Evaluation of Possible Corrosion Enhacement Due to Telluric Currents: Case Study for ~~Brazilian~~ 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 greatest corrosion rate of the analysed events. All the space weather events evaluated with high terminating impedance in this paper have contributed to increase the corrosion process. The applied technique can be used to evaluate the metal loss 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 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 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.

5   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

10   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 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 km, extending from Rio Grande, Bolivia, to Canoas, Brazil. It is the main responsible by gas transportation in Brazilian

15   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 all over the globe. In the present manuscript, we have used magnetic measurements from São José dos Campos (23.2^{o}S; 45.9^{o}W) station to study the

20   corrosion produced by GICs in the first GASBOL route (Rio Grande (17.8^{o}S; 63.1^{o}W) to Paulinia(22.8^{o}S; 47.1^{o}W). The location of GASBOL route under study and the magnetic station location are shown in Figure 1.

     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

25   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 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

30   interior of the Earth from the geomagnetic disturbance. As the magnetic and electric fields are dependent~~s~~ on the conductivity structure of the Earth, the variation of the conductivity with depth was modelled using multiple horizontal layers with a different
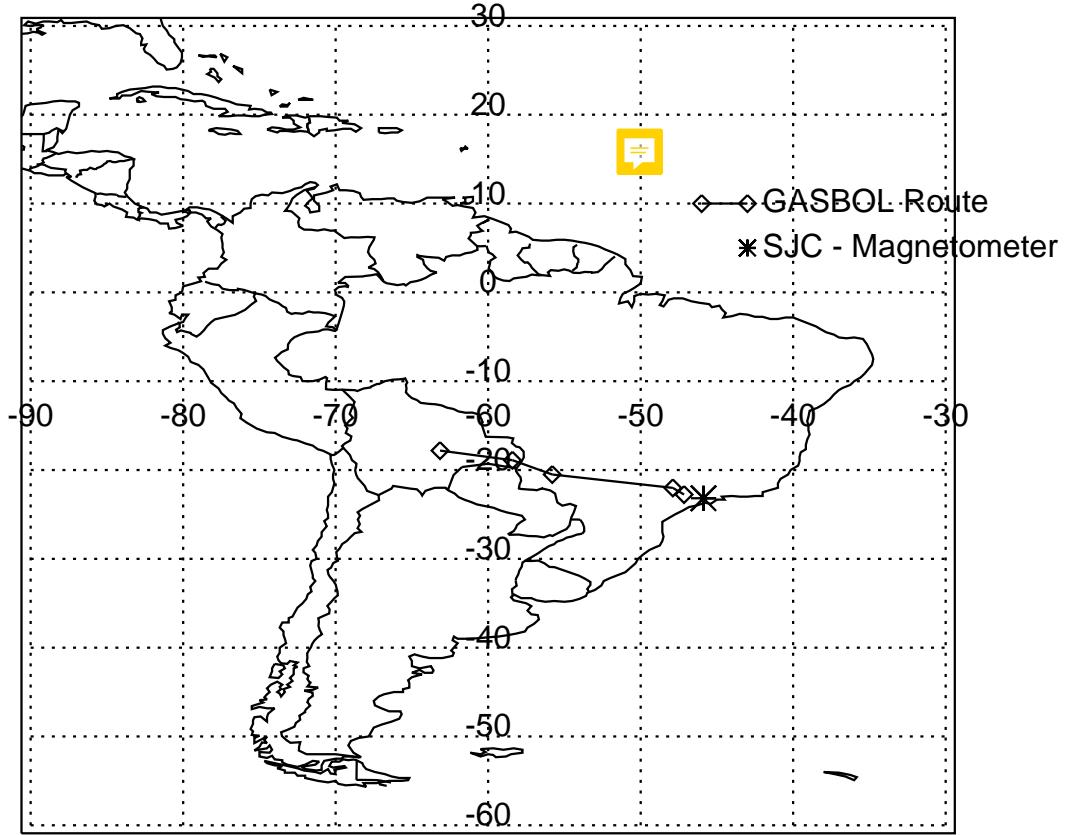
Figure 1. Bolivia - Brazil Gas Pipeline Route(solid line), bends(diamonds) and São José dos Campos (23.2^{o}S; 45.9^{o}W) Magnetic Observatory (star).

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).

The electric field in the surface can be obtained from

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

Table 1. 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)

where H is the magnetic field component obtained from the magnetometer and z is the surface impedance obtained from the multiple horizontal layers (Trichtchenko and Boteler, 2002).

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 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 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 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. 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.

The termination impedances are unknown in our case, ~~then, it was applied the theory~~ considered 5 terminating impedances (0.1-ohm, 1 ohm, 10-ohm, 100 ohm and 1000 ohm). The circuit characteristics for the DSTL modelling of GASBOL are shown in Table 2.

Table 2. 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}

2.4 Loss Material 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:

$$CR = 31.25V F(p)F(t) \tag{3}$$

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 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 east component occur because the variation in of a geomagnetic direction leads a change in electrical component in perpendicular direction. For this event, the magnetic component By (north direction) presented 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~~ caused by the increase of electron precipitation in the South Atlantic Magnetic Anomaly (SAMA) region, which is present in Brazil, can affect the GIC amplitudes. The influence of SAMA area coincides with a region in space close to the Earth with intensive radiation, which is attributed to the entrance of high-energy particles in the magnetosphere (Heirtzler, 2002).

Variations in the magnetic field, that cause changes in electric field, create GICs, which are responsible ~~by~~ PSP fluctuations. The PSP computed in the GASBOL, which is cathodically protected, are shown in Figure 3 and 4. Figure 3 shows the PSP at different sites of the pipeline with low terminating impedance (0.1 ohm). Figure 4 ~~is observed~~ the PSP at different locations with high terminating impedance (1000 ohm). The constants lines are the safe operation region of the pipeline (-0.85 V and -1.45 V).

It is possible to observe that in both cases the largest variations in PSP is relative to largest variations in electric field, that occurred in main stage of the 17th 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 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 the ends of the pipe. This result is confirmed in Figure 5, which is a profile of the PSP as 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~~ authors, it produces a
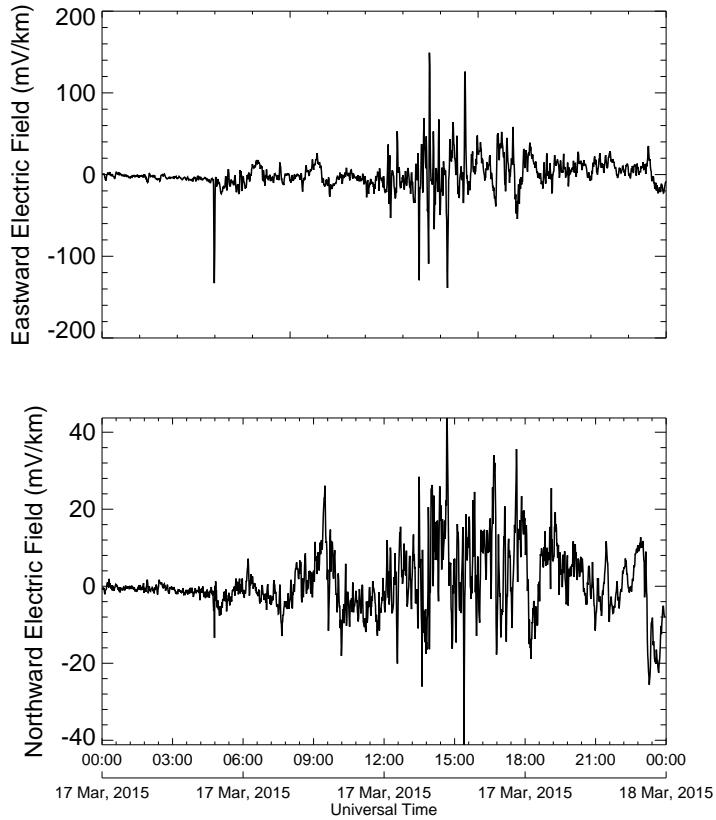
Figure 2. Eastward (top) and Northward (bottom) Electrical Field obtained by Magnetic Data on 17th March 2015 Geomagnetic Storm.

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. During one half electric field, the negative variation of potential of the pipe with respect to the ground causes a current to flow onto the pipe; whereas at the other half, positive variation potential causes the current to leave the pipe.

Figure 6 and 7 shows the corrosion rates in GASBOL as a function of the terminating impedances as well to 8 space weather events in 2015. The events were set by the geomagnetic activity intensity, using the DST index. Figures 6 are relative 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 acceptble limit to corrosion rate quoted by Gummow (2002), which is $0.025 mm/year$, is plotted in Figure 6(a).

In Figure 6a is possible to observe that the corrosion rate during strongs geomagnetic storms was greater than 0.005 mm to terminating impedances greater than 1 ohm for both cases. Moreover, the loss of material presented constant values to impedances greater than 10 ohm/km. During the 17th March geomagnetic storm, the loss was greatest for all impedances
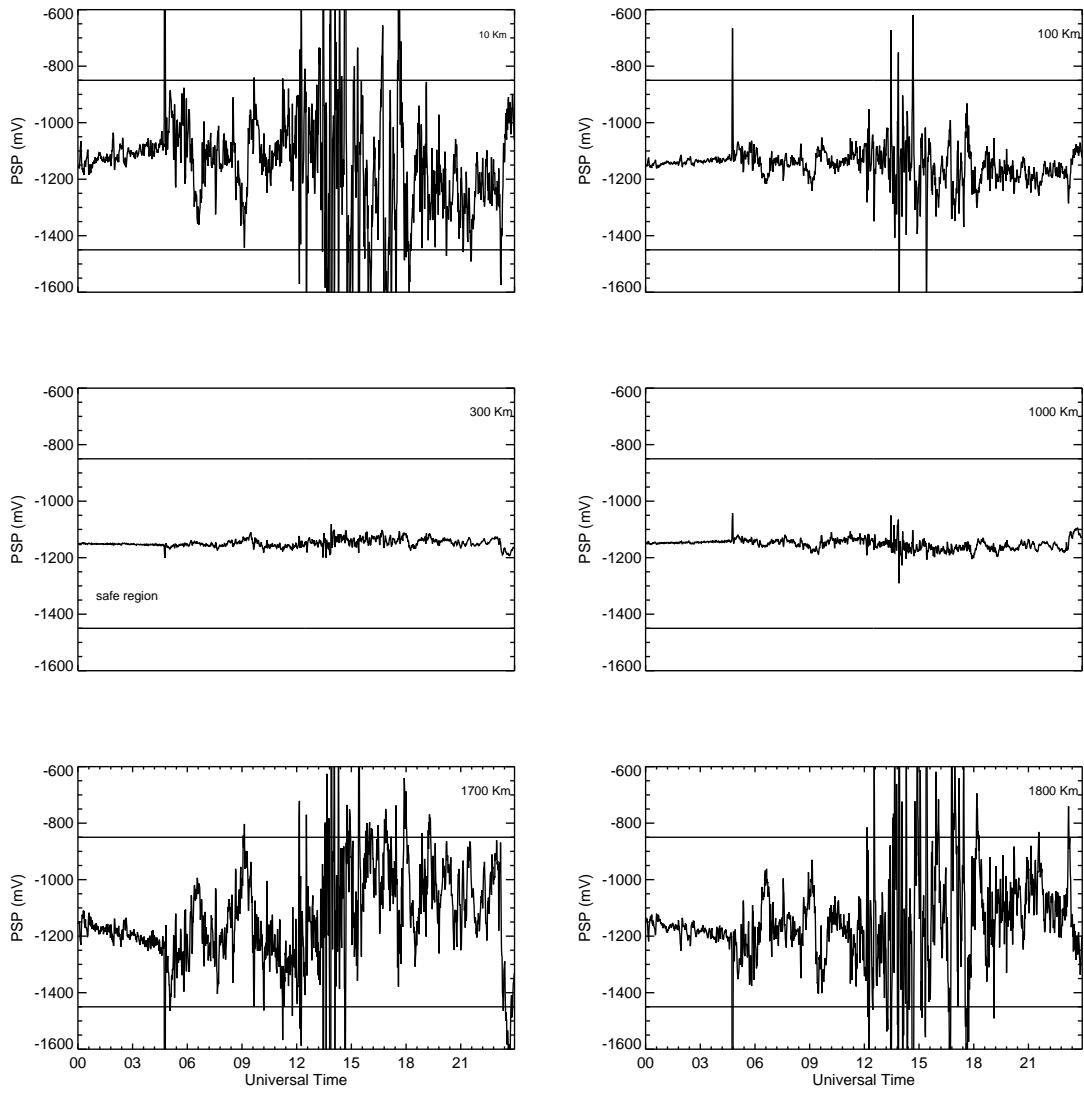
Figure 3. Pipe-to-soil potential obtained by DSLT theory for different sites on the GASBOL pipeline for low terminating impedance on 17th March 2015 Geomagnetic Storm. Solid lines delimit the safe range of the GASBOL operation.

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

5   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 storm and for impedances greater than 1 ohm, the loss of
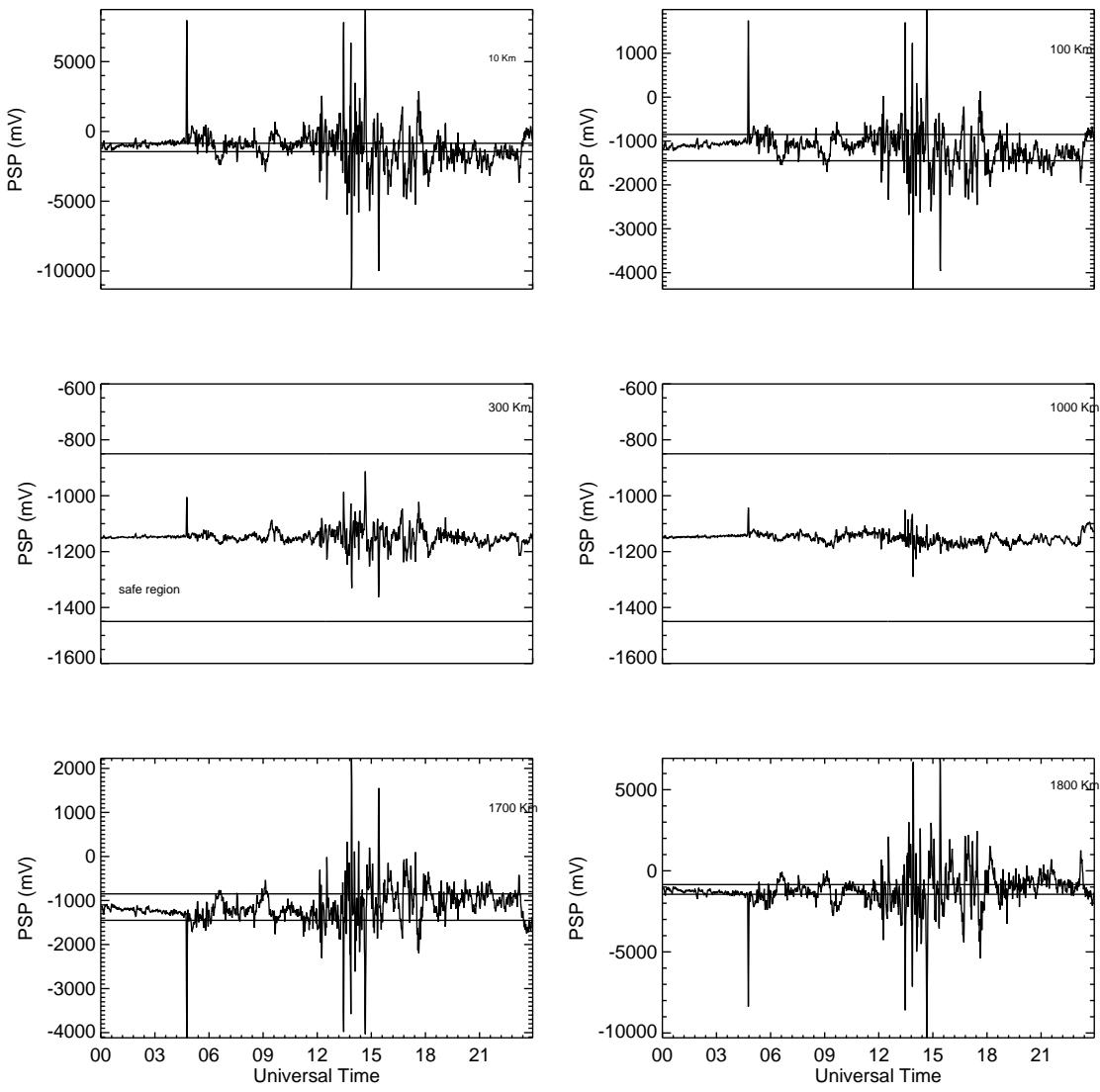
Figure 4. Pipe-to-soil potential obtained by DSLT theory for different sites on the GASBOL pipeline for high terminating impedance on 17th March 2015 Geomagnetic Storm. Solid lines delimit the safe range of the GASBOL operation.

material was greater. In quiet days (Figure 7b), with no geomagnetic storms, the results was reduced related to weak storms, reaching maximum values about 2.10^5 mm in maximum impedances. In general, strongs storms presented more significant values when it compared to weak, moderate and quiet days.

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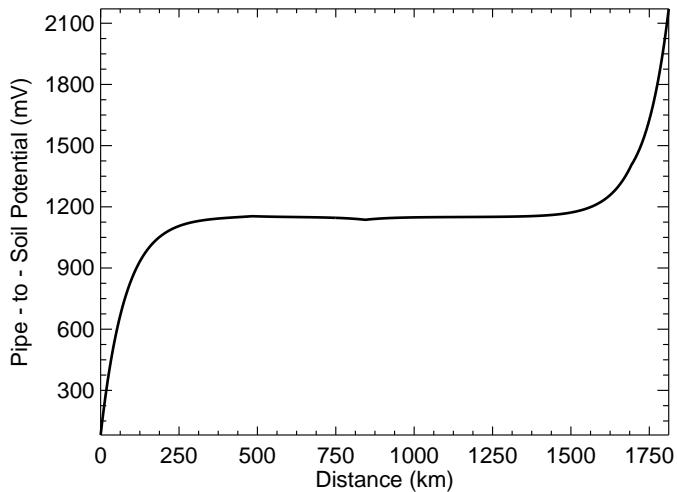
Figure 5. Pipe-to-soil potential profile as function of the distance along the pipeline at 13 UT on 17 March 2015.

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, 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 of the induced current when the pipe is embedded in more resistive media; 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 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.

4   Summary

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

1. The electrical field peaks were computed on 17th March geomagnetic storm occured in the same time of the main stage of the storm, and the currents generated could arrive in Brazil by compressional waves or surface waves.
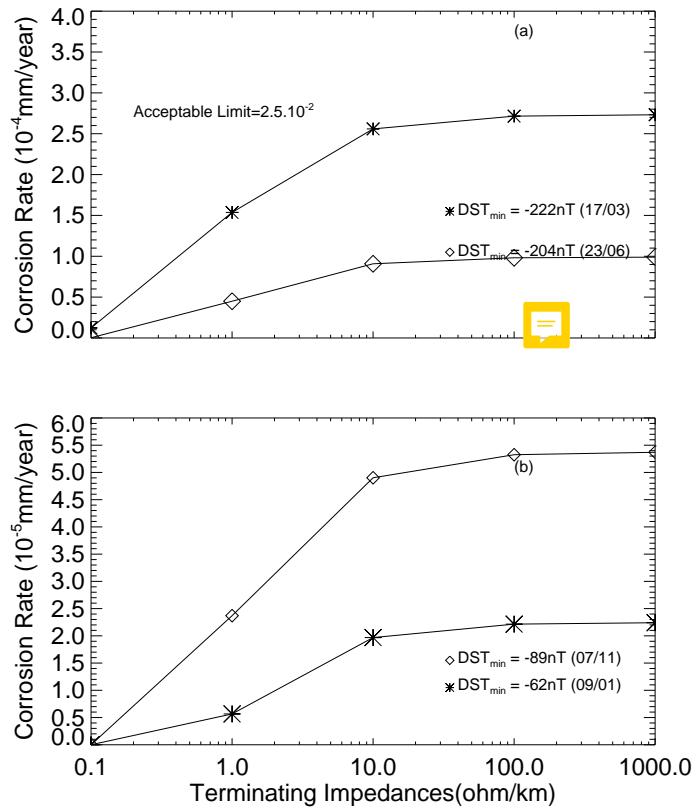
Figure 6. Metal loss estimation as a function of the terminating impedances for strong (a) and moderated(b) geomagnetic storms. The dashed line represent the acceptable limit of corrosion

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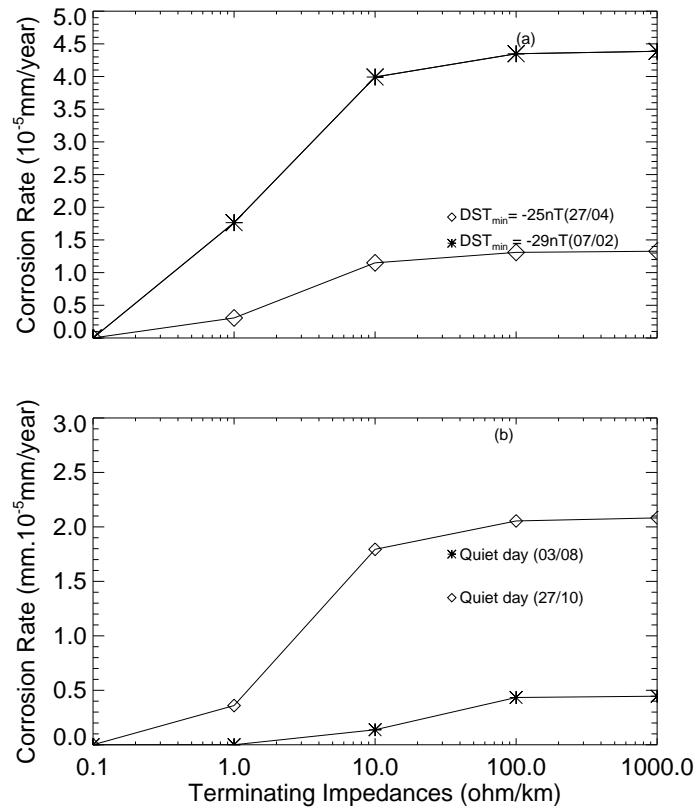
Figure 7. Metal loss estimation as a function of the terminating impedances for weak geomagnetic storms (a) and quite day (b)

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