Analysis of sinking incidence in the San Luis Potosí Valley, México

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Abstract. This research focused on the geospatial method application called Synthetic Aperture Radar Interferometry (InSAR) using Sentinel 1-A satellite images to determine the sinking incidence in the San Luis Potosí - Soledad de Graciano Sánchez conurbation area. In this study was carried out the processing and comparison of the sinking values resulting from the period 2014 to 2019, where the procedures showed that the sinking incidence that occurred in some areas of San Luis Potosí Valley was 13.4 cm, which means that a sinking of approximately 2.6 cm would be generated per year in the specific areas determined, as well as, with the results of the InSAR method was made a profiles graphic of the 5 years analyzed, with the aim of observing the behavior of soil sinking in the area studied. Likewise, 72 GNSS vertices were interpolated, which served to know the ground elevations in 2014, in order to correlate their differences according to the results of the interferometry process in the images using SNAP software.

1. Introduction
The study area corresponds to the San Luis Potosí Valley in México, which is located between coordinates 23° 14' 03.3'', 23° 39' 54.8'' North Latitude and 92° 20' 31.1'', 93° 04' 40.8'' West Longitude and whose surface is 665.95 km² (Figure 1).

Figure 1. Study area location.
The Valley total population is 2,717,820 inhabitants and the territory of the state is described as a stepped terrain, from its lowest part in the coastal plain of the Gulf, with an average altitude above sea level of the order of 200 m., passing towards the west to the high chain of the Sierra Madre, where altitudes close to 3000 m. above sea level are reached, maintaining however, the average at little more than 1500 m., until reaching the elevated part of the staggered relief, where the Altiplano Zone and the Central Zone are located in the south-southwestern portion of the state. This sub-region rises above 1800 m, exceeding 2500 m., and in the Altiplano Area even 3000 m [1].

Currently, the average precipitation in the San Luis Potosí Valley is 358.95mm, likewise, the months of June, July, August and September are seasons with the presence of more precipitation and the remaining months are drought. It is important to bear that in mind because it is during the dry seasons where the soil shows more changes with respect to the subsidence. The San Luis Potosí Valley is an endorheic or closed basin, identified as the San Luis Valley basin, with a surface area of 2,394 km², which due to its rainfall, allows it to be characterized as an arid zone [2]. Likewise, the term subsidence refers to the gradual sinking of the terrestrial, continental or submarine crust. Subsidence affects in urban areas are becoming increasingly frequent, due to the soil alteration by the natural movements of the earth's crust and the soil exploitation due to subsoil alterations such as water extraction, the extraction of energy and the stratigraphy characteristic of the affected area [3].

The InSAR technique has been of vital importance to study the sinking incidence phenomenon in various parts of the world such as China, Taiwan, Iran, etc., and although previously, between the 1960s and the beginning of the second millennium, the way of studying subsidence, faults and cracks was done through geophysical, mathematical, and geological studies, among others [4]. Recently, the use of geospatial technologies has been an important alternative, as it takes advantage of high-resolution data infrastructures and inputs from satellites to analyze a wide variety of phenomena that occur in the earth's crust more precisely. Thus, the Synthetic Aperture Radar Interferometry (InSAR) technique is a technical-scientific principle used to estimate the topography of the soil at a point on the Earth's surface from two observations [5] [6].

2. Methodology

2.1. Materials and data collection

SNAP (Sentinel Application Platform) software developed by ESA (European Space Agency) was used to carry out the calculation of the interferogram. The images were downloaded directly from the Alaska Satellite Facility website. The characteristics of these are shown in Table 1:

| Acquisition Date | Beam Mode | Path | Frame | Ascending/Descending | Polarization | Absolute Orbit | Frequency |
|------------------|-----------|------|-------|----------------------|--------------|----------------|-----------|
| 12/12/2014       | IW        | 114  | 515   | Descending           | VV           | 3686           | C Band    |
| 26/09/2015       | IW        | 114  | 516   | Descending           | VV           | 7886           | C Band    |
| 25/12/2016       | IW        | 114  | 517   | Descending           | VV           | 14536          | C Band    |
| 27/09/2017       | IW        | 114  | 517   | Descending           | VV+VH        | 18561          | C Band    |
| 04/10/2018       | IW        | 114  | 516   | Descending           | VV+VH        | 23986          | C Band    |
| 20/05/2019       | IW        | 114  | 516   | Descending           | VV+VH        | 27311          | C Band    |

2.2. Data Comparison

Data obtained from Sentinel 1- A images over a 5-year period (2014 - 2019) were used to analyze the sinking incidence value presented in the San Luis Potosí - Soledad de Graciano Sánchez conurbation area. For the comparison to be possible it was necessary for both images to coincide in the direction, that is to say descending or ascending, as well as for both images to share the same polarization (VV), because if these requirements are not met, it is likely that the procedure will not be performed correctly [7]. Once the images with these characteristics were available, we proceeded to the treatment and analysis of the results obtained.
2.3. Analysis

The methodology for doing the Interferometric process is shown in Figure 2.

Figure 2. Methodology for obtaining interferogram

Interferometric pair co-registration. The coordinates of points in common between two satellite images are recognized algebraically and the geometric correction between them is carried out almost automatically.

2.3.1. Calculation of the interferogram. The complex interferogram is calculated by multiplying one SAR image by the conjugate complex of the other.

\[
\Delta \varphi = \Delta \varphi_{\text{flat}} + \Delta \varphi_{\text{elevation}} + \Delta \varphi_{\text{displacement}} + \Delta \varphi_{\text{atmosphere}} + \Delta \varphi_{\text{noise}}
\]

\[
\Delta \varphi_{\text{flat}} = -\frac{4\pi B_n}{\gamma R \tan\theta}
\]

\[
\Delta \varphi_{\text{elevation}} = -\frac{\Delta q B_n}{\sin\theta} \cdot \frac{4\pi}{R_0} \cdot \frac{4\pi}{\gamma}
\]

\[
\Delta \varphi_{\text{atmosphere}} = +\frac{4\pi}{\gamma} d
\]

The phase difference can have contributions from five different sources, where

1. \(\Delta \varphi_{\text{flat}}\) is called the flat phase of the Earth, which is the phase contribution due to the earth curvature.
2. \(\Delta \varphi_{\text{elevation}}\) is the topographic contribution to the interferometric phase.
3. \(\Delta \varphi_{\text{displacement}}\) is the contribution of surface deformation to the interferometric phase.
4. \(\Delta \varphi_{\text{atmosphere}}\) is the atmospheric contribution to the interferometric phase. It is introduced due to atmospheric humidity, temperature and pressure change between the two acquisitions.
5. \(\Delta \varphi_{\text{noise}}\) is the phase noise introduced by the temporary change of the dispersers, the different viewing angle and the volume dispersion.

Through interferometric processing, other sources of atmospheric errors, noise, etc., will be eliminated. In order to leave only the element of interest, which is usually elevation or displacement.

2.3.2. Coherence estimation. Due to physical and geometric changes occurring at the scene between acquisitions of SAR images forming an interferometric pair, there is a loss of correlation between them. A parameter to measure this correlation for two complex SAR images is coherence.
Loss of coherence can lead to interferometric poor results and loss of coherence could be caused by time (time between acquisitions), geometric (orbit errors), volumetric (vegetation) or misprocessing.

2.3.3. Multilooking. The process reduces noise in SAR images by averaging adjacent pixels.

2.3.4. Topographic Phase Removal. The interferogram can be flattened by removing the topographic phase. The operator will simulate an interferogram based on a DEM (Digital Elevation Model provided by the same software) reference and subtract it from the interferogram previously processed in previous steps.

2.3.5. Phase development. The altitude of the ambiguity is defined as the difference in altitude generated by an interferometric phase change of $2\pi$ after the flattening of the interferogram. Phase development resolves this ambiguity by integrating the phase difference between neighboring pixels.

\[
H_a = \frac{\lambda R \sin \theta}{B_n}
\]

Where $R$ is the distance from the satellite to the target, $H$ is the ambiguity altitude, $\theta$ is the phase angle and $\lambda$ is the wavelength.

Apply terrain correction by Doppler method: The next step is to get the location of each pixel in the image with respect to a geographic coordinate system and its height with respect to a conventional datum or reference frame [7].

3. Results and Discussion

Each map shows a variation in sinking, as observed, this phenomenon occurs in areas such as Colonia Aeropuerto, Parque Tangamanga II, Colonia Lomita 2da Sección, Fraccionamiento Cecilia 3ra Sección, Fraccionamiento Tercera Chica 3 and 4. Previously these areas were cultivated and also, when it rains the largest catchment of water goes to these areas, i.e., when it is dry season, suffers a greater sinking due to the factors described above [4].
Figure 3. Images resulting from the interferometry process using SNAP software, where the sinking value is shown throughout the period (2014 – 2019).
The results, which indicate the degree of subsidence that occurred in each study period, are shown below (Table 2).

| Period     | Sinking (cm) |
|------------|--------------|
| 2014 - 2015 | -5.8         |
| 2014 - 2016 | -7.7         |
| 2014 - 2017 | -8.7         |
| 2014 - 2018 | -9.5         |
| 2014 - 2019 | -13.4        |

The results show a considerable level of subsidence over the 5 years analyzed, which reflect an average of approximately 2.6 cm per year of deformation. Therefore, it should be noted that the dates of the images correspond to drought seasons (May, October, November and December). Although there are other factors that cause the sinking incidence in the San Luis Potosí - Soledad de Graciano Sánchez conurbated area, one of the main ones is the aquifers overexploitation existing in the area. As a result of urban growth, the demand for water resources continues to increase, so that groundwater is being depleted and the recharge capacity of the San Luis Potosí Valley aquifer is insufficient. Therefore, this causes the space previously occupied by water to increase in a vulnerable space, resulting in the sinking incidence [8].

Likewise, vector data obtained from the cracks determination and Areas of Interest (AOI) of the subsidence generated in a study on the risks atlas of this valley [4] are available, which allowed a comparison with the results of the interferometric imaging process in the different periods analyzed (Figure 4).

![Figure 4. Vector data taken in the field, where cracks, sinkings are observed.](image-url)
results are corresponding in terms of the subsidence locations described. In the case of the urban area of San Luis Potosí - Soledad de Graciano Sánchez, it has been documented for several decades, about the overexploitation of the valley deep aquifer, especially in the urban area, activity that has increased with the city growth, so it is obvious to think of a possible direct influence of this aquifer’s depletion on the phenomenon in question [4].

In the same way, a general longitudinal profile of each year of the vertex’s location and of the sinking values register was made in the inSAR data treatment, where in the Y axis the sinking value is found and in the X axis the GNSS vertices position is plotted and according to the graph a similar behavior could be observed among all of them. So, in the coordinate -100.96, it is where a noticeable decrease in sinking is observed (Figure 5).

![Figure 5. General profile of the subsidence throughout 5 years studied (2014 – 2019).](image)

The interpolation of the position and elevation of the GNSS vertices registered in 2014 was performed in order to correlate with the values of position and elevation registered in the inSAR image processing performed, which yielded the results specified in table 3. In previous studies carried out in the city of Aguascalientes in Mexico, a similar procedure had been carried out in the interpolation of InSAR images and GNSS data [9], in addition to reviewing other similar procedures, a scheme was followed for the implementation of the interpolation process shown below (Figure 6).

![Figure 6. Interpolation processing.](image)

Based on the scheme, 3 interpolation methods were used in order to obtain the surface value based on GNSS data and its comparison of the mean quadratic error:
1. Ordinary Kriging: being an advanced geostatistical method that generates an estimated surface from a set of scattered points with z values [10].
2. Kriging Simple: method that generates a surface from a set of points, likewise, this method uses semivariograms and covariances to use transformations and allow measuring errors [10].
3. IDW: Which uses an interpolation process that estimates cell values by averaging the values of sample data points in the vicinity of each processing cell [11].
Having measured a total of 72 geodesic vertices in 2014, in order to obtain data on their position and elevation in areas vulnerable to subsidence in the San Luis Potosí Valley, with the values determined for that position and elevation, the 3 methods described as Simple Kriging, Ordinary Kriging and the IDW method were tested in order to assess the best behavior of the interpolation processes, the IDW method being the best option, because the average quadratic error of the Ordinary Kriging method gave an error of 36.1, that of Kriging Simple 37 and that of IDW yielded an error of 35.7, that is to say the IDW yielded a smaller value and with less error, for which on the basis of the results obtained and according to the experiences of other works found in the scientific literature relative to similar processes the IDW method was chosen as the best alternative to represent the GNSS vertices interpolation. Figure 7 shows the interpolation result behavior, giving the unknown surface elevation values as a function of the processed GNSS vertices. So, the red zones reflect the surface highest parts (constant surfaces that had no recorded alteration) and the blue zones reflect the zones vulnerable to the sinking incidence.

Figure 7. GNSS data interpolation.

By having the elevation values of the processed GNSS vertices, and the sinking values of 2019, it was possible to achieve through a mathematical process using the Band Math tool in the ArcMAP software, subtract the InSAR images values and the GNSS data values to determine the sinking that has occurred in the San Luis Potosi Valley. In the following list of elevation heights, the numbers that underwent changes are highlighted in red, with vertices 50, 51 and 52 registering the greatest sinking (Table 3).
Table 3. Difference in Elevations between GNSS data and sinkings values of the InSAR method.

| No. Point | GNSS Value   | Sinking Value 2019 |
|-----------|--------------|-------------------|
| 1         | 1852.540     | 1852.548          |
| 2         | 1860.230     | 1860.220          |
| 3         | 1860.760     | 1860.755          |
| 4         | 1860.840     | 1860.800          |
| 5         | 1866.760     | 1866.766          |
| 6         | 1866.190     | 1866.186          |
| 7         | 1868.290     | 1868.296          |
| 8         | 1899.410     | 1899.415          |
| 9         | 1904.360     | 1904.363          |
| 10        | 1931.130     | 1931.142          |
| 11        | 1927.090     | 1927.102          |
| 12        | 1875.640     | 1875.650          |
| 13        | 1855.880     | 1855.893          |
| 14        | 1877.870     | 1877.900          |
| 15        | 1895.910     | 1895.916          |
| 16        | 1923.650     | 1923.665          |
| 17        | 1930.240     | 1930.257          |
| 18        | 1895.180     | 1895.188          |
| 19        | 1908.430     | 1908.447          |
| 20        | 1904.340     | 1904.358          |
| 21        | 1923.940     | 1923.957          |
| 22        | 1901.320     | 1901.340          |
| 23        | 1938.200     | 1938.217          |
| 24        | 1884.050     | 1884.069          |
| 25        | 1879.520     | 1879.535          |
| 26        | 1907.440     | 1907.451          |
| 27        | 1881.460     | 1881.465          |
| 28        | 1873.460     | 1873.462          |
| 29        | 1869.780     | 1869.764          |
| 30        | 1868.120     | 1868.097          |
| 31        | 1870.440     | 1870.407          |
| 32        | 1870.200     | 1870.161          |
| 33        | 1864.890     | 1864.856          |
| 34        | 1870.450     | 1870.412          |
| 35        | 1870.940     | 1870.907          |
| 36        | 1890.000     | 1890.013          |
| 37        | 1878.680     | 1878.648          |
| 38        | 1878.020     | 1877.990          |
| 39        | 1884.970     | 1884.958          |
| 40        | 1883.770     | 1883.756          |

4. Conclusion

Throughout this study, one of the InSAR various uses technique was analyzed, so that the methodology used proved to be effective for measuring soil deformations and subsidence in the San Luis Potosí Valley. Likewise, it is highlighted that the processes and parameters in the formulas application of this methodology allowed reducing the orbit errors, as well as the noise or coherence errors, for the images adequate processing. For this study, reference was made to several works cited in the scientific literature that mainly used this InSAR method, and in the same way, reference was made to the European Espace Agency (ESA), which developed the SNAP software. By integrating the vector data of cracks and subsidence, the comparison was made with the results obtained in the InSAR process, which resulted in various similarities in the results in terms of subsidence recorded in both studies of the analysis areas. Thus, future studies using the InSAR technique and experimentation with other existing interferometry techniques could be of great help in tracking this subsidence phenomenon in later years.
The results obtained from the interpolation of GNSS vertices provide a clearer perspective of the soil deformations behavior and the subsidence record presented in 2014. So these vertices played an important role in knowing the values of unknown surfaces near the location of the GNSS data positioned. The table described from the GNSS vertices comparison and the sinking values resulting from the InSAR method gave a better perspective of the effect on the sinking that occurred in the period 2014 - 2019. This analysis opened the way for the use of recent geospatial tools to measure deformations in soil, given that in previous years the studies carried out to learn about soil deformations in the valley of San Luis Potosí, Mexico, were only analyses of geological and geophysical models that were costlier in terms of resources and time invested.

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