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NEW FREE-AIR AND BOUGUER GRAVITY ANOMALIES MAPS OF BRAZIL

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ABSTRACT. Here we perform the integration of all available data from the BNDG (Banco Nacional de Dados Gravimétricos) and the BDEP (Banco de Dados de Exploração e Produção da Agência Brasileira de Petróleo) to provide new free-air and Bouguer gravity anomaly maps for the Brazilian territory with newly acquired data over the years, mainly in regions with no data coverage in the past. Quality controls and subsequent gridding processes, in the same system of the whole dataset, are developed on the Oasis Montaj software (OM). Subsets of data from various gravity surveys are gridded and upward continued up to 3000 m to avoid high-frequency noise, allowing them to be gathered. We fill areas with no data coverage in the North Region of Brazil with gravity values from the XGM2019e geopotential model. To join the subset grids of ground and airborne surveys and the geopotential model, we use a collection of grids knitting methods from the OM. To verify the consistency of our grids, we compare them with previously derived gravity anomalies maps and geopotential models. Our new free-air and Bouguer gravity anomalies maps show more detailed short-wavelength geological structures than their predecessors. Therefore, these new gravity anomalies maps may be helpful for the development of recent tectonic, oil, and mining studies.

Keywords: gravity anomalies map; data integration; potential methods.

INTRODUCTION

Gravity data are widely used in geosciences and contribute to studies that range from local-scale, as for small mining projects, to regional and global ones, as for sedimentary basin characterization for oil and gas exploration and the modeling of the Earth's shape and its physical properties.

Breville et al. (1973) introduced the first gravity map of Brazil as part of the South America Gravity Map at a 1:10,000,000 scale. The authors used the scarce ground data available at that time, which were collected by Petrobras, the Brazilian National Petroleum Company. Green and Fairhead (1993) compiled a new version of the South American gravity map using ground, sea, and airborne gravity data and from satellite altimetry, most of them obtained by petroleum companies, which restricted their use and presentation, until 2001, and produced a gravity anomaly grid of 5 ' x 5 '. Sá et al. (1993), using all ground gravity data available in Brazil (around 35,000 observations) along with data from a geopotential model, Doppler-derived geoidal heights, astrogeodetic vertical deflections, and a topographic model, derived new free-air and Bouguer anomaly maps of Brazil using the least squares collocation method (Krarup, 1969; Moritz, 1972), with a formal resolution of 0.5 °.

The existence of global geopotential models (e.g., the XGM2019e of Zingerle et al., 2020), which integrate satellite data with terrestrial, satellite altimetry, airborne gravimetry, and topography/bathymetry data, provides a better spatial resolution of the Earth's gravity field. Such models are now based on spherical harmonic coefficients with high degree and order. For areas with poor coverage, they provide the only solution available to the gravity field. Nonetheless, these models usually are not suitable for local studies in areas of scarce terrestrial/marine coverage because of the low resolution caused by the high altitude and velocity of the satellites, which can only recover medium and long wavelength features of the gravity field.

In the 2000s, the Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP), the Instituto Brasileiro de Geografia e Estatística (IBGE), the Serviço Geológico do Brasil (CPRM), Brazilian public universities (USP, UFPR, UnB, UFMT, and others), the Observatório Nacional (ON) and Petrobras, started sharing their geophysical data (gravimetric included) through databases (e.g., BDEP, BNDG, GEOSGB) under special terms to promote the scientific and commercial geological and geophysical activities. The BNDG, for example, keeps over 86,000 ground gravity observations. In 2020, the ANP gave free access to the BDEP onshore surveys, which included ground and airborne gravity surveys covering most of the sedimentary basins in Brazil. The Gravimetric data available gives us the opportunity to derive new free-air and Bouguer anomaly maps.

Here, aiming to derive new free-air and Bouguer maps for Brazil with newly acquired data, mainly in regions with no data coverage in the past, we compile over 900,000 ground observations and 18 airborne surveys, organizing the ground data in a single database, using all information presented in survey reports, and converting them to the same geodetic reference system, the WGS-84, which had already been adopted in most of the airborne surveys. The majority of the survey projects were already well tied to base stations; however, we empirically shift some partial grids by comparing adjacent stations, using the BNDG as a source survey. Thus, we build the final grid using the knitting method from the Oasis Montaj software, joining all partial surveys and combining them with the geopotential model of Zingerle et al. (2020), in the North Region of Brazil, where our terrestrial and airborne gravity data coverage is not homogeneous.

A BRIEF INTRODUCTION OF THE RAVITY RESEARCH AT THE IAG-USP AND THE GRAVITY ANOMALIES MAPS OF BRAZIL

The Instituto de Astronomia, Geofísica e Ciências Atmosféricas (IAG-USP), in the early years of its incorporation into the Universidade de São Paulo (USP), was one of the pioneers in the implementation of the Brazilian Gravimetric Network and the development of gravity studies in Brazil.

With the support provided by federal agencies such as the Instituto Brasileiro de Geografia e Estatística (IBGE), the Brazilian Geological Survey (CPRM), the Observatório Nacional (ON), and National universities such as the Universidade Federal do Paraná (UFPR), N. Cogo de Sá and D. Blitzkow, formers Professors at the IAG-USP, from the middle of 1970, help to expand the gravimetric network and to develop the first Brazilian geoidal model (Castro Junior et al., 2018).

In the early 1980s, Professors W. Shukowsky, M. S. M. Mantovani, and N. Ussami, from the IAG-USP, with more gravity data available, start developing studies on tectonic evolution, mining, and oil in Brazil, demonstrating the importance of this type of observable for mapping key geological features. Later, because of technological advancements, new computers and electronic components are developed, which make it possible to measure Earth's gravity field anomalies with higher precision, as well as satellite missions expand observations to a global scale. At this time, new researchers begin their research based on the use of gravity data at the IAG: Professors E. C. Molina and Y. R. Marangoni.

Taking advantage of the increase in gravity anomaly data availability on a continental scale, Sá et al. (1993) derive one of the most accurate free-air and Bouguer anomaly maps up to that time for Brazil. Almost a decade later, from a new dataset and geopotential models derived from terrestrial data and satellite missions, Sá (2004) builds new gravity anomaly maps, now for the whole of the South American continent. In the last years, some professors have retired, leaving their mission to the new ones to continue the use of gravity data for modeling the crustal and upper mantle density structures to understand their evolution throughout time.

Finally, the research based on gravity data at the IAG-USP has also contributed to the formation of many geophysicists, which currently work in several public and private companies, and universities and help to improve somehow our knowledge about the Earth's structure evolution.

METHODS

The Data

To build the new gravity maps of Brazil, we use the geopotential model of Zingerle et al. (2020), in the North Region of Brazil, along with 905,655 land gravity stations from the BNDG and BDEP databases, sixteen airborne surveys from the BDEP and CPRM databases, and two compilations from airborne surveys provided by the BDEP, as shown in Figure 1.

Geopotential Model

Used to fulfill the North Region of Brazil due to the lack of ground and airborne data outside the Amazon Basin (notice the blank area in Figure 1), the geopotential model XGM2019e (Zingerle et al., 2020) is a mathematical representation of the Earth's gravity field with spherical harmonic coefficients up to degree and order (d/o) 5399. It includes the satellite gravity model GOCO06s (Kvas et al., 2019) for the representation of the longer gravity field wavelength component, combined with ground gravity observations provided by the United States National Geospatial-Intelligence Agency (NGA) at 15' resolution and 1' augmentation dataset from topography-derived gravity anomalies using the EARTH2014 model (Rexer et al., 2017). We use the XGM2019e model up to d/o 2190, which provides us a resolution of approximately 5' (0.082°), which is close to the resolution of our other dataset, avoiding dubious high-frequency artifacts. We also apply an upward continuation to the XGM2019e model grid up to 3000 m so that the integration with our terrestrial and airborne gravity data can be accomplished.

Gravity Data

We manually inspect the gravity survey projects (ground and airborne), seeking the data with the following information present: height, free-air, Bouguer, corrections applied and coordinate systems, and their respective reports (if they exist). We do not use survey projects without enough information or covered by newer ones in the further steps.

The horizontal coordinates are converted to the WGS-84 system when necessary. Nevertheless, most surveys were already set in this geographic system. As the gravity datum, we use the RGFB (Brazilian Gravimetric Reference Network), as established by the ON in 1987. Regarding the gravity gradient airborne systems like FalconTM (Lee, 2001), used in some surveys, they have a different processing system, which does not match any gravity datum. In this work, we use compilations of those projects provided by the ANP. They are transformed into gravimetric data linked to RGFB from the data obtained with the GT-1A gravimetric system (Gabell et al., 2004) and geopotential models as EGM2008 (Pavlis et al., 2012), using the method proposed by Dransfield (2009).

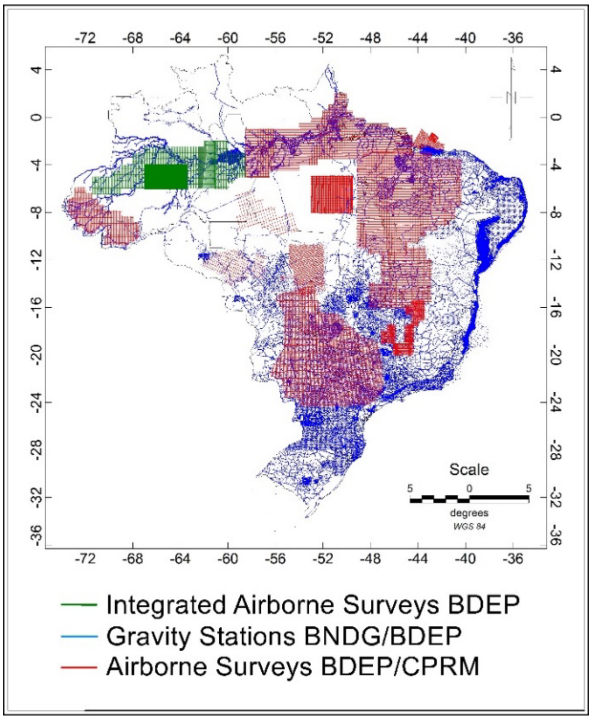

Figure 1: Distribution of gravity data in Brazil. Colors refer to different types of surveys: the blue is for ground data, the red is for airborne surveys, and the green is for integrated data. The polygon shades indicate the closeness of the data. Notice the lack of data in the North Region of Brazil, chiefly outside the Amazonas Basin.

Land gravity surveys

The original BNDG, which represents most of our data, is referenced to Geodetic Reference System 1967 (GRS67) (IAG, 1971). We assume that GRS67 was used on a survey when this information is absent in its processing report. We start our data processing by joining all ground surveys in one single database. Then, we recalculate the gravity anomalies when the provided information was sufficient or use reversal transformation (from gravity anomalies to observations) if only height and gravity anomalies are present, using the following set of equations from Blakely (1995):

$$\gamma_{1967} = 978031.846(1 + 0.0053024 sin\Phi^2 - 0.0000058 sin2\Phi^2) \quad (1)$$

$$g_{fa} = -0.3086 * h, \quad (2)$$

$$\Delta g_{fa} = g_{obs} - g_{fa} - \gamma_{1967}, \quad (3)$$

$$g_{sb} = 0.1119 * h, \quad (4)$$

$$\Delta g_{sb} = g_{obs} - g_{fa} - g_{sb} - \gamma_{1967}, \quad (5)$$

$$\Delta g_{cb} = g_{obs} - g_{fa} - g_{sb} - g_t - \gamma_{1967}, \quad (6)$$

where γ_{1967} is the normal gravity, Φ is the geodetic latitude, h is orthometric height, gobs stands for observations, g_{fa} is the free-air correction, Δg_{fa} is the free-air anomaly, gsb is the Bouguer correction, Δg_{sb} is the simple Bouguer anomaly, Δg_{cb} is the and complete Bouguer anomaly, and g_t is the terrain correction calculated using the methods of Nagy (1966) and Kane (1962) and the digital elevation models (DEM), based on the SRTM30 (Becker et al., 2009) and the SRTM at 1 Arc-Second Global. For Bouguer anomaly corrections, we assume the standard density value of 2670 kg/m^3 (see Hinze, 2003).

When necessary, we convert the data from Geodetic Reference System 1980 (Moritz, 1980) to GRS67 using the following equation (Moritz, 1980):

$$\gamma_{1980} - \gamma_{1967} = (0.8316 + 0.0782 sin\Phi^2 - 0.0007 sin\Phi^4) mGal \quad (7)$$

where γ_{1980} is the normal gravity for the GRS80 system and γ_{1967} is the normal gravity for the GRS67 system. Differences between the original values from the projects and our recalculated data are about ±5 mGal for both Bouguer and free-air anomalies, most likely due to computational and numerical approximations applied during the original processing. We reject data when the differences are higher than mGal or show evidence of possible technical problems.

The surveys generally present data that are accurately referred to in the RGFB system. Despite this, some of them had to be empirically shifted to up to 50 mGal by using cross-over or adjacent stations from different surveys. Then, we visually inspect the data to remove the remaining spurious data from the free-air and Bouguer grids using the inverse distance weighted method.

Our final ground free-air and Bouguer grids are built using the minimum curvature interpolation method with a cell size of 0.05° and upward continued to 3000 m of altitude. The upward continuation is applied to smooth the high-frequency anomalies and allow the integration of land and airborne data at the same height.

Airborne gravity surveys

Different gravimeter systems were adopted by the airborne surveys used in our study, where most of them refer to the RGFB. Here, we also use integrated gravity surveys provided by the ANP (ANP, 2011), which were flown with Falcon gradiometers conformed with the EGM2008 (Dransfield, 2009) or adjacent surveys, which were carried out with the GT-1A or Graviton-M (Lozhinskaya, 1959) gravimeters, referenced to the Brazilian gravity network. As described by Dransfield (2009), such integration allows us to recover the long-wavelength components of the Earth's gravity field that were not recorded by the gradiometer system because we are able to add other gravity sources, such as geopotential models. After this procedure, the data from gravity gradiometry surveys can be empirically shifted to match the adjacent ones.

The surveys carried out with the GT-1A, GT-2A, or equivalent gravimeters were flown only at fixed altitudes, usually 500 or 600 m above the highest value of DEM (Digital Elevation Model). For comparison, the surveys using the Falcon gradiometers were flown at altitudes of 100 m above the terrain. The spacing between flight lines varied from 3000 to 6000 m. Although the mentioned gravimeters have used their own software for data processing, all processing procedures, corrections, filters, and leveling techniques applied are provided in each survey report. The techniques used to process airborne data are quite different from those used in land projects, as described by the ANP (2010a, 2010b).

We choose to interpolate the leveled free-air and Bouguer anomalies, with terrain correction applied to the last one, although these processes have not been applied to land surveys.

We derive grids from the airborne projects using the minimum curvature method with one-quarter of line spacing for Bouguer and free-air anomalies. Then, we apply the upward continuation filter for each survey to level up the projects to 3000 m of altitude.

The Stitch Method

We use the Oasis Montaj software through the GridKnit extension package to join the previously produced grids from land and airborne surveys. The GridKnit process is able to merge any pair of geophysical grids, even if they do not have the same spacing between the grid cells. This package may also calculate and adjust differences among several grids using trend removal equations, providing two ways for stitching: the blending and suture methods.

The suture method works on a suture line that bisects the overlapping area of the grids and adjusts and smooths the values over the transition zone between them using a multi-frequency algorithm via fast Fourier transform (FFT). The algorithm calculates the differences between the two grids along the suture line and splits the obtained curve into a series of "sine" curves, each representing a single frequency and amplitude. Then, it applies a cascading "smooth" correction surface to each frequency proportional to the wavelength of the mismatch found along the suture path and according to the distance between this line and each grid (Oasis Montaj, 2021).

We perform the processing in pairs, setting up the 3000 m upward continued land survey as our master grid and stitching the airborne surveys from south to north and east to west by convention. As shown in Figure 1, we observe that the distribution of the land gravity station is smaller than that from the airborne surveys in the overlap areas. Hence, we decide to cut the airborne survey polygon area from the land grid and then stitch the airborne grids entirely instead of blending the data to obtain more resolution on the site.

The upward continued grids showed good correspondence among them, and only minor adjustments by static shifts were necessary before the grid stitching procedure.

However, exceptions were detected for grids of the North Region of Brazil and of small surveys, requiring a first-order trend removal before the application of the stitching procedure, probably because of conformation or border effects caused by the airborne gravity filtering process. For the mentioned situations, we cut a small part of the airborne grid borders before the stitching to remove artifacts or trends. Then, we fill the remaining gaps in the North Region of Brazil by adding gravity values from the XGM2019e model, which were extracted by closed polygons manually digitized (Figure 2) and further stitched by the same procedure.

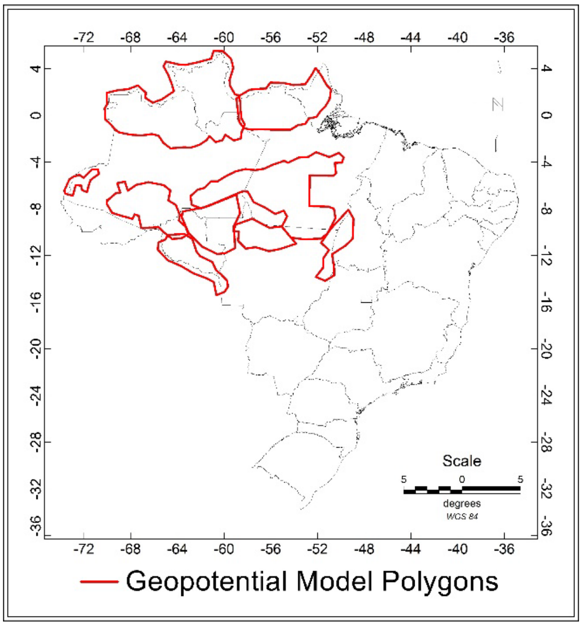

Figure 2: Geopotential polygons (in red) used to complete the grids.

RESULTS

We present our results in the order they were accomplished to allow the reader a proper comparison. We show all grids using a linear scale, with the same range applied to similar themes. The grids are produced with a cell size of 0.05°, using the minimum curvature interpolation, except the grid of Sá et al. (1993), for which we adopt the size of 0.5° as originally derived.

The first product of our study is the DEM map presented in Figure 3, which is obtained from the SRTM data. Most of the altitudes in Brazil are below 1000 m with a few locations with heights above 1500 m. The lowest altitudes are along the Amazonas River, in the North Region of Brazil.

Next, we derive the Bouguer anomaly map using only the ground surveys presented in Figure 4. It shows large empty areas with no data coverage in the North Region of Brazil, outside the Amazon Basin area. In this map, the Bouguer anomalies range from -40 to -100 mGal, with lower values, around -120 mGal, along some Brazilian/Pan African orogenic belts in central Brazil. As expected, the coastal area has positive values.

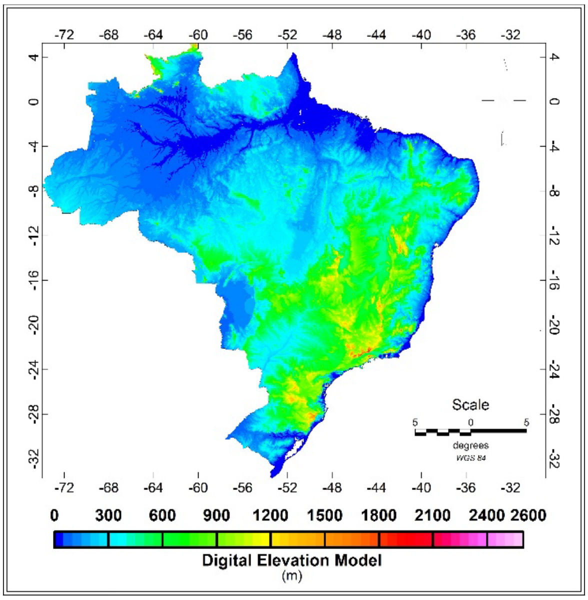

Figure 3: The Digital Elevation Model from the SRTM Model. The size of each color step is 50 m.

Figure 5 shows the integration of the ground data grid (Figure 4) with the airborne surveys. The gravity airborne survey filled some gaps, showing a good resolution for the proposed scale. Notice the correspondence between these two datasets, indicating that reliable stitching was applied. The North Region of Brazil shows the highest values of Bouguer anomaly when compared to the whole country.

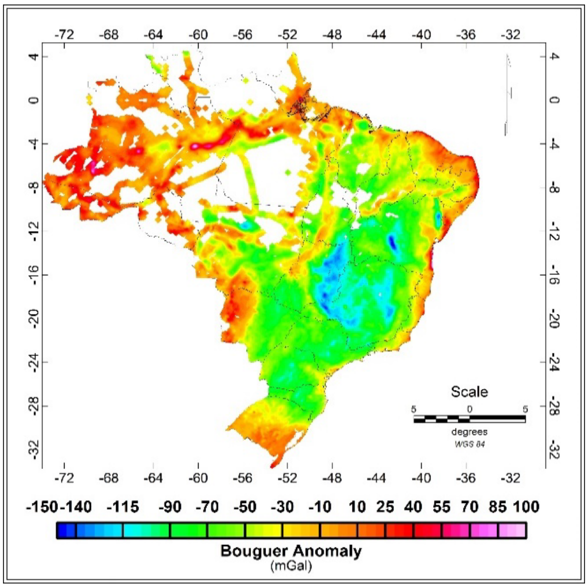

Figure 4: Bouguer anomaly from ground surveys. The size of one color step is 5 mGal.

In Figures 6 and 7, we present the final maps of free-air and Bouguer anomalies, where we use the XGM2019e model to fill the areas with no data coverage. For comparison, in Figures 8 and 9 we provide the geopotential model XGM2019e and the Bouguer anomaly map of Sá et al. (1993).

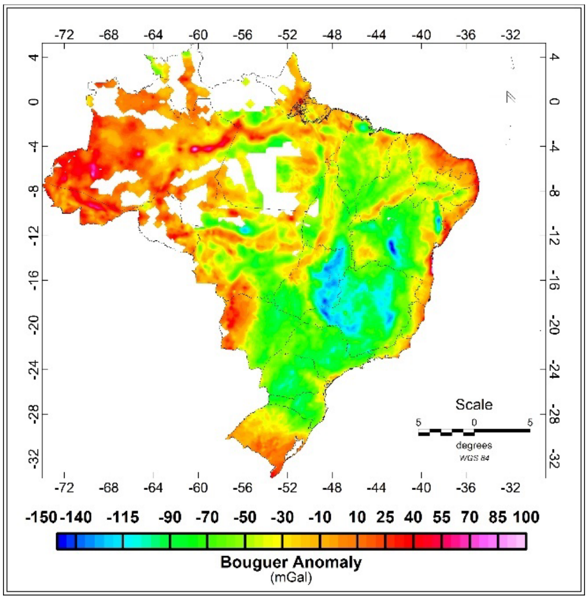

Figure 5: Bouguer anomaly from airborne and ground data integration. The size of one color step is 5 mGal.

The free-air anomalies in Figure 6 range from -50 to -5 mGal. Values higher than -5 mGal appear as linear features in the middle of the country and as small areas in the northeast coastal area, south region, and mainly in the northwest border of Brazil. Some of these positive free-air anomalies are related to low topography areas (see Figure 3), but some of them, especially in the southeast, correspond to the high altitude of Serra do Mar. Our attention is drawn to very low anomalies (~ -80 mGal) scattered in the Brazilian territory. As some of them are present in areas of ground surveys, we do not think that they are an artifact product from the stitching procedure applied to our dataset.

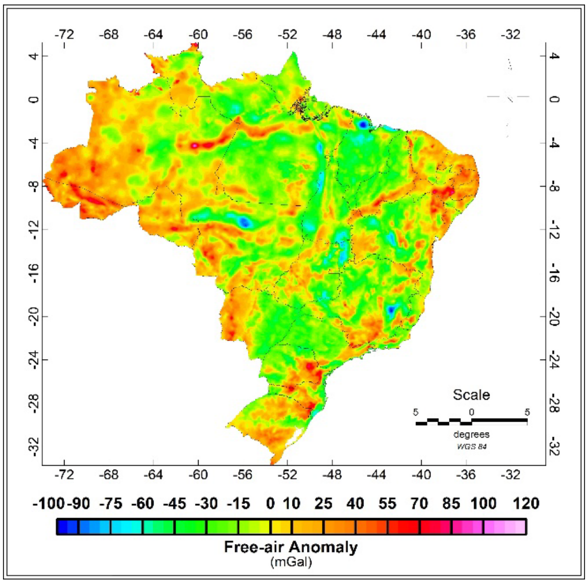

Figure 6: The free-air anomaly map. The size of each color interval is 5 mGal.

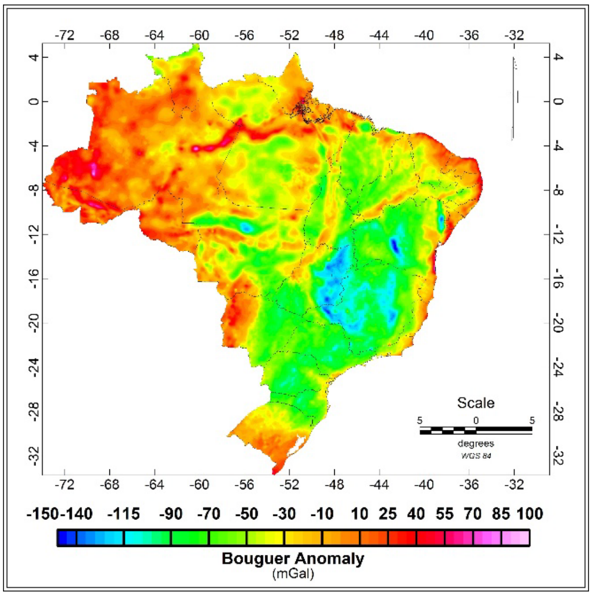

Figure 7: Bouguer anomaly. The size of each color step is 5 mGal.

The integration of the ground and airborne gravity data (Figure 5) with the geopotential model for Brazil (Figure 8) filled some gaps in the Amazon area, reinforcing some tendencies already observed on the map in Figure 5. A significant difference is the linear belt of higher anomalies at the north border, between 58° W and 54° W.

The use of land and airborne surveys helps to hi sharp resolution to gravity signatures compared with older maps (Figure 9) or recent geopotential models using satellite data (Figure 8).

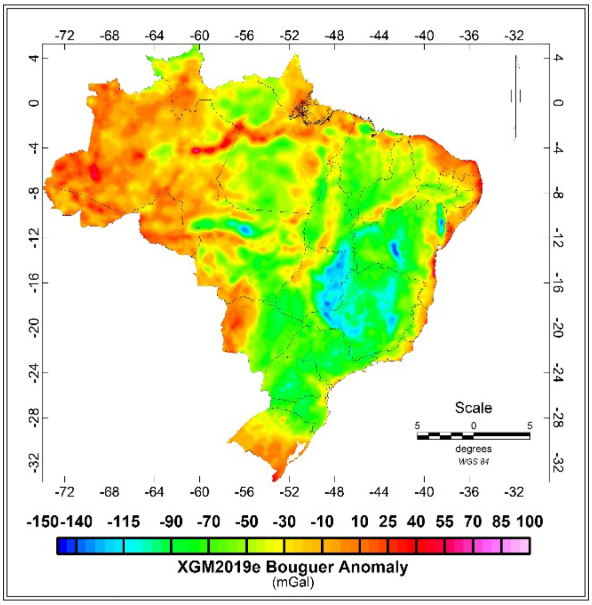

Figure 8: Bouguer anomaly map from the XGM2019e geopotential model. The size of each color step is 5 mGal.

The new proposed maps show a linear trend of higher (-35 to +10 mGal) Bouguer anomalies that are not present in the map of Sá et al. (1993) (Figure 9). We can see smaller anomalies along the territory as the carbonatites from Goiás and the Alto Paranaíba alkaline provinces (Dutra et al., 2012; Marangoni and Mantovani, 2013; Mantovani et al., 2015).

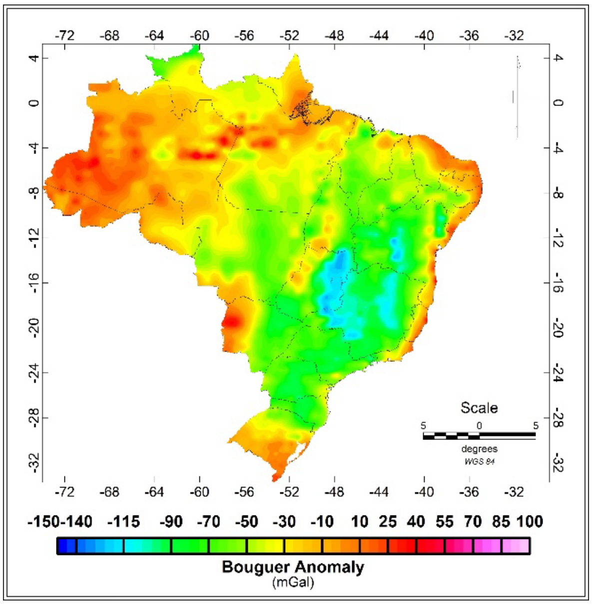

Figure 9: Bouguer anomaly map from Sá et al. (1993). The size of each color step is 5 mGal.

To highlight the differences between the products, we made a map with the difference between our Bouguer anomaly grid and the XGM2019e geopotential model grid. We present the map of disagreements in Figure 10. The minor anomalies and regional trends are emphasized, especially in Acre state and on the east border of Pará state. We show the histogram of the differences in Figure 11.

The average difference between the grids is 1±5 mGal, close to 0 mGal, with maximum and minimum values of 54 and -39 mGal, respectively. In the North Region of Brazil, we observe the most significant differences between the grids, mainly along the Amazon River, where we combine three different datasets. Keep in mind that the highest discrepancies area has ground data from surveys at the river margins and its small tributaries, which are away from any gravity datum. A careful look at Figure 10 also shows that these significant differences are localized, such that we can attribute them to coordinate or altitude errors during the surveys.

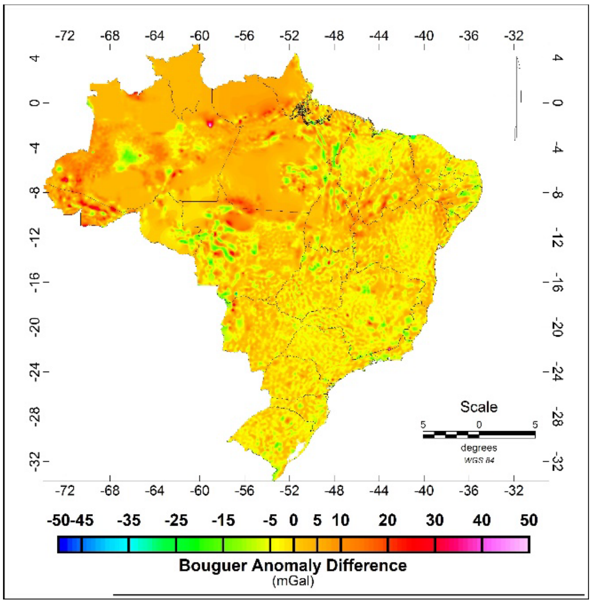

Figure 10: Difference between our Bouguer anomaly map and the Bouguer anomaly from the XGM2019e geopotential model. The size of each color step is 1 mGal.

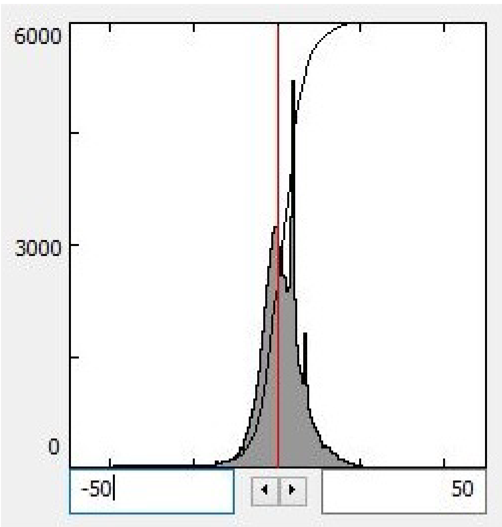

Figure 11: Histogram of the difference between our Bouguer anomaly grid and the one from the XGM2019e geopotential model.

CONCLUSIONS

The availability of BNDG and BDEP gravity data allows us to produce new maps of free-air and Bouguer anomalies for Brazil. The amount of land gravity data, the recent airborne surveys, and the geopotential models from gravity satellite missions provide an increase in the resolution of the gravity anomalies maps derived so far for Brazil, showing new gravity features that will contribute to geophysical and geological studies of different scales.

The evolution of computational power, data storage, and software development permitted the application of a simple method that presented excellent results with less time consumption compared to techniques such as least squares collocation. The increase in airborne surveys in the North Region of Brazil may increase the resolution of the current geopotential and geodetic models in Brazil.

By joining terrestrial airborne gravity data and a geopotential model, we build new gravity anomaly maps for Brazil. Although we are aware that these data are not fully compatible due to differences in acquisition and processing employed in each of them, with the use of the upward continuation filter and the stitching process, the results we obtain, when compared to the previous free-air and Bouguer anomalies maps of Brazil, show a good agreement between them and an improvement in the resolution, indicating our strategy was successfully performed.

The next step is to publish, via CPRM, the new gravity anomaly maps in the same format as the available magnetometric (Correa et al., 2016) and spectrometric (Correa, 2016) maps for the Brazilian geoscience community.

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