Satellite Interferometric Investigations of Subsidence Events Associated with Groundwater Extraction in Sao Paulo, Brazil

B. Mendonça, D. Sandwell

***Abstract*—**The Metropolitan Region of Sao Paulo (MRSP) has suffered from serious water scarcity. Consequently, the most convenient solution has been building wells to extract groundwater from local aquifers. However, it requires constant vigilance to prevent over extraction and future events that can pose serious threat to the population, such as subsidence. Radar imaging techniques (InSAR) have allowed continuous investigation of such phenomena. The analysis of data in the present study consists of 23 SAR images dated from October 2007 to March 2011, obtained by the ALOS-1 spacecraft. Data processing was made with the software GMTSAR, by using the InSAR technique to create pairs of interferograms with ground displacement during different time spans. First results show a correlation between the location of 102 wells registered in 2009 and signals of ground displacement equal or lower than -90 millimeters (mm) in the region. The longest time span interferogram obtained dates from October 2007 to March 2010. As a result, from that interferogram, it was possible to detect the average velocity of displacement in millimeters per year (mm/y), and which areas strong signals have persisted in the MRSP. Four specific areas with signals of subsidence of 28 mm/y to 40 mm/y were chosen to investigate the phenomenon: Guarulhos (Sao Paulo International Airport), the Greater Sao Paulo, Itaquera and Sao Caetano do Sul. The coverage area of the signals was between 0.6 km and 1.65 km of length. All areas are located above a sedimentary type of aquifer. Itaquera and Sao Caetano do Sul showed signals varying from 28 mm/y to 32 mm/y. On the other hand, the places most likely to be suffering from stronger subsidence are the ones in the Greater Sao Paulo and Guarulhos, right beside the International Airport of Sao Paulo. The rate of displacement observed in both regions goes from 35 mm/y to 40 mm/y. Previous investigations of the water use at the International Airport highlight the risks of excessive water extraction that was being done through 9 deep wells. Therefore, it is affirmed that subsidence events are likely to occur and to cause serious damage in the area. This study could show a situation that has not been explored with proper importance in the city, given its social and economic consequences. Since the data were only available until 2011, the question that remains is if the situation still persists. It could be reaffirmed, however, a scenario of risk at the International Airport of Sao Paulo that needs further investigation.

***Keywords*—**Ground subsidence, interferometric satellite aperture radar (InSAR), metropolitan region of Sao Paulo, water extraction.

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I. Introduction

THE use of remote sensing for urban studies has gained increased attention and acceptance within the scientific community. New techniques, such as the Interferometric Synthetic Aperture Radar (InSAR), have made possible the study of vertical displacements in urbanized regions [16], which allows the analysis of different phenomena. Therefore, the use of InSAR with altimetry permits the vigilance of phenomena such as earthquakes, landslides, floods and ground subsidence.

The continuous monitoring of such phenomena can help avoiding future hazards in urban zones. Floods and landslides, for example, can cause economic damage and loss to people that live in those areas. Ground subsidence, on the other hand, is a phenomenon that occurs more gradually due to the removal of underground support, which consequently causes a superficial sinking of the terrain [1]. According to [2], the phenomenon may occur due to hydrocompactation, the dissolution of rock and salts, oil and gas extraction, mining activities and groundwater extraction.

In the southeast region of Brazil, where the Metropolitan Region of Sao Paulo (MRSP) is located, the demand and dispute for water is in critical situation. An estimate made in 2011 by the Department of Sanitation and Water Resources highlights water scarcity in the MRSP due to the high demand for water resources, which are challenges caused by pollution and the location of the region that offers less than 500m^3 of water per inhabitant annually. Of the 39 counties that comprise the area of the MRSP, 20 are completely in the river basin district that covers over 70% of the region [3]. One of the actions that have been taken to ameliorate the situation includes the use of local aquifers to extract groundwater via well construction. The advantages of this have included its readily available water supply and short lead time at a lower cost, as well as the underground reservoirs being more naturally protected from pollutants [4].

Aquifers are geologic formations that work as huge reservoirs of water due to the porosity of their permeable rocks. Not only do they have varying sizes, but aquifers can also be composed of different rock types that are generally divided into two main groups: sedimentary and crystalline. In sedimentary types, water can flow through the pores formed by grains of sand, silt and clay, whereas in crystalline types the circulation occurs through fractures and cracks in the massive rock [1].

In Sao Paulo the aquifer's recharge is generally derived from the rain, whereas its areas of discharge flow are the rivers and drains of the Alto Tiete Basin. This water is responsible for charging the surface reservoirs and thus, providing water for people during dry seasons. In the most urbanized and least permeable regions, 50% of groundwater recharge comes from sewage collectors, storm sewers and public distribution systems [5]. According to [6], the volume of water that recharges the aquifers in the Alto Tiete Basin is estimated at 53 m³/s, whereas the exploitable reserves through deep wells are estimated at 33 m³/s, without interfering with the river base flow.

Deep wells are the vast majority of all wells that still operate in the MRSP, but the number and specific locations cannot be accurately determined. This is due to many wells being drilled illegally and without proper registration in the Department of Water and Electric Power (DAEE), as well as the lack of information regarding the activity status of those wells that are registered. According to the latest estimate from 2009, the existence of 12,000 deep wells was confirmed, of which only 4931 were registered in the DAEE [7].

The forced action of pumping water by wells or channels can sometimes causes the surface to subside depending on the depth of the aquifer and the strength of the rock above the aquifer. Intense extraction of groundwater and the subsequent reduction in water levels cause the reservoir to contract. This causes deformation and breakage of its particles, as well as a vertical, downward movement of the land [1].

The study of topographical changes with remote sensing allows the phenomenon of ground subsidence by groundwater extraction to be analyzed and monitored. Therefore, the present study will analyze possible subsidence phenomena in the MRSP in order to find a correlation between vertical displacement signals and groundwater extraction.

II. Materials and Methods

A. Study Area

The MRSP is located in the Sao Paulo state and comprises in 39 counties, with an area of approximately 7,946 km² [8] (Fig. 1). The MRSP has two types of aquifers, which are part of the Alto Tiete Basin. The sedimentary aquifer is located in the gentle slope areas and has an average thickness of 100 meters. Coincidentally, the areas of its occurrence are the same with high population density, such as the greater Sao Paulo region. The crystalline aquifer is located in rugged areas and also below the sedimentary aquifer, with a total thickness of up to 250 meters [7]. The area of the MRSP covered by the ALOS satellite used in the study corresponds to the frame 6710 and track 060.

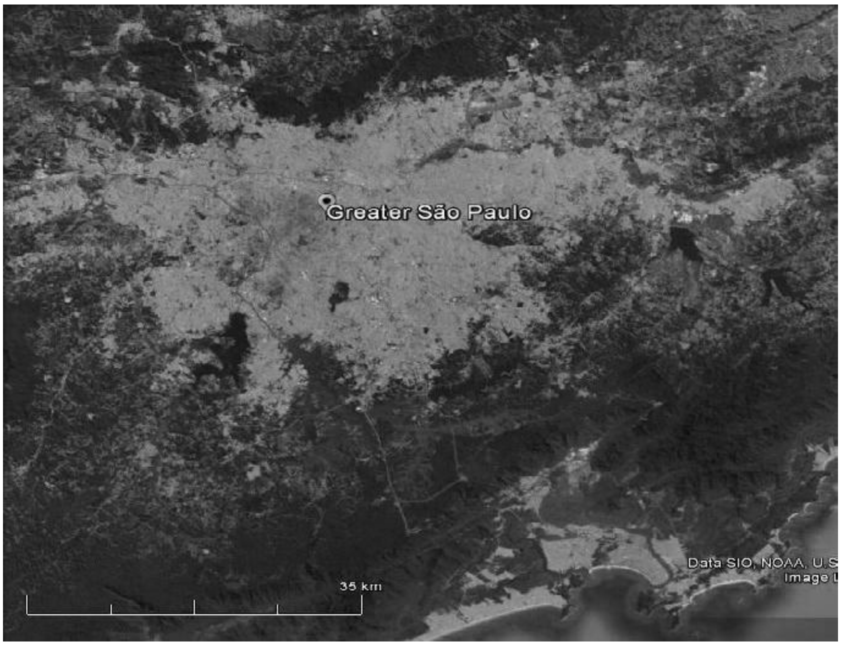

Fig. 1 Google Earth 7.1, 2015. View of the Metropolitan Region of Sao Paulo, represented by the lighter grey color, located at 23º31’52.00” S, 46º38’09.00” W

B. Image Acquisition

The Advanced Land Observing Satellite (ALOS), launched by the Japanese Aerospace Exploration Agency (JAXA) in 2006, was mainly designed with the specific purpose of disaster monitoring and mitigation [9]. Examples of its applications include monitoring crust deformation pre- and post-earthquakes, landslides and subsidence events.

The satellite carries two optical sensors, AVNIR-2 and PRISM, as well as an active radar sensor operating on the microwave region (11 cm). With a mass of 4 tons and a 23 m solar array paddle generating 7 kW of electric power, ALOS has a sun synchronous orbit of 691.65 km altitude and an orbital cycle of 46 days [9].

During its first mission, ALOS-1 provided global data from 2006 to 2011 [9] that are available at no cost to US investigators through the Alaska Satellite Facility (ASF). By processing the data using the InSAR technique and comparing the phase of two Synthetic Aperture Radar (SAR) images, it was possible to calculate the ground variation that occurred in the time interval between the two acquisitions at sub centimeter accuracy. The data used for this study date from 2006 to 2011, downloaded at the ASF website.

C. Image Processing

The interferometric synthetic aperture radar (InSAR) technique relies on the acquisition of repeat-pass satellite-derived SAR images. The acquisition of two SAR images makes possible the creation of an interferogram, which is a spatial map of the distance between the satellite and the ground target between the two images [10].

InSAR deformation measurements have greater spatial resolution (~100 m) than GPS. However, InSAR has several disadvantages of having poor temporal sampling (>35 days), lower accuracy, single look direction and greater susceptibility to troposphere and ionosphere delays [11]-[13].

For the ALOS-PALSAR sensor used in the present study, the full resolution pixel size is approximately 4.7 m and 4 m in range in azimuth, respectively. When two SAR images are aligned to a fraction of a pixel an interferogram can be formed [16].

The phase of the interferogram has seven main components: the earth curvature (known), topographic phase, surface deformation (unknown), orbit error (largely known), ionosphere delay (a plane or a 40 kilometers wavelength waves), troposphere delay (unknown), and phase noise (unknown). Normally, we try to isolate the phase due to surface deformation from all the other contributions. The largest known contributions come from the irregular shape of the earth which can be divided into an earth curvature component and a topography component. The known Earth curvature and topographic phase is removed using a digital elevation model (DEM), which is a regularly gridded topography representation of certain region. The orbital error consists of a plane that is removed in a least squares adjustment [10].

Inherent errors in the InSAR results are introduced by the atmosphere, the satellite orbits, and the topography. These errors primarily occur over length scales greater than 20 km; however, they could be partly suppressed by averaging many interferograms using methods such as stacking and the phase gradients, as suggested by [14]. More important for this study, we were interested in deformation patterns having scales less than about 10 km so we could disregard the large scale patterns.

The software used to process the data was the GMTSAR [15], which is an open source (GNU General Public License) InSAR processing system designed around the Generic Mapping Tools (GMT) framework [16].

After the data and metadata have been downloaded from the Alaska Satellite Facility, the first step was to preprocess all images and plot the spatial and temporal characteristics of the acquisitions by creating a baseline vs. time plot (Fig. 2). Thus, we could select optimal interferometric image pairs to generate input files used on the processing. For ground subsidence analysis it is best to have pairs with short perpendicular baseline because they have better correlation and are less sensitive to topography errors. In order to construct a time series of deformation, a *master* image was selected and all the other images, or *slaves*, were aligned to the master. Once the alignment was done, it was possible to start constructing interferograms from any pair of images in the stack [15]. The first image in an InSAR pair is called *reference* and the second is called the *repeat*.

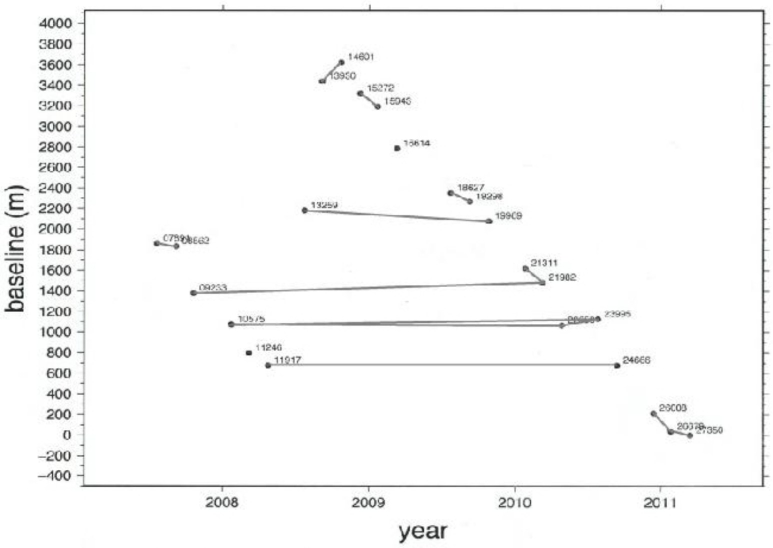

Fig. 2 Perpendicular baseline with pairs selected for ALOS-1, orbit 27350, frame 6710, track 060

The preprocessing of all images is described in details on GMTSAR: An InSAR Processing System Based on Generic Mapping Tools [15]. However, it is important to state that the stacking and alignment process is the most important part when generating the baseline vs. time plot. The interferometric correlation between *reference* and *repeat* images depends on both the perpendicular baseline between images and the time span between the images. Long time spans usually have poorer correlation than shorter time spans.

The baseline plot allows us to choose the most suitable pairs to be correlated. As presented by the gray lines on Fig. 1, the pairs used to generate interferograms are very close in baseline and, consequently, the image alignment demands only local accuracy.

After following all the preprocessing, stacking and alignment steps, it was possible to start generating interferograms. By using the command *p2p_ALOS*.csh, also detailed by [15], the software runs a pair of images that was configured according with my preference. The changes on the line of sight (LOS) of the image, or the ground displacements, are given at centimeter accuracy, being negative values representing ground sinking.

The interferograms generated follow the same pattern as shown on Fig. 3, originally with a scale from blue (negative) to red (positive) to represent ground displacement.

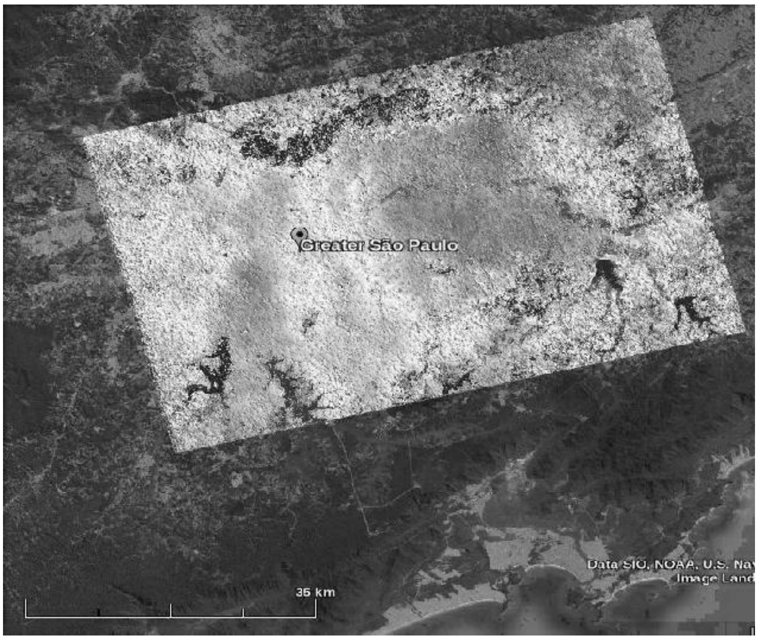

Fig. 3 Example of line-of-sight interferogram from the MRSP generated after processing, also seen with Google Earth. The big dark area represents negative LOS displacement, whereas the lighter grey areas represent positive ground displacement. The largest spatial scale patterns are mostly due to atmospheric delay. It is the smaller-scale features that are of interest for this study

TABLE I
IMAGE PAIRS USED FOR STACKING[A]

Orbits		Dates		Time Span (Days)
Master	Slave			
266796710	273506710[b]	01/27/11	03/14/11	47
078916710	085626710	07/19/07	09/06/07	50
092336710	219826710	10/19/07	04/11/10	875
132596710	199696710	07/21/08	10/24/10	826
139306710	146016710	09/05/08	10/21/08	47
186276710	192986710	07/24/07	08/09/09	778
213116710	219826710	01/24/10	03/11/10	47
226536710	239956710	04/26/10	07/27/10	93
119176710	246666710	04/20/08	09/11/10	875
152726710	159436710	12/06/08	09/21/09	290
260086710	266796710	12/12/10	01/27/11	47
105756710	239956710	01/19/08	04/26/10	829

[a]All images are ALOS-1, frame 6710 and track 060. The products are identified by the satellite, orbit number and frame (i.e., ALPSRP266796710.)
[b]The *master* orbit.

Table I shows the pairs of images that were processed to generate interferograms for the MRSP.

III. Results and Discussion

Even though 12 pairs were used for stacking, the analysis was only possible with 10 pairs. After analyzing them, 102 places were marked using Google Earth with equal or lower signals of ground sinking of -50 millimeters (mm), arbitrarily chosen, in order to compare with the location of wells registered by DAEE in 2009.

The places marked with significant signals of LOS displacement were mostly concentrated in the center of the MRSP region, which coincides with the highest concentration of wells registered by DAEE. The correspondence between the comparisons shows that from 2007 to 2011 ongoing activities, possibly related with groundwater extraction, might still be modifying the topography of the region.

According with the values showed by each *los_ll.grd* file generated with the interferograms, the LOS displacement between 2007 and 2011 for the entire MRSP varied from -178.8 mm to 263.2 mm. Table II shows each product (pair of images) and its respective LOS displacement range with negative values corresponding to ground sinking.

TABLE II
LOS DISPLACEMENT RANGE IN MILLIMETERS (MM) IN RESPECT TO EACH PRODUCT

Products	LOS minimum (mm)	LOS maximum (mm)
2007200_2007246	-120.4	101.1
2007292_2010070	-178.8	178.7
2008019_2010208	-173.5	151.8
2008249_2008295	-103.4	109.5
2008203_2009297	-133.8	263.2
2009205_2009251	-137.5	141.4
2010024_2010070	-134.9	109.1
2010116_2010208	-405.8	121.9
2010346_2011027	-126.7	241.5
2011027_2011073	-99.1	121.3

Again, much of the LOS signal can be related with atmospheric delays, since we are still considering the results for high scale areas (> 10 km).

As observed, the negative average was not lower than -179 mm considering the respective time spans, except for an extreme value of -405.8 mm detected in the product 2010116_2010208, dated from April to July of 2010. The less expressive values of negative LOS were observed within the interferograms with shorter time spans, being -99.1 mm the highest minimum, observed in 2011 from January to March.

From October 2007 to March 2010 and from January 2008 to July 2010 the values are assumed to be more consistent, since they have an 875-day time span.

The interferogram with longest time span, dated from October 2007 to March 2010 shows a minimum LOS displacement of -179.8 mm. From this product it was possible to detect four specific places that have shown the strongest signals of ground sinking. Fig. 4 indicates these four places that correspond to the counties of Sao Caetano do Sul, Itaquera, the Greater Sao Paulo, and Guarulhos, where the Sao Paulo International Airport is located.

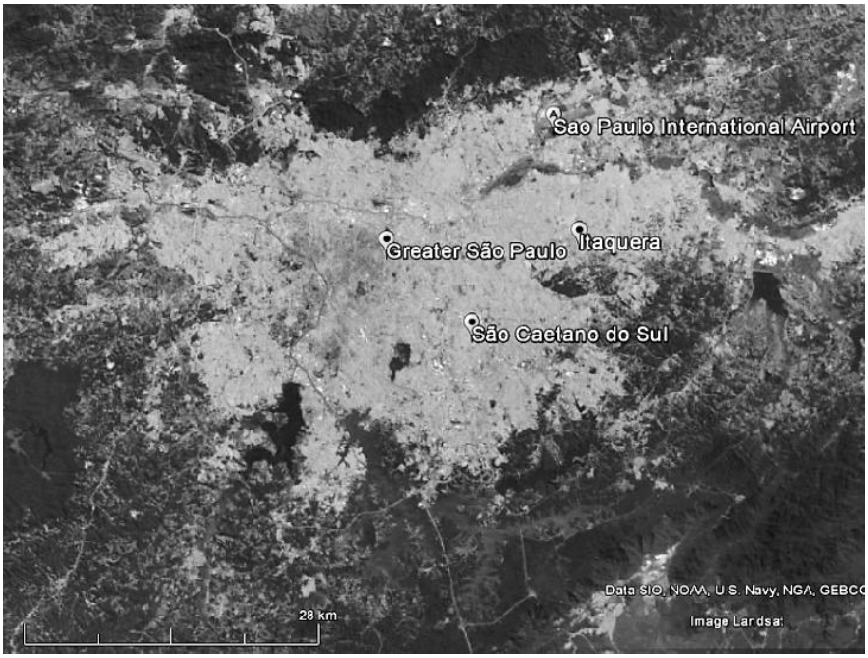

Fig. 4 Strongest signals of negative LOS displacement found on the MRSP located in the counties of Sao Caetano do Sul, Itaquera, Greater Sao Paulo, and Guarulhos (Sao Paulo International Airport region)

The next step was analyzing how and which of the four regions have been affected more significantly. Much of the large spatial scale signal seen in individual interferograms could be suppressed by averaging (or stacking) all the interferograms. This was done by adding all the LOS maps and dividing them by the total time span of the sum. This process revealed which of the marked places on Fig. 4 have been continually showing negative signals of displacement between 2007 and 2011. Each of the interferograms used for the stacking have a time span higher than 80 days; therefore, the final product highlights the most persistent signals. The stacking process provided also the average velocity of displacement in millimeters per year (mm/y) by adding all time spans used on the stacking and dividing them per 365. As a result, a new deformation map was generated with the annual average velocity and the places that have presented the persistent signals. We must consider that since it is an average, the values are not as high as the ones found for each interferogram. Table III shows a sum of this map, presenting each of the four regions with its average velocity of displacement in mm/y and the coverage area of the signal in kilometers (km).

TABLE III
AVERAGE VELOCITY OF DISPLACEMENT IN MM/Y

County	Average Velocity of displacement (mm/y)	Coverage Area (km)
Sao Caetano do Sul	28 to 30	0.72
Itaquera	32	1.65
Greater Sao Paulo	40	0.6
Guarulhos	35 to 40	1.6

The interpretation of the areas was made in terms of line of sight (LOS) displacement detected in different periods, the type of aquifer related to each county and the number of wells detected in the region according to the DAEE estimation of 2009.

The area correspondent to the county of Sao Caetano do Sul is located beside the rive Tamanduatei II, and aquifer type below the region is sedimentary. Since sedimentary rocks have more porosity, it is likely that intense water pumping would affect the topography. The average velocity of ground sinking per year is around 28 mm to 30 mm, which is an expressive rate if considered that the phenomenon has happened since or even before 2007. The presence of the river might be influencing the results. The area comprises in a gas station, commercial buildings and a warehouse. Two wells were correlated with the area according with the DAEE register; nevertheless, it is very possible that other wells were built or have been built without any register until now. The second region is also part of a sedimentary type of aquifer. It is located in Itaquera, a region at the east zone of the Greater Sao Paulo. This place showed a very interesting signal path, extending for almost a straight line of 1.65 kilometers. From 2007 to the beginning of 2010, the data show that this area had gone down more than 100 mm. The average velocity of negative displacement is around 32 mm/y, which suggests that some persistent activity has affected the topography.

The second region is located at the center zone of the greater Sao Paulo, in a commercial area. We should consider that this area is also part of where the Tamanduatei River crosses part of the city, so the signal found could be intensified or influenced by its presence. According with the data, the place has sunk with an annual average velocity of 4 mm/y. The exact area where the persistent signals are taking place comprises in a cultural and educational museum and the Municipal Market of the city. The aquifer's type below this area is also sedimentary and part of the Quaternary Aquifer. According with DAEE, in 2009 no more than 7 wells were registered in this area. Since it is located at the city center, the place consists in many metro lines around, which can also affect the results. It is possible that the region has suffered from the subsidence phenomenon, but further investigation is indispensable in order to regulate water extraction activities and prevent hazardous situations.

The last area is located in the city of Guarulhos, beside the Sao Paulo International Airport, the biggest and most important airport of the country. The information given from the postscript file shows that the average velocity of ground sinking per year has a rate of 35 mm to 40 mm. As an example, during the period between 2008 and 2009 the interferographic result showed a decay of 32 mm for this area. The location where the signal was captured makes part of an industrial area that has around 1.6 kilometers, but it also aggregates a residential perimeter.

Regarding the type of aquifer and wells detected, the area is located above a sedimentary portion of one of the aquifers from the Alto Tiete Basin, the Quaternary Aquifer. According with the map made by DAEE, around 24 wells were registered in the region in 2009. We cannot know, however, how many wells have been constructed since 2007 that are out of vigilance. Also, since the region has suffered from drought for the last two years, it is expected that people have built more wells to have access to water.

Atmospheric interference could influence the results; however, if that was the case, different interferograms from distinct periods of time would show that the signal has moved. Making the staking process also helps to decrease this kind of interference. Another variable that could interfere on the subsidence events is the presence of metro lines, but the place does not have any of them. This area deserves attention also because the International Airport of Sao Paulo, located right beside where the signal was found, is one of the most important airports in the country.

The importance of keeping a continuous monitoring of this region is reaffirmed in a study conducted by [17]. The authors make a diagnosis of the water use at the Airport, in which approximately a volume of 658,000 m³ per year has been extracted from 9 deep wells. In addition, the Airport was built right above a swampy area of the floodplain of the river Baquirívu-Guaçu that has a sequence of clay layers. Consequently, the layers produce a natural impermeability, making the recharge of the sedimentary aquifer naturally slow.

Residential and industrial buildings around might be being affected by continuous ground sinking; therefore, it is necessary to keep a local investigation and to make sure the phenomenon is really happening and is associated with groundwater extraction, which is very likely to be the case.

The major issue is that not only that atmospheric interference could influence the results, but also that the data are scarce and only available from 2007 to 2011. This way, it is very hard to keep investigating how these areas have behaved since the end of the time series. In addition, the fact that many wells are not registered on the Department of Water and Electric Power does not ease the surveillance and control by the state to prevent intense water extraction activities.

Even though the places discussed above were the most significant ones, a great number of smaller areas were also detected with persistent decline in topography. Interestingly, most of them were either at a residential or industrial area, which can be areas with continuous and irregular activities. On the other hand, many significant signals in products with a time span lower than a year did not persist.

IV. Conclusion

Subsidence events related with groundwater extraction is a very actual and concerning issue that has happened in many parts of the world. The Metropolitan Region of Sao Paulo has suffered from serious drought for the last few years, which makes the local industries and citizens to look for an alternative to deal with the lack of water supply.

Proving that subsidence events are related with groundwater pumping only by using InSAR imagery is not easy. However, the present study could exemplify how useful this tool can be in order to detect this kind of phenomenon. In addition, the study can be considered as pioneer, since any other study has been made in Brazil about the subject with help of interferometric techniques. Today, persistent activities have somehow affected the topography of the MRSP, especially in Guarulhos and in the Greater Sao Paulo. Thanks to the InSAR technique, it was possible to detect the average velocity of ground sinking that would probably not have been possible to detect otherwise. The study could show, therefore, that some places might still be being affected. The International Airport of Sao Paulo gives a hint of how the subsidence phenomenon can still be affecting the topography. The suggestion is that further studies are made with ground truth, making possible the validation of the data and identification of other places that need proper attention. The most important thing is to expose a problem that can be missing proper vigilance.

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In March 2014 she was awarded with a scholarship by the Brazilian Scientific Mobility Program, in which she had the opportunity to study for six months at the University of California, Los Angeles, and one more year at the University of California, San Diego. During this period away from the Brazilian institution, in 2015 she had the chance to conduct this research at Scripps Institute of Oceanography, in San Diego. Her current research interests include physical oceanography and remote sensing with focus on altimetry.