COMPARISON OF BI-STATIC RADAR PERFORMANCES WITH AN EQUIVALENT MONO-STATIC MODEL

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ABSTRACT

This paper shows the validity of using a mono-static model for bi-static radar signal-to-noise ratio determination. Analyses are done for one anticipated bi-static radar configuration, taking into account the requirements from the European Space Agency in the frame of the Space Surveillance Awareness program. It is shown what is the error committed on the signal-to-noise ratio in both 2-D and 3-D analyses.

1. INTRODUCTION

In the frame of the upcoming European Space Agency (ESA) Space Situational Awareness (SSA) program [1], the Agency is planning to build a ground based radar system capable of detecting in-flight debris. It is at the date of the conference not yet decided what will be the architecture of the radar. However, one feasible solution would be to build a bi-static radar.

The use of a bi-static radar instead of a mono-static one presents several advantages in terms of performance (e.g. power, continuous wave transmission possibility). However, from the radar performance modelling point of view, it is more complex than a mono-static one. When the distance between the emitter and the receiver is negligible compared to the range of the radar, it is of interest to consider the bi-static radar as quasi mono-static and use its model.

In this paper, it is out of scope to replace the bi-static radar by a mono-static one. One considers here a bi-static radar – one emitter and one receiver – and one compares its model with an approximate one based on the mono-static approach.

The first section of the paper is focused on the anticipated limit parameters that the future SSA radar might have. One defines the assumptions made in the frame of this study. The second section presents how the equivalent mono-static model is derived from the bi-static one. Finally, the third section compares the performance of a ground based bi-static radar for space surveillance and its equivalent mono-static approximation.

2. ANTICIPATED LIMIT PARAMETERS

This section presents the anticipated limit parameters against the requirements of the Agency. A system architectural study is presently on-going and as an output, the Agency should have more refined requirements. In the frame of this paper, one anticipates on purpose such refined requirements.

One requirement of the radar is its location. It shall be placed in one of the member states countries. This limits the range between the emitter and the receiver. Several studies conducted by the Agency in the past have shown that one optimal configuration is to place the emitter a few hundred kilometres from the north of the receiver. We assume here that the stations are 500 km far away from each other.

The main requirement for the radar performance is defined as “the radar shall be capable of tracking 98 % of the objects above 10 cm size at 1,000 km of altitude.” There is somehow a trade-off to do between flight dynamics which determines the best position/orientation/range of the radar, and what is technical and financially feasible. We consider in this paper that the debris must be detected at 1,000 km altitude when the receiver is pointing at 45° elevation towards the sky.

We also assume that the minimal signal-to-noise ratio SNR required to detect an object is 13 dB. We focus in this paper on the SNRs above 13 dB. The maximum SNR will be determined hereafter by geometrical considerations.

As a wording issue, we consider here that the mono-static approximation to the bi-static formulation is valid when the error committed on the signal-to-noise ratio is below 0.5 dB.

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3. MONO-STATIC EQUIVALENT MODEL OF THE RADAR

As described earlier, it is of interest to consider an equivalent mono-static model of the bi-static radar. The Fig 1 shows how the mono-static equivalent model is derived from the bi-static model: one considers the virtual location V of the mono-static emitter/receiver at the exact middle (point V) between the bi-static emitter E and receiver R.

The in-flight debris (point M) to be detected here is a 10 cm diameter object. The location of this object over the baseline between the emitter and the receiver defines one major parameter of the bi-static radar: the bi-static angle (angle between the emitter E and the receiver seen from the debris M). The bi-static angle characterises the system performance. If the bi-static angle is close to zero, the emitter E and the receiver R are separated by a small distance compared to the ranges, and the bi-static radar can be regarded as mono-static or pseudomono-static.

In terms of system performances, the detection of a debris at a determined signal-to-noise ratio SNR is described by the bi-static radar equation (1) [2]:

$$(R_e R_r)^2 = \frac{K}{\mathrm{SNR}} \tag{1}$$

with

$$K = \frac{\mathrm{EIRP}\, G_r \lambda^2\ \mathrm{RCS}}{(4\pi)^3 k T_0 B\ \mathrm{NF}\ L} \tag{2}$$

The following variables are used:

R_e	Emitter to target range
R_r	Target to receiver range
K	Bi-static constant
EIRP	EIRP of the emitter
G_r	Gain of the receiver
RCS	Radar Cross section
λ	Wavelength
k	Boltzmann's constant
T_0	Receiver system noise temperature
B	Bandwidth
NF	Noise factor
L	Total losses of the system

The bi-static constant K defines on one side the emitter E and receiver R parameters (radiated power, gain, losses…..) and on the other side the target ability to reflect the radar signals (radar cross section). The loci of points in the space verifying the bi-static equation at various SNRs are called the ovals of Cassini [3,4].

An error committed on the signal-to-noise ratio induces errors in the estimation of the object position and leads to improper RCS estimation. As the position and the radar cross section of the debris must be accurate, it is of importance to minimise the error committed on the SNR.

4. VALIDITY OF THE MONO-STATIC EQUIVALENT MODEL

With a bi-static constant $K = 8.10^{25}$ and SNR = 13 dB, it is possible to reach an altitude of 1,000 km in the bi-static plane (plane containing emitter, receiver and centre of the Earth) with the subsequent emitter and receiver ranges: R_e = 1,607 km and R_r = 1,234 km. The Fig 2 shows the ovals of Cassini in this particular case (thick lines).

The closer the debris to either the emitter or the receiver is, the higher the signal-to-noise ratio is. For SNRs below 36.8 dB, the oval looks like a continuous ellipse. In this case the maximum altitude reachable by the radar is 250 km (cf. Fig 3). The particular case of SNRs between 36.8 and 43 dB is interesting to point out because the oval takes the shape of a dog-bone shape (e.g. 40 dB SNR curve in Fig 2). However, its applicability to space debris detection is rather limited since only a few objects are flying below this altitude.
The use of a mono-static approach would simplify tremendously the equation above because the ovals of Cassini would become concentric circles around the virtual location of the emitter/receiver, as shown in Fig 2 by thin lines.

The comparison of the iso-SNR curves for both bi-static and mono-static models (cf. Fig 2) gives the first results:

- for low SNRs (e.g. 13 or 20 dB) , the mono-static approximation seems to be feasible since mono-static and bi-static curves are close each other;
- for high SNRs (e.g. 35 or 40 dB) there is a greater deviation between the bi-static and the mono-static models. When the oval shrinks (case of SNR=40 dB), the maximum altitude reachable using the mono-static approximation is about 100 km more than in reality (bi-static case). This means that in order to estimate the altitude of the flying object with accuracy the mono-static model is not applicable anymore without modifying the constant.

The Fig 4 below shows in the plane what is the error committed on the SNR when using the mono-static approximation.

It is of interest to notice the zero-error line whose slope is 45 degrees. Along this line – which means for all debris located near this region – the error committed using a mono-static equivalent model is negligible. The error is even more negligible for high altitudes. As one considers here that the mono-static approximation is valid for errors below 0.5 dB, the region located outside the 0.5 dB curves is the validity region.

The results presented above are shown in the bi-static plane. The analysis of these results is useful to understand the bi-static radar geometry and to establish the basis of the comparison with the mono-static equivalent model. However, the debris will be detected in space and the emitter and receiver will use steering antennas to scan the space in azimuth and elevation.

In reality, a 3-dimensional model is necessary to determine the operating limits of the bi-static radar and to estimate the real error committed when using the mono-static approximation. The Fig 5 is an extension in 3D of Fig 2 . The ovals of Cassini in the three dimensional space are surfaces of constant SNR delimiting the bi-static coverage volume. Inside this volume are contained all the possible locations where the target is visible both by the transmitter and the receiver. Following the same approach, Fig 6 is an extension in 3D of Fig 4 and shows the signal-to-noise-ratio constant error in the space.

The conclusions obtained in the 2D case are applicable here. The volume outside the 0.5 dB surface is the region where the mono-static approximation is valid. Fortunately this volume is representing the major part of the sky. When the debris at 1,000 km of altitude is not located in the bistatic plane, the approximation is even more valid.

5. CONCLUSION

This paper was focused on the validity of using a mono-static model for representing a bi-static radar. Improper modelling may lead to errors in the debris position evaluation (ranging) and also in the radar-cross-section estimation.

The bi-static radar presented here has on purpose feasible parameters in terms of emitter-receiver distance and field of view of the radar. This will not be the final configuration but is only estimating a feasible solution. Analyses were performed in both bi-static plane and space and showed graphically indicated when the mono-static model was valid (less than 0.5 dB error on the signal-to-noise ratio).

Using a mono-static model is valid when the debris to be detected is located far away (at least the distance emitter-receiver) from the emitter and the receiver. The error is in any cases minimised when both emitter and receiver are pointing to a position close to 45° elevation. The zone where the mono-static approximation is not valid is in any case located in the vicinity of the receiver.

6. REFERENCES

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[3] M.I. Skolnik. “Radar Handbook”, MacGraw-Hill, 1900.

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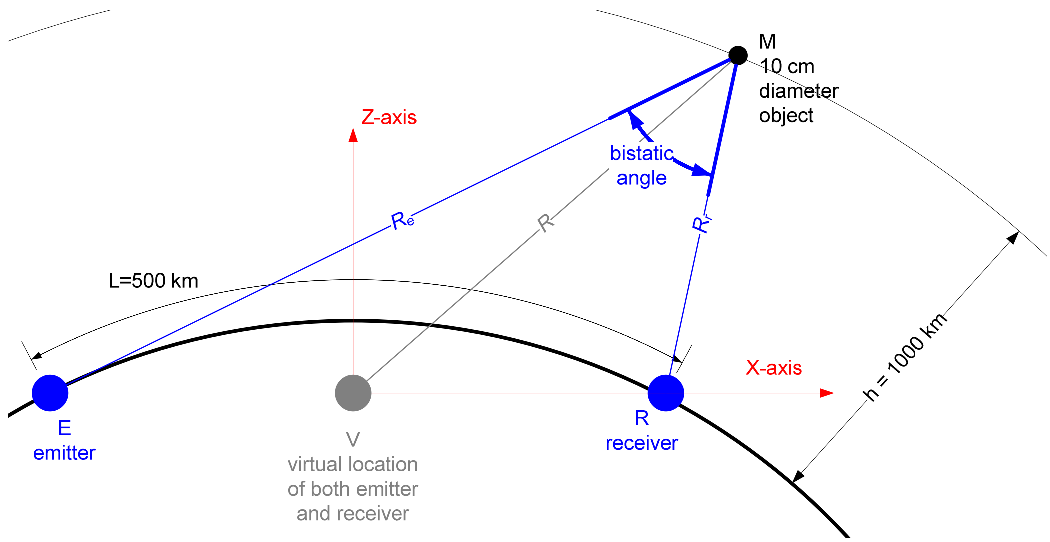

Fig 1. Position of the mono-static virtual radar location. The drawing is not to scale.

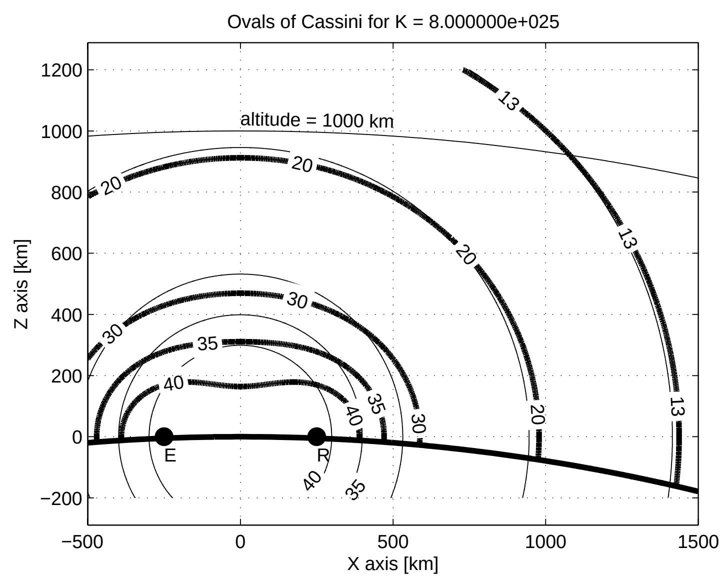

Fig 2. Illustration of the ovals of Cassini in the bi-static plane (thick lines). The value on the line indicates the signal-to-noise ratio. E and R are placed respectively at the emitter and receiver positions. The thin lines are representing the ovals of Cassini considering the mono-static equivalent model. They are concentric circles at the virtual mono-static emitter/receiver location V at the exact middle between E and R.

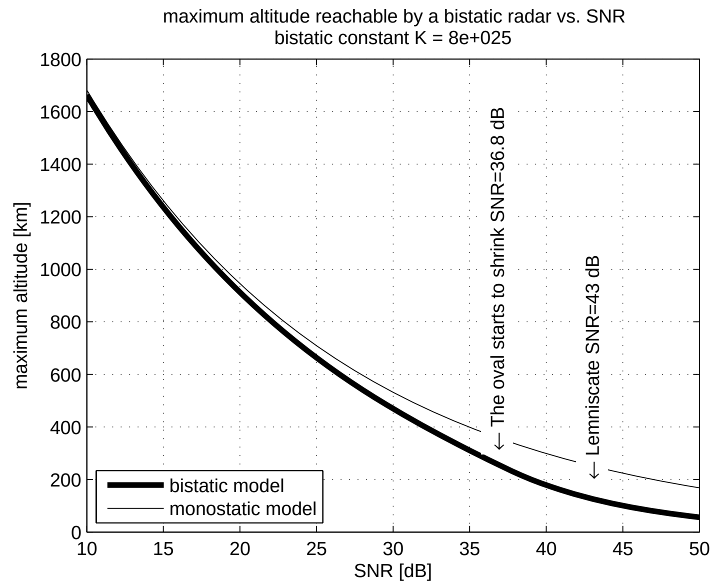

Fig 3. Maximum altitude reachable for various signal-to-noise ratios. Both models results are shown here (bi-static and its equivalent mono-static).

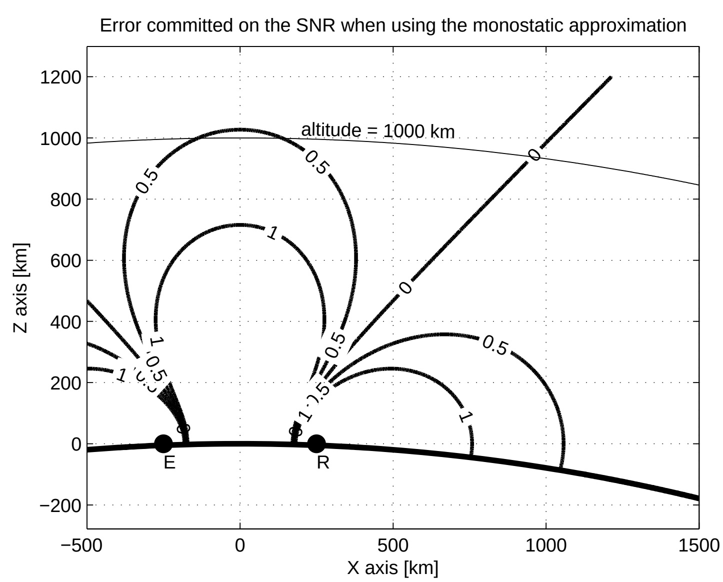

Fig 4. SNR constant error curve when using the mono-static approximation to model bi-static radar.

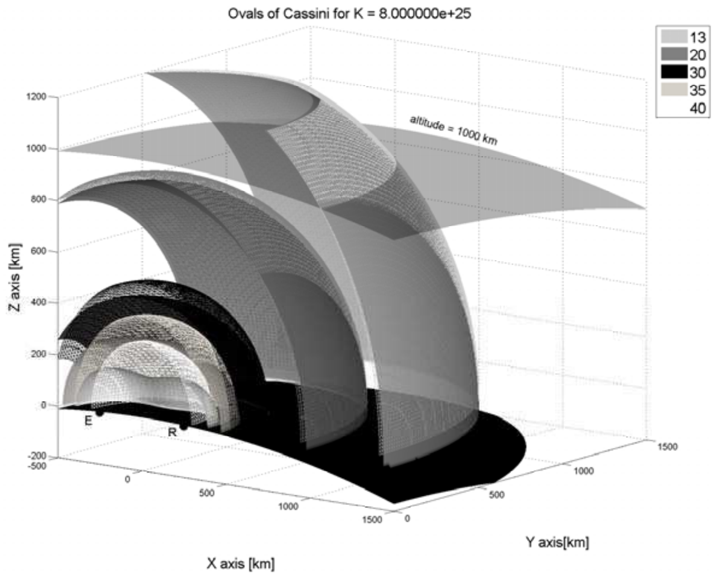

Fig 5. Illustration of the ovals of Cassini in the three dimensional space (continuous surfaces). The different colours indicate the constant signal-to-noise ratio SNR. The meshed surfaces are representing the ovals of Cassini considering the mono-static equivalent model. E and R represent respectively the emitter and receiver positions. This figure shows also the Earth surface (in black) and the 1,000 km of altitude surface (in gray).

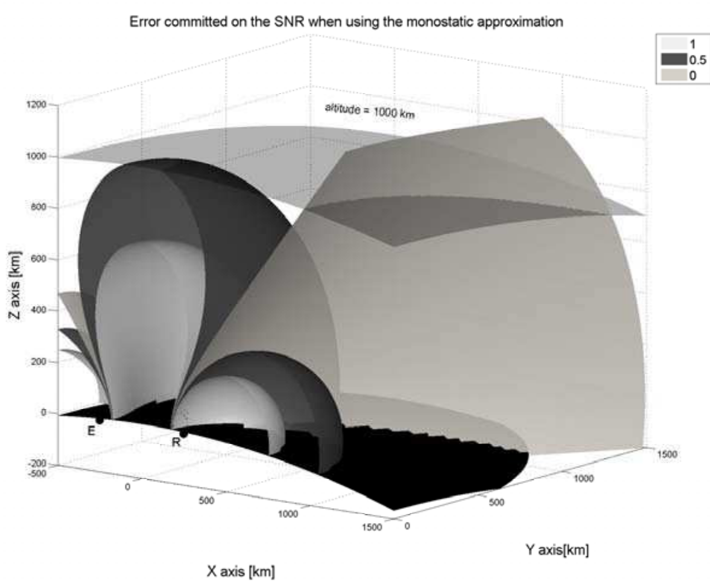

Fig 6. Constant SNR error surfaces when using the mono-static approximation to model a bi-static radar. The different colours indicate the constant error committed on the SNR using the mono-static approximation. E and R represent respectively the emitter and receiver positions. This figure shows also the Earth surface (in black) and the 1,000 km of altitude surface (in gray).