Evaluation of Possible Corrosion ~~Enhacement~~ Enhancement Due to Telluric Currents: Case Study for ~~Brazilian~~ Brazil Bolivia – Pipeline

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Abstract. Electric field induced in the “Brazil – Bolivia” pipeline was calculated using a distributed source line transmission (DSLT) theory during several space weather events. It was made with using geomagnetic data collected by a fluxgate magnetometer located at São José dos Campos ($23.2^oS; 45.9^oW$). The total corrosion rate was calculated with using the Gummow (2002) methodology and based in the assumption of 1-cm hole in pipeline coating. The calculations were performed for the ends of pipeline, where the largest "out of phase" pipe-to-soil potential (PSP) variations were obtained. The variations in PSP during the 17th March 2015 magnetic storm have led to the ~~corrosion rate beyond the acceptable limit for the system~~greatest corrosion rate of the analysed events. All the space weather events evaluated with high terminating impedance ~~in this paper have~~ must contributed to increase the corrosion process. The applied technique can be used to evaluate the ~~metal loss~~ corrosion rate due to the high telluric activity associated with the geomagnetic storms at specific locations.

1 Introduction

Telluric electric currents that flow within the Earth or on its surface are significantly enhanced during disturbances of the Earth’s magnetic field (magnetic storms).These currents can propagate through conducting systems at the Earth’s surface, such as, pipelines (Campbell Alaska pipeline), phone cables (Anderson et al., 1974), and electrical power systems (Lanzerotti et al., 1999), which in extreme events can produce blackouts (Guillon et al., 2016).

The Geomagnetic Induced Currents (GIC) propagation throughout pipelines can changes the pipe-to-soil potential (PSP) which changes the electrochemical environment at the pipeline surface, which can take to a corrosion process. In pipelines cathodically protected, the PSP is maintained at negative potential of at least -850 mV. Fluctuations in PSP caused by GICs can lead the potential beyond -850 mV, resulting in corrosion (Seager, 1991). According to Place and Sneath (2001), PSP fluctuations also interfere in pipeline surveys.

Previous works on this topic GICs were done in high latitudes, which revealed specific interactions of geomagnetic field with solar wind disturbances (Campbell, 1980; A. Fernberg et al., 2007). Effects of GICs in pipelines have been observed and published also in Argentina (Osella et al., 1998), Australia (Marshall et al., 2010) and New Zealand (Ingham and J. Rodger, 2018), where engineers had tried to find ways to dealing with the problem.

Boteler and Cookson (1986) have shown that the telluric voltage induced on a pipeline can be calculated using distributed source transmission line (DSTL) equations and telluric effects in pipeline is influenced not only by space weather events, but it is also dependent on the Earth's conductivity, the pipeline electromagnetic properties and geometric parameters. These calculations, when applied to modern well-coated pipelines, suggest that telluric current effects may not be as innocuous as originally thought especially for long pipelines located in high latitudes (Gummow, 2002). The DSLT theory was first described in Schelkunoff (1943) and has been used in several studies (Pulkkinen et al., 2001).

In this paper, the model for induced effects in pipelines proposed by Trichtchenko and Boteler (2002), using the DSLT theory, is used to compute the loss of material corrosion rates in Bolivia- Brazil gas pipeline (GASBOL) during chosen space weather events , with focus on 17th March 2015 Geomagnetic Storm. The GASBOL is the largest pipeline in Latin America, with a total extension of 3.159 3,159 km, extending from Rio Grande, Bolivia, to Canoas, Brazil. It is the main responsible by responsible by the main amount of gas transportation in Brazilian territory. The GASBOL is buried about 0.5 m in the ground to ensure it integrity.

2 Instrumentation and Methodology

2.1 Magnetometer

The Earth's magnetic field and its variations are recorded at geomagnetic observatories and station stations all over the globe. In the present manuscript, we have used magnetic measurements from São José dos Campos (23.2^oS; 45.9^oW) station to study the corrosion produced by GICs in the first GASBOL route (Rio Grande (17.8^oS; 63.1^oW) to Paulinia(22.8^oS; 47.1^oW) which has 1814 km of length. The location of the GASBOL route under study and the magnetic station location are shown in Figure 1.The red line represents the geomagnetic equator. We chose 8 events to study the effects of space weather in the pipe with different intensities. The events was chosen based on Disturbed Storm Time Index (DST), as it is shown in Table 1.

Table 1. DST Index of the events in 2015

Date	17/03	23/06	07/11	09/01	27/04	07/02	03/08	27/10
$DST_{min}(nT)$	-222	-204	-89	-62	-29	-25	Quiet day	Quiet day

Such magnetic station is part of the Embrace MagNet and it is operated by the "Brazilian Studies and Monitoring of Space Weather" (Embrace/INPE). The Embrace MagNet cover most of the eastern South American longitudinal sector (Denardini et al., 2015). This network fills the gap with magnetic measurements available online in this sector and aims to provide magnetic

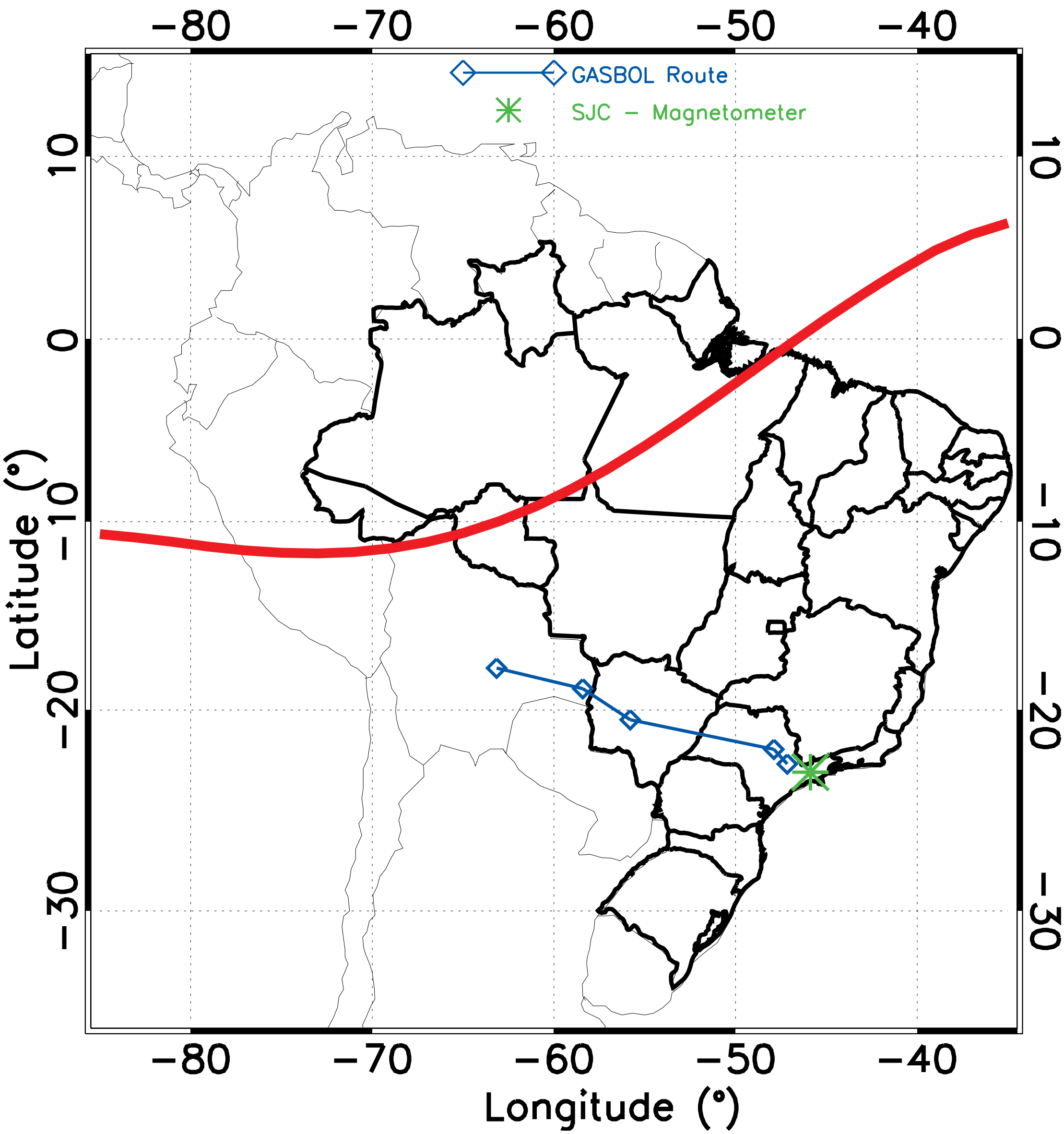

Figure 1. Bolivia - Brazil Gas Pipeline Route(solid line), bends(diamonds) and São José dos Campos (23.2^{o}S; 45.9^{o}W) Magnetic Observatory (star).The red line represents the geomagnetic equator. The route length is 1814 km

data to be used to study changes in space weather. All the details on the magnetic network, type of magnetometers, data resolution, data quality control, and data availability are provided by (Denardini et al., 2018).

2.2 Electric Field

The electric fields produced by geomagnetic disturbances drive electric currents in into the Earth. These currents are one of the responsible to cause fluctuations in PSP. According to Trichtchenko and Boteler (2002), GICs have the effect of shielding the interior of the Earth from the geomagnetic disturbance. As the magnetic and electric fields are dependents on the conductivity structure of the Earth, the variation of the conductivity with depth was modelled modeled using multiple horizontal layers with a different uniform conductivity. The Earth model layers organized in Table 1 and used in this paper was obtained in São José dos Campos in previous geophysical surveys and published by (Padilha et al., 1991).

Table 2. Multiple Horizontal Layers Model

Layers	1	2	3	4	5	6
Thickness(m)	0.2	10	2	20	200	-
Resistivity(Ω.m)	160	12	5000	500	5000	300

Source: Padilha et al. (1991)

The electric field in the surface can be obtained from

$$E_{surface} = zH_{surface} \tag{1}$$

where H is the magnetic field component obtained from the magnetometer and z is the surface impedance obtained from the applying the recursion relation for the impedances at the multiple horizontal layers (Trichtchenko and Boteler, 2002). In our case, we are considering z as a scalar, hence, the $E_{surface}$ is orthogonal to $H_{surface}$.

2.3 DSLT Theory

The electrical response of a pipeline can be modeled by the distributed source transmission line (DSTL) equations. In the DSTL approach, each uniform section of the pipeline is represented by a transmission line circuit element with specific series impedance and a parallel admittance. The PSP voltage in any section of the pipeline can be calculated applying (Trichtchenko and Boteler, 2002) equation

$$V_p = E_p/\gamma(A_p e^{-\gamma(x-x_1)} - B_p e^{-\gamma(x_2-x)})) \tag{2}$$

where E_p is the electric field induced in the pipe, x_1 and x_2 are the positions of the ends of the pipeline, A_p and B_p are constants dependent on the boundary conditions at the ends of the pipeline, and and γ is the propagations constant along the pipeline, defined as $\gamma = \sqrt{ZY}$, and $Y = G + iwC$ is the parallel admittance and $Z = R + iwL$ is the series impedance per unit length with G = conductance to ground, C = capacitance, R = resistance of pipeline steel, L = inductance. Equation (2) is a solution of a partial differential equation, then A_p and B_p are constants dependent on the boundary conditions at the ends of the pipeline. According to Trichtchenko and Boteler (2002), the pipeline is independent of frequency, for that reason, C and L, were not necessary to apply the theory. From the same argument, we can consider the $E_p = E_{surface}$

The According to Trichtchenko and Boteler (2002), 0.1 ohms means low resistance connection to ground, and 1000 ohms means no ground connection. Since the termination impedances are unknown in our case, then, it was applied the theory we considered 5 terminating impedances (0.1 ohmohms, 1 ohm, 10 ohm10 ohms, 100 ohm ohms, and 1000 ohmohms). The circuit characteristics for the DSTL modelling of GASBOL of GASBOL were obtained from the company website and material manufacturers for the pipeline industry and they are shown in Table 2. 3 .

2.4 Loss Material Corrosion Rate Estimation

Gummow (2002) suggested a general expression to estimate the corrosion rate (in mm/year) through a 1 cm diameter hole in pipeline coating given by:

$$CR = 31.25VF(p)F(t) \quad (3)$$

where V is the change in PSP, F(p) is the percentage of direct corrosion current due to an alternating current in a given period, and F(t) is the fraction of time for which the pipe was unprotected, which is dependent of the geomagnetic activity. Gummow (2002) quoted 0.025 mm/year as the generally acceptable maximum value for corrosion rate in a pipeline. In this work, the CR was computed only for cases when the cathodic protection level was greater than -850 mV.

3 Results and Discussion

Figure 2 shows the electric field obtained during the 17th March 2015 magnetic storm. The electric field was obtained using the Equation 1. The eastward electric field was greater than 0.15 V/km, and the northward electric field reached 0.05 V/km. These peaks were observed during the main stage of the magnetic storm. The larger values in the east component occur because the variation in of a geomagnetic direction leads to a change in the electrical component in perpendicular direction. For this event, the magnetic component By (north direction) presented the greatest values.

The geomagnetic field variation rate is a function of the latitude where the measurements are made and the ionospheric current system, which can affect the amplitudes of the variations. According to Trivedi et al. (2005) larger amplitudes of the magnetic horizontal component are can be caused by the increase of electron precipitation in the South Atlantic Magnetic

Table 3. GASBOL Technical Informations

Coating thickness(in)	0.156
Coating conductivity(S/m^2)	10^{-6}
Diameter(in)	32
Steel thickness(in)	0.5
Steel resistivity(Ω.m)	2.10^{-7}

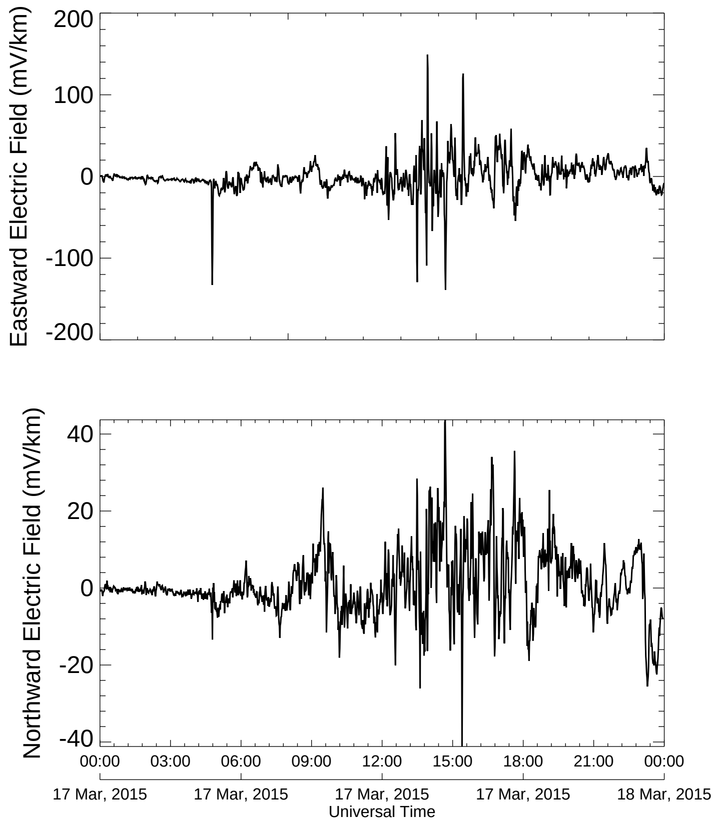

Figure 2. Eastward (top) and Northward (bottom) Electrical Field obtained by Magnetic Datas Data on 17^{th} March 2015 Geomagnetic Storm.

Anomaly (SAMA) region , which is present in Brazil, can affect the GIC amplitudes. The influence of SAMA area . The SAMA is a region with a minimum intensity of the geomagnetic field. This fact implies in a major entrance of high-energy particles (Heirtzler, 2002). The region also coincides with a region in space close to with the intensive presence of radiation. According to Paulikas (1975) ionospheric ionization is produced in the E layer of the ionosphere when energetic particles come closest to the Earth's surface and interact with the dense atmosphere. This procedure increases the ionospheric conductivity which lead to the rise of the Earth with intensive radiation, which is attributed to the entrance of high-energy particles in the magnetosphere (Heirtzler, 2002)GIC intensity during disturbed periods.

Variations in the magnetic field, that cause changes in the electric field, create GICs, which are responsible by for PSP fluctuations. The PSP computed was computed for each point in the GASBOL , which is cathodically protected, are shown in using Equation (2). Figure 3 and 4. Figure 3 shows the PSP at different sites of the pipeline with low terminating impedance

(0.1 ~~ohm).~~ ohms). Which site represents a position in the pipeline, that begins in $x = 0$ km and ends in $x = 1814$ km, which represents the total extension of the first route of the pipeline. Figure 4 ~~is observed~~ also contains the PSP at different ~~locations~~ sites with high terminating impedance (1000 ~~ohm~~ohms). The constants lines are the safe ~~operation~~ operating region of the pipeline (-0.85 V and -1.45 V).

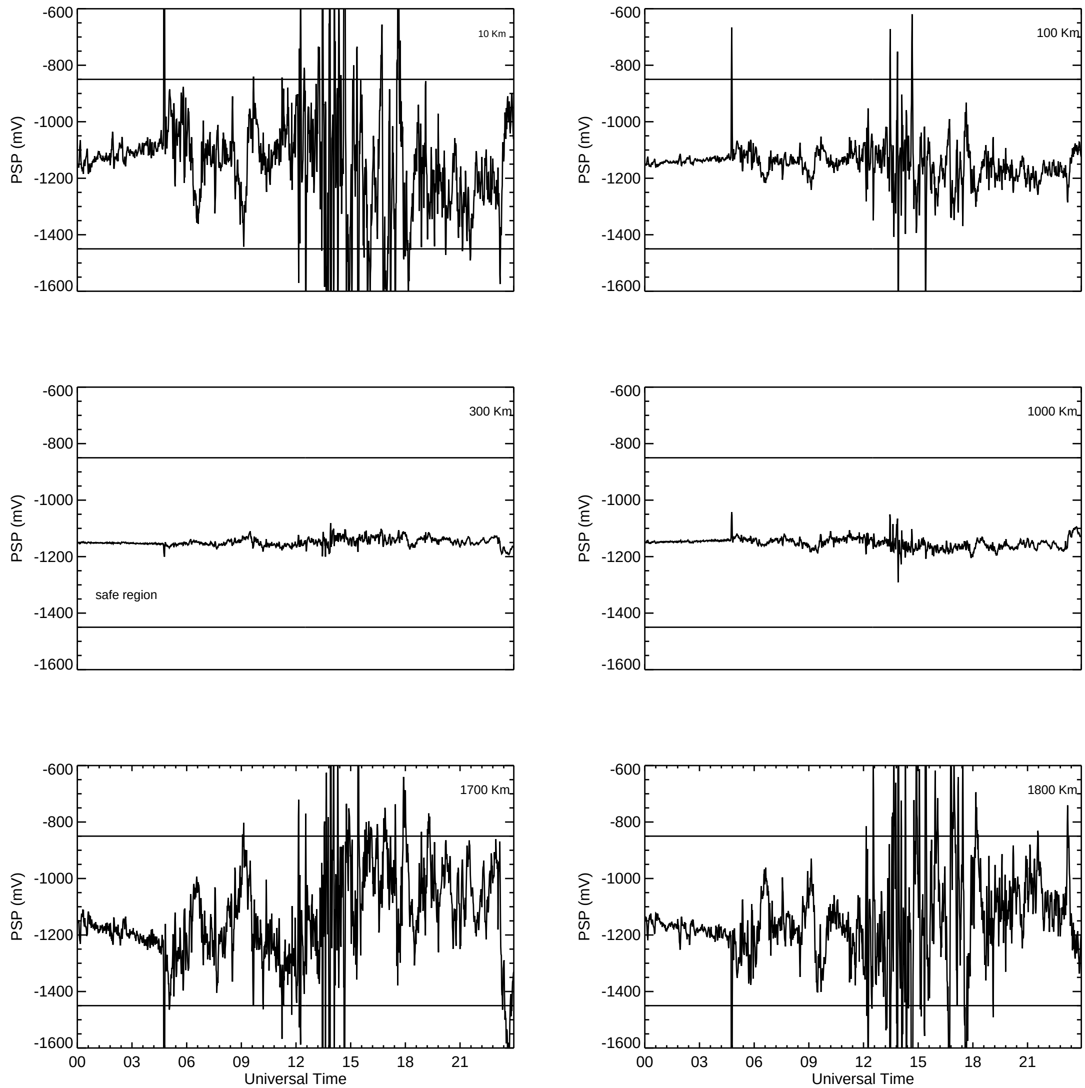

Figure 3. Pipe-to-soil potential obtained by DSLT theory for different sites (values in km at the top) on the GASBOL pipeline for ~~low~~ a terminating ~~impedance~~ impedanceof 0.1 ohms on 17^{th} March 2015 Geomagnetic Storm. Solid lines delimit the safe range of the GASBOL operation. The route has a total extension of 1814 km

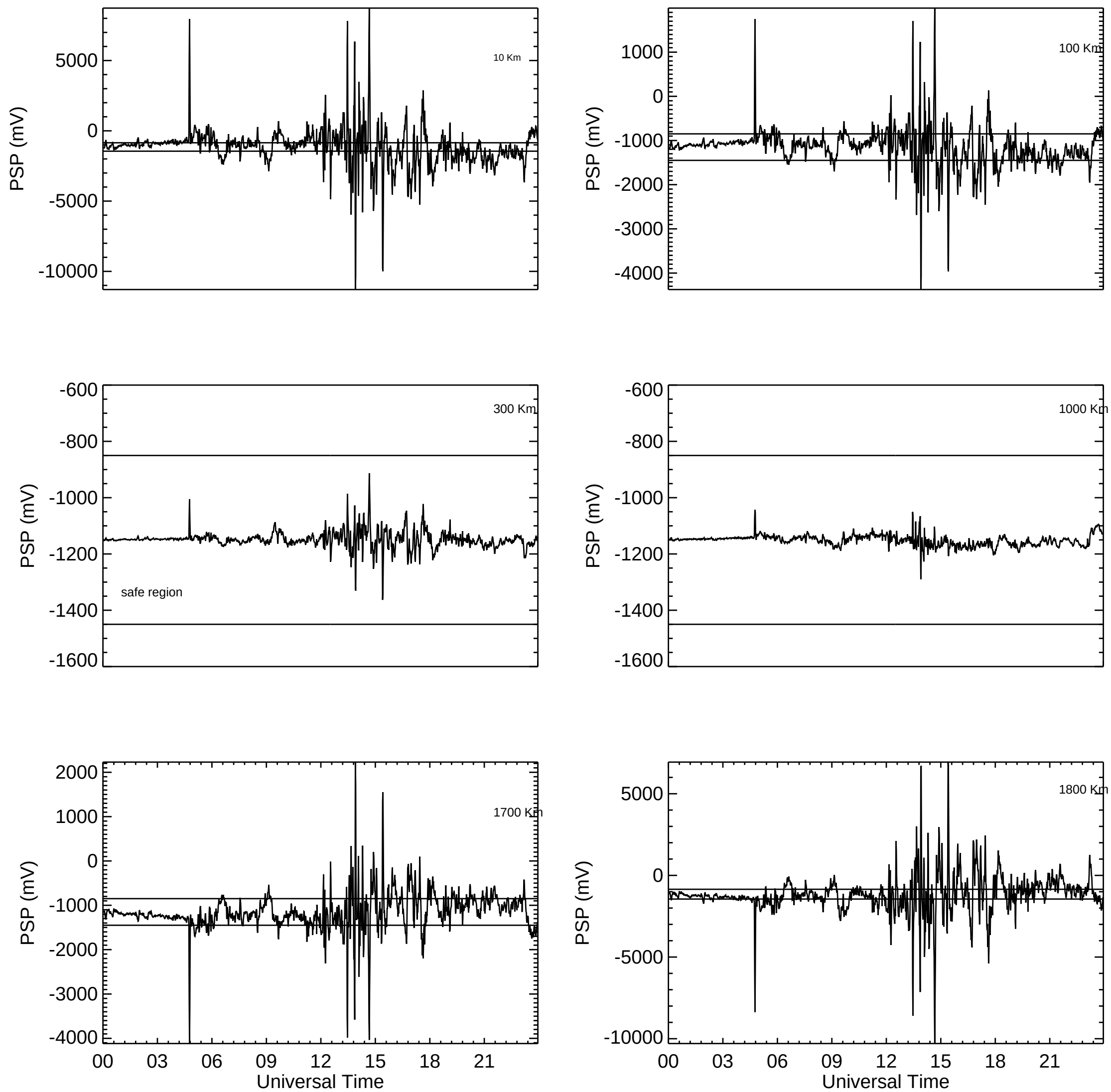

Figure 4. Pipe-to-soil potential obtained by DSLT theory for different sites (values in km at the top) on the GASBOL pipeline for ~~high~~ a terminating impedance of 1000 ohms on 17^{th} March 2015 Geomagnetic Storm. Solid lines delimit the safe range of the GASBOL operation.

It is possible to observe that in both cases the largest variations in PSP is relative to the largest variations in electric field, that occurred in the main stage of the 17th ~~march~~ March geomagnetic storm. The PSP was out of the safe region to low terminating impedance, and mainly ~~,~~ when the pipe was considered with high terminating impedance. The terminating ~~impedance~~ impedances are responsible to allow the entrance of GICs in the pipe, and high terminating impedance is relative to the pipe connected to the ground.

From Figures 3 and 4, it was also observed that the largest PSP fluctuations were ~~in~~ at the ends of the pipe. This result is confirmed in Figure 5, which is a profile of the PSP as a function of the length of the pipe at 13 UT, on 17th March 2015. This result confirms the mathematical theory described by Boteler and Seager (1998).According to ~~that~~ those authors, it produces a movement of electrical charge away from one end and a buildup of charge at the other end, resulting in the S-shaped potential profile observed. At ~~one end~~the beginning of the pipe up to 250 km, the negative variation of the potential of the pipe with respect to the ground causes a current to flow onto the pipe~~; whereas at the other end, positive~~ . Meanwhile, on the other side, at about 1600 km, positive variation potential causes the current to leave the pipe.

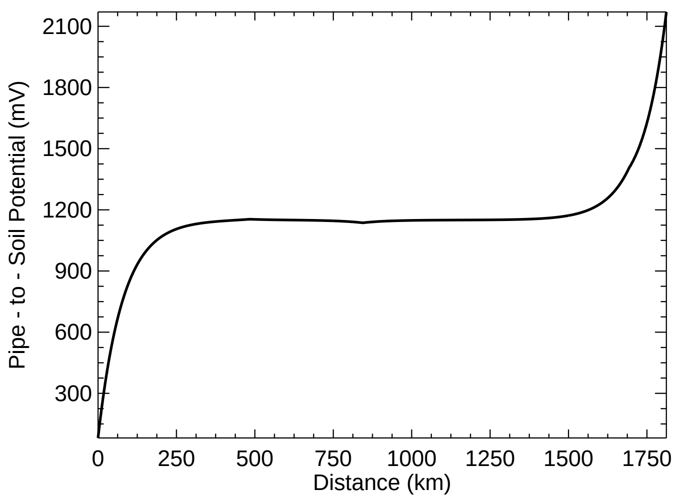

Figure 5. Pipe-to-soil potential profile as function of the distance along the pipeline at 13 UT on 17 March 2015.

Figure 6 and 7 shows the ~~estimate loss of material~~ corrosion rates in GASBOL as a function of the terminating impedances as well to 8 space weather events in 2015. The corrosion rate was estimated using Equation (3). The events were set by the ~~geomagnetic activity intensity~~intense geomagnetic activity, using the DST index. Figures 6 ~~are relative~~ is related to loss of material during strong ($DST_{min} < 100$) and moderated($< -30 < DST_{min} < -100$) geomagnetic storms. Figures 7 show the weak storms ($DST_{min} < 30$) and quiet days. The ~~dotted line, plotted only in Figure~~ markers in Figures 6 ~~is the acceptble limit to~~ and 7 are related to the different event for each level of storm intensity. The acceptable limit to the corrosion rate quoted by Gummow (2002) ~~-~~

is $0.025 mm/year.$

In Figure 6a it is possible to observe that the ~~loss of material during strongs~~ corrosion rate during strong geomagnetic storms was greater than 0.005 mm~~to terminating impedances greater than~~ /year when the terminating impedances were above the 1 ~~ohm for both cases. Moreover, the loss of material~~ ohms. In addition, the corrosion rate presented constant values to impedances greater than 10 ~~ohm~~ohms/km. During the 17th March ~~geomagnetic storm~~2015 geomagnetic storm (star), the loss was ~~greater~~

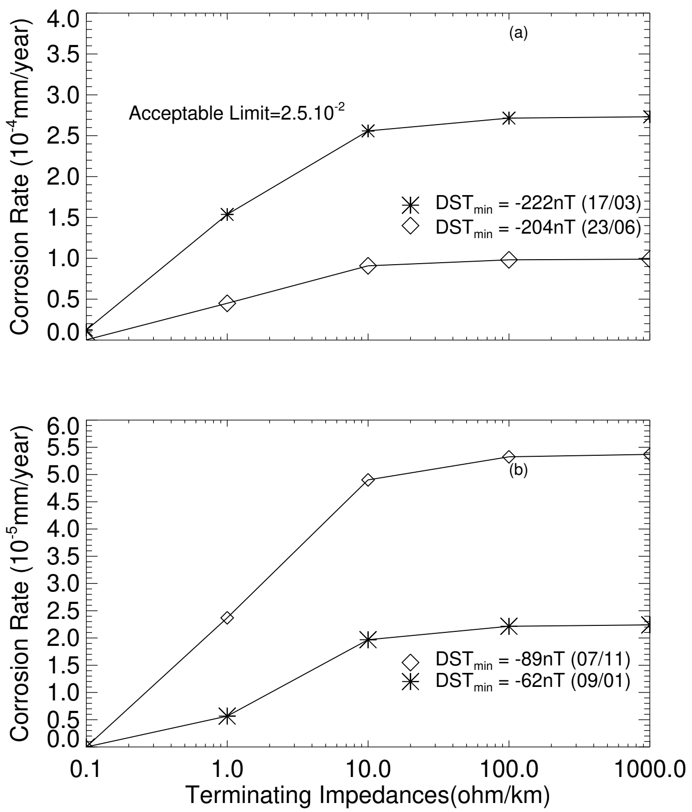

Figure 6. ~~Metal loss estimation~~ Corrosion rate as a function of the terminating impedances for strong (a) and moderated(b) geomagnetic storms. The ~~dashed line represent the~~ acceptable limit of corrosion is indicated at the top painel.

~~than the accepteble limit~~ the greatest for all impedances ~~greater than~~ above the 10 ~~ohm~~ohms. Figure 6b is relative to moderated storms. It shows that the 7th November 2015 (diamond) reached greater values than ~~2.10^5~~ 2.10^{-5} mm for impedances equal and greater than 1 ohm/km. These results are close to loss of material observed on ~~23th~~ 23rd June geomagnetic storm (diamond on the Figure 6a), considered strong, however, the loss of material was not close to the 17th March 2015 storm, which was 10 times greater than the moderated storms.

Figure 7a shows the corrosion rates for weak storms. It is possible to observe that the loss of material on 07th February 2015 geomagnetic storm was close to the result found in ~~01th January~~ 01st January 2015 storm and for impedances greater than 1 ohm, the loss of material was greater. In quiet days (Figure 7b), with no geomagnetic storms, the results ~~was reduced related~~ were reduced relative to weak storms, reaching maximum values about ~~2.10^{-5}~~ 2.10^5 mm in maximum impedances. In general, ~~strongs storms presented~~ strong storms have more significant values when ~~it~~ compared to weak, moderate and quiet days.

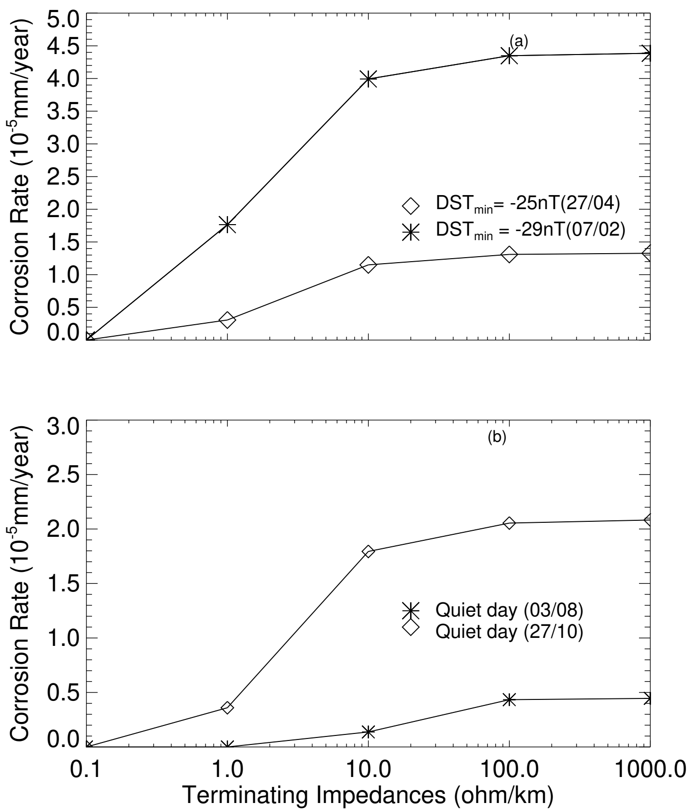

Figure 7. ~~Metal loss estimation~~ Corrosion rate as a function of the terminating impedances for weak geomagnetic storms (a) and quite day (b).

A. Martin (1993) observed corrosion rates in the north region of Australia (similar latitude to Brazil). They found corrosions rate ranging between 0.01 mm/year and 0.038 mm/year. According to the ~~author, this is responsible by a~~ A. Martin (1993), high corrosion rate is responsible for penetration in pipe of 10 % in 14 years. Henriksen et al. (1978) studied a Norway pipeline with 300 telluric events found a corrosion rate of 0.04 mm/year caused by these events.

Considering that geomagnetic storms occur several times a year, primary during the high solar activity periods there would be many days when currents are flowing along the pipes. According to Osella and Favetto (2000) ~~this fact implies two main risks . The first one is directly correlated with the enhancement~~ two risks are related to this. One of them is related to the enforcement of the induced current when the pipe is ~~embedded in more resistive media; a~~ installed in a less conductive medium. This implies that a sector of the pipe would be ~~anodic with respect to the other, with the consequent risk that the excess of the currents could drain~~ the anode, and the soil, would be the cathode. This configuration is responsible for the penetration of the excess of currents through the pipe, to the soil. ~~Moreover, as the common practice is to increase the current if the medium is conductive the final result would lead to an actually improper setting of the cathodic protection voltages.~~ The other risk is ~~related to the intensity of the currents, since values of some amperes could contribute to the degradation of the coating~~ associated with the deterioration of the coating caused by high levels of current intensity.

4 Summary

The presented application of the DSLT theory to evaluate the ~~metal loss in the~~ corrosion rate in first Bolivia - Brazil gas pipeline route has provided ways to a new understanding of telluric current effects on the pipeline during extreme space weather events. The use of magnetometer data to compute the electrical field, allows to ~~estimate~~ estimating the PSP and ~~metal loss~~ corrosion rate which brought the following conclusions:

1. The electrical field peaks were computed on 17th March geomagnetic storm ~~occured in~~ occurred at the same time of the main stage of the storm, and the currents generated could arrive in Brazil by compressional waves or surface waves.

2. The GASBOL pipeline presented fluctuations in PSP which exceed the cathodic protection levels caused by GICs, mainly in the ends of the pipe with high and low terminating impedances during the 17th March geomagnetic storm.

3. The GASBOL presented significant corrosion levels for terminating impedances greater than 10 ohm/km, mainly in the 17th Geomagnetic Storm. Beside the event did not exceed the ~~accepetble~~ accepetable level, but they can contribute to accelerate the corrosion process of the pipe. Therefore, the effects of GICs in pipelines can not be negligible, even in middle latitudes, since they can reduce the lifetime of a pipeline.

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