Some Results of Effective Ground Conductivity for São Paulo

Antonio Luiz P. S. Campos, Marcio E. C. Rodrigues
Department of Communication Engineering
Federal University of Rio Grande do Norte (UFRN)
Natal, Brazil
antonio.luiz@pq.cnpq.br, marcio.rodrigues@ct.ufrn.br

Marta Pudwell Chaves de Almeida, Rodrigo Pereira David, João Alfredo Cal Braz
Division of Metrology in Telecommunication (DITEL)
National Institute of Metrology, Quality and Technology (Inmetro)
Rio de Janeiro, Brazil
{mpalmeida, rpdavid, jabraz}@inmetro.gov.br

Luiz da Silva Mello
Center for Telecommunications Studies (CETUC)
Pontifical Catholic University of Rio de Janeiro (PUC-Rio)
Rio de Janeiro, Brazil
Division of Metrology in Telecommunication (DITEL)
National Institute of Metrology, Quality and Technology (Inmetro)
Rio de Janeiro, Brazil
smello@cetuc.puc-rio.br

Flavio Ferreira Lima
Department of Electrical Engineering
University of Brasília (UnB)
Brasília, Brazil
flima@nmi.unb.br

Abstract—**This paper describes the calculation of the average ground conductivity through the analysis of field intensity measurements on medium wave band carried out in São Paulo, Brazil. Regarding digital radio services, this effort aims to provide an accurate information on the ground conductivity, which is a parameter related to broadcast system planning at frequencies below 30 MHz. Some of the achieved values are different from the ones in the current world atlas presented in Recommendation ITU-R 832-3 for the considered region. It means that the coverage area may be higher than the area predicted by regulatory organization, which may cause interference between analog and digital simulcast systems. Measurements were performed in 1200 kHz and 780 kHz.**

Keywords-ground conductivity; medium wave; digital radio systems; analog systems; ITU-R 832

I. INTRODUCTION

The interest in AM broadcasting has grown since the definition of digital broadcasting standards, in particular the Digital Radio Mondiale (DRM) [2] and HD Radio (IBOC, In-Band On-Channel) [3], which can provide high-quality audio services and complementary data services. These systems use the radiofrequency (RF) channels currently employed for analog AM broadcasting, using on-channel simulcast technology. The digital system planning has different issues from analog system planning [4] [5], requiring very reliable propagation data that affects the coverage estimation.

Propagation of radio waves in low and medium frequency bands (LF, 30-300 kHz and MF, 300-3000 kHz), traditionally used for analog audio broadcasting with amplitude modulation (AM), is strongly dependent on ground conductivity at these frequencies. The ground conductivity is an important parameter employed in radio broadcasting service planning, particularly in the prediction of coverage area and protection against interferences from other stations, because it determines the attenuation of the ground wave. The ground conductivity information can be achieved from many methods [6] and the calculations always involve some complexity. The ITU maintains a global atlas of ground conductivity [7] and claims worldwide data providers to improve its accuracy and resolution.

In this work the field intensity measurements were performed in São Paulo and they are source for the achievement of average ground conductivity in that region. This work is based on a previous one employing field measurements in Natal (Brazil) [1], and the same methodology described there is applied herein. The measurements in São Paulo were carried out in two frequencies, 1200 kHz and 780 kHz, along different routes having two corresponding AM stations as the approximate convergence point for each of the two sets of routes.

II. METHODOLOGY

The measurements of field intensity in 1200 kHz and in 780 kHz were performed along 6 routes up to 54 km and 4 routes reaching 67 km respectively, during diurnal period, when surface wave propagation is predominant. Both AM stations are placed in urban environment, although the last sites of some routes extend to rural locations. Table I presents the characteristics of both AM stations. For the 780 kHz measurements, there is one route extending through two regions of different ground conductivities, according to the

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current ITU atlas [7], which implied in breaking the route into two.

Fig. 1 and Fig. 2 present the orientation of the routes and Table II presents the descriptions of them. Although the IDs of the routes are the same in Station #1 and Station #2, they do not refer to the same paths. Only R3 (for Station #1) and R7 (for Station #2) are almost the same; also, R6 (for Station #1) and R6 (for Station #2) are located near.

Measurements were performed in around 50 sites along the planned routes with spectrum analyzer model ANRITSU MS2724B (9 kHz - 20 GHz) and omnidirectional active loop antenna, attached to a laptop, combined with GPS information. All setup devices, excepting the antenna, were mounted inside a vehicle which traveled along the routes.

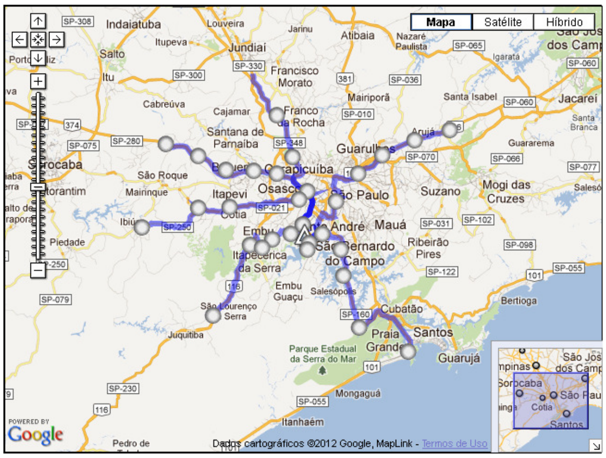

Figure 1. Measurement routes of Station #1

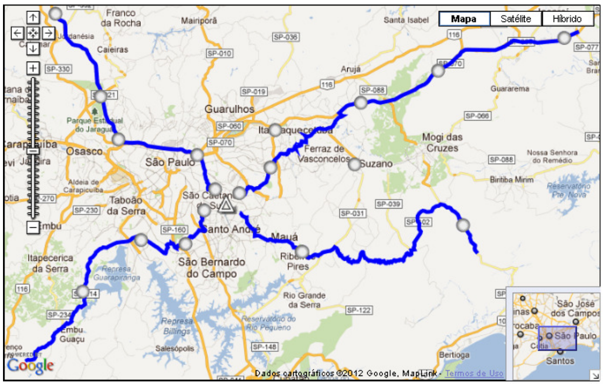

Figure 2. Measurement routes of Station #2

TABLE I. TRANSMISSION CHARACTERISTICS

Parameter	***Station #1***	***Station #2***
Frequency	1200 kHz	780 kHz
Transmission power	50 kW (day)	43 kW (day)
Antenna type	Vertical monopole	Vertical monopole
Tower height	70 m	122 m

TABLE II. DESCRIPTION OF MEASUREMENT ROUTES

Station	***Route ID***	***Orientation***	***Distance to the last site (km)***
Station #1	R1	South	46.9
	R2	East	54.2
	R3	North	36.9
	R4	Northwest	49.9
	R5	West	49.6
	R6	Southeast	36.8
Station #2	R2	Southeast	42.6
	R3A / R3B	Northeast	67.5
	R6	Southwest	30.2
	R7	Northwest	45.9

III. SURFACE WAVE PROPAGATION

At low frequencies as the ones in the VLF, LF and MF bands, radio-wave propagation is performed mainly by means of surface (ground) waves. The electromagnetic wave does not disperse into space (sky waves are weak, specially at large distances from the transmitter) and boundary conditions relative to the ground conductivity require an almost vertical electric field.

A simplified procedure for the computation of the electric field of a surface wave is described in [1]. Basically, the module of the electric field is obtained from (1), where E_0 is the electric field in free space, given by (2) [1] [8] and A is computed by the sequence of equations from (3) to (9).

The attenuation factor of the surface wave, A, is caused by power dissipation in the medium. The electrical characteristics of the ground are included in this factor. These properties are not constant along the propagation path, changing according to the composition of the ground, the degree of moisture and salt concentration, among other factors.

$$E = E_0 A \tag{1}$$

$$E_{0(mV/m)} = \frac{174\sqrt{P_T(kW)G_T}}{d(km)} \tag{2}$$

$$A = A_1 - \left(\sqrt{\frac{p}{2}}\right) e^{-5p/8} sen(b) \tag{3}$$

$$A_1 = \frac{2+0.3p}{2+p+0.6p^2} \tag{4}$$

$$p = \frac{0.5817 f^2(MHz) d(km) cos^2(b'')}{\sigma_i(mS/m) cos(b')} \tag{5}$$

$$b = 2b'' - b' \tag{6}$$

$$tg(b') = \frac{\varepsilon_r - 1}{x} \tag{7}$$

$$tg(b'') = \frac{\varepsilon_r}{x} \quad (8)$$

$$x = \frac{18x10^3 \sigma_i(mS/m)}{f(MHz)} \quad (9)$$

This work is aimed at the assessment of the effective ground conductivity, σ. Since electric field strength was obtained for several points along the routes, the desired parameter can be retrieved by inverting the field expression. It can be verified in the above equations that the dependence of the field equation with respect to σ_i (the ground conductivity which is the average for the path from the transmitter to each measurement site) is not trivial. For every site, once one have the measured field intensity E, the free space field E_0 , and the distance d_i, the problem is solved by a software tool developed for this purpose [1].

IV. Results

Along a route, the computed σ_i values for every measurement site are input to (10), which outputs the average (effective) ground conductivity [6]. Table III presents the retrieved σ values, approximated to one decimal.

For each route, measured electric field strength is plotted against two curves of predicted electric field computed from (1): one using σ value obtained from ITU atlas and the other one using σ value assessed by the methodology used in this work. Fig. 3 to Fig. 7 show these plots for some routes. These plots were done using the exact σ values retrieved with (10), as indicated in the legends.

$$\sigma = \frac{\sigma_1 d_1 + \sigma_2 d_2 + \sigma_3 d_3 + \dots + \sigma_n d_n}{d_1 + d_2 + d_3 + \dots + d_n} \quad (10)$$

Mean and RMS errors of field intensity were computed in order to make a comparison between predicted and measured electric fields, E. Table IV presents the results for mean electric field errors, given by (11), whereas Table V presents the RMS errors for these fields, computed by (12). The errors are computed in dB and some comments are made.

TABLE III. Retrieved Average Ground Conductivities

Route	***Assessed σ (mS/m)***
Station #1	
R1	2.8
R2	1.2
R3	1.5
R4	1.0
R5	1.0
R6	1.1
Station #2	
R2	1.5
R3A	0.6
R3B	2.5
R6	1.2
R7	0.9

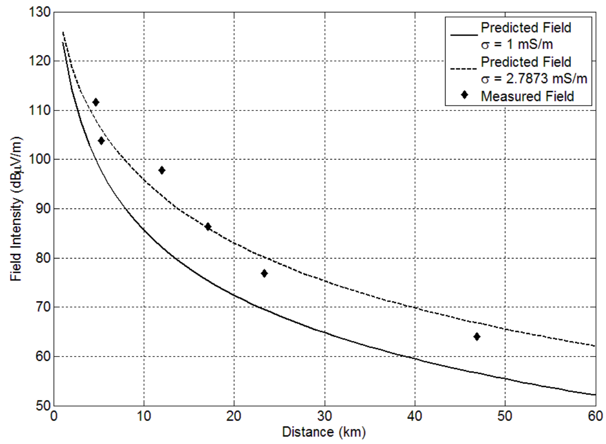

Figure 3. Predicted and measurement field strenght for route R1 (Station #1)

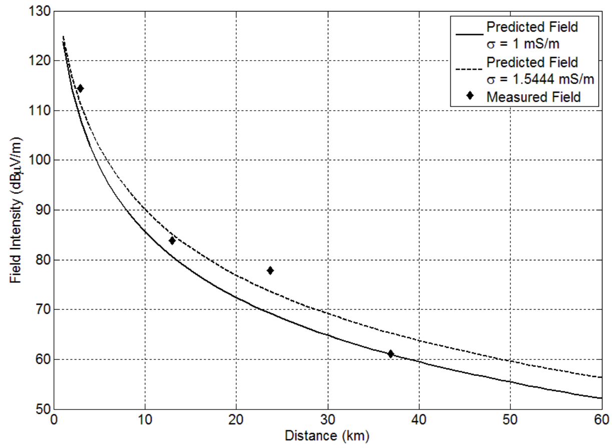

Figure 4. Predicted and measurement field strenght for route R3 (Station #1)

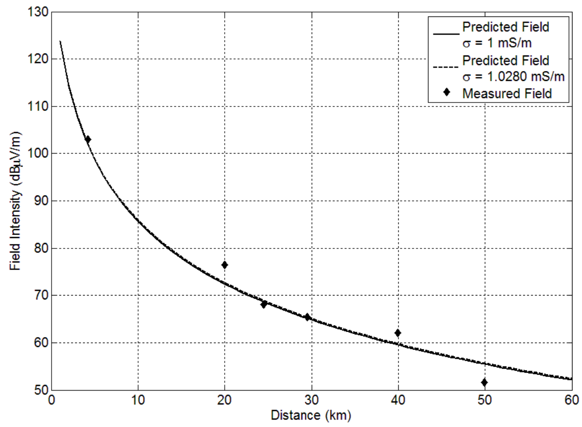

Figure 5. Predicted and measurement field strenght for route R4 (Station #1)

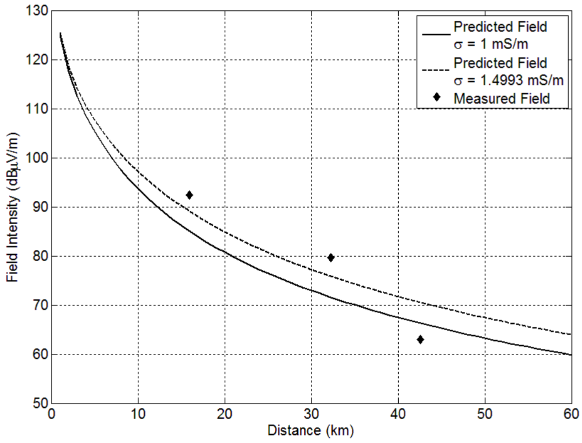

Figure 6. Predicted and measurement field strenght for route R2 (Station #2)

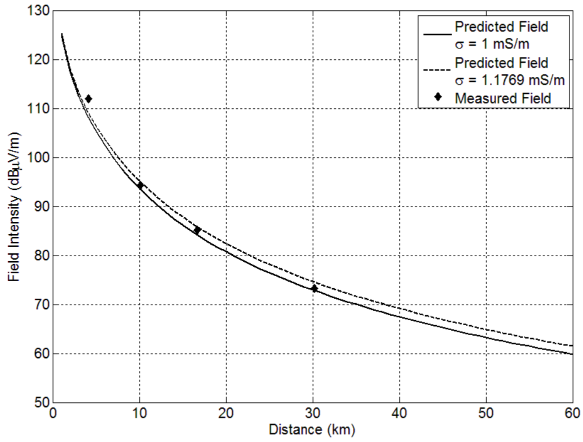

Figure 7. Predicted and measurement field strenght for route R6 (Station #2)

TABLE IV. MEAN ERRORS (IN DECIBELS) BETWEEN MEASURED AND PREDICTED FIELDS FOR ASSESSED AND ITU ATLAS σ VALUES

Route	*E (assessed σ) vs. E (measured σ)*	*E (ITU σ) vs. E (measured σ)*	*E (assessed σ) vs. E (ITU σ)*
Station #1			
R1	0.12	-9.84	9.72
R2	0.08	-1.97	1.88
R3	-0.91	-2.45	3.36
R4	0.31	-0.58	0.27
R5	-0.60	0.42	0.19
R6	0.57	-1.46	0.89
Station #2			
R2	-0.08	-4.08	4.15
R3A	-2.67	7.28	-4.61
R3B	0.11	4.57	-4.68
R6	0.04	-1.48	1.44
R7	-0.39	1.80	-1.41

$$eMean = \frac{\sum_{i=1}^{n}(E_{1,i}-E_{2,i})}{n} \quad (11)$$

$$eRMS = \sqrt{\frac{\sum_{i=1}^{n}(E_{1,i}-E_{2,i})^2}{n}} \quad (12)$$

TABLE V. RMS ERRORS (IN DECIBELS) BETWEEN MEASURED AND PREDICTED FIELDS FOR ASSESSED AND ITU ATLAS σ VALUES

Route	*E (assessed σ) vs. E (measured σ)*	*E (ITU σ) vs. E (measured σ)*	*E (assessed σ) vs. E (ITU σ)*
Station #1			
R1	3.29	10.38	9.78
R2	4.56	4.88	1.89
R3	4.33	5.72	4.35
R4	2.50	2.55	0.27
R5	3.71	3.66	0.21
R6	6.87	7.45	1.24
Station #2			
R2	5.23	6.61	4.16
R3A	4.85	7.96	4.75
R3B	5.00	6.93	4.69
R6	1.68	2.01	1.47
R7	5.39	5.69	1.45

In (11) and (12), computed for every single route, $E_{1,2,i}$ are each of the n^{th} pair of fields being compared. Parameter n is the number of measurement sites in the route. Predicted field values to be input in these expressions were derived through linear interpolation of the predicted field (originally calculated for each kilometer) for the d_i value of the site where the measurement was done. Even for the comparison between predicted fields (third column in Tables IV and V), the only chosen field values to compute the error were the ones corresponding to the measured distances d_i (it was done to provide the same basis for comparison).

Regarding "ITU σ" in both Table IV and Table V, i.e, predicted field using conductivity obtained from the ITU worldwide atlas, σ = 1 mS/m is the value for every route with the exception of route R3B (Station #2), which has an ITU σ value of 4 mS/m. Due to this different σ value along a path, route R3 for station #2 was broken into two routes, in order to allow the comparison between the assessed and ITU recommended σ values. The field intensity registered along that path showed increased values when reaching the separation of regions. This fact is in accordance to the higher σ value recommended by the ITU atlas and to the value retrieved in this work, for the second portion of path R3 (R3B, Station #2).

Regarding the errors, for both tables the value in the first column is lower or equal to the one for the same route in the second column (for mean errors, the absolute value is the one of concern). With respect to mean errors, it means that the measured values are more uniformly distributed above and below the curves for the fields computed from the assessed σ values. Moreover, when analyzing the RMS errors, the lower values in the first column mean that the field curve for the assessed σ values is the one leading to the best overall fit to the measured field values. From the obtained results, the methodology for σ retrieval seems to have adequate performance: as expected, the field curves computed with these values follow the trend of measured values, with no remarkable offset or deviation.

The third column in Table V provides a quantitative perception on how far predicted fields using assessed σ values are from the ones computed using σ values in the ITU atlas. It is just another way of analyzing the results, providing no further information. In the case of Table IV, this same column is the difference between the other two.

According to the results in Table III, the ground for every route relative to Station #1 has conductivity values equal or above the one in the ITU global atlas. Although more measurements should be done, if this trend is confirmed propagation of ground waves over these terrains extend somewhat longer than ITU predicts which could impact coordination distances for neighbor broadcast systems. As far as Station #2 is concerned, there is no clear behavior: some σ values are higher and others are lower than the ones recommended by ITU.

V. Conclusions

Results for electric field intensity in the MF frequency band were presented for several routes over São Paulo state, in Brazil. The field strength was used for the retrieval of the effective ground conductivity, a major parameter impacting the planning of the forthcoming commercial digital radio systems to be adopted in Brazil. The results presented in this work point that there are differences with respect to Recommendation ITU-R P.832-3 for the considered region. More measurements must be made in order to complement the current database and then to continue helping the improvement of the atlas accuracy.

For future works, it is envisaged the creation of a digital map through interpolation over measured points and also the definition of a methodology for the identification of the point in a given route after which the route should be broken into two (and then another effective conductivity value should be assessed for the remaining path).

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