Investigation of the Control and Monitoring of Onshore Wind Structures, Buildings, Built and/or Natural Soils with the Employment of Geodetic Measurement

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Key words: Geodetic Monitoring, Onshore Wind Towers, Measurement of settlements and Landslides, Point-cloud Calibration and Classification

SUMMARY

This article presents applied geodesy approaches to monitor the structural conditions of buildings, onshore wind towers, built and natural soils, which are the least contemplated with dimensional control. This control is provided by the applications of geodetic measurement methods, especially using the GNSS system and terrestrial measurement methods. The measurement methods are responsible for determining the exact position and area of the building and other concrete and/or metal structures to be built or already built. They also, to investigate, over time, if they suffer deformation, to prevent natural and structural risks. The geometric and dimensional representation of these structures were carried out from the geodetic survey, defined based on the geodesic vertices of an official reference system. The connection of these structures (measurement objects) to a Geodetic Reference System, occurred through reference points, measured by GNSS Positioning methods and Terrestrial Measurement Methods. The studies of wind towers and inclined land susceptible to settlements and landslides were carried out from an altimetric network in a wind farm, located in the municipality of Gravatá-PE, Brazil, involving two wind towers and the area around them, taking measurements at four different times, and applying very high-precision geometric leveling. In all, the elapsed interval was 536 days. Altimetric elevations were adjusted via parametric model of the Least Squares Method (LSM), applying quality tests of the Chi-Square distribution. The geodesic network of planialtimetric reference that involved the wind towers was expanded with the implantation of points at the bases of the towers and encrusted in the rocky outcrops on the ground. With technological advances and the advent of the laser profiling technique, it is possible to obtain planialtimetric data with high precision. The trust and certainty of the quality of the point clouds are extremely important for them to be used in the generation of cartographic products with the discretization of buildings. In this context, the creation of a geodesic infrastructure is of fundamental importance to enable the control and verification of the quality of this product. Thus, in Olinda-PE, Brazil, these experiments were carried out in the Historic Center. In this context, this work aims to address the geodetic measurements developed in the discretization of the cited structures, also establishing metrological reference standards for data acquisition and use of methods and instruments in the field.

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1. INTRODUCTION

This work involves the areas of Topography and Geodesy, regarding the definition of geodesic infrastructures in urban and/or rural areas for studies of control, three-dimensional representation and monitoring of structures (buildings, wind towers and built-up and/or natural soils), applying the respective Instrumental Metrology, necessary for the use of equipment and their respective accessories and the execution of technical methods in the field.

In this context, geodetic/topographic concepts are necessary for the applicability of geodesic structures, when dealing with the definition and materialization of one-dimensional, two-dimensional and/or three-dimensional reference systems, the transformations carried out between the different reference systems, as well as, when dealing with the representation and studies of geodetic/topographical methods for the dimensional analysis of observed structures and their surroundings.

Geodesy, through various methods and measurement techniques, is a Science used in the dimensional control of engineering works. This control is provided by the application of methods: geodetic measurement (survey using the GNSS Satellite Positioning System, among others) and Terrestrial Measurement Methods (survey using Total Station, Digital Level, Laser Scanner, among others). These measurement methods are responsible, for example, for determining the exact position and area of the building and other concrete and/or metal structures to be built or already built, in addition to providing monitoring of these, to investigate over time if they suffer deformation, thus avoiding the so-called landslides and thus preventing risks to the lives of people who live or work there or who work adjacent to them.

In this sense, three surveys were carried out, the first involving the monitoring of onshore wind towers, the second involving the survey of inclined land susceptible to landslides and settlements. And the third involving a methodology to classify and calibrate Lidar point clouds. All surveys were based on a geodetic infrastructure of points determined from measurement techniques with GNSS receivers, total stations and digital levels.

2. THEORETICAL BASIS

The control and monitoring of buildings require the basic knowledge and experience of the technical methods of construction and use of geodetic equipment. Collapses, landslides, soil subsidence, as well as displacements of building structures are increasingly being detected in urban environments, where the development of buildings is prominent. As a result, in recent years, in addition to the performance of geotechnical and structural engineering, the growth and appreciation of the use of geodetic methods in the Brazilian civil construction environment. From the analysis and field observations in geodesic structures, as a reference to the precise positioning of objects, the displacements, deformations and most appropriate solutions for the stability of constructions are studied (SEIXAS et al., 2006; SEIXAS et al., 2007; SEIXAS et al., 2008; SEIXAS et al. 2009; SEIXAS et al., 2012; SEIXAS et al., 2014; SILVA and SEIXAS, 2017; SILVA and SEIXAS, 2019; SEIXAS and SEIXAS, 2020).

Theodolite and tachymeter measurement methods are used both for strain measurements and for surface measurements (3D reconstruction), when the measurement system with theodolite use is based on triangulation or when the tachymeter has a distance meter (polar method) (SEIXAS, 2004; SEIXAS & BURITY, 2005; SEIXAS, 2009; SANTOS, SEIXAS, GARNÉS and POVOAS, 2021).

The basic principle of determining three-dimensional coordinates with the use of theodolites, a theodolite-based measurement system, is based on the forward spatial intersection method. The object point is determined from two theodolites, whose stations may or may not be freely chosen. In addition to determining the scale factor, the coordinates of the object point will be determined from the direction measurements (STAIGER, 1988). Currently, theodolite-based measurement systems contain total stations and/or robotic theodolites and are widely used in industry (DEUMILICH; STAIGER, 2002) and (SILVA and SEGANTINE, 2015).

It is worth mentioning and highlighting the existence of digital levels with completely automatic readings in bulwark sights, with barcode division (binary standard), through digital image treatment and correlation calculations (INGENSAND, 1990) and (INGENSAND, 2002). With the geometric leveling method, the differences in height (unevenness) between points close to each other are determined by horizontal views (KAHMEN, 2006).

The use of three-dimensional optical measurement techniques through theodolite-based measurement systems has advantages with respect to the geometric leveling method, when the object points to be observed are at different elevations. Theodolites allow, in this case, targets inclined to the measuring points. In works related to Engineering, the reference points must be properly materialized and the data must be observed with instruments classified according to the standards as high, very high and/or very high precision instruments (MOESER et al., 2012).

It is of great importance to analyze field observations in geodetic structures (geodetic networks) as a reference for the precise positioning of objects, so that the different engineering works can be studied and analyzed, such as in the studies of vertical displacements, verticality and dimensional control of structures, enabling more appropriate solutions to the stabilities of building constructions (SEIXAS and SEIXAS, 2020; SILVA and SEIXAS, 2019; SANTOS, SEIXAS, GARNÉS and POVOAS, 2021; CANTO, 2018; CANTO and SEIXAS, 2020; SANTOS, SEIXAS and SANTOS, 2019; PESTANA, 2020).

The physical establishment of fixed points defining an altimetric, planimetric and/or planialtimetric reference frame, in the vicinity of the building and/or other structures, provide studies of vertical, horizontal and/or three-dimensional movements of these structures. The definition of a Reference System based on a Coordinate System and fixed points is of fundamental importance for the analysis of the measurement and monitoring of the work with respect to its displacement.

The adjustment of observations is the process used to estimate a single value for the measured and calculated quantities, using appropriate mathematical models and the principle of the Method of Least Squares (MMQ) and estimating the accuracy of the quantities. The precision measurements are given by the result of the adjustment through the variance – covariance matrix (GEMAEL, 1994) and (NIEMEIER, 2002).

It is noteworthy that the Historic Center of Olinda-PE since 2007 has been an area of activity of Geodesic Engineering applied in Historic Centers involving the development of master's research, scientific initiation, in addition to Undergraduate Course Completion Works, Monitoring and involvement of disciplines of the Cartographic Engineering Course of UFPE. This technical-scientific collection includes: five (05) completed Master's research, three (03) scientific initiations; three undergraduate course completion works. In addition to the works developed in the Historical Center of João Pessoa-PB, which promoted the completion of two (02) undergraduate course completion works and two scientific initiations in a high school technical education course. The work and research developed in these areas promoted the qualification of human resources, involving real themes of Geodetic Engineering in Historic Centers, besides benefiting the region with a high quality geodetic data infrastructure, which allows the continuity of studies and the evaluation of measurement methods and procedures applied to historic buildings, as well as the sustainability of this built cultural heritage.

In addition to these works, it is also noteworthy the development of applied research in wind farms with the improvement of a test and survey area involving two master's dissertations with the themes: geodetic monitoring of onshore wind towers (Canto, 2018), (Canto and Seixas, 2020), (Canto and Seixas, 2021) and geodetic surveys on lands susceptible to landslides and settlements (Santos, 2020) (Santos et al., 2020), (Santos and Seixas, 2021). In the first research (Canto, 2018), attention was paid to the relative monitoring between the bases of the foundations of the two investigated wind towers and the study of a better geometric configuration for the measurement of the wind tower formed by an equilateral triangle and a hexagon with concentric centers to the circular cross sections of the wind tower along its height, whose cross welds are possible to be observed from the measurements of their respective edges. Obtaining 3 central alignments was possible with the forward intersection method to investigate the center of each cross-section investigated. Enabling the study of the vertical behavior of the tower. In the second research (Santos, 2020), the expansion of the geodesic network of the wind farm was studied in order to raise crusty points in rocky outcrops near the wind tower. Thus, the 3D study of these points was sought from measurements with short and long ranges and application of the 3D irradiation method and the forward intersection method. For this, it was necessary pins and screws adapted to the observation circumstances with total station and digital level.

3. METHODOLOGY (MATERIALS AND METHODS)

The studies were carried out in the area of the wind farm in the municipality of Gravatá (Fig. 1 (a) and (b)) and the area of the historical center of Olinda (Fig. 1 (c)), both from the state of Pernambuco, Brazil. The first encompassing wind towers and built and/or natural soils and the second involving historical building buildings. The following topics present in detail the methodologies employed.

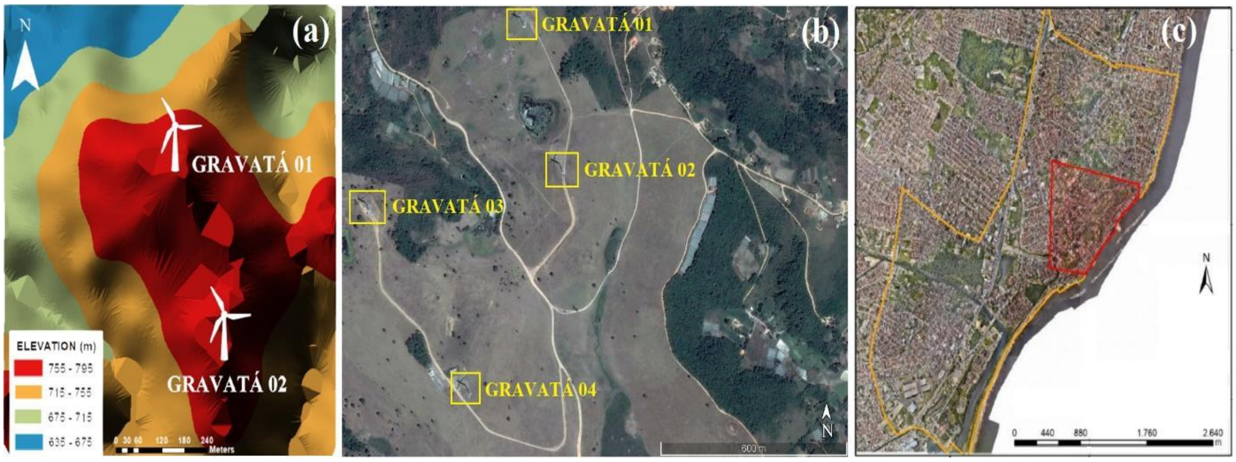

Figure 01 – Areas of study.

3.1 **Wind Towers**

The implementation of the reference points was carried out taking into account the topographic operation of recognition and the planialtimetric survey of the area around the towers, as well as the location and survey of the reference points, using methods with the use of total station, digital level and dual frequency GNSS receivers. The Reference Points (L1, L2 and L3) were georeferenced to the SIRGAS2000 Geodetic Reference System, through the GNSS survey through the static positioning method and the others required the transport of a GNSS Base that allowed to link all geodetic infrastructures to an official system, as illustrated in Figure 3. All Reference Points were adjusted by the Least Squares Method (LSM).


Figure 03 - GNSS survey campaign.

The spatial definition of the Reference Points field was to have targets with a minimum of three directions from the tower, through an equilateral triangle and regular hexagon, where both have the center of symmetry of the geometry coinciding with the center of the wind tower, to obtain greater feasibility for monitoring the nascelle and components at different times, according to the orientation of the rotor in relation to the wind. Three pins with semi-spherical heads were deployed at each base of the monitored towers and fixed in the same alignment of the reference points of the equilateral triangle and the center of the tower, being defined as a local altimetric geodetic network between the two towers to be monitored. Figure 4(a) illustrates the geometric configuration of the geodetic network deployed around the onshore wind tower and Figure 4(b) shows the field procedure performed for the measurement of the NRNRs deployed at the bases of the two towers, in addition to the path of almost 450m distance between them. Figure 5 shows a geometric leveling campaign with double walk through the circuits described, using the method of equal targets and auxiliary points with support of shoes.

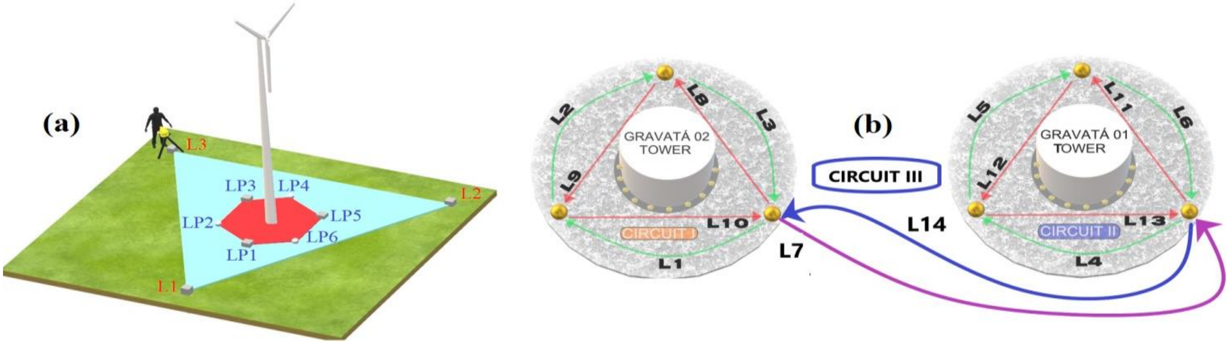

Figure 04 – Geometric configuration of the geodetic network

Figure 05 – Geometric leveling performed around the towers and between the two towers.

Wind towers are usually composed of prefabricated cylindrical steel parts, pre-assembled by welds and joined by rings called flanges. For this reason, the object points to evaluate and monitor the verticality of the tower were defined through the transverse welds between the segments of the tower and through reflective targets aligned with the reference points of the regular triangle. Figure 6 illustrates the object points.

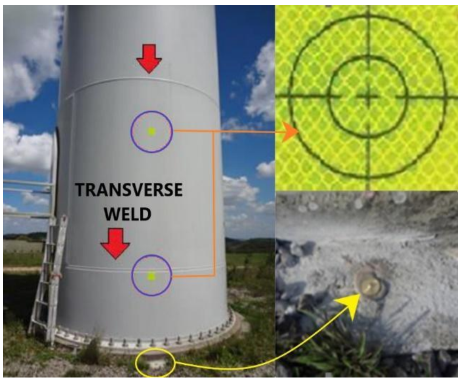

Figure 06 - Object points materialized by reflective targets, pins with semi-spherical head and transverse welds.

For the measurements of the object points along the tower, the methods of three-dimensional irradiation and edge measurement are proposed. The edge measurement method consists of determining the central horizontal direction of a given structure, by defining the average value of the observations of horizontal directions$Hz_{average}$, from the measurement of horizontal directions at the edges of the structure (Hz_{left} e Hz_{right}). Figure 7 illustrates the method and view in a wind tower.

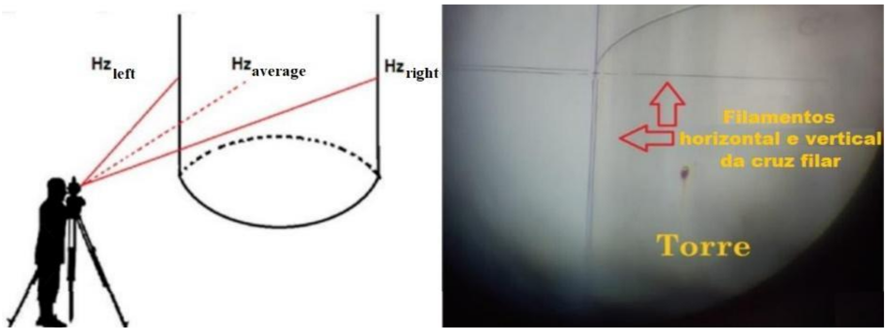

Figure 07 – Method of measuring edges.

3.2 Geodetic surveys on landslide-prone and settlement-prone terrain

In a second context, the study was directed to the detection and analysis of landslides and settlements, from the observation of the sloping terrain existing between the two wind towers initially investigated. In this second situation, the configuration and densification of the geodesic network for the planialtimetric survey of object points/reference points deployed in a quadrangular configuration over rock outcrops is studied. For this densification four pyramid trunks (LP7, LP8, LP9 and LP10) were added to the geodetic reference network, spatially distributed in locations that could serve as observation bases for monitoring the sloping terrain observed in the region. The planning of the planialtimetric network measured with a total station was done in order to obtain from a triangulation network, adjusted via a parametric model of the Least Squares Method, the coordinates of the new geodetic landmarks, but only the coordinates of LP7, LP8 and LP10 were determined from this network, as illustrated in Figure 08.

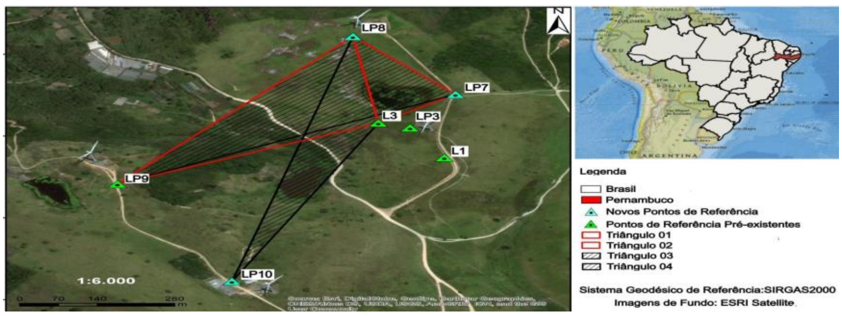

Figure 08 - Triangulateration Network.

In order to provide better security to the triangulateration network, it was decided to determine the coordinates of LP9 via the backward intersection method from L1, L3 and LP3. This provides a base of fixed coordinates (L3-LP9) for the adjustment of the network.

The layout of the Local Planialtimetric Geodetic Network, as shown in Figure 08, was carried out in order to materialize on the terrain, bases of observations with short and long distances that allowed the monitoring of the inclined terrain at different times.

In an initial arrangement, taking into consideration the Altimetric Reference Network deployed between the Gravatá 01 and Gravatá 02 wind towers and the existence of a sloping terrain susceptible to mass movement in the vicinity of these towers, the deployment of object-points/reference points was defined on the rocky outcrops exposed on the aforementioned terrain. In all, eight new points were implanted, which can be analyzed both under the aspect of mass landslides, since they are implanted on a sloping terrain, and can also be taken as a reference for the measurement of settlements and vertical movements, assuming in this case that the deformations occurred in the rock on which they were positioned is lower than the level of accuracy of the equipment used.

The materialization of the points was planned in order to consider their double hypothesis of use, so they were made in a male/female screw format with a diameter of 20 mm, adapted to allow the possibility of collecting angular and linear measurements claimed from a total station, as well as the connection of metal rods aimed at positioning barcode sights used in geometric leveling of very high precision. Figure 09 illustrates the materialization and observation of the points fixed on the inclined terrain.

Figure 09 – Densification of the Geodesic Network.

The definition of the planimetric coordinates of the object points fixed in the rocky outcrops occurred through the application of the forward intersection method with forced centering. In a first survey, the observations made from the observation bases L3-LP9/LP9-LP10 were considered. The maximum distance order from the bases towards the targets was respectively 750 m and 936 m. The procedure is illustrated in Figure 10.

The adaptations made to the targets deployed on the rocky surface allowed the definition of an absolute reference system for the control and vertical monitoring of wind towers. Such structures were monitored through very high precision geometric leveling through a monitoring time series started in (CANTO, 2018; CANTO and SEIXAS, 2020). The complete time series has a period of 537 days, of which in 237 days it was possible to consider the densification of the network with the materialization of an absolute reference system for measurements.

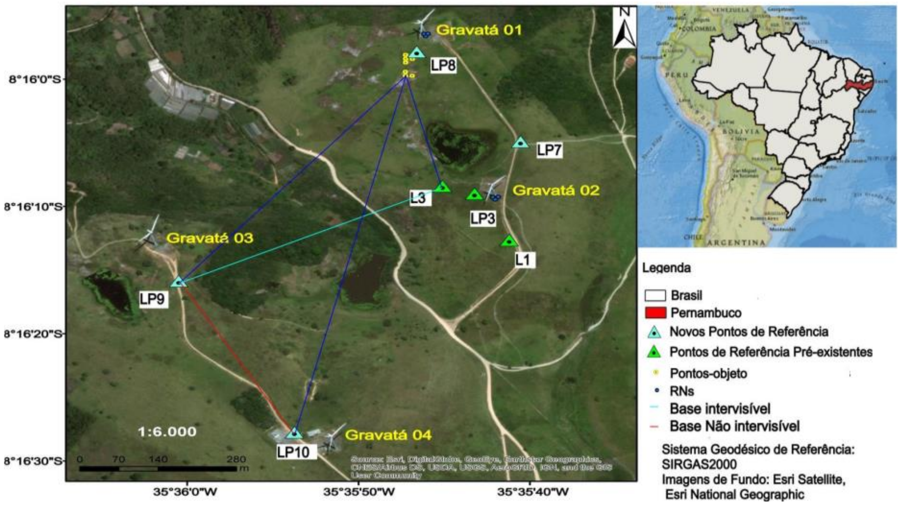

Figure 10 – Definition of the planimetric reference points

3.3 Methodology for classifying and calibrating LiDAR points

The Olinda Historical Site presents a Local Altimetric Geodetic Network (RGAL) with twenty-two Level References (RRNN) obtained through high-precision leveling (Figure 11). The quality of the altimetric network surveyed with a digital level of very high precision allows us to verify the methodology developed for point cloud calibration, contributing to the procedures for classifying products from LiDAR technology and others.

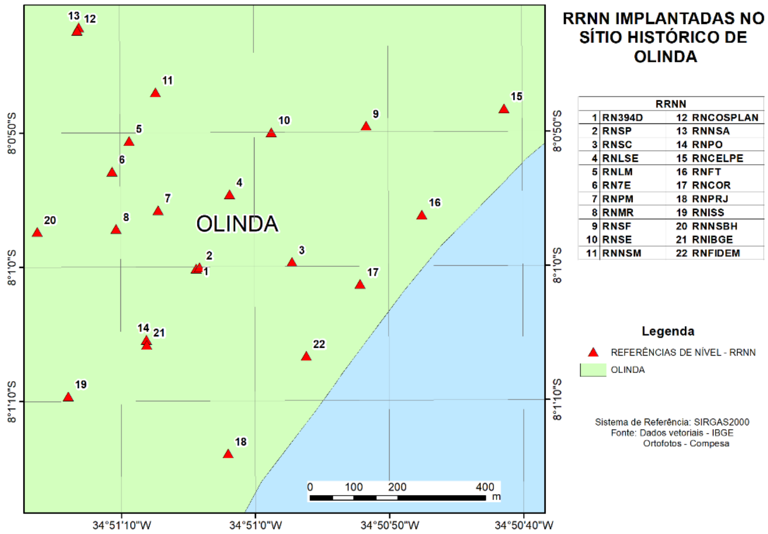

Figure 11 - Pre-existing Level References at the Historic Site of Olinda

Some of the NRNRs (Level References) were found obstructed and in this case GNSS survey campaigns were carried out in fifteen of the NRNRs that make up the RGAL of the Historic Site of Olinda, applying the static relative positioning. These NRNRs served as a control for statistical analysis. Two survey campaigns were carried out. In these campaigns, the field survey methodology adopted was the Polygonal GNSS with “frog jump” and simultaneously GNSS Irradiation and GNSS Networks (figures 12 and 13). The method consists of the GNSS receiver must have at each station simultaneous tracking with the anterior point, as well as with the posterior point, until it reaches the last point of the polygon.

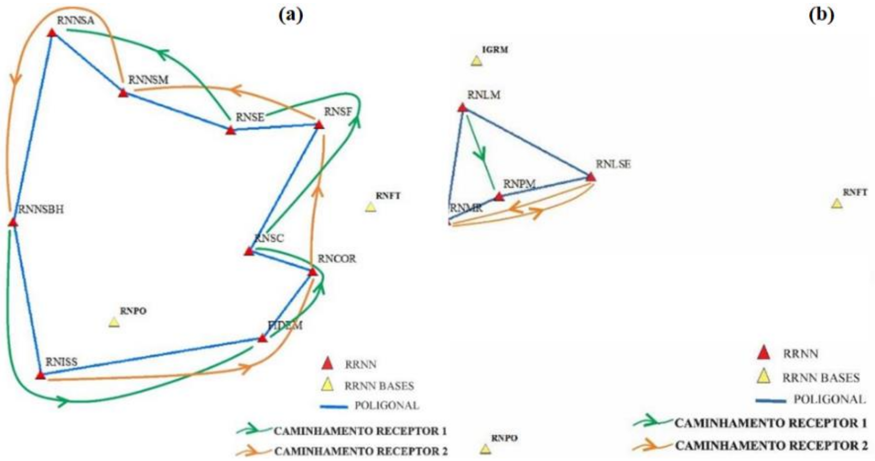

Figure 12 – Schematics of the surveys carried out in the first campaign. (a) First day. (b) Second day

The first campaign was carried out in two days (Figure 12), and consequently, two polygonal. The first (Figure 12a) had two basis points the RNNN RNFT and RNPO, defined considering their locations in relation to the other points. The second (Fig. 12b) had one more RN base, the RN IGRM, in addition to the other two mentioned.

The second campaign took place in just one day, but in two stages (Figure 13), with the objective of improving some points that during processing problems were identified. The first stage (Figure 13a) considered the same base points of the first day of the first campaign and the RNNN RNLM, RNPM and RNLSE were raised simultaneously. The second step (Figure 13b) was applied again the frog jump survey method.

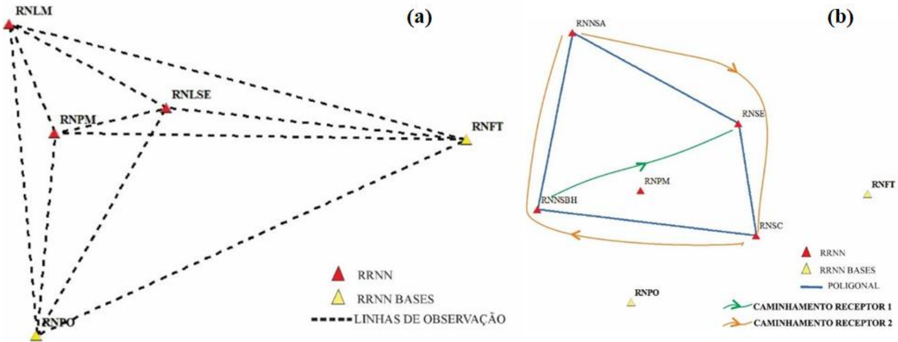

Figure 13 - Schematics of the surveys carried out in the second campaign. (a) first stage (b) Second stage.

With the geodetic, orthometric and normal altitudes, the Local Geoidal Model and the Local Quasi-Geoid Model were generated in the AstGeoTop software (GARNÉS, 2020), where the accuracy of ±0.0183 m was obtained in both cases. Figure 14 shows the behavior of the geoidal ripple and Altitude Anomalies in the study area, through geoidal curves with an equidistance of 2 mm.

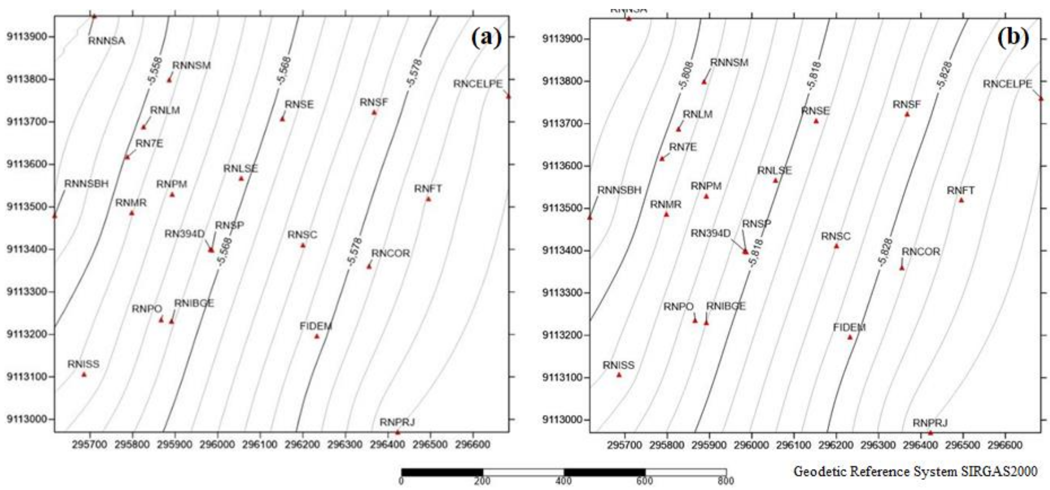

Figure 14 - Geoidal curves for the geoidal undulation (a) and Anomaly curves for altitude anomalies (b) calculated by the model N=Ax+By+C.

For the calibration and classification of the MDT point cloud, obtained through LiDAR technology, the AstGeoTop software module tools were applied. For this analysis, the orthometric altitudes resulting from the very high precision geometric leveling were considered as point cloud control, as an ideal method to be performed in evaluations of this type. In this analysis, the inverse-weighted mean of the square of the distance was used. During the analysis, a separation of -4.9 cm was observed between the surface on which the NRNRs are implanted and the point cloud, with this information it was possible to calibrate the point cloud to the surface.

To control this result, four samples of 3 in 3 NRNR were defined where for each NRNR sample a model was generated without these Level References and the respective NRNR interpolated in the model was verified in order to control the quality of the calibrated model. It was observed that for the four samples tested, these showed discrepancies and standard deviations lower than the standard deviation of the calibrated model, where this is equal to ±0.088 m.

From this, we obtained the interpolated coordinates in the cloud of points referring to the NRNRs and with this, we applied the classification methodology for digital cartographic products according to the PEC-PCD. When considering the equidistance between the 1m level curves, the tabulated values are equal to 0.27 m and 0.17 m for class A, respectively maximum permissible error and standard error. According to the calculation of the error between the interpolated and control NRNRs, it was possible to verify that all points presented values lower than the table for the maximum permissible error. And when comparing the mean squared error with the standard error, the same conclusion was obtained. In this way, the MDT point cloud was classified as class A, meeting the highest standards of this class.

4. DISCUSSION & CONCLUSION

In general, the monitoring of structures is one of the areas of geodesic engineering, which has the purpose of analyzing and predicting over time the geometric behavior of an object of study.

With the advent of new geotechnologies, the quality of observations and the mode of observation had a significant advance, as in the case of robotic stations and lasers scanners, in addition to the various possibilities of technical visualization of the object raised and under monitoring.

The definition of a Reference System, based on a Coordinate System and a field of reference points, is an initial stage of work, followed by the measurement and analysis of the three-dimensional coordinates obtained by different measurement methods. Thus, for the monitoring of structures, the definition of a Geodetic Reference System is fundamental, as well as the definition of object points, which provide the best behavior of the structure to be investigated.

Due to the dependence of current society on the consumption of electricity for its needs and because of the scarcity and environmental impacts for its generation, alternative clean and renewable energy sources have aroused special interest, as is the case of wind energy, with an exponential worldwide growth of its installed capacity annually. Wind towers are often subjected to extreme loads, in which it is necessary to monitor the structural integrity and geometric deviations of these structures for the safety of their operation, requiring a periodic system of measurements. Therefore, geodetic methods are the most appropriate for monitoring temporal variation and possible deformations and/or displacements, adding more information compared to monitoring using strain gauges and inclinometers.

Through a stable Measurement Reference System, obtained through the GNSS survey, positional control and temporal monitoring of the tower and base verticality are ensured, with the purpose of observations in the same alignment of all object points at different heights of the tower and ensuring better observations at the base. The measurement of the object points counted on the evaluation of vertical movements in the foundation through the geometric leveling of very high precision and the horizontal movements of the tower were used methods of measuring the edges and three-dimensional irradiation.

Similarly to the search for renewable energy sources, contemporary society deals daily with the effects caused by the significant increase in the world population experienced from the second half of the twentieth century. One of the immediate consequences of this demographic explosion is the increasingly frequent occupation of sloping land susceptible to settlements and landslides. Buildings built nearby or even on these grounds are often in a state of transitory equilibrium that may be altered by natural phenomena or anthropic actions, causing physical, material and patrimonial impacts to its inhabitants.

The monitoring and continuous monitoring of these terrains aim to predict the occurrence of phenomena such as the gravitational movement of masses, therefore it is recommended the periodic application of topographic and geodetic surveys in such locations, since the data obtained at different times, integrated the analyzes conducted by sciences such as geotechnics, help to consolidate a detailed study that allows the knowledge of the parameters of movement of the inclined terrain. The definition of a stable Measurement Reference System, composed of reference points and object points under safe conditions, combined with the application of the appropriate survey method to the particularities of the terrain under analysis, provides accurate and accurate data that allow managers to propose interventions that mitigate or even prevent the occurrence of events harmful to society.

The data from LiDAR Technology contribute significantly to the territorial management of cities, because through it can be obtained altimetric data, with high precision, in less time, when compared to traditional methods. With regard to the reliable use of LiDAR data, geodetic control through a geodetic reference network allows managers of this data to have a framework of geodetic information, which helps verify this information, and if necessary, calibrate this data, so that it meets the quality standards required nationally and internationally.

In the case of the historical site of the municipality of Olinda-PE, it has a robust pre-existing geodetic infrastructure that has been implemented in research projects since 2007, which help the geodetic control of historical monuments. The data obtained by Laser added to this geodetic infrastructure, contribute to the monitoring of this historical and cultural heritage. The complementation of the Local Altimetric Geodetic Network with GNSS data and updating of altitudes with the altitude anomaly, allowed through the algorithms of the AstGeoTop *software* to identify the necessary corrections to the Laser data, according to the worked surface MGL or MQGL. Meeting the quality standards required by the PEC-PCD.

The research developments in the two areas of study brought a consolidation of the areas with new geodetic structures implemented, in order to conduct investigations of current issues involving onshore wind towers, sloping land susceptible to studies of settlements and landslides and building buildings. With the application of the concepts of Geodetic Sciences and their Measurement Technologies in engineering and in the management and territorial urban and rural dimensioning.

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