Design of an application which computes the Bistatic coverage zone for The Republic of Cabo Verde

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Abstract. The purpose of this paper is to design an application which can compute the bistatic system coverage zone for the archipelago of Cabo Verde, where a specific study of bistatic geometry was made. From its triangular configuration, known as bistatic triangle (transmitter, target, receiver), we obtained the parameters, and subsequently, the equations necessary to obtain the Oval of Cassini that delimits the coverage zone that it guarantees. The direct synchronization method was chosen, and the line of sight between transmitting and receiving antennas was required, permitting us to measure the distances from the transmitter to the target and from the target to the receiver. After obtaining all the theoretical validities, a tool was created, for the user to choose the positions of the antennas. Then, the software will paint the coverage zone with the qualities index required in accordance with the chosen data and technical parameters.

1. Introduction

Recently bistatic radar has received attention for its potential to detect stealth targets due to enhanced target forward scatter. Furthermore, the feasibility of hitchhiker radar has been demonstrated, which allows passive radar receivers to detect and track targets, using a transmitter of opportunity. Thus, it is likely that bistatic radar will play a much bigger role in near-future military warfare.

The following problematic situation, which currently exists in Republic of Cabo Verde, is that it only benefits from a secondary radar system, which guarantees the coverage of its region of responsibility. It ensures the air traffic control of the commercials aircrafts that need this service, but non-cooperative aircrafts (enemy, smuggling, rapists, etc.) cannot be detected, as well as some commercials airplanes that for technical reasons cannot respond. This shows the need of having a more efficient radar system, which cannot only depend on secondary radars but also capable of detecting all targets in order to ensure better surveillance and airspace control. Therefore, as Cabo Verde does not have sufficient technical, human and financial resources to produce radars, in this case primary radars, it will need to buy radars in the near future.

Radar designers spend much energy and time on radar development and testing, thus, there are many software applications available for the radar simulation but none exits in the public domain for bistatic coverage zone for a specific country. Since it is the first time that a study is being conducted on bistatic radar systems for Cabo Verde, it requires a simulation and modeling on computer before the hardware implementation. The purpose of this paper is to design and develop a Graphical User Interface (GUIs) in Delphi XE5 to integrate the bistatic geometry and radar parameters and predict the
bistatic coverage zone for the archipelago of Cabo Verde map, with the required quality index, without taking into consideration the environment influences on wave propagation.

The end product is a program named CVBistC, which provides a convenient instructional tool for any user to analyze, and predict bistatic radar system coverage zone performance.

2. Basic theory and background of the bistatic radar system

In bistatic radar systems, the transmitting and receiving antennas are separate and widely spaced. This is in contrast to monostatic radar, which is the conventional configuration for radar. The term is used to distinguish it from bistatic or multistatic radar. Monostatic radar uses a single transmit and receive antenna [1] which are collocated: its first functions as a transmitter to send a pulsed signal to the target. The signal is reflected and sent back as an echo signal to the antenna, which then acts as a receiver. By measuring the time taken for the pulse to travel to the target and back, the range of the target can be determined [1]. In a bistatic radar system, the transmitter and receiver are located a distance apart that is comparable to the expected target distance [2]. The transmitted signal from the transmitter reaches the target and the reflected echo signal travels to the receiver. In addition, there is a direct signal between the transmitter and the receiver.

This fundamental difference in the bistatic radar over monostatic radar has offered certain advantages for particular tasks [3]:

- The receiver is completely passive, and hence undetectable, by the electronic support measures, and it is safe from attack by anti-radiation missiles or deliberate directional interference and jamming.
- The receiver can be located in a favorable area where transmitters are not allowed, such as flammable-liquids stores, gas terminals, etc.
- No transmit-receive switch or duplexer is required. These devices are lossy, expensive, and heavy.
- With certain configurations, less transmitter power is required compared to the monostatic radar.
- Higher pulse repetition frequencies (PRFs) can be used because a bistatic system does not suffer the same range blindness as the equivalent monostatic system.
- If the target angle can be measured at both sites, as well as the bistatic range, data can be checked for self-consistency to remove false alarms.

In most cases of bistatic and multistatic operation, antenna separation is selected to achieve an operational, technical, or cost benefit, this configuration is applied nowadays both in commercial and military applications, such as improvement of stealth target detection, semi active homing missiles, planetary explorations, air surveillance, ionospheric and wind measurement, barrier coverage and so on.

2.1. Bistatic radar equation

Bistatic radar is a radar that uses antennas for transmission and reception at quite different locations in which the angles or intervals from those locations to the target are significantly different [4]. Figure 1, is used to illustrate this definition, showing the transmitter (Tx) and receiver (Rx), being located in two sites with a separation distance designated baseline $L$ and the target, if a line passes through these points will form a triangle, usually known as a bistatic triangle, and the bistatic angle ($\beta$) is one of the important parameters that characterize bistatic radar and affects the system performance [5].

The equation that relates the range of the radar with the main parameters of the medium, target and the radar can be obtained, in which it is used to carry out the initial range prediction, during the design of radar system or when is analysed the use of a system that was already designed.

The bistatic maximum range product can be written as [6]:

$$ (R_T R_R)_{\text{max}} = \left[ \frac{P_T G_T G_R \sigma_T \sigma_R P_T^2 P_R^2}{(4\pi)^3 K_\text{Ts} B_n (S/N)_{\text{min}} l_T L_R} \right]^{1/2} $$

(1)
or

\[(R_TR_R)_{\text{max}} = k\]  

(2)

Where

\(R_T\) = transmitter to the target range (m); \(R_R\) = receiver to the target range (m),

\(P_T\) = transmitter power output (W); \(G_T\) = transmitter power gain; \(G_R\) = receiver power gain,

\(\lambda\) = wavelength (m); \(\sigma_B\) = bistatic radar target cross section (m\(^2\)),

\(F_T\) = pattern propagation factor for transmitter-to-target-path,

\(F_R\) = pattern propagation factor for target-to-receiver path; \(k\) = Boltzmann's constant \(1.3807 \times 10^{-23}\) J/K,

\(T_S\) = receiving system noise temperature; \(Bn\) = noise bandwidth of receiver (Hz),

\((S/N)_{\text{min}}\) = signal to noise power ratio required for detection, \(L_T\) = transmitting system losses (>1),

\(L_R\) = receiving system losses (>1); \(k\) = bistatic maximum range product.

Figure 1. Bistatic radar geometry converted into to polar coordinate system [5].

2.2. Ovals of Cassini

The oval of Cassini is the locus of points, the product of whose distance from two fixed points is a constant. In the bistatic radar case, it is interesting to analyze the system performance by plotting the ovals of Cassini as a function of the signal to noise power ratio, \(S/N\), with the ranges, \(R_T\) and \(R_R\), at the vertices of the triangle [7].

The constant \(S/R\) can consequently be plotted as ovals of Cassini [6] using the following equation, which was derived from (1):

\[(S/N) = \frac{K}{r^2 + \frac{L^2}{4} - r^2 L^2 \cos^2(\theta)}\]  

(3)

In Figure 2 is shown the oval of Cassini, with \(K\) arbitrarily set to \(30L^4\) and constant \(S/N\) ratios from 10 dB to 30 dB.
A series of plots shows that bistatic radar operation can be divided into three distinct regions:

1. $L > 2\sqrt{K}$. Two separate ellipses result enclosing the transmitter and receiver. It is considered receiver centered when $R_T >> R_R$; transmitter centered when $R_R >> R_T$.
2. $L < 2\sqrt{K}$. A single continuous ellipse result.
3. $L = 2\sqrt{K}$. A lemniscate with a cusp at origin results.

These parameters describe the system geometry, so that through (3) their influences can be evaluated in the SNR, when represented by the contour of the same SNR, the bistatic coverage zone can be obtained, being that the maximum range will be obtained with the minimum $S/R$ which guarantees the required quality index. In order to evaluate the behavior of the quality index through the obtained $S/R$, it will take as a reference the model that establishes that the observations obtained by the receiving site satisfy with all the definitions and equations exposed in the detection, based on multiple observations defined in the general theory of detection, chapter 11 of [7]. In this case, was chosen the model Swerling II, in [7], the analysis of detection based on a pulse train with pulse-pulse Rayleigh fluctuation is performed, where (4) and (5) where extracted:

$$P_f = \frac{1}{\sqrt{2\pi N Y_b - N + 1}} \exp \left[-Y_b + N \left(1 + \frac{Y_b}{N}\right)\right]$$ \hspace{1cm} (4)

$$P_d = 1 - I \left[\frac{Y_b}{\sqrt{N(1+R_b/2)}}, N - 1\right]$$ \hspace{1cm} (5)

Where $P_f$ = probability of false alarm; $P_d$ = probability of detection; $N$ = pulse quantity in the package. $I(u, s)$ = incomplete gamma function; $Y_b$ = Threshold of detection; $R_b$ = represents the signal-to-noise ratio.

The relationship of the quality index with the geometry of the bistatic system, can be seen initially through (3), because it can evaluate mathematically its influence on the SNR, so that with the obtained values from (3), the quality index guaranteed by the system in the coverage zone for different distributions of the integral elements of bistatic radar system for Cape Verde map can be calculated.

2.3. Analysis of synchronization between the transmitting and receiving sites

To perform the analysis of the bistatic coverage system, the synchronization time between the bistatic transmitter and receiver is required for distance measurement. The accuracy of time in the order of a fraction of the pulse width of the transmitter (compressed), is also a typical requirement. There are two methods of synchronization, direct and indirect, and in this paper, we choose the direct synchronism method, due to its simplicity. Yet, in order to apply this method, the line of sight distance must be taken into consideration, in other words, the separation between the transmitter and receiver sites, through which the direct ray passes tangentially to the earth’s surface [8].

Figure 2. Ovals of Cassini, with constant $S/R$ plots for $K = 30L^4$ [8].
Equation (6) of the line of sight distance will be used taking into consideration the relative radius of the earth:

\[ r_0 = 3.57\sqrt{K} \left( \sqrt{h_T(m)} + \sqrt{h_R(m)} \right) [Km] \]  

Where

\[ K = \frac{a_{ef}}{a} \]  \hspace{2cm} (7)  
\[ a_{ef} = \frac{a}{1 + \frac{4N}{dn} \cdot 10^{-6}} \]  \hspace{2cm} (8)

Where \( r_0 \) = line of sight distance, \( K \) = relative radius of earth, \( h_T \) = height of transmitter antenna, \( h_R \) = height of receiver antenna, \( a_{ef} \) = earth effective radius and \( \frac{4N}{dn} \) = is refraction index.

Both \( h_T \) and \( h_R \) heights should be high, satisfying this condition \( h_T, h_R \geq (2 \div 3)\lambda \).

After analyzing all the theoretical validations and mathematical expressions that allow to determine the bistatic coverage zone, and the need to calculate the line of sight distance to guarantee the direct synchronization between the transmitter and receiver sites, we are now in a position to realize the tool capable to calculate the bistatic coverage zone for Cabo Verde.

3. The algorithm development and realization of the software capable to compute the bistatic coverage zone for Cabo Verde

3.1. Design of the software algorithm

The application algorithm was developed to obtain the bistatic coverage zone for Cabo Verde. Its goal is to show the behavior of the quality index guaranteed by the system within the coverage zone for different geometric situations. For that, the line of sight between the Tx and Rx sites must be first guaranteed, so as to guarantee the direct synchronization between them. Only this way will it be possible to calculate the coverage zone.

In Figure 3, it is presented the flowchart for software programming.

![Figure 3](image-url)
3.2. Experiments with the developed software

The application obtained will allow us to paint the bistatic coverage zone in Cabo Verde map evaluated with the required quality index. Some practical experiments were done, to show the performance of our application in the calculation of bistatic configuration for Cabo Verde.

**Figure 4.** Main Window.

- **Case 1**

  The application initializes, as shown in Figure 4, with a window with the Cabo Verde map and, on the right side, a manipulation tool area. In the first experiment, with the help of the cursor, the transmitter antenna was placed on Santiago island and the receiver antenna on Boavista island. After that, the antennas heights were inserted by a left click on the box “Cálculo das Distâncias em (km)” = distance calculation. Then, the program analyses if there is the line of sight between the antennas or not. If the condition is satisfied, the program allows you to go to the next step, which is the insertion of the technical parameters of the radar, with a click in the box “Entrada de dados do radar” = entry of radar data. Then a window opens, as shown in Figure 5, where the data of the transmitter, receiver, RCS and $P_d$ can be entered. The application is already filled by default with some standard values that can be changed.

  Table 1 shows the chosen values.

  The next step is the calculation of the data, through the button “Cálculo dos dados” = Calculation of the data. To plot the bistatic coverage zone for the selected geometry by clicking on the button “Calcular a zona de cobertura” = calculation of coverage zone, then on the map the coverage zone painted as shown in Figure 6 (a). The application also allows us to focus the study in an area with a probability of detection chosen by the user through the box “ver contorno de Pd=___” = see contours of $P_d = ____$. Then, with a click on the box “representar Ovais de Cassini” = show ovals of Cassini, we
obtain the zone limited with black color as shown in Figure 6 (b) and also the application allows us to save the screen that we want by clicking on the button “Guardar” = save.

![Image of a radar entry parameter window](image_url)

**Figure 5.** Radar entry parameter Window.

**Table 1.** Radar technical parameters used in these experiments.

| Radar data  | Entry value | Unit |
|-------------|-------------|------|
| $P_P$       | 210         | Kw   |
| $B_n$       | 500         | KHz  |
| $G_T$       | 30          | dB   |
| $G_R$       | 30          | dB   |
| $L_T$ and $L_R$ | 5       | dB   |
| $f_0$       | 1000        | MHz  |
| $\sigma B$  | 1           | $m^2$|
| $F_N$       | 2.3         | dB   |
| $h_T$       | 1000        | m    |
| $h_R$       | 200         | m    |
Figure 6. Bistatic coverage zone plotted on Cabo Verde map: (a) with Tx antenna placed in Santiago and Rx antenna in Boavista, (b) same Bistatic Coverage Zone with $P_d = 0.5$. 
Figure 7. Absence of line of sight between Tx and Rx antennas.

- Case 2

In case that the condition of the line of sight between the transmitter and receiver antenna is not satisfied, the software will present the following message on the screen “Não há visibilidade directa, aumente a altura das antenas ou aproxime as posições” which mean, there is no line of sight, increase the height of the antennas or select a closer site as shown in Figure 7. The software can also compute two pairs of bistatic geometry simultaneously as shown in Figure 8.

4. Conclusions

According to the mathematical analyses presented and the results stated in this paper, it can be said that the proposed objectives were fulfilled, the proposed algorithm conducted to the programming in Delphi XE5 was successful with satisfactory results. Some experiments were done where we could calculate the bistatic coverage zone for Cabo Verde. The developed application allows the user to choose its own bistatic geometry, taking into consideration the line of sight between the transmitter and receiver sites which is necessary for the validation of the software. The result of the bistatic coverage zone is calculated according to the chosen geometry and technical parameters of the radar, and the painted area is appreciated by the behaviour of the quality index from high (red) to low (blue), probability of detection.
Figure 8. Two bistatic geometric plotted simultaneously.

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