_S L} \frac{t_{pulse}\sigma}{R^4} \qquad (1)$$

The study must consider the worst case, which takes place when $\frac{t_{pulse}\sigma}{R^4}$ reaches the absolute minimum. Parameters involved in the study are,

R : Range. It is related to the scan elevation angle θ as,

$$R(\theta, h_p) = -R_{Earth}\sin(\theta) + \sqrt{R_{Earth}^2 \sin^2(\theta) + h_p^2 + 2R_{Earth}h_p}$$

σ : Also known as Radar Cross Section (RCS). The minimum detectable diameter target depends on its distance to the ground as,

$$d_{\min}(h_p) = \max\left(\frac{h_p^2}{h_{ref}^2} d_{ref}, 5cm\right)$$

where $h_{ref} = 2000Km, d_{ref} = 32cm$

t_{pulse} : Pulse width. It determines the radar blind range. Depending on the elevation, the $R_{\min}$ will be calculated and $\frac{c \cdot t_{pulseMax}}{2} = R\min \rightarrow t_{pulseMax} = \frac{2\left(R_{\min}(Min.Elev.Angle)\right)}{c}$

In order to optimize the array, two primary steps must be kept in mind:

- A grating lobes analysis will provide the maximum distance between elements with no grating lobe in the scanned FoR, setting the maximum distance between elements.

- t_{pulse} will be determined by the minimum range per instantaneous elevation angle. By taking $t_{pulse} = t_{pulseMax}$, effective antenna areas will be minimized.

In Section III, array optimizations for two different possible stages of the SSA will be analyzed as shown above. Assumptions considered will be:

- Full SSA Radar FoR: maximum angle A deflection 60º, minimum angle A deflection -60º, maximum angle B deflection 40º, minimum angle B deflection 20º.
- An equivalent system noise temperature T_S of 152.7K.
- Total system losses of 3.13 dB.
- 1 kW peak power per transmitter.
- The area of the receiving antenna is twice the transmitting one. Antenna gain for huge arrays is considered as $G_{antenna} = \frac{4\pi}{\lambda^2} A_{eff} = \frac{4\pi}{\lambda^2}\eta A_{physical}$ with a radiation efficiency $\eta = 0.7$.

Case 1 will consider the radar implementation as an integration of a process of three stages of three tuples, in which two transmitter antennas and one receiving one integrate each tuple. Each tuple must cover the whole specified FoR. This method provides a good behavior since the first tuple, not fulfilling the entire requirements but significantly approaching. It main drawback is that the system will be oversized in the end, increasing the cost of the whole architecture. Case 2 evaluate the implementation of the whole radar by assuming the final real FoR per tuple, optimizing them individually.

It is important to remark that both cases need a minimum pulse width of 2.74 ms with 1kW of peak power. Nowadays, solutions shown in cases 1 and 2 find European technological limitations that set the maximum time pulse width in 1 ms for 1kW peak power. Analyzing previous case 2 with this limitation (case 2'), it is shown the need of a strong research on the field of pulse width/peak power in order to low the cost of the system. Table 1 presents the results in terms of number of elements per transmission and reception arrays.

CASE	Tx	Rx	$SNR_{WorstCase}$
	$N_{Elements}$	$N_{Elements}$	
1	23446	29683	18.45 dB
2	34452	44778	18.51 dB
2'	48204	62622	18.52

Table 1: Number of elements per transmission and reception arrays.

Section IV will present the simulation of the worst situation for the case 1 with the help of the Matlab tool available at ESA-ESOC. After defining signal characteristics, transmitter/receiver properties, radiation and propagation effects and target skills, simulation is run. Firsly, a LFM pulse signal is emitted for the transmitted array after passing through the whole transmission chain, which always involve a power amplifier and an electrical beamforming in the receptor, it is obtain the IQ data. Then, this IQ data are introduced in the matched filter, which is a replica of the transmitted pulse waveform. Matched filter data output plotted, where is possible to observe a maximum peak in the expected sample related to the range of the target. Then, signal is integrated. If there is more than one pulse, they are sum coherently. Each pulse is composed of a double polarization and this module also sums those polarizations in power to enhance the detectability. Once signal is integrated, the data flow is treated by the CFAR process where it will be applied three steps: hits detection with CFAR algorithm to select possible targets, hits association to distinct targets to determine real targets, and target coordinates estimation to locate the target with monopulse processing. Finally, the target is detected and located. Figure 1 depicts receiver radiation pattern and target detection.

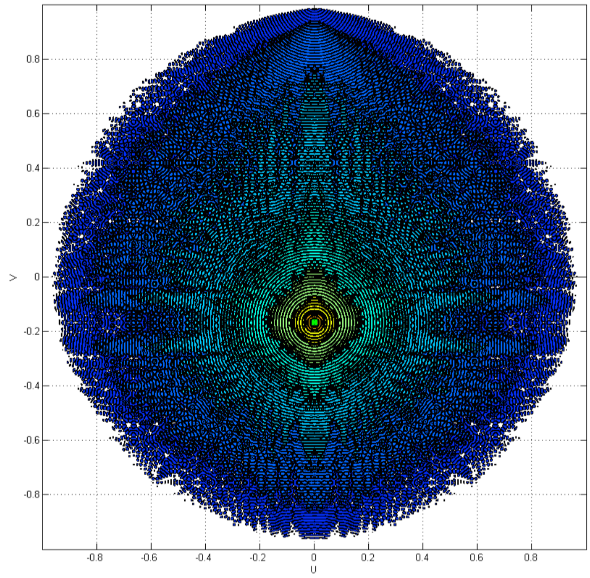

Fig. 1:Receiver radiation pattern and target detection

A proper accuracy is reached in the case under study as shown in Table 2.

	Real Target	Detected Target	Accuracy
Azimuth [deg]	154.15	154.1158	0.0342
Elevation [deg]	43.34	43.3152	0.0248
Range [Km]	1460.0324	1460.0	0.0324

Finally, Section V will present the conclusions drawn in the paper. Arrays must be optimized between different stages. Otherwise, number of elements composing the architecture will increase unnecessarily, oversizing the architecture. A logistic strategy must be designed in order to reduce the intrinsic over cost assumed by dividing the project in different stages. Moreover, European power amplifier technology should be improved to support larger pulse widths which could help to reduce the total cost of the whole array. Particularly, power amplifiers must be able to deal with signals with at least a pulse width of 2.74ms with a duty cycle of 12.75%.

REFERENCES

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