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Estimation and Mapping of the Received Power Level of Digital Signals TV Using Spatial Interpolation Methods

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***Abstract*— The signal digitization process of the open television system is still in progress, therefore, the study of the digital signal propagation has great importance so that broadcasters can develop and improve the transmission service. The field measurement of digital signal parameters is one of the most reliable means to analyze the signal propagation in a given area. In this work, received power measurements of a TV station digital signal in the city of Mossoró, Rio Grande do Norte, Brazil were performed. The objective is to implement interpolation methods and identify which is the most suitable for the spatial representation of power data in this region through the Mean Error (ME) and Root Mean Squared Error (RMSE) evaluation metrics. A good representation of the received power level contributes to the mapping of greater and lesser intensity of the digital signal in the region. The implementation of the interpolation methods was performed in Surfer® software (Golden Software, LLC), which provides the cross-validation report with the ME and RMSE values associated with each method. The Ordinary Kriging method with exponential variogram model obtained the lowest RMSE value (7.6083) and, therefore, the most adequate estimates.**

***Index Terms*—** Cross validation, Received power of digital signal television, Received signal power measurements, Spatial interpolation methods.

I. INTRODUCTION

The transition process from analog to digital signal in Brazil's open television system, which started in 2016, is still in progress. The first stage of this process was completed in January 2019, where 1,378 cities had the analog signal completely turned off [1]. The end of the transition is scheduled for December 2023, when the TV signal digitization process will be completed [2].

Among the advantages of digital transmission technology compared to analog transmission is the possibility for television transmission networks to deploy a smaller number of frequency channels using Orthogonal Frequency Division Multiplexing [3]. According to the importance of the television system in the information dissemination, distance learning, appreciation of culture and entertainment, it is important to perform studies to assess the propagation of the digital signal that allow for the

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improvement of this service.

Field measurement is one of the most reliable ways to assess digital signal propagation in a given area. In [4], the characteristics of the propagation channel of a Digital TV Single-Frequency Network (SFN) are obtained through field measurements. In [5] and [6] field measurements are used to evaluate propagation models. A survey of digital signal propagation in Curitiba – PR, Brazil, is shown in [7], where transmission and reception tests of a digital TV broadcaster are described in order to know the propagation characteristics in the region to determine if there are critical points or shading areas.

However, field measurement is unlikely to cover the entire coverage area of the TV system or a particular region of interest. In order to obtain more reliable conclusions, densely sampled data over the entire region can be obtained from interpolation methods, which allow estimating the values of the studied variable in places where there was no measurement. In [8] and [9], the interpolation methods were applied to obtain contour maps that allow the analysis of the exposure level to the electromagnetic fields intensity. In [10], the interpolation methods were applied to predict the received signal strength of a communication system in a certain region with the objective of mapping the existing faults. The contour map of radio waves in a given region can provide important information for designing and optimizing the performance of wireless communication networks [11].

In this work, digital signal received power measurements of a TV station in the city of Mossoró, located in the state of Rio Grande do Norte (RN), Brazil, were performed. The focus of the measurements was in the urban region of the city, as this presents more severe propagation conditions with a greater amount of obstacles and agglomerations. The interpolation methods were applied to obtain densely sampled data over the entire region and compared to assess which is the most suitable for representing the distribution of the digital TV signal in the city of Mossoró - RN. This article is divided into five sections. After this introductory section, Section II provides a brief explanation of interpolation methods. Section III describes the methodology adopted to carry out this work. In Section IV are the results and discussion and in Section V the conclusion.

II. INTERPOLATION METHODS

The realization of punctual measurements of the digital signal received power does not cover the entire area of interest of the TV system. Through the interpolation methods, it is possible to estimate the received power values in places where there was no measurement. In this way, from the measured data, the values at all other points in the area delimited for study are estimated. The densely sampled spatial data of received power over the entire area helps in making reliable decisions [12].

There are several interpolation methods, each of which produces a different spatial representation of the data. Therefore, it is important to have knowledge about the variable studied to assess which method best represents reality [13]. Interpolation methods can be deterministic or stochastic, to which geostatistical methods belong.

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Deterministic interpolation methods depend only on the geometric distribution, not taking into account the correlation between the data [14], [15]. In this work, the following deterministic methods were addressed: Inverse Distance Weighting; Modified Sherpard's Method; Minimum Curvature; Radial Basis Function. The Inverse Distance Weighting method is calculated using (1) [16].

$$w_i = \frac{h_i^{-p}}{\sum_{j=0}^{n} h_j^{-p}} \tag{1}$$

Where p is the power parameter and h_j is the distance from the sampled points to the interpolation point. The Modified Sherpard's Method is calculated using (2) [17].

$$F(x,y) = \frac{\sum_{k=1}^{N} Q_k(x,y) W_k(x,y)}{\sum_{k=1}^{N} W_k(x,y)} \tag{2}$$

Where $F(x,y)$ is the value to be interpolated for the (x,y) coordinate, $Q_k(x,y)$ is a nodal function and $W_k(x,y)$ is the modified weight function. In the Modified Sherpard's Method the Inverse Distance Weighting weight function is modified so that it works only locally [18].

The Minimum Curvature or spline method consists of a polynomial of degree p being local rather than global and can be called linear ($p=1$), quadratic ($p=2$) or cubic ($p=3$). Typically, they are of degree 3, called cubic splines [12]. The Radial Basis Function is calculated using (3) [18].

$$Z_j = \sum_{i=1}^{n} \lambda_i B(h_i) \tag{3}$$

Where Z_j is the unknown value, λ_i is the derivative of the weight, $B(h_i)$ is the basis function and h_i is the distance between the interpolation points to point i. Table I presents five main types of basis function. The variable R in the radial basis function represents the smoothing factor.

TABLE I. RADIAL BASIS FUNCTION TYPES [19]

Radial Basis Function	**Equation**
Multiquadric	$B(h_i) = \sqrt{(h_i^2 + R^2)}$
Inverse Multiquadric	$B(h_i) = 1/\sqrt{(h_i^2 + R^2)}$
Multilog	$B(h_i) = \log(h_i^2 + R^2)$
Natural Cubic Spline	$B(h_i) = (h_i^2 + R^2)^{3/2}$
Thin Plate Spline	$B(h_i) = (h_i^2 + R^2)\log(h_i^2 + R^2)$

Geostatistics requires correlation and spatial dependence between data. A geostatistical method is divided into two steps: variographic analysis and estimation of unknown values. Variographic analysis takes into account the spatial dependence between data and the estimation of unknown values is performed by one of several kriging algorithms [20], [12]. In this work, the linear, exponential, spherical and Gaussian variogram models and the Ordinary Kriging estimator were applied. Estimates for unknown points by Ordinary Kriging can be calculated using (4) [21].

$$Z^*(x_0) = \sum_{i=1}^{N} \lambda_i Z(x_i) \tag{4}$$

Where $Z^*(x_0)$ is the estimated value, λ_i are the weights associated with the sampled data and $Z(x_i)$ is the known value.

Spatial interpolation methods have a certain degree of error associated with the estimate. Cross-validation is a process that determines the accuracy of estimated values in places where there was no measurement. In this process, a sampled data is removed and its value is estimated using the rest of the data, this is repeated for each sample data [22]. The difference between the real values and the interpolated values is used to determine the error [15].

The error measurements used in the article are Mean Error (ME) and Root Mean Squared Error (RMSE). The ME indicates how much the method is overestimating (positive value) or underestimating (negative value) the forecast of the received power in relation to the measured data, varying up and down around zero. The RMSE expresses the accuracy of the results, the lower its value, the better the result.

III. METHODOLOGY

Aming to analyze the digital signal TV in the city of Mossoró – RN, a sound and image radio broadcasting generator station – digital for commercial purposes was chosen. Through the Mosaico System, created by National Agency Telecommunications (Anatel), it is possible to access the database of the basic broadcasting services plans (TV, RTV, TVD, FM and OM). Accessing the Mosaico System Channel Search Module, channel reports with their main information are made available.

The chosen TV station occupies channel 47 in the electromagnetic spectrum, has a bandwidth of 6 MHz (668 MHz – 674 MHz) and a central frequency of 671 MHz. The transmission system consists of a transmitter with an operating power of 0.3 kW; 62 m transmission line, attenuation 1.796 dB/100 m and ancillary losses of 0.25 dB; elliptical polarization transmit antenna, 4.24 dBd gain, Radiant System Phase Center Height (HCI) 52.01 m, and maximum Effective Radiated Power (ERP) 0.58 kW. The study of the propagation of the digital signal transmitted by this station consisted of two steps: measurement campaign and the implementation and comparison of interpolation methods.

A. Measurement campaign

The measurement campaign aimed to measure the strength of the digital TV signal in the urban area of the city of Mossoró. For that, a spectrum analyzer, a receiving antenna and a Global Positioning System (GPS) were used, shown in Fig. 1. The spectrum analyzer has the function of measuring and recording the signal power in dBm. The Rohde & Schwarz Spectrum Rider FPH Model .06, shown in Fig. 1(a), operates in the frequency range 5 kHz – 6 GHz frequency range.

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The digital receiving antenna model is Proeletronic's PROHD-2400, shown in Fig. 1(b). Among the different types of antennas, the monopole antenna facilitates the measurement work because it is omnidirectional, eliminating the need to be directed to the transmission antenna. The receiving antenna has a gain of 4 dBi and operates in the VHF (174 MHz – 216 MHz) and UHF (470 MHz – 806 MHz) bands. The antenna was positioned on a 3 m pole and connected to the spectrum analyzer to measure the signal strength. And the Garmin® GPSMAP 78S, shown in Fig. 1(c), was used to record the geographic coordinates of the locations where the measurements took place.

(a) (b) (c)

Fig. 1. Measurement system equipment: (a) spectrum analyzer; (b) receiving antenna; (c) GPS.

To perform the measurement, it was necessary to configure some parameters in the spectrum analyzer. Anatel Act No. 942 of February 8, 2018, which approves the technical requirements for assessing the compliance of transmitters and retransmitters for the Brazilian Digital Terrestrial Television System, defines requirements related to output power. The power of the digital TV signal is evenly distributed across the transmission channel. Therefore, the measurement must take into account the full bandwidth of the modulated signal. In the case of digital signals, the average power value is the most appropriate for the type of modulation used. Table II specifies the parameter values that must be configured in the spectrum analyzer. Power is determined by reading the spectrum analyzer and calibrating the loss of the cable connecting the analyzer to the antenna [23]-[24].

TABLE II. SPECTRUM ANALYZER CONFIGURATION [15]

Central Frequency	Span	RBW	VBW	Detection Mode	Channel BW
Center frequency of channel OFDM carriers	10 MHz	30 kHz	300 kHz	Sample	5.7 MHz

According to the methodology developed by the digital TV laboratory of Universidade Presbiteriana Mackenzie, the measurement points are defined by plotting 24 radials originating from the transmission tower and spaced at an angle of 15º and 10 concentric circles of radii of 1, 2, 3 , 5, 7, 10, 20, 30, 40 and 57 km, which may vary according to the channel protected contour. The intersection between the radials and the concentric circles determines the coordinates of each point, establishing a set of 240 measurement points [24]-[25].

Adapting this methodology to the reality of this work, the 24 radials were drawn, as described, and 10 concentric circles of radii 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 km, which are within of the coverage area of the transmission system that was analyzed, as shown in Fig. 2. The objective is to measure the

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signal strength in the urban area of the city, where there is a greater concentration of obstacles and agglomerations, therefore, only the intersection points between radial and circle within the urban area were considered. The Instituto Brasileiro de Geografia e Estatística (IBGE) website provides the network of census sectors in the cities of each state, making it possible to identify the urban area of the city of Mossoró [25]-[26].

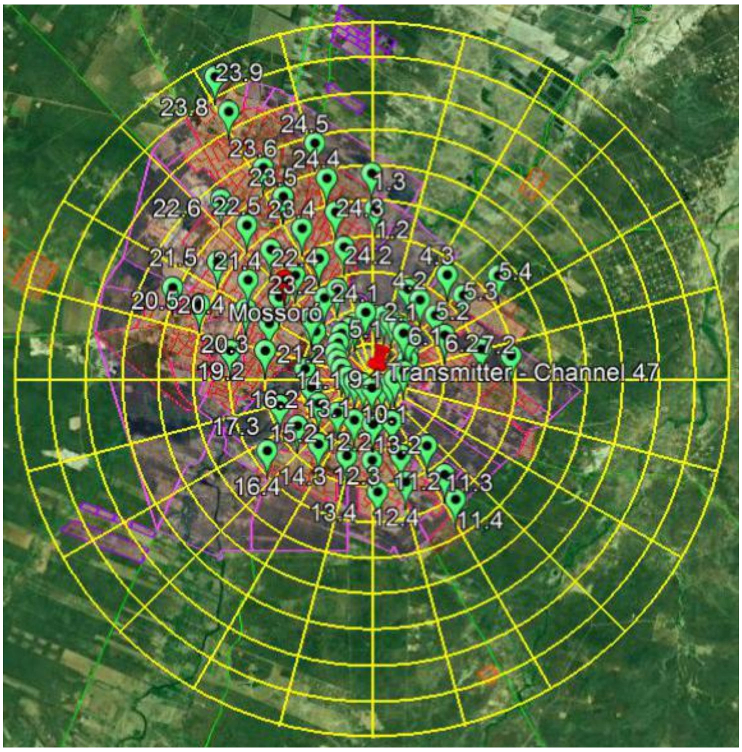

Fig. 2. Measurement points in the urban area of the Mossoró – RN.

Within the urban area, the coordinates of some points led to inaccessible or unfeasible places, when it was not possible to carry out the measurement in a closer location, the point was removed from the measurements. Thus, a total of 82 measurement points was reached. The adopted methodology seeks to represent the signal loss with distance, making it effective in evaluating the propagation of the digital signal of a TV system.

B. Implementation of Interpolation Methods

After the measurement step, the digital signal strength data and the respective geographic coordinates were interpolated using the methods described in the previous section. This process was carried out using the Surfer® 13 software, which provides a wide range of spatial interpolation methods. This software generates a continuous surface (map) after applying the interpolation method. Through the map it is possible to visualize how the signal strength is distributed in the analyzed area. Methods analysis is performed through cross-validation, which measures the accuracy of the estimates by determining the associated error. Surfer® 13 software provides Mean Error (ME) and Root Mean Squared Error (RMSE) values.

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IV. RESULTS

The contour maps and analysis of spatial interpolation methods are presented below: Inverse Distance Weighting; Modified Sherpard's Method; Minimum Curvature; Radial Basis Function; Ordinary Kriging.

A. Inverse Distance Weighting

Inverse Distance Weighting (IDW) considers that measured values closer to the forecast location have more influence on the predicted value than those further away [26-16]. The advantage of this method is that it is intuitive and efficient [16-17]. On the other hand, the method often does not reproduce the implicit local form in the data and produces local extremes at sample points [13]. The estimates were calculated using (1), where the power parameter $p = 2$ was adopted. The contour map of the TV's digital signal received power (Pr) in the urban area of Mossoró using the IDW interpolation method is shown in Fig. 3.

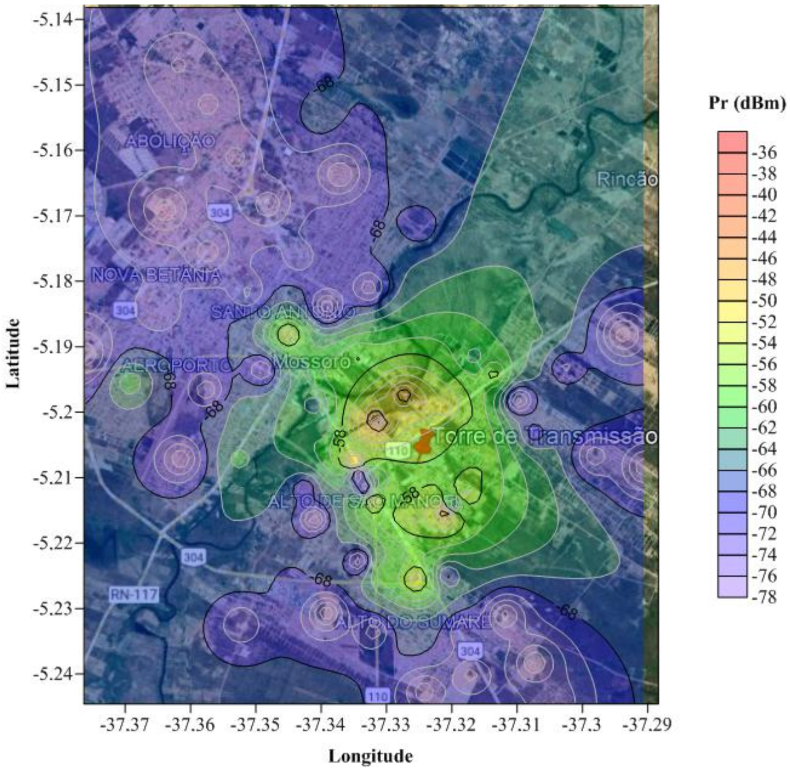

Fig. 3. Contour map of the received power of the digital signal TV using Inverse Distance Weighting.

It is noticed that the power gradually decreases as the distance from the transmitting antenna increases. In the center of the contour map, there is a predominance of the greenish color, which corresponds to the power range from -64 dBm to -54 dBm. Note also the presence of circular areas around the sampled points that are inconsistent with the estimated contours on the map. This is a flaw in the IDW method, known as the Bull's eye effect.

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B. Modified Sherpard's Method

The Modified Shepard's Method (MSM) is considered an improved version of the IDW method. It uses the least squares method to eliminate the Bull's eye effect present in the IDW [18]. The contour map of the digital signal received power using the MSM interpolation method is shown in Fig. 4.

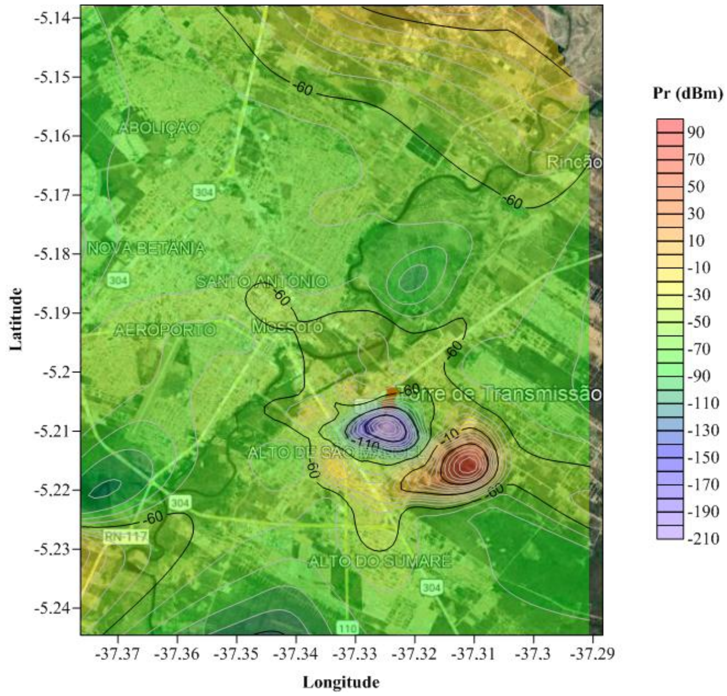

Fig. 4. Contour map of the received power of the digital signal TV using Modified Sherpard's Method.

Unlike the contour map of the IDW method, Fig. 3, where the power gradually decreases with the distance from the transmitting antenna, the MSM contour map has central regions with very different power ranges. This format does not match the actual power distribution received from the digital TV signal.

C. Minimum Curvature

The Minimum Cuvarture or Spline method uses a mathematical function to smooth the total surface curvature, resulting in a minimum curvature surface that passes exactly through the sampled points [16-17]. The contour map of the received power of the digital signal using the Minimum Cuvarture interpolation method is shown in Fig. 5.

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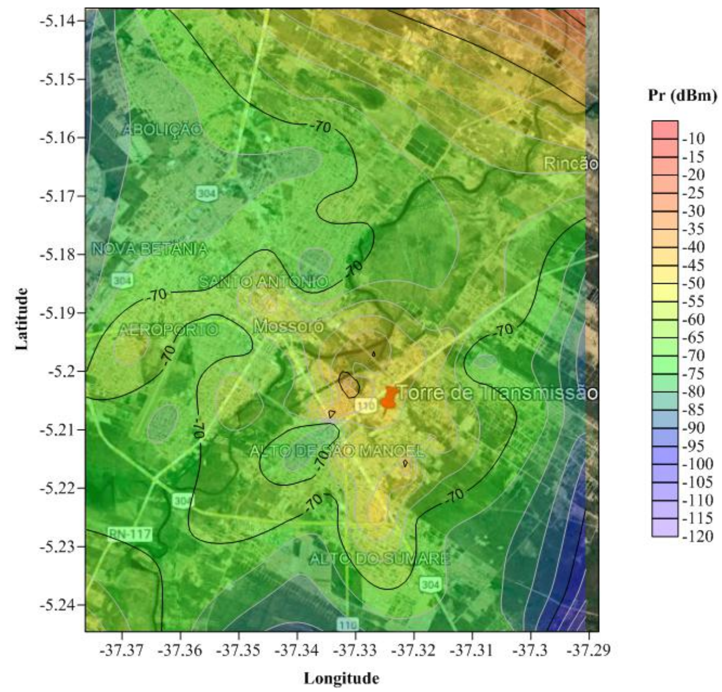

Fig. 5. Contour map of the received power of the digital signal TV using Minimum Cuvarture.

The contour map shown in Fig. 5 fulfills the purpose of this method in providing a surface of minimal curvature, where the power variation is smoothed. There is a predominance of yellow and green colors, which correspond to the power range from -75 dBm to -40 dBm. At some specific points in the central region there is a hue turned to orange, which indicates a higher level of signal strength.

D. Radial Basis Function

The Radial Basis Function uses the distance between the interpolation points and the discrete points as a single variable function and as the base function. It introduces a smoothing coefficient, which improves interpolation accuracy but also increases the amount of data [18]. The Radial Basis Function method can be calculated by different types of basis function. The five main base functions are: Multiquadric; Inverse Multiquadric; Multilog; Natural Cubic Spline; Thin Plate Spline. Each basis function has the variable R^2, which represents the smoothing factor and improves the interpolation accuracy. The value of the smoothing factor used was $R^2 = 9.1 x 10\text{-}6$. Contour maps using these five types of base function are shown in Fig. 6.

The radial basis function types Multiquadric, Inverse Multiquadric and Multilog, shown in Fig. 6(a), Fig. 6(b) and Fig. 6(c) respectively, have similarities in the shapes of the contours. There is a concentration of green color in the center of the map with some points of greater intensity of power. The base functions Natural Cubic Spline, Fig. 6(d), and Thin Plate Spline, Fig. 6(e), have different power levels in the central region of the map. This shape of the contours distances itself from the real representation in which the power decreases with distance.

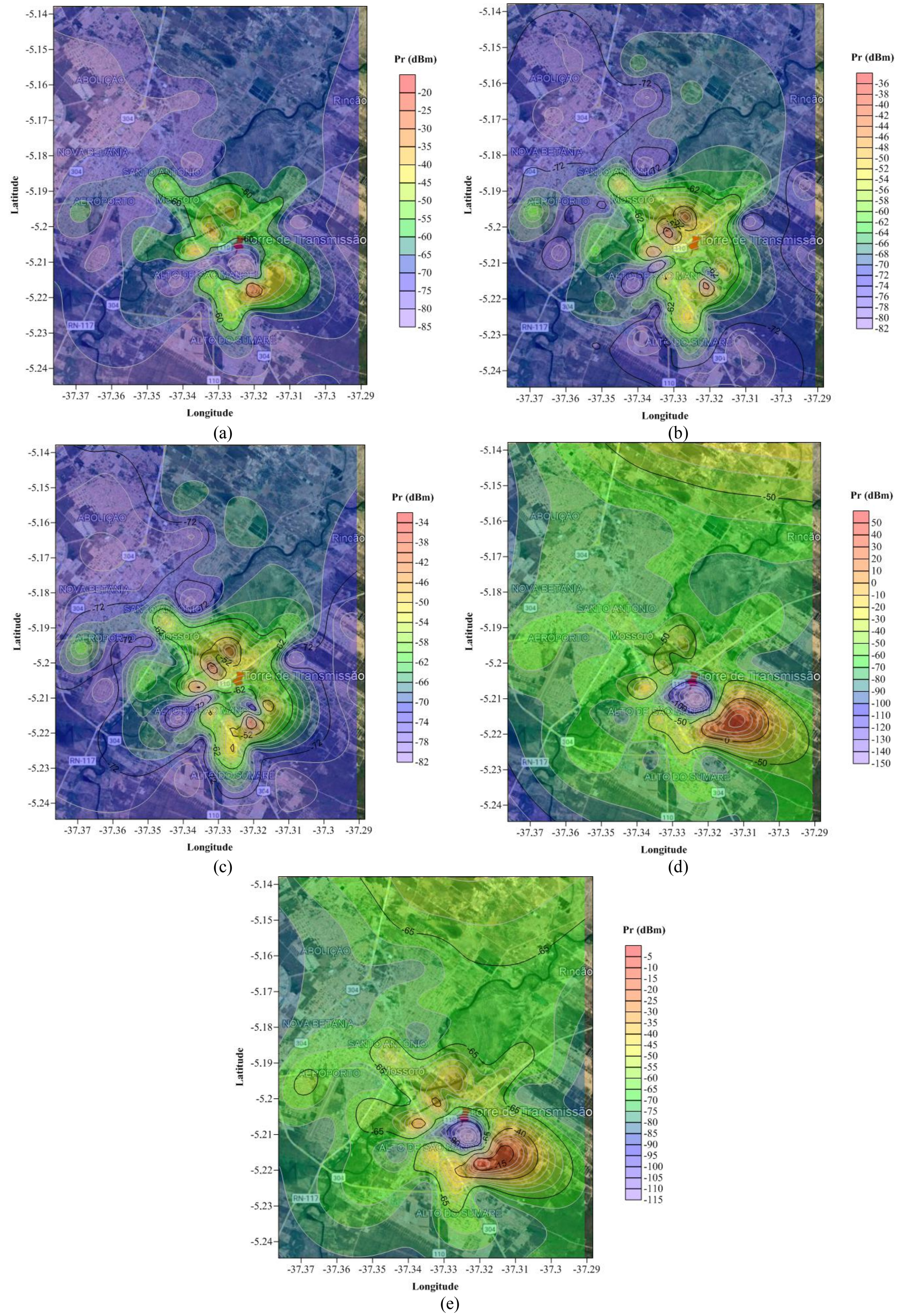

Fig. 6. Contour map of the received power of the digital signal TV using Radial Basis Function: (a) Multiquadric; (b) Inverse Multiquadric; (c) Multilog; (d) Natural Cubic Spline; (e) Thin Plate Spline.

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E. Ordinary Kriging

Ordinary Kriging is a stochastic method that uses a linear combination of weights at known points to estimate the value at an unknown point taking into account the spatial correlation through variogram [27-21]. In Fig. 7 the contour maps of the received power of the digital TV signal resulting from the Ordinary Kriging interpolation method using the linear, exponential, spherical and gaussian variogram models are shown.

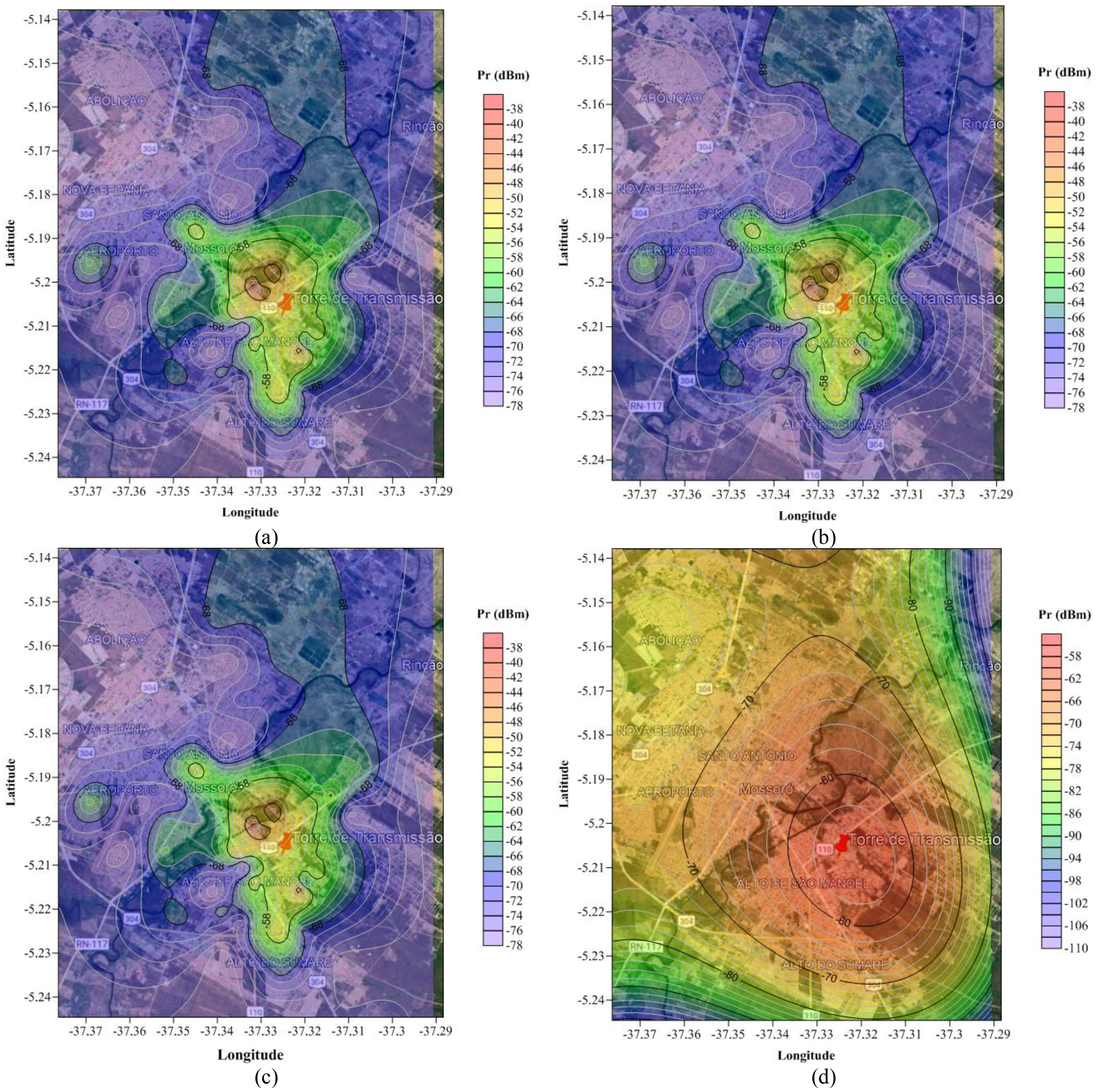

Fig. 7 Contour map of the received power of the digital signal TV using Ordinary Kriging and variogram model: (a) linear; (b) exponential; (c) spherical; (d) gaussian.

The contour maps in Fig. 7(a), Fig. 7(b) and Fig. 7(c) of the linear, exponential, and spherical variogram models, respectively, are very similar. They show that signal strength decreases with distance, with greater color variation in the center. The contour map Fig. 7(d), of the Gaussian variogram model, also represents the reduction in the received signal power with distance. However,

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the contour map using the Gaussian variogram model has less color variation in the center, providing a smoother surface compared to the other models.

F. Cross Validation

Table III shows the ME and RMSE values of the interpolation methods applied to obtain the contour maps. These error values associated with the methods were obtained through the cross-validation process in the Surfer® 13 software.

The Modified Sherpard's Method, Minimum Curvature, Radial Basis Function (Natural Cubic Spline and Thin Plate Spline) and Ordinary Kriging – Gaussian interpolation methods have negative ME values, which indicates that the estimation of received power values is pessimistic in relation to the data measured. All other methods studied have a positive ME value, that is, they were optimistic and overestimated the received power predictions in relation to the measured values.

TABLE III. CROSS VALIDATION OF INTERPOLATION METHODS

Interpolation Method	ME (dB)	RMSE (dB)
Inverse Distance Weighting	2.2256	7.6713
Modified Sherpard's Method	-0.4999	7.6659
Minimum Curvature	-0.0099	7.9154
Radial Basis Function – Multiquadric	0.4202	9.0242
Radial Basis Function – Inverse Multiquadric	0.5607	7.8751
Radial Basis Function – Multilog	0.0849	8.8113
Radial Basis Function – Natural Cubic Spline	-6.4858	17.8770
Radial Basis Function – Thin Plate Spline	-5.5793	13.8492
Ordinary Kriging - Linear	0.1902	7.6087
Ordinary Kriging - Exponential	0.1902	7.6083
Ordinary Kriging - Spherical	0.1901	7.6087
Ordinary Kriging - Gaussian	-0.2899	7.8511

Among the analyzed methods, Ordinary Kriging with the Linear, Exponential and Spherical variogram models presented the lowest RMSE values. With a small difference in the fourth decimal place the Exponential variogram model, Fig. 7(b), has the lowest RMSE value (7.6083), which makes it the method that presented the most coherent prediction with the data collected in the field.

In [10] the Ordinary Kriging method was used to estimate the surface distribution of the values of the Received Signal Strength Indicator (RSSI) in the well-automation region called Canto do Amaro, Brazil. The spherical variogram model presented the most satisfactory performance providing the contour map of the spatial distribution of RSSI levels with greater precision. In reference [9] it was concluded that the Inverse Distance Weighting interpolation method presented the most satisfactory performance to estimate the magnitude of the intensity of the electric fields in the central region of the city of Mossoró, Brazil.

Based on the results of this and other articles, it is clear the importance of analyzing which method presents the best results for a given application, considering that each case has its own characteristics, for example, environment, parameter being analyzed, number of measurements, among others.

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V. CONCLUSION

This work carried out a campaign to measure the power of the digital TV signal, channel 47, in the urban region of the city of Mossoró in Rio Grande do Norte. From the collected data, the received power was estimated in the entire area of interest by means of interpolation methods. A good representation of the received power level contributes to the mapping of greater and lesser intensity of the digital signal, serving as a parameter for broadcasters to make improvements in the transmission system. Through the Surfer® 13 software, the contour maps of the received power were generated using the methods: Inverse Distance Weighting; Modified Sherpard's Method; Minimum Curvature; Radial Basis Function; Ordinary Kriging. The implementation of these interpolation methods shows different interpretations.

The contour maps of the IDW, Minimum Curvature and Ordinary Kriging methods were closer to reality, representing the signal loss with distance. Cross-validation provided ME and RMSE values for each method. The ME metric allowed to identify the Modified Sherpard's Method, Minimum Curvature, Radial Basis Function (Natural Cubic Spline and Thin Plate Spline) and Ordinary Kriging – Gaussian as methods pessimistic, that is, these methods underestimated the received power predictions, while the other methods overestimated the received power predictions in relation to the measured values. And the lowest RMSE value (7.6083) indicated that the Ordinary Kriging method with Exponential variogram model obtained the most accurate predictions.

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REFERENCES

[1] ANATEL. "Televisão digital," Brazil. Mar. 25, 2021. [Online]. Available: https://www.gov.br/anatel/pt-br/regulado/radiodifusao/televisao-digital. Accessed on: Oct. 11, 2021.

[2] MCTIC. 3,492nd Ordinance, (2016, Aug. 26). [Online]. Available: https://www.abratel.org.br/wp-content/uploads/2016/08/Portaria-MCTIC-N.%C2%BA-3493-2016-Altera-SBTVD-T-Ago-2016_merged2.pdf. Accessed on: Oct. 17, 2021.

[3] C. F. F. Rodrigues, F. A. Peres, and L. Lovisolo, "Receivers Behavior in a ISDB-T's Single Frequency Network," *SET IJBE*, vol. 2, Article 7, pp. 44–54, 2016.

[4] M. V. Guerra, J. L. A. Filho, C. V. R. RON, L. A. R. S. Mello, and P. V. G. Castellanos, "Channel Characteristics for Fixed and Portable DTV Reception in a Single Frequency Network," *Journal Of Microwaves, Optoelectronics And Electromagnetic Applications*, vol. 18, no. 3, pp. 439–451, Jul. 2019.

[5] L. C. Eras, M. Almeida, D. K. N. Silva, H. R. O. Ferreira, N. Santos, F. J. B. Barros, and G. P S. Cavalcante, "Avaliação de Modelos de Radiopropagação para TV Digital em Percursos Mistos," in *XXXIV SBRT*, Santarém, PA, Brazil, 2016, pp. 732–736.

[6] C. F. Rodrigues, L. Lovisolo, and L. Muratori, "On the Parameters of ITU-R P.1546 Propagation Model for Dual-Polarization Links," *IEEE Transactions on Broadcasting*, vol. 66, no. 1, pp. 56–65, Mar. 2020.

[7] C. L.Vasco, J. F. Rehme, R. A. Martins, E. Agostinho, A. A. P. Pohl, R. D. Souza, K. V. O. Fonseca, and M. E. Pellenz, "Transmission and Reception Tests of Digital Terrestrial TV in the Metropolitan Region of Curitiba," *SET IJBE*, vol. 1, no. 1, pp. 19–25, 2015.

[8] H. D. de Andrade, A. L. Figuêiredo, B. R. Fialho, J. L. S. Paiva, I. S. Q. Júnior, and M. E. T. Sousa, "Analysis and development of an electromagnetic exposure map based in spatial interpolation," *Electronics Letters*, vol. 56, no. 8, pp. 373–375, Apr. 2020.

[9] T. A. A. Santana, H. D. de ANDRADE, I. S. Q. Júnior, and I. B. T. DA Silva, "Comparison of spatial interpolation methods to determine exposure ratio to electric fields in urban environments," *Electronics Letters*, vol. 53, no. 18, pp. 1250–1252, Aug. 2017.

[10] B. R. Fialho, H. D. de Andrade, G. Fontgalland, J. L. S. PAIVA, and I. S. Q. Júnior, "Variographic analysis to evaluate the coverage area of a wireless system at 5.8 GHz band in a region of oil fields," *Electronics Letters*, vol. 55, no. 11, pp. 652–654, May 2019.

[11] R. Augusto and C. Panazio, "On Geostatistical Methods for Radio Environment Maps Generation under Location Uncertainty," *Journal of Communication and Information Systems*, vol. 33, no. 1, pp. 62–77, 2018.

[12] J. Li and A. D. Heap, *A review of spatial interpolation methods for environmental scientists.* Canberra, Australia: Geoscience Australia, 2008.

[13] L. Mitas and H. Mitasova, "Spatial interpolation," In: *Geographical information systems: principles, techniques, management and applications*, 2nd ed., New Jersey, USA: John Wiley & Sons, 2005, pp. 481–492.

[14] P. Correia, "Modelação e estimação: uma introdução à geoestatística," 2010. [Online]. Available: http://www.leg.ufpr.br/lib/exe/fetch.php/disciplinas:geoesalq:pira2012:numist_-_modelacao_e_estimacao_-sgems.pdf. Accessed on: Oct 11, 2021.

[15] S. C. Graaf, "Natural neighbour kriging: and its potential for quality mapping and grid design," M.S. Thesis, Delft University of Technology, 2016.

[16] M. A. Azpurua and K. A. Ramos "Comparison of spatial interpolation methods for estimation of average electromagnetic field magnitude," *Progress In Electromagnetics Research M*, vol. 14, pp. 135–145, 2010.

[17] A. S. A. Silva, "Ferramentas para modelagem e interpolação de dados ambientais em escala regional," Ph.D. Dissertation. Universidade Federal Rural de Pernambuco, Recife, Brazil, 2015.

[18] S. Liu, X. Chen, S. Peng, Y. Ma, and J. Qian, "A study of two data grid interpolation algorithm based on surfer software," *2010 International Conference On Machine Learning And Cybernetics*, pp. 1045–1049, Jul. 2010.

[19] K. Gumus, A. Sen "Comparison of spatial interpolation methods and multi-layer neural networks for different point distributions on a digital elevation model," *Geodetski vestnik*, vol. 57, no. 3, pp. 523–543, 2013.

[20] R. P. Oliveira, C. R. Grego, and Z. N. Brandão, *Geoestatística aplicada na agricultura de precisão utilizando o vesper*. Brasília, Brazil: Embrapa, 2015.

[21] J. K. Yamamoto and P. M. B. Landim, *Geoestatística: conceitos e aplicações*. São Paulo: Oficina de Textos, 2013.

[22] S. Chaudhari, M. Kosunen, S. Makinen, C. Ramanathan, J. Oksanen, M. Laatta, J. Ryynanen, V. Koivunen, and M. Valkama, "Spatial interpolation of cyclostationary test statistics in cognitive radio networks: methods and field measurements," *IEEE Transactions on Vehicular Technology*, vol. 67, no. 2, pp. 1113–1129, Feb. 2018.

[23] ANATEL. 942nd Act, (2018, Feb. 8). [Online]. Available: https://informacoes.anatel.gov.br/legislacao/index.php/component/content/article?id=1191. Accessed on: Oct 17, 2021.

[24] R. E. Motoyama, "Proposta de um procedimento de teste de recepção de TV digital com antena indoor," M.S. Thesis, Universidade Presbiteriana Mackenzie, São Paulo, Brazil, 2010.

[25] IBGE. "Geociências: downloads," Brazil [Online]. Available: https://www.ibge.gov.br/geociencias/downloads-geociencias.html. Accessed on: Sep 07, 2021.

[26] W. Luo, M. C. Taylor, and S. R. Parker, "A comparison of spatial interpolation methods to estimate continuous wind speed surfaces using irregularly distributed data from England and Wales," *International Journal of Climatology*, vol. 28, no. 7, pp. 947–959, 2008.

[27] M. Rufo, A. Antolín, J. M. Paniagua, and A. Jiménez, "Optimization and comparison of three spatial interpolation methods for electromagnetic levels in the AM band within an urban area," *Environmental Research*, vol. 162, pp. 219–225, Apr. 2018.