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Instituto de Astronomia, Geofísica e Ciências Atmosféricas

Departamento de Geofísica

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# Atenuação de intensidades em terremotos intraplaca no Brasil com reavaliação de sismicidade histórica e implementação da ferramenta Macroseismic Intensity Data Online Publisher (MIDOP)

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Versão Corrigida. O original encontra-se disponível na Unidade.

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Orientador: Prof. Dr. Marcelo Sousa de Assumpção

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Agradeço também a Mario Locati (INGV, Itália) e novamente a Prof. Paola Albini pela disponibilização e suporte a implementação da ferramenta MIDOP no Brasil.

# RESUMO

Este trabalho é dividido em dois projetos: estudo da atenuação de intensidades em regiões intraplaca brasileiras com reavaliação de sismicidade histórica; e a implementação da ferramenta Macroseismic Intensity Data Online Publisher (MIDOP), capaz de disponibilizar dados macrossísmicos de intensidade na internet.

ATENUAÇÃO DE INTENSIDADES

Medidas de intensidade buscam quantificar a descrição qualitativa dos efeitos observados em um terremoto em termos de quão forte foi sentido e da quantidade de danos. Apesar de sua natureza qualitativa, dados de intensidade são essenciais no estudo de tremores de terra históricos e recentes, como em estudos de risco sísmico e em regiões onde faltam dados acelerométricos. A magnitude de terremotos históricos no Brasil tem sido determinada com relações que envolvem a magnitude e área sentida. Equações de atenuação de intensidades (diminuição da intensidade em função da magnitude, profundidade e distância) determinadas em outras regiões do mundo são intrinsicamente dependentes das características tectônicas crustais para onde foram calculadas e não podem ser aplicadas no Brasil sem uma avaliação apropriada. Foi determinada uma equação de atenuação de intensidades usando 20 terremotos no Brasil e regiões intraplaca vizinhas, no intervalo de magnitude 3.5 a 6.2 mb e distâncias hipocentrais de até 720 km.

O melhor modelo de atenuação foi $I = 0.995\,M - 1.505\log R - 0.00116\,R + 2.08$ (desv. pad. = 0.778) onde $M$ é a magnitude (mb) e $R$ a distância hipocentral (km). As incertezas de magnitudes estimadas usando essa equação são por volta de $\pm 0.72$ mb para eventos com 30 ou mais medições de intensidade.

Nós testamos a nova equação com dados de intensidade de dois importantes eventos: O terremoto *offshore* de 1939 no sudeste brasileiro (6 mb) e o terremoto venezuelano de 2018 (6.9 mb). O ajuste foi razoável para os dois terremotos, com um resíduo *rms* de 1.0 e 1.1 unidades de intensidade, respectivamente.

Nós também reavaliamos os tremores de 1861 (Lorena – SP) e 1946 (Cananéia – SP) no sudeste brasileiro.

O novo epicentro do evento de 1861 foi 23.1°S 44.7°O com magnitude de 5.0 mb. O epicentro foi localizando *onshore*, mas as incertezas estimadas incluem uma grande região *offshore*. Devido a isto, a localização do evento de 1861 permanece incerta.

O novo epicentro do evento de 1946 foi 24.9°S 47.7°O com magnitude de 4.3 mb. A localização do epicentro foi próxima da costa, com uma incerteza englobando semelhantemente as porções *onshore* e *offshore* (sem chegar ao talude). A nova localização é muito próxima do epicentro original para este terremoto, reforçando a possibilidade de o evento ter sido localizado *offshore*.

MIDOP

Quando trabalhamos com dados macrossísmicos de intensidade um dos principais problemas é a falta de uma plataforma que unifique a contribuição e pesquisa desse tipo de informação. É comum que cada pesquisador compile individualmente sua base de dados, possivelmente em diferentes formatos, e que nem sempre está disponível num meio digital.

Para superar tais problemas, o Archive of Historical Earthquake Data (AHEAD) coordenado no Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Milano na Itália desenvolveu a primeira solução dedicada a publicar dados macrossísmicos de intensidade na internet. A equipe do AHEAD criou MIDOP, uma solução que não requer experiência de programação *web* que permite usuários criarem uma interface simplificada e segura na internet, capaz de transformar tabelas de dados brutos em mapas interativos de intensidade. A interface permite buscar, baixar dados e contribuir informação macrossísmica, que estará disponível a qualquer usuário na internet.

Foi implementado MIDOP com um compilado de diversos terremotos históricos brasileiros (maioria eventos do livro “Sismicidade do Brasil” de Berrocal *et al.*, 1984). MIDOP está disponibilizado no endereço (acessado 31 de julho de 2019):

http://moho.iag.usp.br/midop/

A expectativa é de que MIDOP permitirá maior colaboração entre pesquisadores através do uso de formatos de arquivos padronizados e facilitação de acesso a dados macrossísmicos no Brasil.

**Palavras Chave:** intensidade, atenuação, macrossísmico, sismicidade histórica, midop.

# ABSTRACT

This thesis is split in two projects: an attenuation of intensities study of intraplate regions in Brazil with re-evaluation of historical seismicity; and an implementation of Macroseismic Intensity Data Online Publisher (MIDOP) tool, capable of publishing macroseismic intensity data on the web.

INTENSITY ATTENUATION

Intensity evaluation attempts to quantify a qualitative description of the effects observed in an earthquake ranked in terms of how strong it was felt and the amount of damage. Despite its qualitative nature, intensity data is essential to study both historical and recent earthquakes, such as in earthquake hazard studies and where dense accelerometric data are missing. The magnitude of historical earthquakes in Brazil have been determined with relations involving magnitude and felt area. Intensity attenuation equations (decay of intensity as a function of magnitude, depth and distance) determined in other regions of the world are intrinsically dependent on the crustal tectonic characteristics and cannot be applied to Brazil without proper evaluation. We determined an intensity attenuation equation using 20 earthquakes in Brazil and neighboring intraplate areas, in the magnitude range 3.5 to 6.2 mb and hypocentral distances up to 720 km.

The best attenuation model was $I = 0.995\,M - 1.505\log R - 0.00116\,R + 2.08$ (std. dev. = 0.778) where $M$ is the magnitude (mb) and $R$ the hypocentral distance (km). The uncertainties of the estimated magnitudes using this equation are around $\pm 0.72$ mb for events with 30 or more intensity points.

We tested the new equation with intensity data from two important events: The 1939 offshore earthquake (6 mb) in Southern Brazil and the 2018 Venezuela earthquake (6.9 mb). The fit was reasonable for both earthquakes, with an rms residual of 1.0 and 1.1 intensity units, respectively.

We also re-evaluated the 1861 (Lorena – SP) and 1946 (Cananéia – SP) earthquakes in SE Brazil.

The new epicenter of the 1861 earthquake was 23.1°S 44.7°W with a magnitude of 5 mb. The epicenter was located onshore, but the estimated uncertainties include a large offshore region. Given that, the location of the 1861 event remains uncertain.

The new epicenter of the 1946 earthquake was 24.9°S 47.7°W with magnitude of 4.3 mb. The epicenter was located close to the coast, with an uncertainty encompassing mostly equally the onshore and offshore (without reaching the continental slope) regions. The new location is close to the original defined epicenter for this earthquake, reinforcing the possibility of the event taking place offshore.

MIDOP

When working with macroseismic intensity data one of the main issues is the lack of a common platform that unifies contributing and searching for this kind of data. It is common that each researcher compiles individually his/her dataset, possibly in different formats, and not always available in a digital medium.

To overcome such issues, the Archive of Historical Earthquake Data (AHEAD) coordinated at *Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Milano* in Italy developed the first dedicated solution to publish macroseismic intensity data on the internet. The AHEAD team created MIDOP, a coding-free approach that allows users to create a secure and lightweight web interface capable of transforming raw macroseismic data tables in interactable intensity maps. That interface allows for easy search, download and upload of macroseismic information, that is accessible to any user on the internet.

The MIDOP was implemented with a compilation of several Brazilian historical earthquakes (mainly historical events from the book “Sismicidade do Brasil” from Berrocal *et al.*, 1984). MIDOP is already deployed in the address (accessed 31 of July of 2019)

http://moho.iag.usp.br/midop/

Is expected that MIDOP will allow for further collaboration between researchers though the use of standard formats and easier access to Brazilian macroseismic data.

**Keywords:** intensity, attenuation, macroseismic, historical seismicity, midop.

# SUMÁRIO

# Capítulo 1

## INTRODUÇÃO

### 1.1 Organização do projeto

Este trabalho está dividido em dois projetos: estudo da atenuação de intensidades em regiões intraplaca brasileiras com reavaliação de sismicidade histórica; e a implementação da ferramenta Macroseismic Intensity Data Online Publisher (MIDOP), capaz de disponibilizar dados macrossísmicos de intensidade na internet.

### 1.2 Atenuação de Intensidades

A introdução e todo desenvolvimento restante dessa parte do projeto foi escrito como artigo científico submetido e revisado pela revista *Seismological Research Letters* (maiores explicações no Capítulo 2).

### 1.3 MIDOP

Outro objetivo desde trabalho é aproveitar a compilação de sismicidade histórica efetuada em 1.2 (em sua maioria eventos de Berrocal *et al.*, 1984) e disponibilizá-la numa plataforma online de dados macrossísmicos, permitindo um acesso aberto, simples e padronizado aos dados macrossísmicas de intensidade brasileiros.

A principal motivação para a implementação do MIDOP está relacionada com a inexistência de uma base unificada de dados macrossísmicos brasileiros e com a falta de um formato de arquivo de dados padrão. Esses problemas dificultam o compartilhamento entre pesquisadores e torna o uso de dados macrossísmicos mais complexo. Outro fator é a maior dificuldade de pesquisa de dados, atualmente se encontram disseminados em diversas fontes, por vezes ainda em formatos de mídia clássicos (livros, jornais, etc.).

Uma solução encontrada foi a implementação da plataforma “Macroseismic Intensity Data Online Publisher” (MIDOP). Criada e continuamente desenvolvida desde 2006 pelo “Instituto Nazionale di Geofisica e Vulcanologia” (INGV) na Itália. Locati e Cassera (2010), criaram o MIDOP sob iniciativa do “European Archive of Historical Earthquake Data” (AHEAD) que tem como objetivo estabelecer padrões comuns de compilação e formatos entre os diferentes institutos que trabalham com dados macrossísmicos na Europa. Atualmente está presente países como: Reino Unido (“UK Historical Earthquake Database” – BGS); França (“SISFRANCE” – BRGM, IRSN e EDF); Suíça (“ECOS” – ETHZ); Itália (“DBMI” – INGV); Espanha (“Bases de datos de intensidad macrosísmica” – IGN); Catalunha (“Base de Dades Macrosísmica” – IGC); Grécia (“Hellenic Macroseismic Database” – UoA); entre outros.

O MIDOP permitirá o acesso de pesquisadores a uma interface online, com a possibilidade de interagir com um mapa de eventos macrossísmicos no território brasileiro. Nessa interface será possível pesquisar e baixar as informações relevantes de algum evento, como: epicentro, magnitude e medidas de intensidade. Outras informações também podem estar disponíveis dependendo da quantidade de dados que se tem sobre um evento, como: área sentida, nível de danos, artigos, jornais e histórico de sismicidade da região.

# ARTIGO

Este capítulo é referente ao estudo da atenuação de intensidades intraplaca no Brasil e reavaliação de sismicidade histórica e foi submetido como artigo científico no dia 13/05/2019 na revista *Seismological Research Letters*. No dia 17/06/2019 três revisores solicitaram pequenas alterações no texto.

# Seismic Intensity attenuation for intraplate earthquakes in Brazil with the re-evaluation of historical seismicity.

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## ABSTRACT

Intensity evaluation attempts to quantify a qualitative description of the effects observed in an earthquake ranked in terms of how strong it was felt and the amount of damage. Despite its qualitative nature, intensity data is essential to study both historical and recent earthquakes, such as in earthquake hazard studies and where dense accelerometric data are missing. The magnitude of historical earthquakes in Brazil have been determined with relations involving magnitude and felt area. Intensity attenuation equations (decay of intensity as a function of magnitude, depth and distance) determined in other regions of the world are intrinsically dependent on the crustal tectonic characteristics and cannot be applied to Brazil without proper evaluation. We determined an intensity attenuation equation using 20 earthquakes in Brazil and neighboring intraplate areas, in the magnitude range 3.5 to 6.2 mb and hypocentral distances up to 720 km.

The best attenuation model was $I = 0.995\,M - 1.505\log R - 0.00116\,R + 2.08$ (std. dev. = 0.778) where $M$ is the magnitude (mb) and $R$ the hypocentral distance (km).

The uncertainties of the estimated magnitudes using this equation are around ±0.72 mb for events with 30 or more intensity points.

We tested the new equation with intensity data from two important events: The 1939 offshore earthquake (6 mb) in Southern Brazil and the 2018 Venezuela earthquake (6.9 mb). The fit was reasonable for both earthquakes, with an *rms* residual of 1.0 and 1.1 intensity units, respectively.

We also re-evaluated the 1861 earthquake in SE Brazil. The new epicenter was 23.1°S 44.7°W with a magnitude of 5 mb. The epicenter was located onshore, but the estimated uncertainties include a large offshore region. Given that, the location of the 1861 event remains uncertain.

# 1. INTRODUCTION

Despite great advances in seismology concerning instrumentation and data processing, intensity evaluation as a qualitative assessment of sometimes subjective descriptions of earthquake effects is still an important field of study (such as demonstrated by the comprehensive report of Musson and Jiménez, 2008) widely used both in scientific research as well as in communication with the public as shown below in more detail.

Intensities can be over- or underestimated depending on the previous experience of the person describing the earthquake effects (for example, people who never felt earthquakes before usually give more dramatic descriptions). Also, the assigned intensity value also depends on how the seismologist interprets the reports, as observed by Musson, Grünthal and Stucchi (2010) who noted that a more literal-minded seismologist could assign an intensity value substantially different from one who is not, especially when interpreting second-hand reports from newspapers. Despite these limitations, intensity studies contribute to a better assessment of the earthquake hazards and vulnerability (Bakun and Wentworth, 1997; Eleftheriadou and Karabinis, 2011). Given the widespread availability of smartphones and mobile internet, huge quantities of intensity data can quickly become available for studies through apps such as *Did you feel it?*, developed by the United States Geologic Survey (USGS) (see for instance Wald *et. al.*, 1999; Atkinson and Wald, 2007), and *Sentiu Aí?*, developed in the Seismology Center of the University of São Paulo, Brazil, by Lion and Bianchi (2016).

Here we developed attenuation curves to predict Mercalli Modified (MM) intensities as a function of magnitude and distance using 20 intraplate earthquakes in Brazil. These new curves should give more reliable estimates of epicenter and magnitude of historical earthquakes, including their uncertainties.

## 1.1. Historical dataset

Intensity prediction equations depend strongly on the seismic attenuation properties of the crust and so must be developed for specific regions of application. Two approaches are commonly used: equations that fit the raw intensity values, or equations that fit the average isoseismal radii.

For example, Stromeyer and Grünthal (2009) adjusted by least-squares regression 14714 intensity values from 31 earthquakes in Central Europe, getting an *rms* residual of 0.7 intensity units. Similarly, Goff, Borges and Bezzeghoud (2014) presented a new intensity-distance relation for the continental region of Portugal using a logarithmic regression of 25 events, with an *rms* residual of 0.63 units. On the other hand, Musson (2005) used 727 isoseismals from 326 historical and recent earthquakes in the UK to calculate an attenuation equation. In this case, the isoseismal predicted intensities have an *rms* residual of 0.46 units. The estimations using the average isoseismal radii can have smaller *rms* residual, because each isoseismal radii is already an average of several intensities.

Because Brazil is in a stable continental region (mid-plate region of the South American Plate) seismic attenuation is lower when compared with active plate boundaries (e.g., Assumpção *et al.*, 1983), and specific intensity prediction equations have not been published yet.

The magnitude of historical earthquakes in Brazil have so far been determined with relations involving magnitude and felt area (e.g., Berrocal *et al.*, 1984; Assumpcao *et al.*, 2014). An early attempt to determine an intensity attenuation curve was made by Assumpção and Burton (1985) based upon average isoseismal radii of 36 Brazilian earthquakes, both historical and instrumental. More recently, Souza (2017) fitted raw intensity values of 24 earthquakes to determine a preliminary intensity attenuation equation. We added two more earthquakes and revised the data set used by Souza (2017), discarding a few poorly determined earthquakes. We determined a new intensity prediction equation, compared it to the previous equation established by Assumpção and Burton (1985) and applied it to re-evaluate the location and magnitude of an old and important historical earthquake in SE Brazil.

# 2. DATA AND METHODS

## 2.1. Historical dataset

The main source of intensity data for our study is the book "*Sismicidade do Brasil*" (Berrocal *et al.*, 1984), a compilation of historical and instrumental Brazilian earthquakes up to 1981. We selected all events having a known instrumentally determined epicenter and magnitude, that had many intensity values. 20 events were used, with an average of 30 intensity data points (or "MDP" = "Macroseismic Data Point"). The mb magnitudes ranged from 3.3 to 6.2. The mb body-wave magnitude was used as it has been the standard magnitude in the Brazilian catalogs. Brazilian earthquakes are also measured with the regional magnitude scale, $m_R$ (Assumpção, 1983), which is equivalent to the teleseismic mb scale in the range 3.5 to 5.5.

We also adopt the *Modified Mercalli Intensity* (MMI) scale (Wood and Neumann, 1931) because of its widespread usage in Brazil. Conversion to another scale would add more qualitative issues, as described by Musson, Grünthal and Stucchi (2010), with no contribution to a better description of the events.

We checked the data for all MDP sites mentioned in the book of Berrocal *et al.* (1984), starting from a list provided by CERESIS (Centro Regional de Sismología para América del Sur). The initially assigned intensities were checked against the description and macroseismic maps from Berrocal's book. Coordinates of the towns were taken from present-day databases. A common problem in analyzing old macroseismic data is that some descriptions refer to farms, train stations, old villages and towns, not easily locatable today (such as towns that changed their names). In these cases, the original map was digitized to retrieve the coordinates.

We included more recent events (after 1981) as used by Souza (2017), with macroseismic information published in the Seismic Bulletins of the Brazilian Geophysical Journal, or in published papers such as Ferreira *et. al.* (1983;1987), Assumpção *et al.* (1983), Barros *et al.* (2009), Chimpliganond *et al.* (2010), and Dias *et* *al.* (2016). The earthquakes used to determine the intensity attenuation curves are listed in Table 1. Fig. 1 shows a map of the epicenters and distribution of intensity MDPs.

**Table 1**. Earthquakes used for the intensity attenuation curve.

| Evt. #[1] | Locality (State) | Date | | | Origin Time | | | Latitude | Longitude | Depth km | mb | mR | Io[2] | MDP[3] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | São Paulo | 1922 | 01 | 27 | 06 | 50 | 40 | -22,17 | -47,04 | 10 | 5,4 | - | 6 | 135 |
| 2 | Mato Grosso | 1955 | 01 | 31 | 05 | 03 | 06 | -12,52 | -57,35 | 10 | 6,2 | - | 5 | 15 |
| 3 | Espírito Santo | 1955 | 03 | 01 | 01 | 46 | 13 | -19,84 | -36,75 | 10 | 6,1 | - | 5 | 10 |
| 4 | São Paulo | 1967 | 03 | 23 | 12 | 15 | - | -23,3 | -45 | 5 | 4,1 | - | 7 | 14 |
| 5 | Rio Grande do Norte | 1968 | 02 | 15 | 13 | 20 | 48 | -6,09 | -38,44 | 5 | 4,14 | 3,87 | 6 | 3 |
| 6 | Rio Grande do Norte | 1968 | 02 | 23 | 14 | 23 | 02 | -6,09 | -38,44 | 5 | 4,56 | 4,8 | 7 | 17 |
| 7 | Rio de Janeiro | 1972 | 10 | 24 | 15 | 36 | 36 | -21,72 | -40,53 | 8 | 4,84 | 4,87 | 5 | 19 |
| 8 | Minas Gerais | 1974 | 02 | 24 | 03 | 19 | 40 | -20,04 | -48,47 | 2 | 4,11 | 4,27 | 6.5 | 4 |
| 9 | Goiás | 1976 | 01 | 05 | 13 | 06 | 58 | -15,38 | -50,43 | 5 | - | 3,7 | 5.5 | 13 |
| 10 | Paraná | 1979 | 03 | 27 | 12 | 54 | 45 | -22,84 | -51,01 | 2 | - | 3,7 | 5.5 | 13 |
| 11 | Goiás | 1979 | 08 | 22 | 23 | 01 | 40 | -15,26 | -49,95 | 5 | - | 3,5 | 4 | 6 |
| 12 | Ceará | 1980 | 11 | 20 | 03 | 29 | 45 | -4,3 | -38,4 | 5 | 5,15 | 5,33 | 7 | 23 |
| 13 | Asuncion/Paraguay | 1982 | 04 | 08 | 05 | 58 | 52 | -24,8 | -58,1 | 12 | 4,94 | 4,79 | 6 | 7 |
| 14 | Amazonas | 1983 | 08 | 05 | 06 | 21 | 44 | -3,58 | -62,14 | 23 | 5,51 | 5,51 | 7 | 42 |
| 15 | Rio Grande do Norte | 1986 | 08 | 05 | 23 | 13 | 30 | -5,53 | -35,75 | 3 | - | 3,3 | 5.5 | 20 |
| 16 | Paraná | 1989 | 01 | 07 | 11 | 36 | 39 | -22,93 | -51,01 | 2 | - | 3,7 | 6 | 7 |
| 17 | Mato Grosso | 1998 | 03 | 10 | 23 | 32 | 44 | -11,6 | -56,74 | 4 | 5,27 | 4,92 | 5 | 27 |
| 18 | Minas Gerais | 2007 | 12 | 09 | 02 | 03 | 28 | -15,03 | -44,3 | 1 | 4,68 | 4,33 | 7 | 35 |
| 19 | Mato Grosso do Sul | 2009 | 06 | 15 | 22 | 15 | 45 | -18,49 | -55,8 | 6 | 4,89 | 4,82 | 5 | 17 |
| 20 | Maranhão | 2017 | 01 | 03 | 12 | 43 | 42 | -3,33 | -43,94 | 12 | 3,99 | 4,6 | 6 | 70 |

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[1] Event number
[2] Maximum earthquake intensity
[3] Macroseismic Data Point

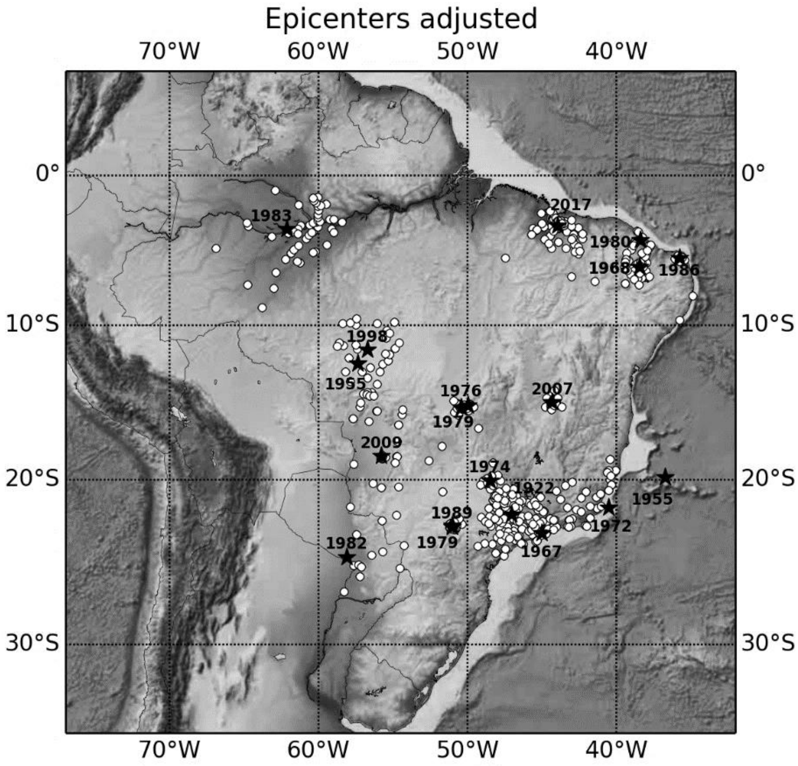


**Figure 1**. Epicenters (stars) of all earthquakes from Table 1 used to determine the intensity attenuation curves. The white circles indicate the MDP.

## 2.2. Attenuation equation models

Several equations relate the intensity (MMI, for example) empirically with the hypocentral distance (R) and magnitude (M). The majority is equivalent to the relation described in Howell and Schultz (1975):

$$I = aM - b \ln R - cR + d \tag{1}$$

That equation assumes an empirical concept that the intensity is proportional to the logarithm of the energy density and that the seismic energy is radiated from a point source through a space of simple geometry (Howell and Schultz, 1975). The constant $b$ represents the geometric spreading and $c$ is a constant representing inelastic attenuation (Howell e Schultz, 1975).

When the inelastic attenuation is too small in relation to the geometric spreading, equation (1) becomes

$$I = aM - b \ln R + d \tag{2}$$

When the inelastic attenuation is very strong, equation (1) can be simplified to

$$I = aM - cR + d \tag{3}$$

## 2.3. Brazilian models

Assumpção and Burton (1985) had calculated an attenuation equation for Brazil using 36 earthquakes (both historical and instrumental) with magnitudes between 3.5 and 5.5 and intensities ranging from III to VI in the MMI scale. Their equation was:

$$M = -0.02 + 0.43 I_{iso} + 1.51 \log R$$
$$or \qquad (4)$$
$$I_{iso} = 2.33M - 3.51 \log R + 0.05$$

where, $R = \sqrt{r^2 + h^2 + D^2}$, with $h$ the event depth (km), $r$ the epicentral distance, and $D$ an empirical constant to avoid intensities extremely large when $r = h = 0$. Assumpção and Burton (1985) used D = 7km.

A preliminary attenuation equation was found by Souza (2017) who used 24 instrumental earthquakes, with magnitudes between 3.1 and 6.2 and intensities between II to VII (MMI). Here, we updated her dataset, excluding some poorly constrained events and kept data for 20 earthquakes (Table 1 and Fig. 1).

Using this revised dataset (Fig. 1 and Table 1) we fit equations (1), (2), and (3) as:

$$I = 0.995\,M - 1.505 \log R - 0.00116\,R + 2.08 \qquad (\sigma = 0.778) \qquad (5)$$

$$I = 0.987\,M - 1.715\,\log R + 2.36 \qquad (\sigma = 0.782) \qquad (6)$$

$$I = 1.496\,M - 0.0057\,\mathrm{R} + 0.659 \qquad (\sigma = 0.884) \qquad (7)$$

The intensity data, fit, and the coefficient uncertainties are shown in Fig. 2. Eq. 5 and 6 (Fig. 2a,b) are very similar and fit the data equally well (both with *rms* residual of approximately 0.78). This was expected because the constant $c$ is related to the inelastic attenuation ($\alpha$) of the crust and upper mantle, usually ranging from $0.001 \leq \alpha \leq 0.01$ (Sponheuer, 1960 *apud* Stromeyer and Grünthal, 2009; Ahorner, 1983). In stable regions like Brazil, the attenuation is lower in relation to active plate boundaries (Souza and Mitchell, 1998a, 1998b) which explains the small value of $c$ and therefore, the similarity between Eqs. 5 and 6. Eq. 5 will be selected because it is a more comprehensive description of the wave propagation, given that it does not exclude the inelastic attenuation effect. Eq. 7 (Fig. 2c) has a larger *rms* residual, as also observed by Souza (2017) and will not be used.

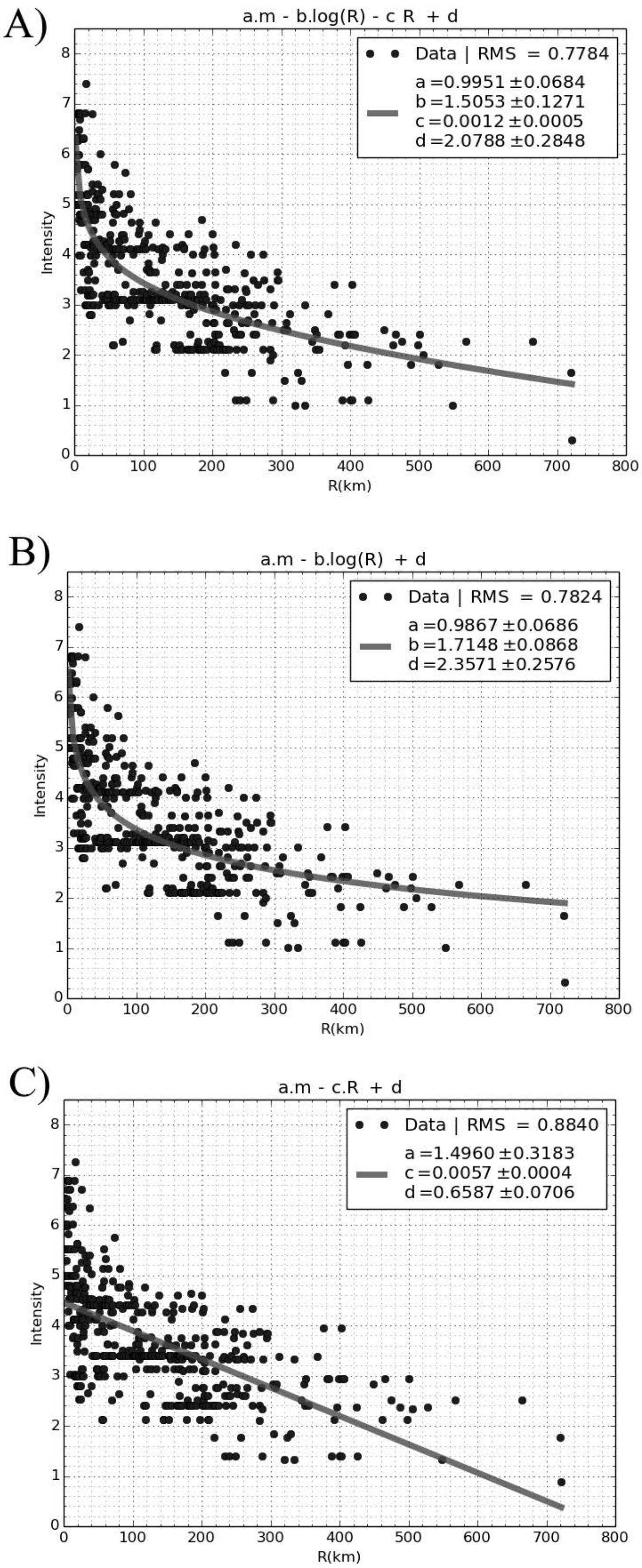


**Figure 2**. Fitting of the intensity attenuation curves (Eqs. 5 to 7) to the data of the 20 earthquakes from Table 1. a), b) and c) are Eqs. 5, 6 and 7 respectively. Take note that the parameters adjusted have two significant digits. Intensity data normalized to a magnitude of 4.5 mb.

We compared Eq. 4 (Assumpção and Burton, 1985) with our dataset (Fig. 3). To make this comparison, we assume that the isoseismal intensity ($I_{iso}$ of Eq. 4) corresponds to MDP $I = I_{iso} - 0.5$. Although the general trend is coherent, the *rms* deviation, 1.65, is much higher than the newly derived curves.

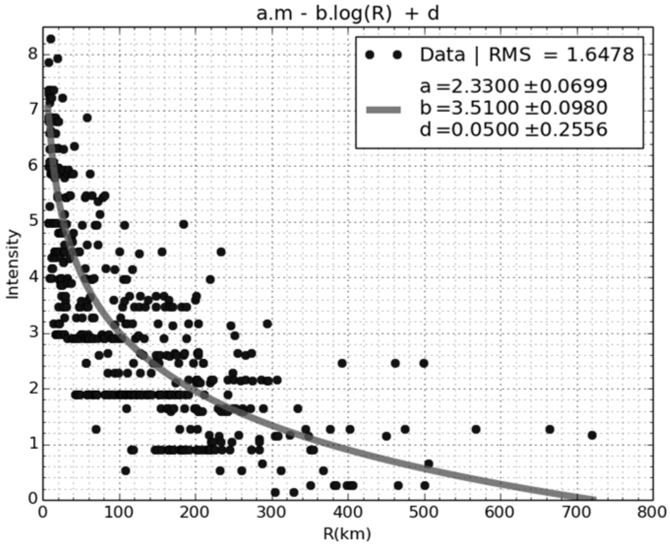


**Figure 3** – Comparison of Eq. 4 with the MDP dataset. Observed intensity values normalized to magnitude 4.5 mb.

Fig. 4 shows that our new Eq. 5 is very similar to the preliminary estimate of Souza (2017), with a slightly steeper decay at short distances. On the other hand, the previous equation of Assumpção and Burton (1985) predicts relatively higher intensities before 120 km and lower intensities at longer distances due in large part to their predicting isoseismals rather than individual intensities.

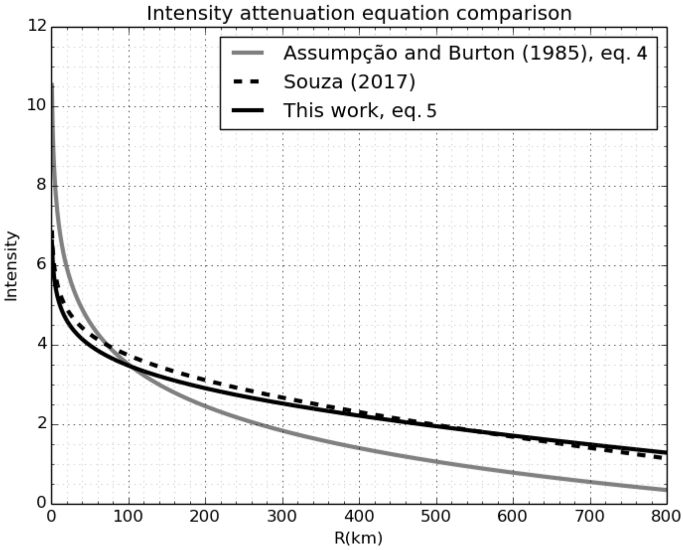


**Figure 4** – Comparison of different intensity attenuation equations for Brazil. Intensity (vertical scale) was normalized for a magnitude m=4.5 mb.

## 2.4. Test of the new equation

We compared Eq. 5 with two events in South America: a) the 1939 earthquake offshore Southern Brazil, with a magnitude of Ms=5.6 felt up to 1000 km, and b) a recent, large (6.9 mb) earthquake occurred in Venezuela felt in northern Brazil at more than 2000 km (sampling mostly the Precambrian Guyana shield).

a) 1939 offshore Brazil.

The only instrumental magnitude for this old event is an Ms=5.6 measured at Pasadena (ISC, 2018). The compilation of mb and Ms values of Assumpção and Suárez (1988) suggests that 5.6 Ms corresponds to ~6.0 mb. Fig. 5 shows that Eq. 5 fit the data with a *rms* residual of 1.0.

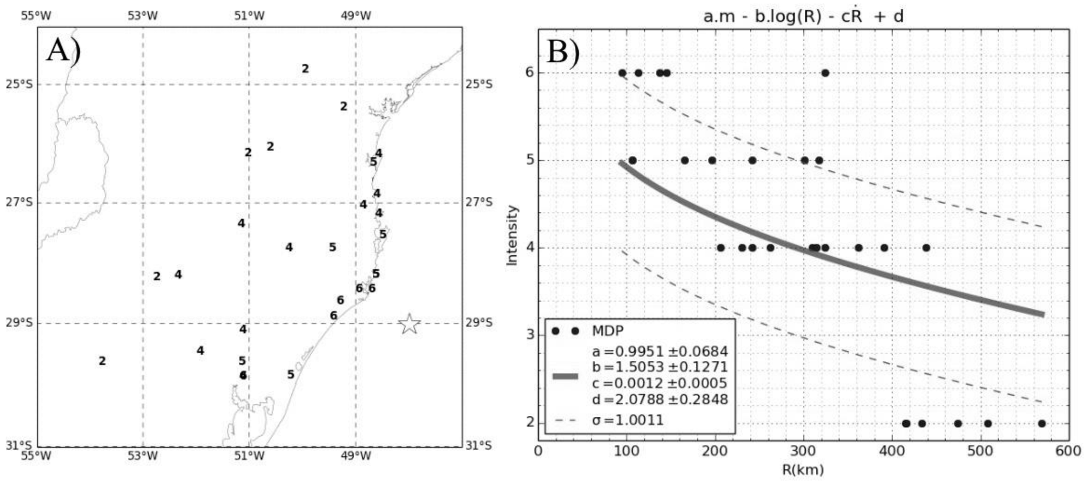


**Figure 5 –** a) MDP map for the offshore event (1939-06-28 11:32:22 UTM), 6.0 mb. b) Comparison of Eq. 5 with the observed MDP. The gray curve is Eq. 5 giving an *rms* residual of $\sigma = 1.0$.

b) 2018 Venezuela

This earthquake (Fig. 6a) occurred near the coast of Venezuela in 2018-08-21 21:31:40 with a teleseismic short-period magnitude of 6.9 mb (USGS/ISC). The depth of this earthquake was 110 km, which can make the intensity field very different from the shallow events used in our study. However, we do not have any other large earthquake to test the equation. It is an important earthquake, and its data may be useful in future studies. We used intensity data compiled by FUNVISIS (*Fundación Venezolana de Investigaciones Sismológicas*), in addition, we compiled reports from Brazilian newspapers and social media, mainly in northern Brazil, and classified the intensities in the MMI scale. Fig. 6b shows that the observed intensities are higher than the predictions of Eq. 5, giving an *rms* residual of 1.1. Our Eq. 5 was determined with earthquakes up to 6.2 mb and felt at distances up to 700 km. Comparison with this large Venezuelan earthquake is a test of how well our Eq. can be extrapolated for longer distances and larger magnitudes. Although the rate of intensity decrease with distance agrees well with Eq. 5, the level of our curve is about 1 intensity unit lower than indicated by the data. The lower intensities predicted by our Eq. 5 can have two possible explanations:

a) the Venezuelan earthquake had a hypocentral depth of 110 km, and a centroid depth of 160 km (ISC, 2018). Deeper earthquakes tend to produce higher amplitudes and intensities, compared to the shallow (upper crust) Brazilian earthquakes used to derive our Eq. 5.

b) the teleseismic, short-period $m_b$ for large earthquakes tend to saturate near ~7. If we use a magnitude value of 7.3 Mw, the *rms* residual is reduced to 0.83 intensity units.

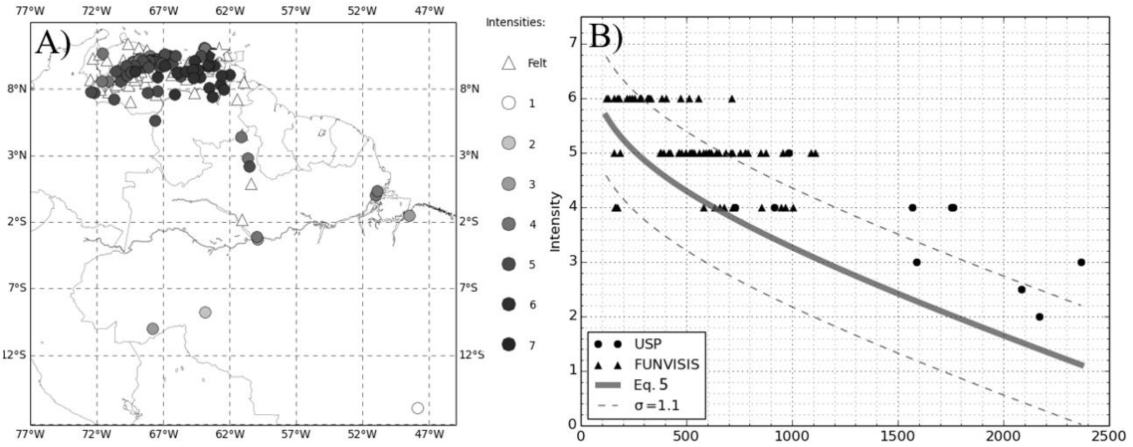


**Figure 6** – A) MDP map for the Venezuela event (2018-08-21 21:31:40 UTM), 6.9 mb, as compiled by FUNVISIS and USP. B) Comparison of Eq. 5 with the observed MDP. Triangles and circles are, respectively, FUNVISIS and USP data. The gray curve is Eq. 5 giving an *rms* residual of $\sigma = 1.1$.

Because of the earthquake depth more tests with other events will be necessary to see if Eq. 5 can be extrapolated to larger magnitudes.

## 2.5. Determination of Epicenter and Magnitude

We now compare the known epicenter and magnitude of our data set (Table 1) with the values estimated using only the intensity data. We used our best fitting equation (Eq.

5) to do a global grid search for the best epicenter and magnitude. First, we define a rectangular search grid, with 0.1° spacing, with limits around 2 to 5 times the region with intensity data, to cover the situations where the epicenter is outside the region of available MDP (especially for coastal epicenters). The number of times that we increase the search grid was empirically defined. Although the depth could be determined, we usually do not have enough intensity data close to the epicenter to allow a good enough inversion of it.

Using Eq. 5, we calculated for every point in the grid the best magnitude (testing values from 2.0 to 8.0, in steps of 0.1) that would fit the MDP. For every cell, we kept the best *rms* residual (the difference between the observed and predicted intensities) and its corresponding magnitude. The search continues for all points in the grid. The grid point with the least *rms* value is the inverted epicenter, and its magnitude is the "intensity-based magnitude estimate".

## Results for the data set

Fig. 7 shows four examples of inversion of the intensities of the dataset. The calculated errors of all inversions (Fig. 8) tend to decrease with the number of MDP, and epicentral errors are mostly less than 30 km. Only four events had large epicentral error (> 50 km) corresponding to events where intensities are available only to one side of the epicenter: nos. 2 (1955 Mato Grosso), 3 (1955 Espírito Santo offshore event), 7 (offshore 1972 Rio de Janeiro), and 13 (1982 Asuncion, Paraguay). Magnitude errors (Fig. 8) are mostly between +0.7 and -0.5.

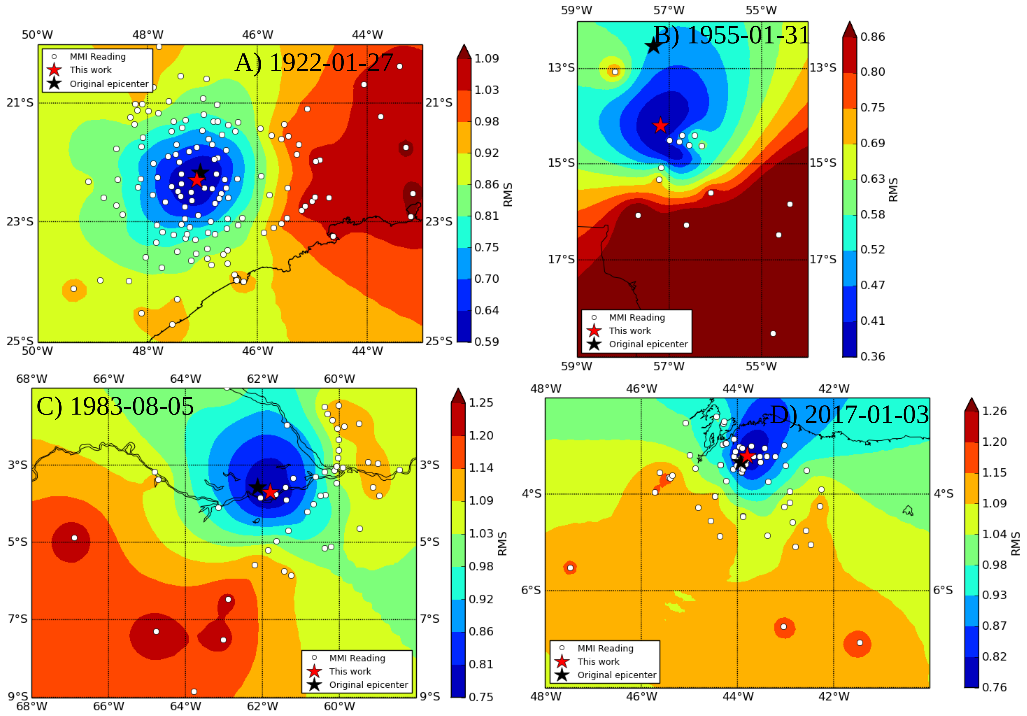
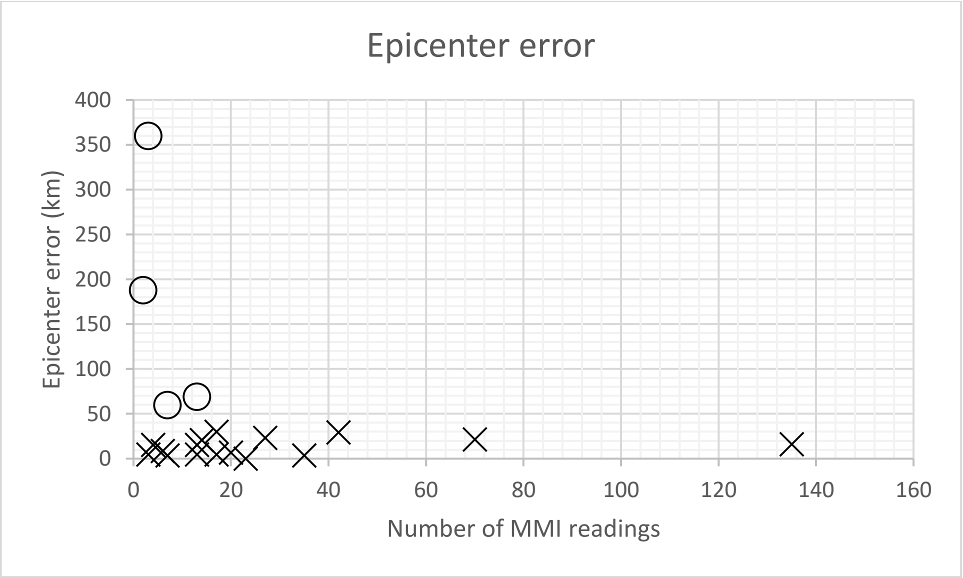


**Figure 7** – Epicenter inversions for the events of A) 1922-01-27, B) 1955-01-31, C) 1983-08-05, and D) 2017-01-03. The black star is the observed epicenter, and the red star is the best estimated epicenter, i.e., the one with the least *rms* residual. The contours are the *rms* intensity residuals for all grid points.



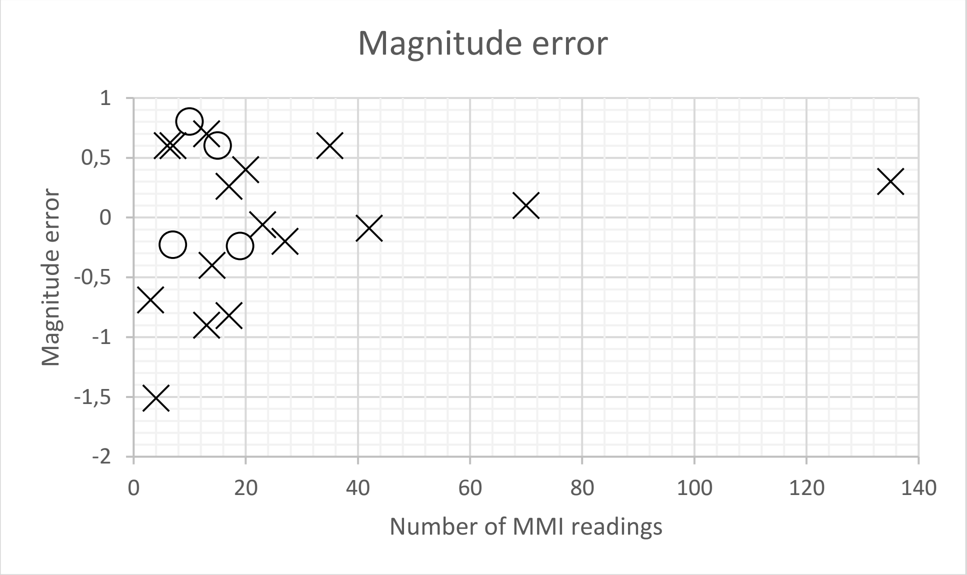


**Figure 8** – Epicenter and magnitude error for each of the 20 events (Table 1) versus the number of MDPs. The circles are events with MDP predominantly in just one side of the epicenter.

## Felt (F) and Not Felt (NF) measurements

In many newspapers, it is common to see the information that an earthquake "was felt" in some towns, with little additional data to allow assignment of an intensity value. In reports of macroseismic field surveys, it is also common to find places where the event was "not felt". We tested if including this kind of data ("Felt" and "Not Felt") would improve the estimated epicenter and magnitude. Naming the calculated intensity from Eq. 5 as Icalc, our grid-search defined the residual as:

a) If Icalc >= 2 and the observation is "Felt", residual = 0,

b) If Icalc < 2 and the observation is "Felt", residual = 2 - Icalc,

c) If Icalc < 2 and the observation is "Not Felt", residual = 0,

d) If Icalc >= 2 and the observation is "Not Felt", residual = 2 - Icalc.

The criteria above consider that intensity II is very close to the threshold of perception. Therefore a "Not Felt" report in a town where the calculated intensity is close to II should have small residual. Similarly, a high intensity calculated in a point with "Not Felt" should have some penalty in the search for the best fitting epicenter.

We evaluated if the inclusion of F (Felt) and NF (Not-Felt) data helped improve the epicenter and magnitude estimates. As we can see in Table S1 (Supplementary Material), the inclusion of F and NF data does not affect the average epicentral and magnitude uncertainties. In both situations the average error is 0.5 mb and (removing the 4 poorly constrained of Fig. 8) 0.11° (~12 km). We believe including FNF data did not improve the inversion because of two reasons: the intensity attenuation equation was derived without FNF data; and usually, the FNF data have poor quality. However, we included F and NF reports in the epicenter inversion. The supplementary material shows the inverted epicenter and magnitude for the remaining 16 earthquakes (Figs. S1 to S16) using the FNF search criteria.

## 2.6. Confidence limits for the epicenter and magnitude

The method that we used to evaluate the epicenter inversion error to any event inverted using an attenuation equation is the one developed by Bakun and Wentworth (1997). This method consists in evaluating the inversion for each event several times using a random sub-sample of the data set (bootstrap). For example, for the 1983 earthquake (Fig.7c) we can define a set of 30 MDP from a total of 42. For each set of 30 we can recalculate the epicenter determining the difference between the minimum *rms* and the *rms* at the location of the true epicenter (this number is always positive since the solution corresponds to the minimum rms position). We execute this process 1000 times for all the 20 events and we consider only the best 95 percent rms solutions (where the difference between location and true epicenter rms are the smallest). A similar process is made for the magnitude, but considering that the difference values can be both positive or negative. The 95% confidence level calculations for the MDP sets are shown in Fig 9a,b.

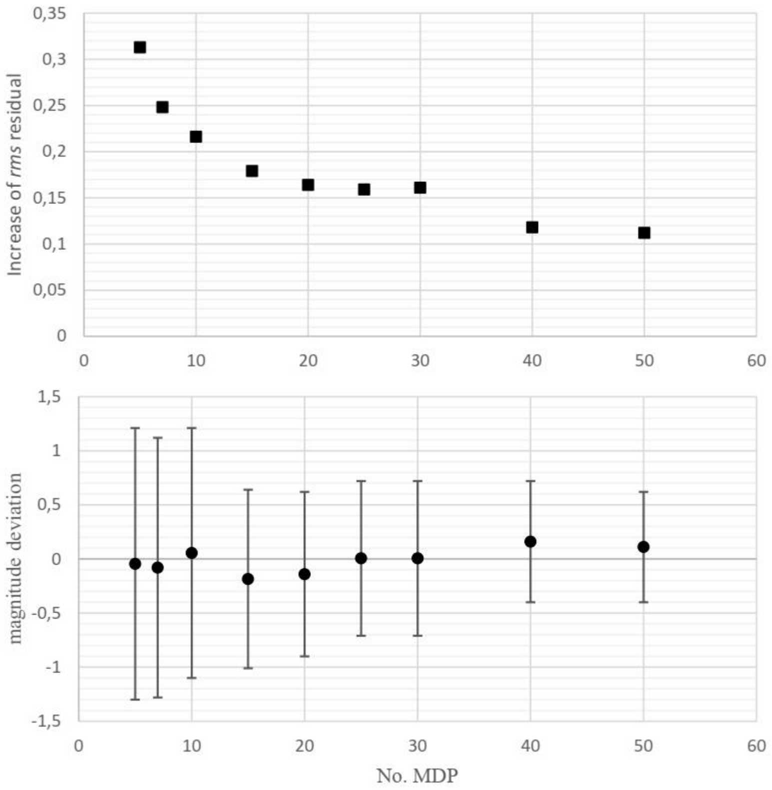


**Figure 9** - A) Eq. 5 rms residual increase (intensity units) corresponding to a 95% confidence-level of the epicenter versus the number of MDP values in the bootstrap sub-sample.

B) Eq. 5 rms magnitude deviation with a 95% confidence-level versus the number of MDP values in the bootstrap sub-sample. The bar represents the maximum and minimum variance. The black circle is the average.

There is a sharp decrease of the inversion uncertainty after 10 MDP sets (Fig. 9b), especially in magnitude where the variance shrinks from around 1.16 to 0.83 and tends to get smaller with increasing number of MDP. The curve presented in Bakun and Wentworth (1997) is smoother, given the quantity of data they used is around 7 times bigger.

# 3. RE-EVALUATION OF HISTORICAL EVENT

We now re-evaluate an important historical earthquake: the 1861 earthquake in the state of São Paulo, SE Brazil.

## 1861, Lorena (SP), SE Brazil

Information for this event was compiled by Assumpção *et al.* (1980) and Berrocal *et al.*, (1984) who had estimated a magnitude of ~4.4 mb based on the total felt area of 52,000 km$^2$. Very few intensities had been assigned before. Additional information from old newspapers was made available by Souza (2017) showing a larger felt area and allowing more intensities to be assigned.

Fig. 10 shows our estimated epicenter for this event, with a magnitude of mb = 5 ± 0.56 and epicenter of 23.1°S 44.7°W with an error of 240 km (both uncertainties estimated using Fig. 9a,b). Given the similarity with epicenter determined by Berrocal *et al.*, (1984) it is possible that this event happened onshore, but the uncertainty also allows for the offshore epicenter found by Assumpção and Burton, (1985) using Eq. 6. Therefore, the true location of this event remains uncertain, and further work is required.

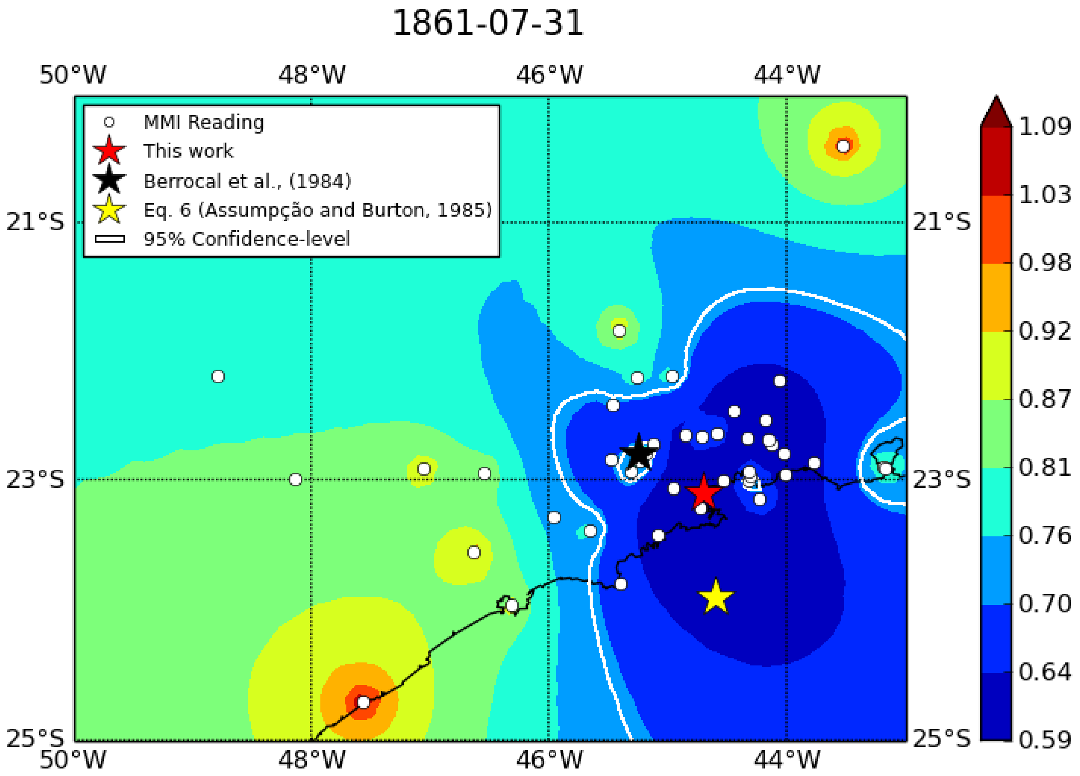


**Figure 10:** Epicenter inversion of the 1861 Lorena event in São Paulo, Brazil, using Eq. 5 (red star). The white circles are the MDPs. The black star is the epicenter according to Berrocal *et al.* (1984). The yellow star is the epicenter based on the equation of Assumpção and Burton (1985). The white line represents the confidence limit of 95% for that event (42 MDP that gives an *rms* deviation of ~0.12 or 0.71 *rms*, as seen in Fig. 9a).

# 4. CONCLUSION

We determined a new intensity attenuation equation that we can use to evaluate the raw estimates of intensities, instead of the older Brazilian intensity equation that required the isoseismal radii estimates. The new equation also allows for a further re-evaluation of historical seismicity, with possible implications for future Brazilian seismic hazard studies.

The application of the new equation with the 2018 Venezuela 6.9 mb earthquake was a test of how well it can be extrapolated to higher epicentral distances and magnitudes.

Although the rate of intensity decrease with distance agrees well and the fit was reasonable (std. dev. = 1.1), the level of our curve is about 1 intensity unit lower than indicated by the data. Therefore, as discussed previously, more tests will be necessary.

The epicenter and magnitude inversions of our dataset presented reasonable results, where 80% of the data has an epicentral error of less than 30 km and a variance in magnitude between +0.7 and -0.5. However, we note that the distribution of intensity measurements to just one side of the epicenter can significantly increase the uncertainties.

We also showed that using "Felt" and "Not Felt" data does not change the magnitude/epicenter uncertainties. Another finding was that using 10 or more MDP greatly reduces the epicentral and magnitude uncertainties of our equation.

The re-evaluation of the 1861 Lorena earthquake determined a new epicenter at 23.1°S 44.7°W with a magnitude of 5 mb. The magnitude error (±0.56 mb) was reasonable, but the epicenter was not well defined in this case (95% confidence uncertainty of 240 km). The large epicentral error is coherent with the offshore epicenter of Assumpção and Burton (1985). Given that, the true location of the 1861 event remains uncertain. Further studies adding and reviewing intensity data would be beneficial.

## 5. DATA AND RESOURCES

The data from the 20 historical earthquakes were gathered mainly from the book "*Sismicidade do Brasil*" (Berrocal *et al.*, 1984). Others sources used were the following: Ferreira *et al.* (1987;1983), Assumpção *et al.* (1983), Barros *et al.* (2009), Chimpliganond *et al.* (2010), Dias *et al.* (2016), and Souza (2017). The Souza (2017) can be found for download in

http://www.iag.usp.br/pos/sites/default/files/d_ana_p_t_souza_original.pdf

accessed March 2019.

## 6. ACKNOWLEGMENTS

This study was carried out with CNPq and CAPES M. Sc. scholarships (L.Q. and A.P.T.S. respectively), and grant CNPq 30.1284/2017-2 (M.A.). We thank Paola Albini for an initial search of historical newspapers for the 1861 earthquake and Julian Bommer for motivating that search. The University of Brasilia provided the intensity data for the

2010 and 2017 earthquakes. We thank CERESIS for an initial file with intensity data of all Berrocal et al. (1984) historical earthquakes. Intensity data were also provided by Moisés Gadea (UNA, Paraguay) for the 1982 event in Paraguay, and by Lucas Barros (UnB, Brasília) for the 2009 Minas Gerais, and the 2017 Maranhão earthquakes. We also thank Marcelo Bianchi for helping with the text revision. We thank Roger Musson and two other reviewers and the editor for critically reading the manuscript and helping to improve it.

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# SUPPLEMENTARY MATERIAL

## Seismic Intensity attenuation for intraplate earthquakes in Brazil with the re-evaluation of historical seismicity.

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We present here the inversions for epicenter for each of the earthquakes in our data-set (Figures S1-S20) using FNF (Felt, Not-felt) data. Tables S1 and S2 compare the inversion with and without FNF data. Table S3 shows the data used in Figure 9 of the main text.

## All intensity inversions from the dataset

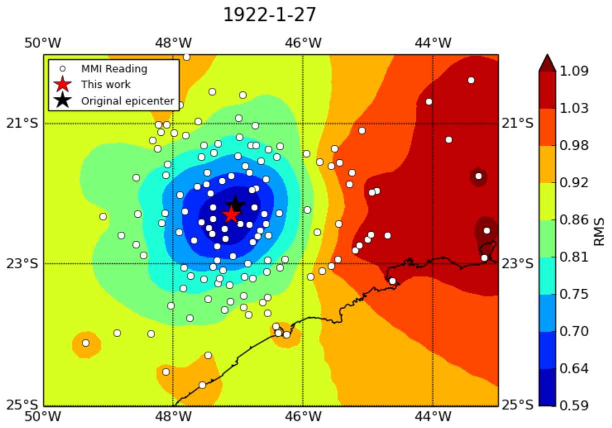

1922-1-27

**Figure S1** – Epicenter inversion for the São Paulo event of 1922-01-27 using Eq. 5.

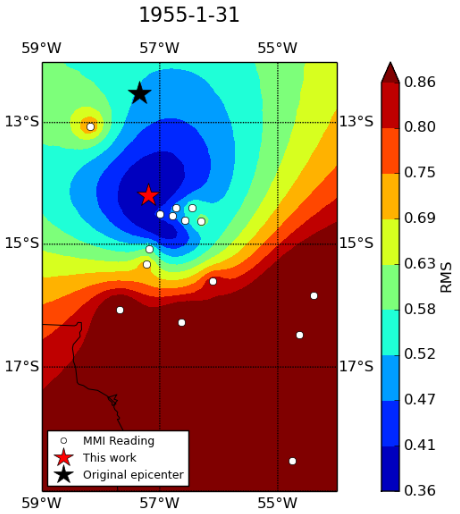

1955-1-31

**Figure S2** – Epicenter inversion for the Mato Grosso event of 1955-01-31 using Eq. 5.

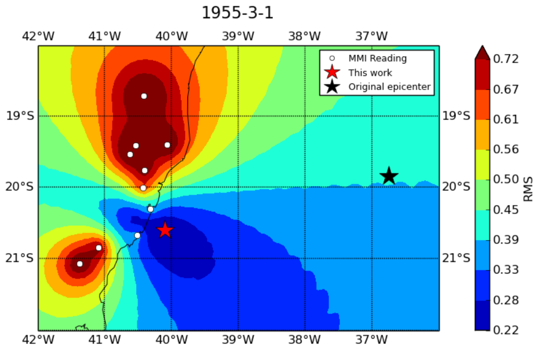

1955-3-1

**Figure S3** – Epicenter inversion for the Espírito Santo event of 1955-03-01 using Eq. 5.

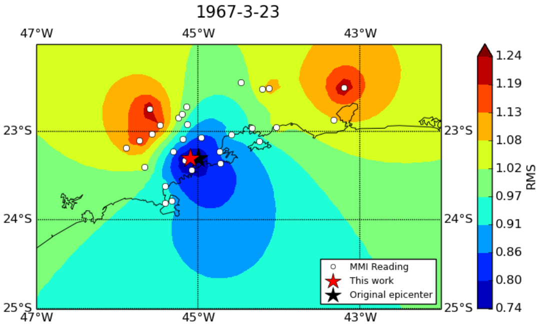


**Figure S4** – Epicenter inversion for the São Paulo event of 1967-03-23 using Eq. 5.

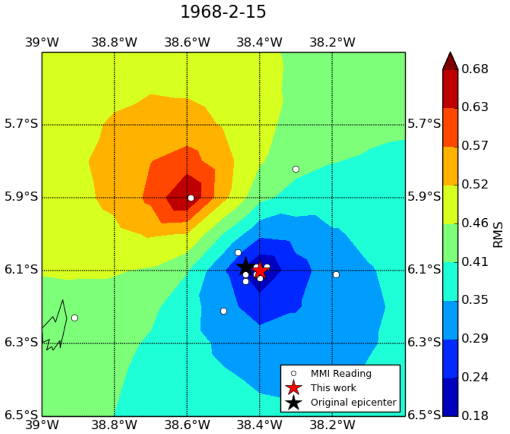


**Figure S5** – Epicenter inversion for the Rio Grande do Norte event of 1968-02-15 using Eq. 5.

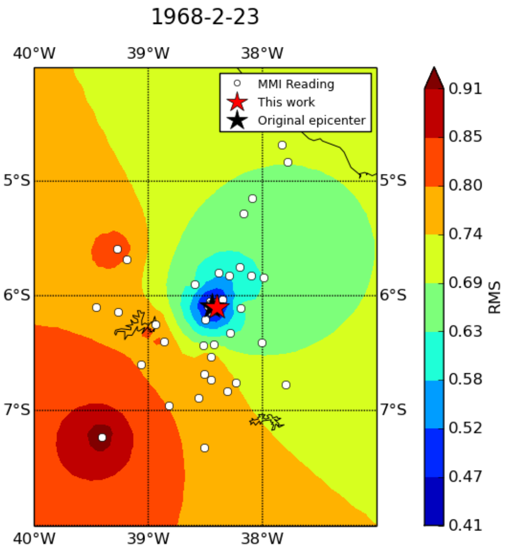


**Figure S6** – Epicenter inversion for the Rio Grande do Norte event of 1968-02-23 using Eq. 5.

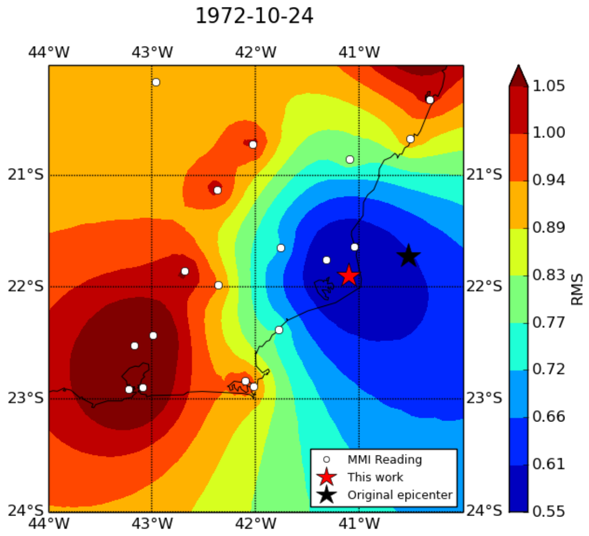


**Figure S7** – Epicenter inversion for the Rio de Janeiro event of 1972-10-24 using Eq. 5.

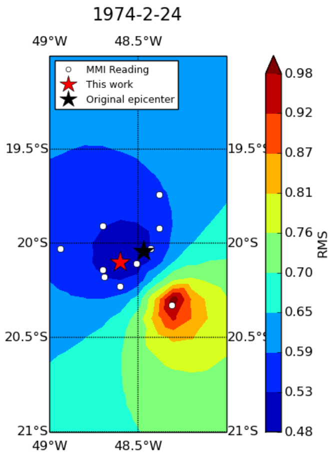


**Figure S8** – Epicenter inversion for the Minas Gerais event of 1974-02-24 using Eq. 5.

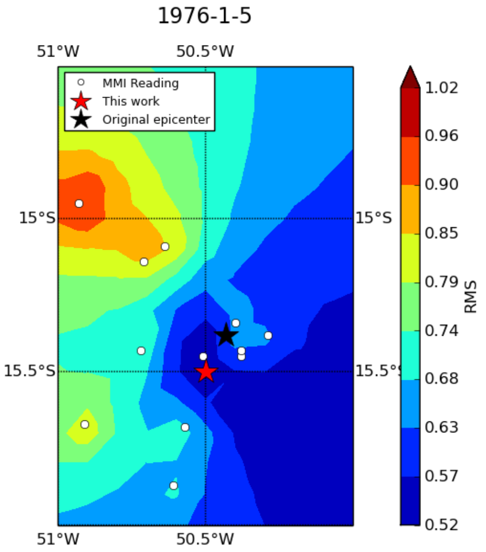


**Figure S9** – Epicenter inversion for the Goiás event of 1976-01-05 using Eq. 5.

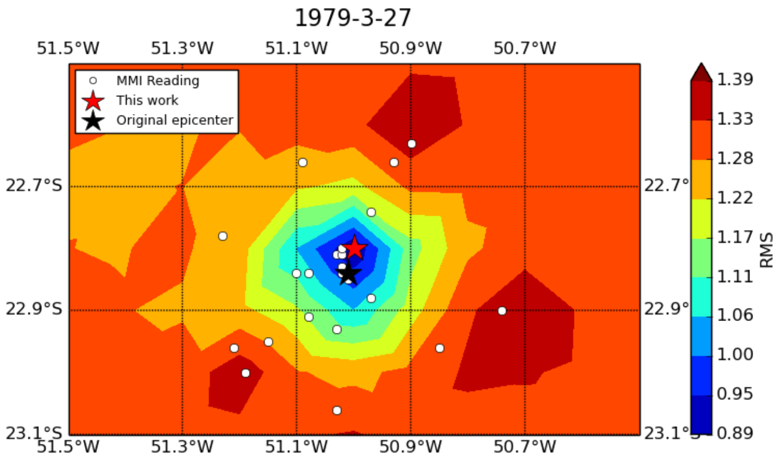


**Figure S10** – Epicenter inversion for the Paraná event of 1979-03-27 using Eq. 5.

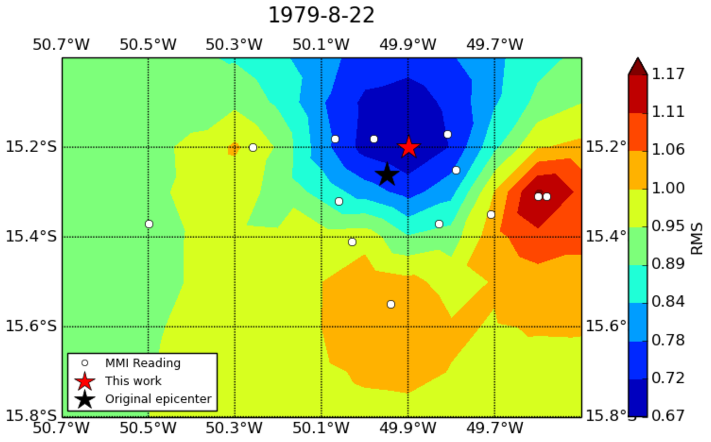


**Figure S11** – Epicenter inversion for the Goiás event of 1979-08-22 using Eq. 5.

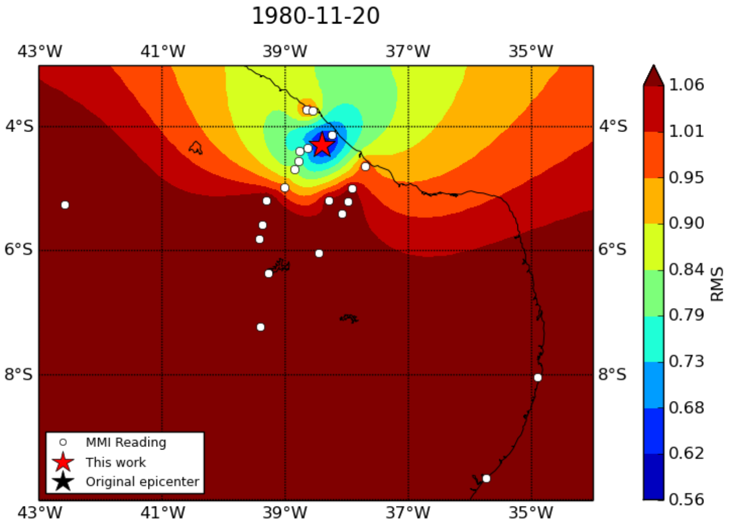


**Figure S12** – Epicenter inversion for the Ceará event of 1980-11-20 using Eq. 5.

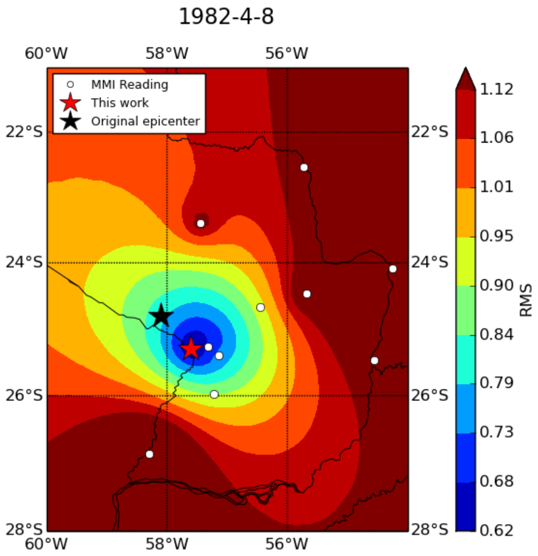


**Figure S13** – Epicenter inversion for the Asuncion/Paraguay event of 1982-04-08 using Eq. 5.

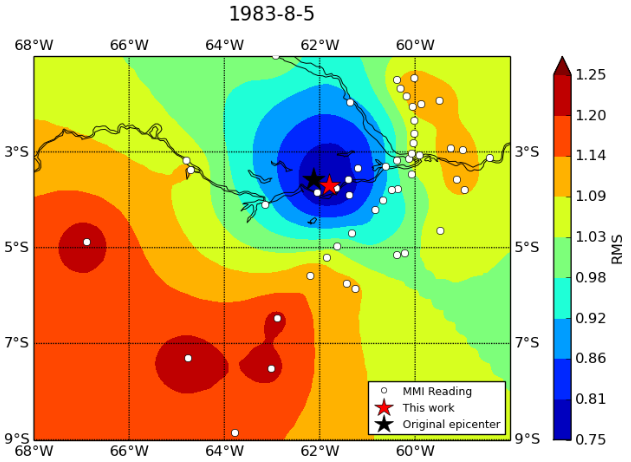


**Figure S14** – Epicenter inversion for the Amazonas event of 1983-03-05 using Eq. 5.

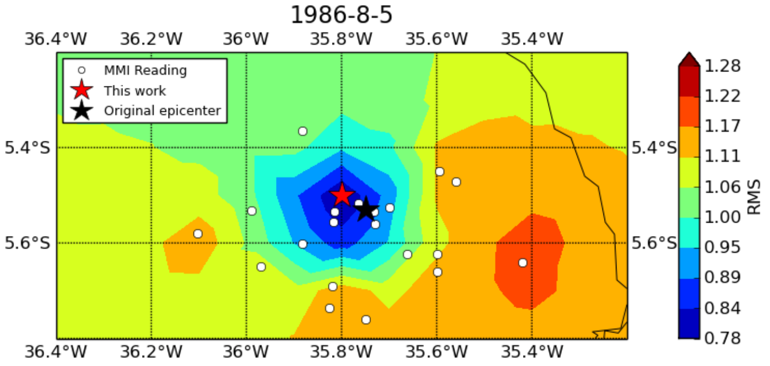


**Figure S15** – Epicenter inversion for the Rio Grande do Norte event of 1986-08-05 using Eq. 5.

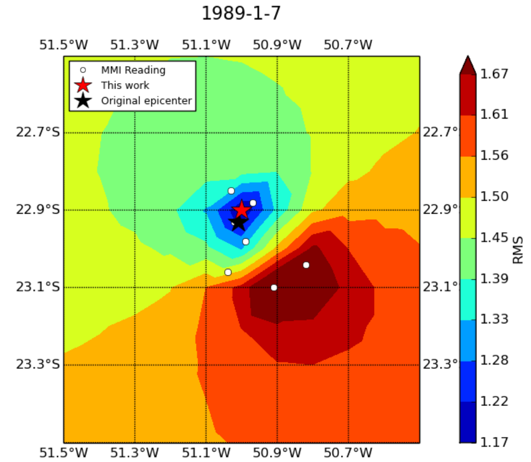


**Figure S16** – Epicenter inversion for the Paraná event of 1989-01-07 using Eq. 5.

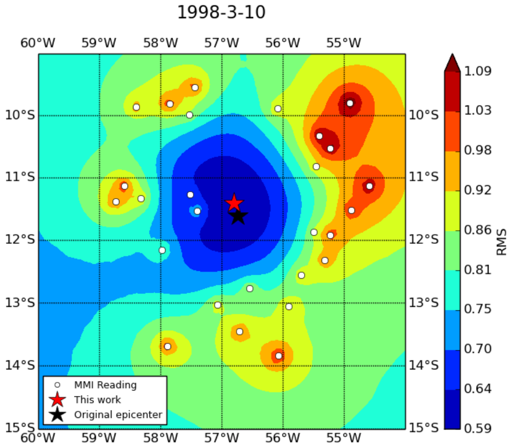


**Figure S17** – Epicenter inversion for the Mato Grosso event of 1998-03-10 using Eq. 5.

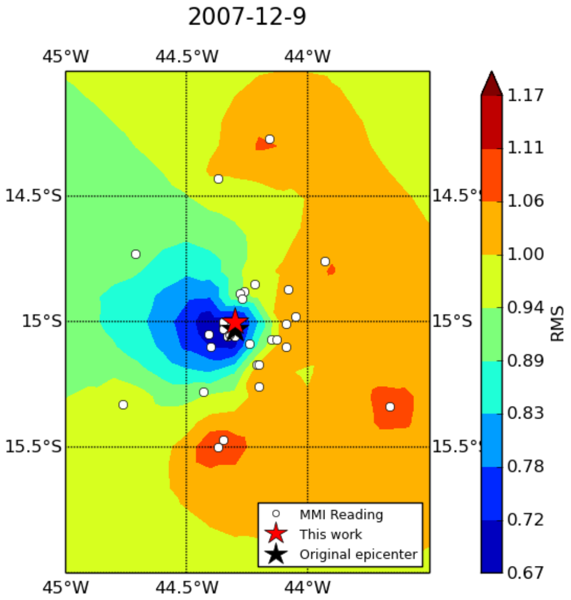


**Figure S18** – Epicenter inversion for the Minas Gerais event of 2007-12-09 using Eq. 5.

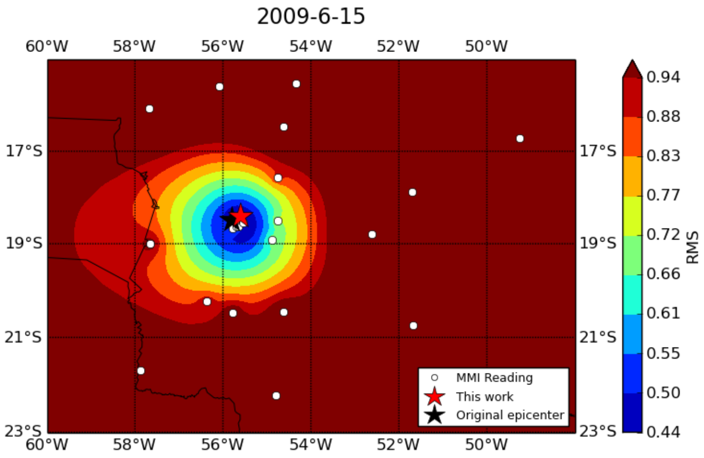


**Figure S19** – Epicenter inversion for the Mato Grosso do Sul event of 2009-06-15 using Eq. 5.

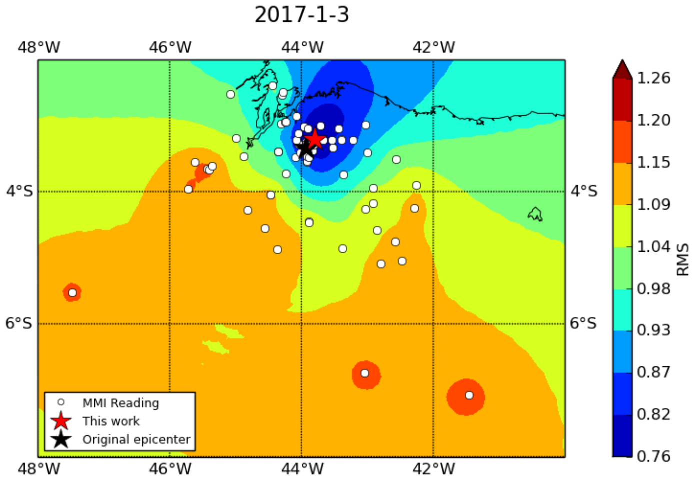


**Figure S20** – Epicenter inversion for the Maranhão event of 2017-01-03 using Eq. 5.

# Felt/Not Felt measurements

**Table S1** – Residue (dmag) between the average of the observed magnitudes $m_b$ and $m_R$ (obs), and the calculated one (calc), with (w) or without (w/o) Felt and Not Felt (FNF) data. Average with and without FNF data: 0.5 $m_b$.

| | | MAGNITUDE | | | | |
|---|---|---|---|---|---|---|
| Evt. # | Date/Place | obs | calc w/o FNF | calc w FNF | dmag w/o FNF | dmag w FNF |
| 1 | 1922/1/27 (São Paulo) | 5.4 | 5.1 | 5.1 | 0.3 | 0.3 |
| 2 | 1955/1/31 (Mato Grosso) | 6.2 | 5.6 | 5.6 | 0.6 | 0.6 |
| 3 | 1955/3/1 (Espírito Santo) | 6.1 | 5.3 | 5.3 | 0.8 | 0.8 |
| 4 | 1967/3/23 (São Paulo) | 4.1 | 5 | 4.5 | -0.9 | -0.4 |
| 5 | 1968/2/15 (Rio Grande do Norte) | 4.01 | 4.7 | 4.7 | -0.7 | -0.7 |
| 6 | 1968/2/23 (Rio Grande do Norte) | 4.68 | 5.5 | 5.5 | -0.8 | -0.8 |
| 7 | 1972/10/24 (Rio de Janeiro) | 4.86 | 5.1 | 5.1 | -0.2 | -0.2 |
| 8 | 1974/2/24 (Minas Gerais) | 4.19 | 5.7 | 5.7 | -1.5 | -1.5 |
| 9 | 1976/1/5 (Goiás) | 3.7 | 4.6 | 4.6 | -0.9 | -0.9 |
| 10 | 1979/3/27 (Paraná) | 3.7 | 3.5 | 3 | 0.2 | 0.7 |
| 11 | 1979/8/22 (Goiás) | 3.5 | 3.5 | 2.9 | 0.0 | 0.6 |
| 12 | 1980/11/20 (Ceará) | 5.24 | 5.3 | 5.3 | -0.1 | -0.1 |
| 13 | 1982/4/8 (Asuncion/Paraguay) | 4.87 | 5.6 | 5.1 | -0.7 | -0.2 |
| 14 | 1983/8/5 (Amazonas) | 5.51 | 5.8 | 5.6 | -0.3 | -0.1 |
| 15 | 1986/8/5 (Rio Grande do Norte) | 3.3 | 3 | 2.9 | 0.3 | 0.4 |
| 16 | 1989/1/7 (Paraná) | 3.7 | 3.1 | 3.1 | 0.6 | 0.6 |
| 17 | 1998/3/10 (Mato Grosso) | 5.1 | 5.3 | 5.3 | -0.2 | -0.2 |
| 18 | 2007/12/9 (Minas Gerais) | 4.5 | 3.9 | 3.9 | 0.6 | 0.6 |
| 19 | 2009/6/15 (Mato Grosso do Sul) | 4.86 | 4.8 | 4.6 | 0.1 | 0.3 |
| 20 | 2017/1/3 (Maranhão) | 4.3 | 4.3 | 4.2 | 0.0 | 0.1 |

**Table S2** - Residue (dlat/dlon) between the observed epicenter latitude and longitude (lat obs/lon obs) and the calculated one (calc), with (w) or without (w/o) Felt and Not Felt data (FNF). Average with and without FNF data (removing poorly constrained events): 0.11° or ~12km.

| | | EPICENTER | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Evt. # | Date/Place | lat obs | lon obs | lat calc w/o FNF | lon calc w/o FNF | lat calc w FNF | lon calc w FNF | dlat w/o FNF | dlon w/o FNF | dlat w FNF | dlon w FNF |
| 1 | 1922/1/27 (São Paulo) | -22.2 | -47.04 | -22.3 | -47.1 | -22.3 | -47.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| 2 | 1955/1/31 (Mato Grosso) | -12.5 | -57.35 | -14.2 | -57.2 | -14.2 | -57.2 | 1.7 | -0.1 | 1.7 | -0.1 |
| 3 | 1955/3/1 (Espírito Santo) | -19.8 | -36.75 | -20.6 | -40.1 | -20.6 | -40.1 | 0.8 | 3.4 | 0.8 | 3.4 |
| 4 | 1967/3/23 (São Paulo) | -23.3 | -45.0 | -23.3 | -45.2 | -23.3 | -45.1 | 0.0 | 0.2 | 0.0 | 0.1 |
| 5 | 1968/2/15 (Rio Grande do Norte) | -6.09 | -38.44 | -6.1 | -38.4 | -6.1 | -38.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| 6 | 1968/2/23 (Rio Grande do Norte) | -6.09 | -38.44 | -6.1 | -38.4 | -6.1 | -38.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| 7 | 1972/10/24 (Rio de Janeiro) | -21.7 | -40.53 | -21.8 | -41.1 | -21.9 | -41.1 | 0.1 | 0.6 | 0.2 | 0.6 |
| 8 | 1974/2/24 (Minas Gerais) | -20 | -48.47 | -20.1 | -48.6 | -20.1 | -48.6 | 0.1 | 0.1 | 0.1 | 0.1 |
| 9 | 1976/1/5 (Goiás) | -15.4 | -50.43 | -15.5 | -50.5 | -15.5 | -50.5 | 0.1 | 0.1 | 0.1 | 0.1 |
| 10 | 1979/3/27 (Paraná) | -22.8 | -51.01 | -22.8 | -51.0 | -22.8 | -51.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 11 | 1979/8/22 (Goiás) | -15.3 | -49.95 | -15.2 | -49.9 | -15.2 | -49.9 | -0.1 | -0.1 | -0.1 | -0.1 |
| 12 | 1980/11/20 (Ceará) | -4.3 | -38.4 | -4.3 | -38.4 | -4.3 | -38.4 | 0.0 | 0.0 | 0.0 | 0.0 |
| 13 | 1982/4/8 (Asuncion/Paraguay) | -24.8 | -58.1 | -25.3 | -57.7 | -25.3 | -57.6 | 0.5 | -0.4 | 0.5 | -0.5 |
| 14 | 1983/8/5 (Amazonas) | -3.58 | -62.14 | -3.8 | -62.0 | -3.7 | -61.8 | 0.2 | -0.1 | 0.1 | -0.3 |
| 15 | 1986/8/5 (Rio Grande do Norte) | -5.53 | -35.75 | -5.5 | -35.8 | -5.5 | -35.8 | 0.0 | 0.0 | 0.0 | 0.0 |
| 16 | 1989/1/7 (Paraná) | -22.9 | -51.01 | -22.9 | -51.0 | -22.9 | -51.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 17 | 1998/3/10 (Mato Grosso) | -11.6 | -56.74 | -11.4 | -56.8 | -11.4 | -56.8 | -0.2 | 0.1 | -0.2 | 0.1 |
| 18 | 2007/12/9 (Minas Gerais) | -15 | -44.3 | -15.0 | -44.3 | -15.0 | -44.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| 19 | 2009/6/15 (Mato Grosso do Sul) | -18.5 | -55.8 | -18.3 | -55.6 | -18.4 | -55.6 | -0.2 | -0.2 | -0.1 | -0.2 |
| 20 | 2017/1/3 (Maranhão) | -3.33 | -43.94 | -3.2 | -43.8 | -3.2 | -43.8 | -0.1 | -0.1 | -0.1 | -0.1 |

## 95% Confidence limit tables

**Table S3** – 95% confidence-level *rms* (units above the inversion minimum) and magnitude deviation. Data used in Fig. 9a (EPICENTER) and 9b (MAGNITUDE).

| EPICENTER | | MAGNITUDE | |
|---|---|---|---|
| # MDP | 95% RMS | Upper Limit | Lower Limit |
| 5 | 0,313 | -1,3 | 1,21 |
| 7 | 0,248 | -1,28 | 1,12 |
| 10 | 0,216 | -1,1 | 1,21 |
| 15 | 0,179 | -1,01 | 0,64 |
| 20 | 0,164 | -0,9 | 0,62 |
| 25 | 0,159 | -0,71 | 0,72 |
| 30 | 0,161 | -0,71 | 0,72 |
| 40 | 0,118 | -0,4 | 0,72 |
| 50 | 0,112 | -0,4 | 0,62 |

# REAVALIAÇÃO DO TERREMOTO DE 1946 (LORENA – SP)

Posteriormente a submissão do artigo (Capítulo 2) foi feita mais uma reavaliação referente ao terremoto de 1946 em Cananéia – SP, Brasil. A reavaliação é apresentada aqui como uma continuação do terceiro capítulo do artigo.

## 1946, Cananéia (SP), SE Brasil

A informação sobre esse evento foi compilada por Assumpção *et al.* (1980) e Berrocal *et al.* (1984) que estimaram uma magnitude de 4.5 mb levando em consideração área sentida de 60.000 km$^2$.

Fig. 3.1 mostra o epicentro estimado para este evento. Foi determinado uma magnitude 4.3 ± 0.20 (mb) e epicentro 24.9°S 47.7°O com uma incerteza com um nível de 95% de confiança de 154 km. O epicentro é próximo (22 km) do epicentro determinado por Berrocal *et al.* (1984), localizado na plataforma continental. A incerteza permite que o epicentro esteja localizado tanto *onshore* ou ao longo da plataforma (*offshore*), embora sem chegar na região do talude.

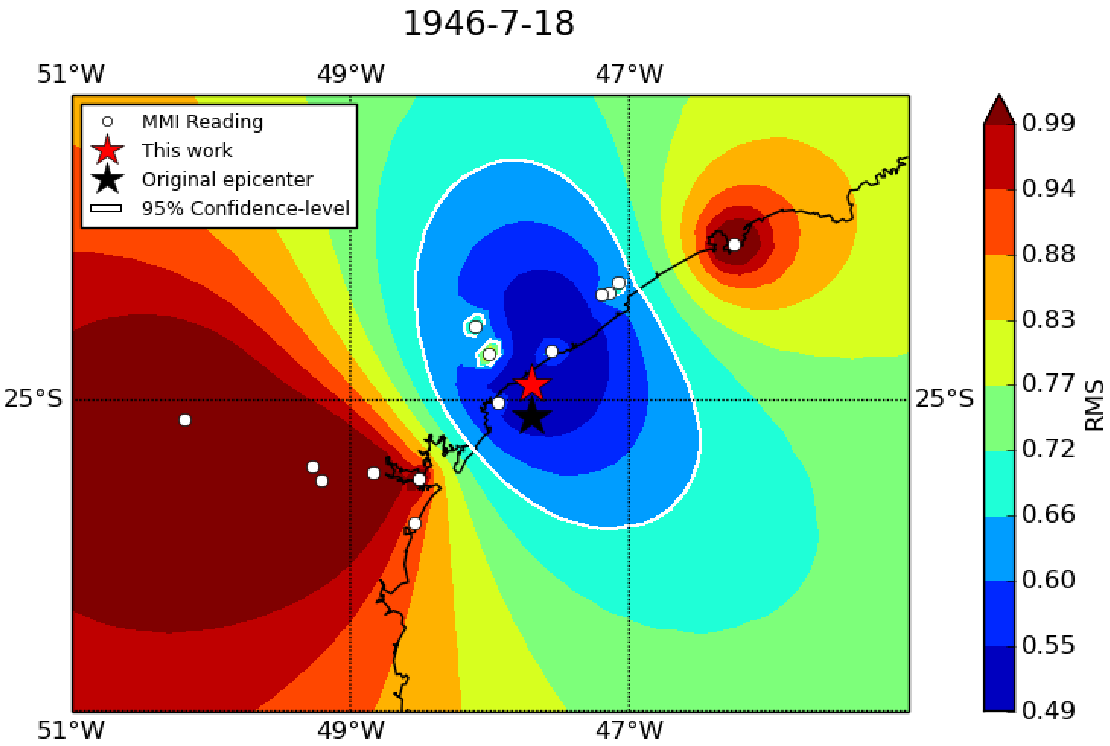


**Figura 3.1:** Inversão do epicentro (estrela vermelha) do evento de 1946 em Cananéia – São Paulo, Brasil usando a equação Eq. 5 determinada no artigo (Apêndice I). A estrela preta é o epicentro de acordo com Berrocal et al. (1984). A linha branca representa a curva de 95% de confiança

.

# EXEMPLO *BOOTSTRAP*

Foi sugerido pela banca incluir um capítulo com exemplos de utilização do método *Bootstrap* que foram apresentados durante a defesa desse trabalho de mestrado no Instituto de Astronomia, Geofísica e Ciências Atmosféricas na Universidade de São Paulo (12-09-2019). Esse capítulo é uma extensão do capítulo 2.6 do artigo.

## Exemplo de aplicação

De maneira a ilustrar a determinação de incerteza associada ao epicentro e magnitude calculados no capítulo 2.6 do artigo, utilizaremos o evento de 1998-03-10 que ocorreu no norte do estado do Mato Grosso (Figura 4.1) de magnitude 5.27 mb.

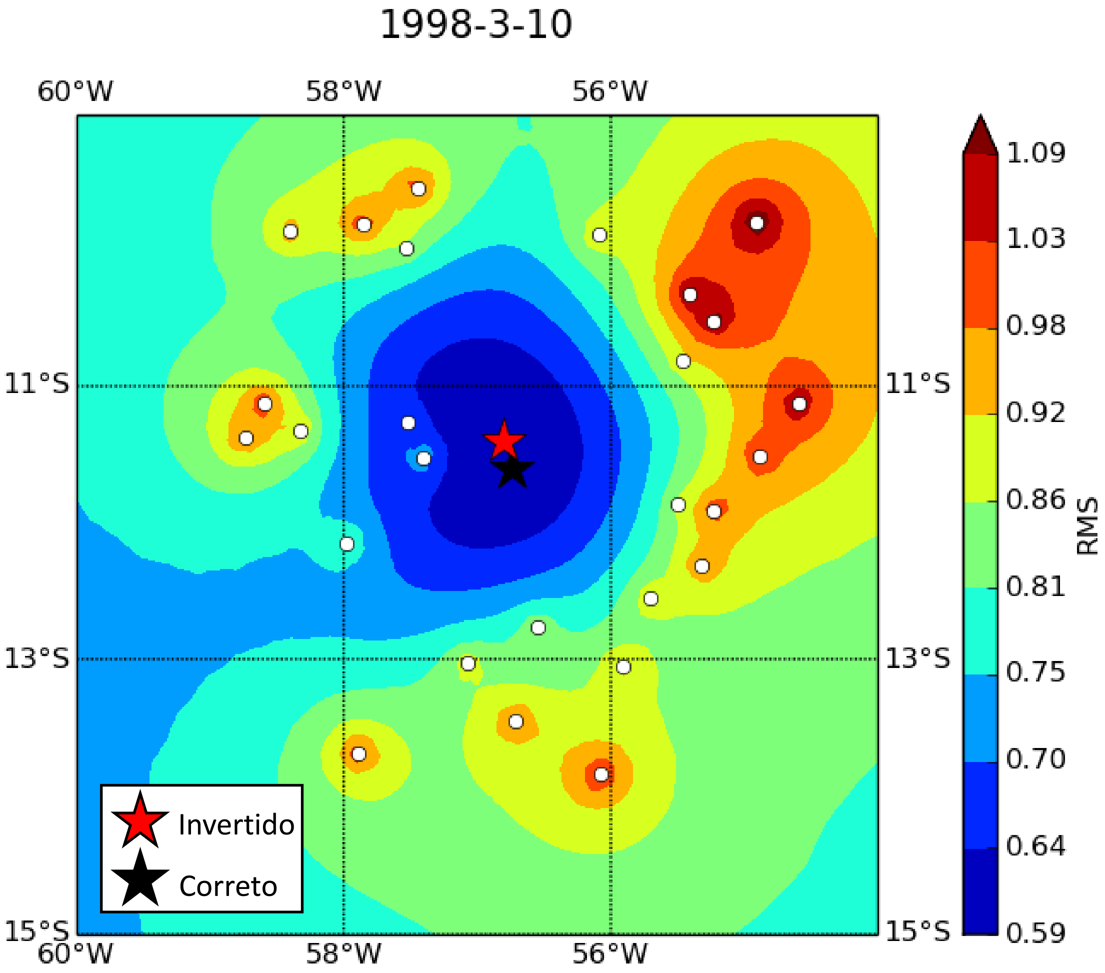

1998-3-10

**Figura 4.1:** Terremoto ao norte do estado do Mato Grosso (1998-03-10 23:32:44 UTM) com epicentro em 11.6°O 56.74°S e magnitude 5.27 mb. O evento possui 27 MDP (círculos brancos). A estrela vermelha é o epicentro invertido usando a Eq. 5 usando todos os MDP deste evento e a estrela preta o epicentro correto.

*Bootstrap* é um método de reamostragem que permite determinar estimativas de acurácia, como intervalos de confiança. Assim, o objetivo é recalcular o epicentro deste evento reamostrando aleatorialmente os 27 MDP em subgrupos. No caso deste trabalho, estimamos as incertezas da Eq. 5 nos subgrupos de MDP de 5, 7, 10, 15, 20, 25, 30, 40, 50 e 60 utilizando todos os 20 eventos (Tabela 1 do artigo).

Neste exemplo, estimaremos a incerteza da Eq. 5 usando apenas o evento de 1998 para o subgrupo de 7 MDP. O primeiro passo, é escolher aleatoriamente 7 MDP do total de 27 e refazer a inversão usando um algoritmo de busca global (capítulo 2.5 do artigo). Então, determinamos o quanto o epicentro invertido se deslocou em relação ao correto, isso é feito em termos da diferença do *rms* residual sob o epicentro invertido e sob o epicentro correto (Figura 4.2). O aumento de *rms* encontrado foi de 0.08 para este subgrupo MDP. Novamente, refazemos o mesmo procedimento com outros 7 MDP aleatórios (Figura 4.3).

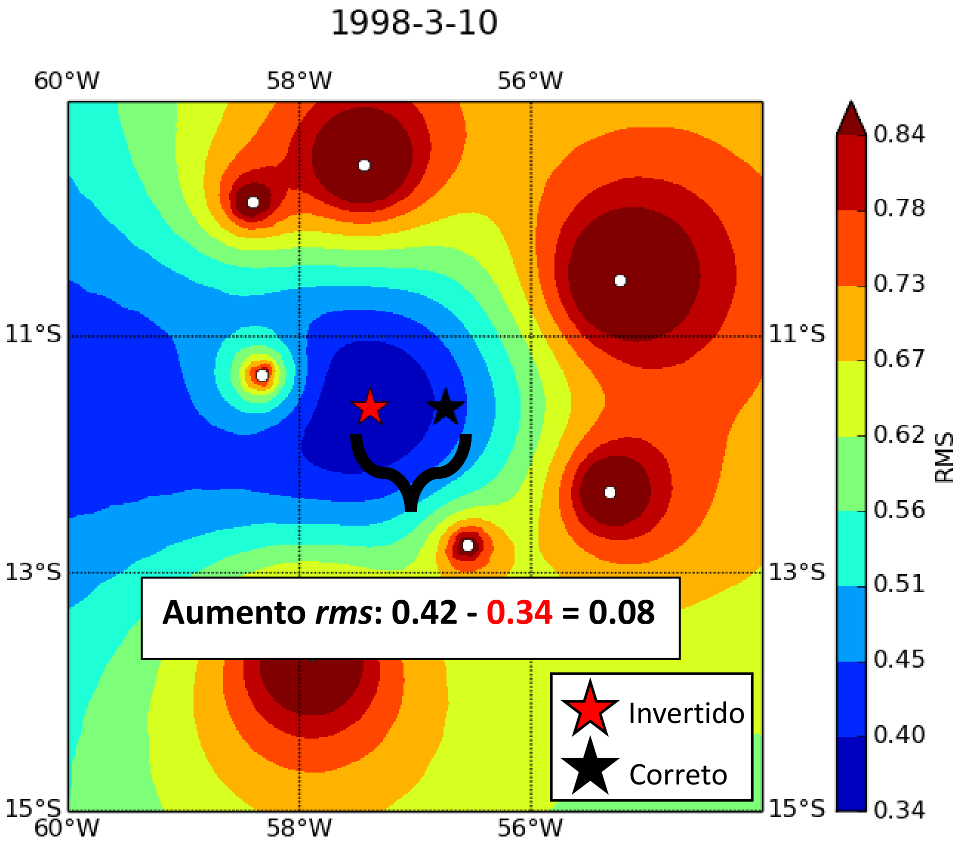


**Figura 4.2:** Inversão do terremoto de 1998 usando 7 MDP escolhidos aleatoriamente. O deslocamento do epicentro é calculado como a diferença do *rms* residual sob o epicentro correto (0.42) com o epicentro invertido (0.34), resultando numa diferença de 0.08.

Como observamos na nova inversão (Figura 4.3), o aumento *rms* foi de 0.09. Porém são necessárias mais inversões para a estimativa ser mais significativa. Seguindo a metodologia de Bakun e Wentworth (1997), o as inversões foram refeitas 1000 vezes (Figura 4.4) e o maior *rms* das 95% melhores soluções (0.21) foi escolhido. Isto significa que o epicentro correto estará 95% do tempo dentro de um aumento *rms* de 0.21 acima do epicentro invertido.

O valor de 0.21 encontrado neste exemplo é próximo de 0.25 encontrado da Figura 9a do artigo para 7 MDP, que usou o mesmo procedimento para todos os 20 eventos.

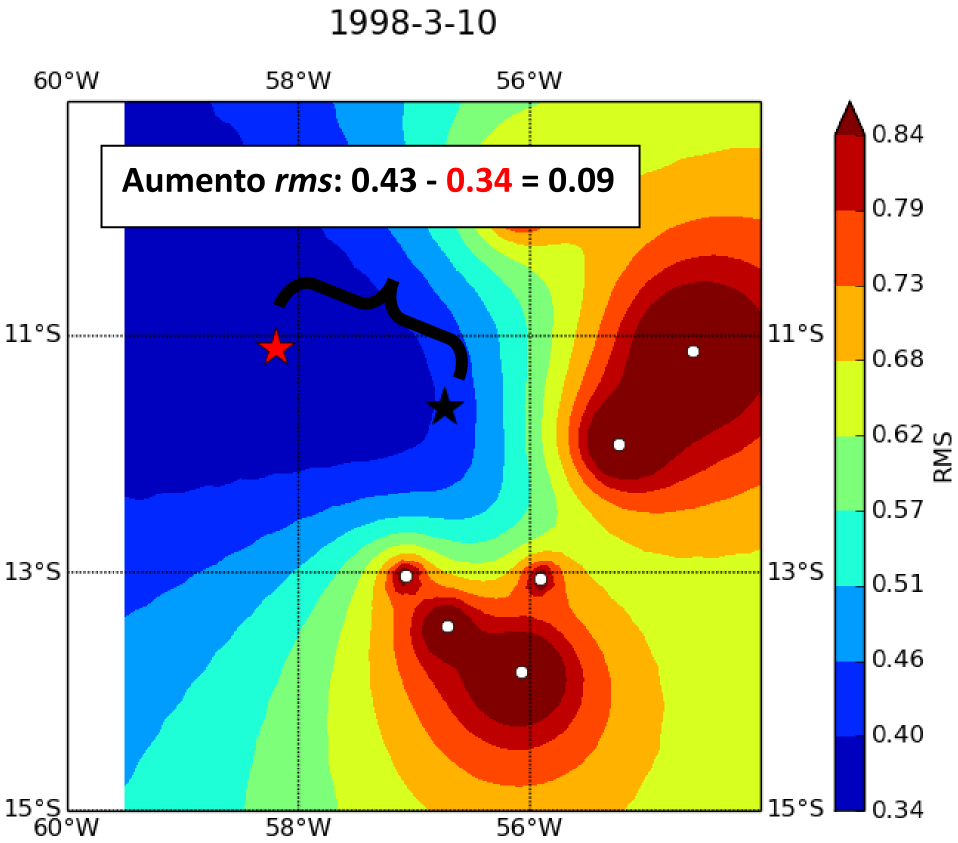


**Figura 4.3:** Inversão do evento de 1998 com 7 novos MDP escolhidos aleatoriamente.

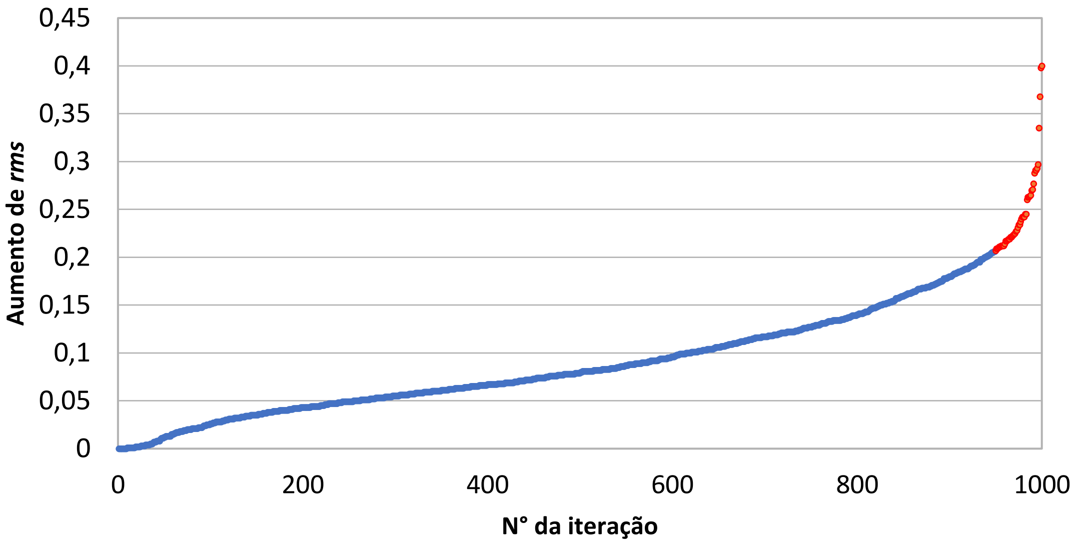


**Figura 4.4:** Aumento *rms* das 1000 iterações feitas para o evento de 1998. Os pontos azuis são as 95% melhores soluções. O valor máximo das melhores soluções é aproximadamente 0.21. Note que cada iteração produz um aumento de *rms* aleatório, os valores de *rms* foram ordenados de maneira crescente para melhor visualização.

# MIDOP

A ferramenta MIDOP cria sites na internet que são gerenciáveis através de qualquer servidor web padrão (por exemplo, Apache2).

Todas as fontes de requisitos abaixo foram retiradas do site do desenvolvedor (Locati, 2017).

Os requisitos mínimos de *hardware* testados para utilizar o MIDOP:

- mínimo: CPU 2Ghz, RAM 2Gb (melhor 4Gb)
- windows: 2000, XP, Vista, 7, 8;
- mac: OSX Tiger (10.4), Leopard (10.5), Lion (10.6);
- linux: Ubuntu, OpenSuse, Fedora, CentOS.

Os *softwares* de terceiros (basta qualquer ambiente AMP[4]):

- servidor web: Apache 2.x;
- linguagem: PHP 5.4.x, pode ocorrer problemas com PHP 5.5.x;
- sistema de gerenciamento de banco de dados (DBMS): MySql 5.x;
- *software* para organizar os dados de intensidade macrossísmica (exemplos):
    - fase preparatória: Microsoft Access ou OpenOffice/LibreOffice;
    - quando os dados já estão no MySQL: phpMyAdmin, MySQL workbench.

A quantidade mínima de informação necessária para utilizar o MIDOP e gerar o site:

- lista de terremotos com:
    - código único que identifique o tremor;
    - tempo de origem, separado em diferentes campos: ano, mês, dia, hora, minutos, segundos;
- lista de dados de intensidade macrossísmica:
    - um campo com um identificador único que associe um ponto de intensidade com um terremoto e que seja o mesmo para cada outro ponto de intensidade no mesmo terremoto.
    - dois campos para as coordenadas geográficas (latitude e longitude), expressas de graus decimais;
    - dois campos para as coordenadas geográficas de grandes territórios (ex. “São Paulo”, “Minas Gerais”, “Rio de Janeiro”, etc.) que não serão inseridas no mapa, mas usadas internamente. Uma coordenada para a latitude e outra para a longitude, ambas em graus decimais;
    - dois campos para as intensidades macrossísmicas: um para a intensidade em si (ex. “7”, “7-8”, “F”[5], etc.) e outro para o valor

---

[4] Acrônimo para pacotes Apache-MySQL-PHP (AMP) que são coletâneas de *softwares* usados para criar sites e servidores na internet. Exemplos são: LAMPs (Linux); WAMPs (Windows); e MAMPs (macOS).

[5] “F” significa *Felt*, isto é, um sísmico que foi apenas “sentido” numa região, mas não se sabe um valor de intensidade associado.

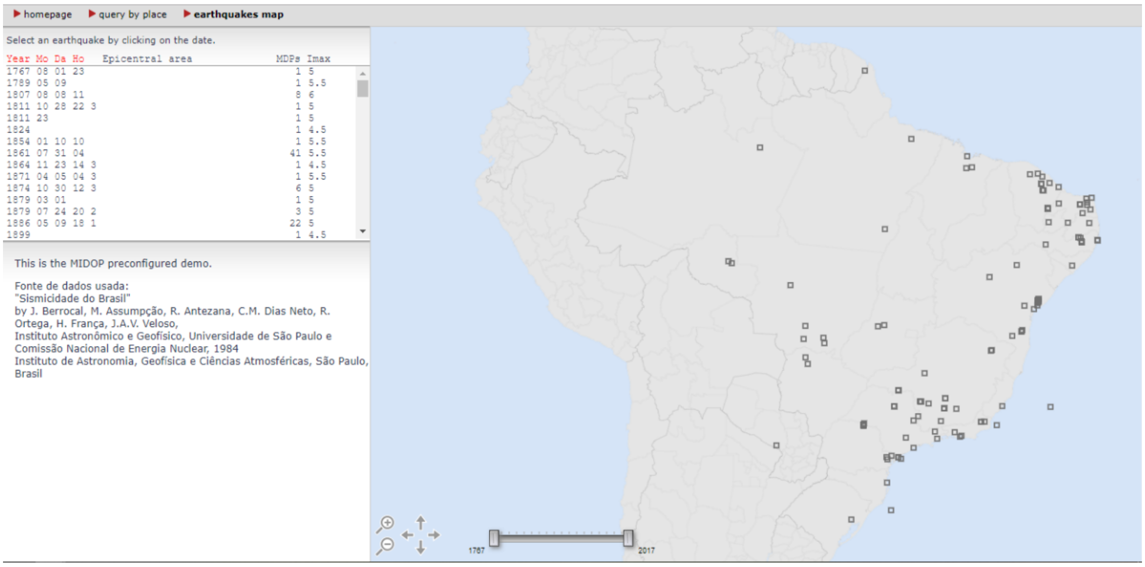
numérico correspondente que será usado internamente para ordenar os eventos (ex. “7”, “7.5”, etc.).

MIDOP possibilita criar sites onde é possível: criar mapas epicentrais de terremotos (Fig. 4.1); mapas de medidas de intensidade (MDP) para cada evento (Fig. 4.2); histórico de Sismicidade da região (Fig. 4.3); buscar estudos sobre um evento; e baixar dados macrossísmicos, exportando nos formatos KML (Google Earth) e QuakeML. Outro benefício é a ferramenta estar disponível em código aberto, possuindo alto grau de customização. É uma plataforma segura de ataques via web, devido a existência de apenas *scripts* em *JavaScript* e HTML.

Os mapas interativos gerados pelo MIDOP podem ser navegados de forma *offline*, devido a utilização de imagens no formato *Scalable Vector Graphics* (SVG) e a linguagem *JavaScript*. Ações como zoom, navegação pelo mapa e buscas de eventos dependem apenas do navegador (ou *browser*) do usuário final, sem a necessidade de qualquer outra ação por parte do servidor (Locati, 2017).

Inicialmente o MIDOP foi implementado num sistema Ubuntu 14.04 LTS, estando disponível, em fase de testes, no site do Centro de Sismologia do IAG – USP pelo endereço (acessado 31/07/2019)

http://moho.iag.usp.br/midop/



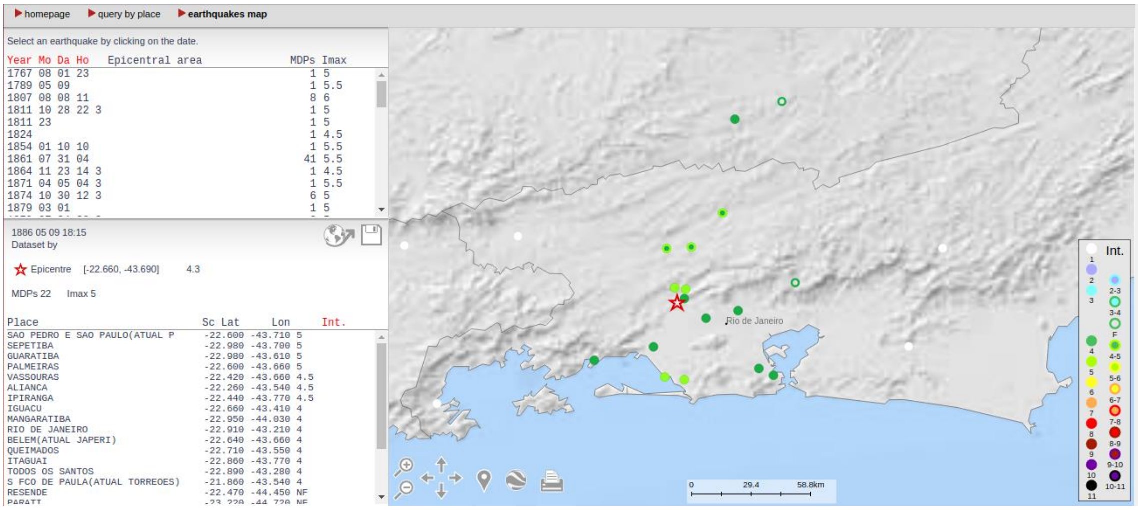
Select an earthquake by clicking on the date.

```
Year Mo Da Ho    Epicentral area                MDPs Imax
1767 08 01 23                                      1 5
1789 05 09                                         1 5.5
1807 08 08 11                                      8 6
1811 10 28 22 3                                    1 5
1811 23                                            1 5
1824                                               1 4.5
1854 01 10 10                                      1 5.5
1861 07 31 04                                     41 5.5
1864 11 23 14 3                                    1 4.5
1871 04 05 04 3                                    1 5.5
1874 10 30 12 3                                    6 5
1879 03 01                                         1 5
1879 07 24 20 2                                    3 5
1886 05 09 18 1                                   22 5
1899                                               1 4.5
```

This is the MIDOP preconfigured demo.

Fonte de dados usada:
"Sismicidade do Brasil"
by J. Berrocal, M. Assumpção, R. Antezana, C.M. Dias Neto, R. Ortega, H. França, J.A.V. Veloso,
Instituto Astronômico e Geofísico, Universidade de São Paulo e Comissão Nacional de Energia Nuclear, 1984
Instituto de Astronomia, Geofísica e Ciências Atmosféricas, São Paulo, Brasil

**Figura 5.1:** Imagem da tela de busca de eventos do MIDOP. Os quadrados pretos no mapa representam os epicentros de eventos entre os anos de 1767 e 2017.



Select an earthquake by clicking on the date.

```
Year Mo Da Ho   Epicentral area             MDPs Imax
1767 08 01 23                                  1 5
1789 05 09                                     1 5.5
1807 08 08 11                                  8 6
1811 10 28 22 3                                1 5
1811 23                                        1 5
1824                                           1 4.5
1854 01 10 10                                  1 5.5
1861 07 31 04                                 41 5.5
1864 11 23 14 3                                1 4.5
1871 04 05 04 3                                1 5.5
1874 10 30 12 3                                6 5
1879 03 01                                     1 5
```

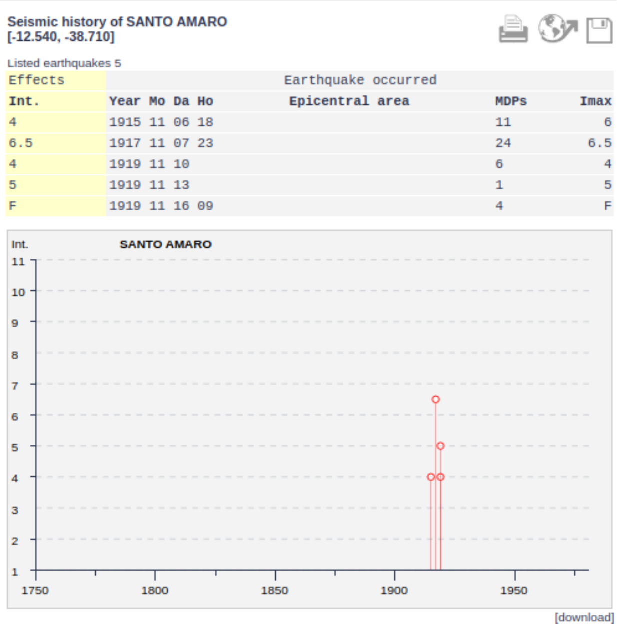
1886 05 09 18:15
Dataset by

☆ Epicentre [-22.660, -43.690] 4.3

MDPs 22 Imax 5

```
Place                            Sc Lat     Lon     Int.
SAO PEDRO E SAO PAULO(ATUAL P    -22.600 -43.710 5
SEPETIBA                         -22.980 -43.700 5
GUARATIBA                        -22.980 -43.610 5
PALMEIRAS                        -22.600 -43.660 5
VASSOURAS                        -22.420 -43.660 4.5
ALIANCA                          -22.260 -43.540 4.5
IPIRANGA                         -22.440 -43.770 4.5
IGUACU                           -22.660 -43.410 4
MANGARATIBA                      -22.950 -44.030 4
RIO DE JANEIRO                   -22.910 -43.210 4
BELEM(ATUAL JAPERI)              -22.640 -43.660 4
QUEIMADOS                        -22.710 -43.550 4
ITAGUAI                          -22.860 -43.770 4
TODOS OS SANTOS                  -22.890 -43.280 4
S FCO DE PAULA(ATUAL TORREOES)   -21.860 -43.540 4
RESENDE                          -22.470 -44.450 NF
```

**Figura 5.2:** Mapa de intensidades do terremoto de 09/05/1886 no Rio de Janeiro de magnitude 4.3 (mb) e intensidade máxima 5 na escala Mercalli Modificada (MM). A estrela representa o epicentro. Os pontos coloridos correspondem as intensidades conforme a legenda (direita).



Seismic history of SANTO AMARO
[-12.540, -38.710]

Listed earthquakes 5

| Effects | Earthquake occurred | | | |
|---|---|---|---|---|
| Int. | Year Mo Da Ho | Epicentral area | MDPs | Imax |
| 4 | 1915 11 06 18 | | 11 | 6 |
| 6.5 | 1917 11 07 23 | | 24 | 6.5 |
| 4 | 1919 11 10 | | 6 | 4 |
| 5 | 1919 11 13 | | 1 | 5 |
| F | 1919 11 16 09 | | 4 | F |

**Figura 5.3:** Histórico de sismicidade do município de Santo Amaro, Bahia. A tabela mostra a ocorrência de 5 eventos nesse município. O gráfico mostra as intensidades (MM) observadas no município em função do tempo (anos).

# Capítulo 6

## CONCLUSÃO

### ATENUAÇÃO DE INTENSIDADES

Foi determinado uma nova equação brasileira de atenuação de intensidades que pode ser usada em dados brutos de intensidade, ao invés da equação anterior que requer estimativa de isossistas. A nova equação permite a reavaliação da sismicidade histórica, com possíveis implicações para estudos futuros de risco sísmico.

A aplicação da nova equação com o terremoto venezuelano de 2018 (6.9 mb) foi um teste de quão bem ela pode ser extrapolada para maiores distâncias hipocentrais e magnitudes. Apesar do decaimento de intensidade com a distância possuir boa concordância e o ajuste ser razoável (desv. pad. = 1.1), a curva está por volta de 1 unidade de intensidade abaixo do indicado pelos dados. Assim, como discutido, mais testes serão necessários.

Os epicentros e magnitudes invertidos do conjunto de 20 eventos apresentaram resultados razoáveis, onde 80% dos dados tem erro epicentral menor do que 30 km e uma variância na magnitude entre $+0.7$ e $-0.5$, porém, foi notado que a distribuição de medidas de intensidade em apenas um lado do epicentro pode aumentar significantemente as incertezas.

Nós também mostramos que usar dados "Sentidos" (*Felt*) e "Não sentidos" (*Not Felt*), ou dados FNF, não mudam a incerteza da magnitude/epicentro. Nós acreditamos que esses dados não melhoraram a inversão devido a duas razões: a equação de intensidades foi derivada sem dados FNF; normalmente dados FNF possuem baixa qualidade.

Pelo método *bootstrap* mostramos que usar 10 ou mais MDP reduz de maneira significativa as incertezas epicentrais e em magnitude de eventos invertidos usando nossa equação.

A reavaliação do evento de 1861 em Lorena – SP determinou um novo epicentro em 23.1°S 44.7°O com magnitude de 5 mb. O erro na magnitude foi razoável ($\pm$0.56 mb), mas incerteza epicentral com um nível de 95% de confiança não foi bem definida (240 km). A incerteza epicentral engloba o epicentro *offshore* de Assumpção and Burton (1985). Logo, a localização do evento de 1861 permanece incerta. Estudos posteriores adicionando e revisando os dados de intensidade seriam benéficos.

A reavaliação do evento de 1946 em Cananéia – SP determinou um novo epicentro em 24.9°S 47.7°O com magnitude de 4.3 mb. O erro na magnitude foi razoável ($\pm$0.88), mas com uma incerteza epicentral com um nível de 95% de confiança grande (154 km). A proximidade do epicentro (22 km) com o determinado anteriormente por Berrocal *et al.* (1984) reforça a possibilidade do evento ter de fato ocorrido na plataforma continental.

MIDOP

A implementação do MIDOP ocorreu com sucesso e já está disponível no site do Centro de Sismologia – IAG – USP (http://moho.iag.usp.br/midop/). A ferramenta continuará a ser estudada, com possibilidade de inclusão de novos eventos e adição de mais dados aos eventos existentes. Também será estudada a expansão futura das funcionalidades do MIDOP dependendo da necessidade dos usuários.

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