3D VISUALISATION OF PERIODIC SPATIAL TIME SERIES FROM RADAR INTERFEROMETRY MEASUREMENTS OVER UNDERGROUND GAS STORAGE

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Abstract

Radar interferometry is a powerful tool for monitoring terrain movement, for example, above the underground gas storage facility. Radar interferometry results in a relatively large volume of data describing the time evolution of permanent scatterers distributed in space. For their analysis, it is necessary to find a suitable method that well supports visual analytics. Due to the main characteristics of these time series, which are the length and annual periodicity caused by the cyclical injection/withdrawal of natural gas, spiral graphs have proved to be a suitable means. The article shows both the visualisation of an individual time series and the visualisation of time series generated for clusters of nearby and similarly behaving points above the map.

Keywords: synthetic aperture radar; periodic spatial time series; 3D visualisation; Sentinel-1

1. INTRODUCTION

Radar interferometry (InSAR) has brought significant progress in the systematic and long-term monitoring of terrain movement in large areas. It is used, among other things, to monitor the terrain's behaviour over underground gas storage facilities (UGS). These are primarily built in underground geological structures, such as depleted oil and gas reservoirs. Their area extent is on the order of units and tens of square kilometres. UGS is characterised by periodic natural gas injection in the warm season and withdrawal in the cold season. This regime is also associated with periodic vertical terrain movements over the UGS. Their RI monitoring is a common task today. However, problems remain in the appropriate visualisation of monitoring results, which would support the visual analysis of data and facilitate their interpretation. One method that has been proposed is spiral graphs. In this paper, we deal with the possibility of using a spiral graph in 3D in combination with a map. Spiral graphs provide information about the periodic behaviour of individual places above the UGS; their placing on the map then shows the spatial context of the behaviour of individual places.

2. MATERIALS AND METHODS

2.1. Radar interferometry

Radar interferometry is a remote sensing method based on interferometric processing of repeated radar measurements performed from satellites equipped with synthetic aperture radar (SAR; Hanssen 2001). Due to the very short wavelength of the radio waves used, the method is susceptible to changes in the distance between the satellite and the terrain surface from which the signal is backscattered. The change in this distance can be caused, among other things, by the movement of the terrain surface. This method is quite sensitive; it allows the detection of terrain movements in the order of millimetres per year. Data is usually collected periodically. For example, Sentinel 1 satellites capture the same terrain with a period of 6 days, which allows one to study terrain movements in great detail throughout the year and thus evaluate periodic terrain movements during the year, or compare individual cycles of periodic movements with each other. Several radar data processing methods have been developed. Frequently used methods include Permanent scatterers interferometry (PS-InSAR; Ferretti et al., 2000; Ferretti et al., 2001), which is based on the automatic detection of points that permanently backscatter the radar signal and for which it is possible to evaluate the time series of their movement.

2.2. Spiral graphs in 3D

The time series obtained during UGS monitoring possess both linear and cyclic properties. Therefore, spiral graphs are well suited for their visualisation (Fang et al. 2020). The linear property is represented along the spiral, while the cyclic property is represented along the radii. One cycle fills just one lap of the spiral. The most commonly used are spirals in the plane (Weber et al. 2001). Attempts have also been made to use the 3D helix (Hewagamage et al. 1999), but the results were not convincing. Their main disadvantage is that in the isometric view of the map, the helices themselves always overlap the helix's distal part, and their complete visual analysis is therefore tricky. The third possibility is using planar spiral graphs in 3D, where the third dimension, perpendicular to the spiral plane, is reserved for visualising the studied attribute. The so-called Archimedean Spiral (Carlis, Konstan 1998) is used as a basis here, which has a constant pitch and thus allows to visualise even longer time series with many consecutive periods. For the sake of readability at the beginning of the graph, we will use a spiral with an offset so that the lap representing the first cycle has a sufficient length (Tominsky, Schumann 2008).

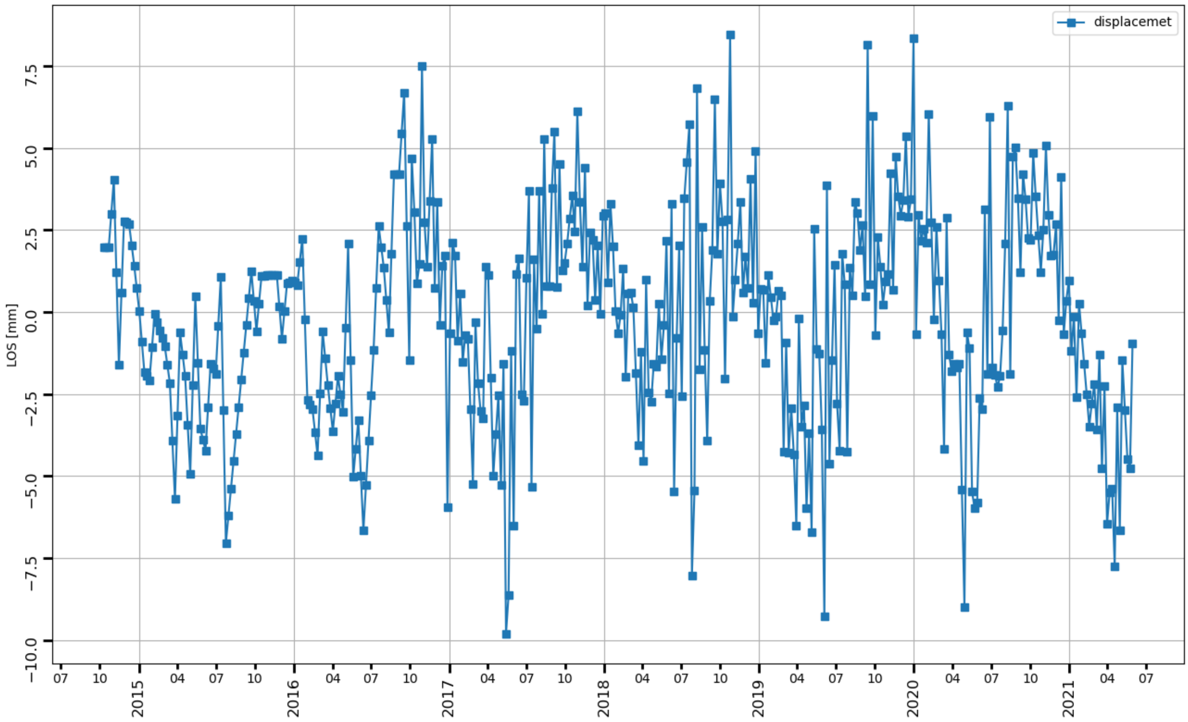
2.3. Spiral graphs in 3D on the map

First, the correlation coefficient between time-series on points and theoretical curve derived from processes in UGS is calculated for all points. Then the DBSCAN algorithm is used for clustering. It calculated the final matrix as a combination Euclidean distance matrix for geographical coordinates of individual points and cosine distance matrix calculated from correlation coefficient. The centroid and average time series are calculated for each cluster. From these time-series is removed outliers as three times of standard deviation. These corrected time series are interpolated for regular sampling six days. Each cluster's spiral graph is created with the matplotlib library in python.

Spiral is created using modified equations (Weber et al. 2001):

$$x = r * \sin(\varphi)$$
$$y = r * \cos(\varphi)$$

$$\varphi = 2\pi * r$$



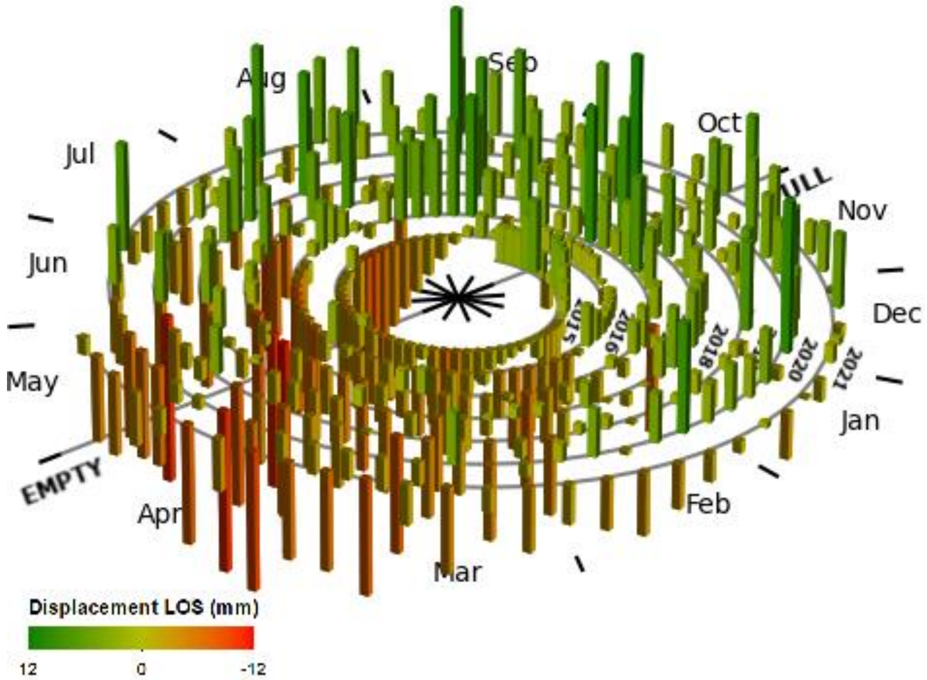


Figure 1 Comparison of a linear plot (up) and plane spiral graph (bottom) for one cluster. Each spiral lap corresponds to one injection/withdrawal cycle and is one year long. The time series starts in October 2014 and ends in May 2021. From the linear plot, there is a clear periodic course of the time series and a general trend, but it is not easy to compare the individual cycles. Conversely, the plane spiral graph allows for easy comparison of individual cycles, but dims out the long-term trend.

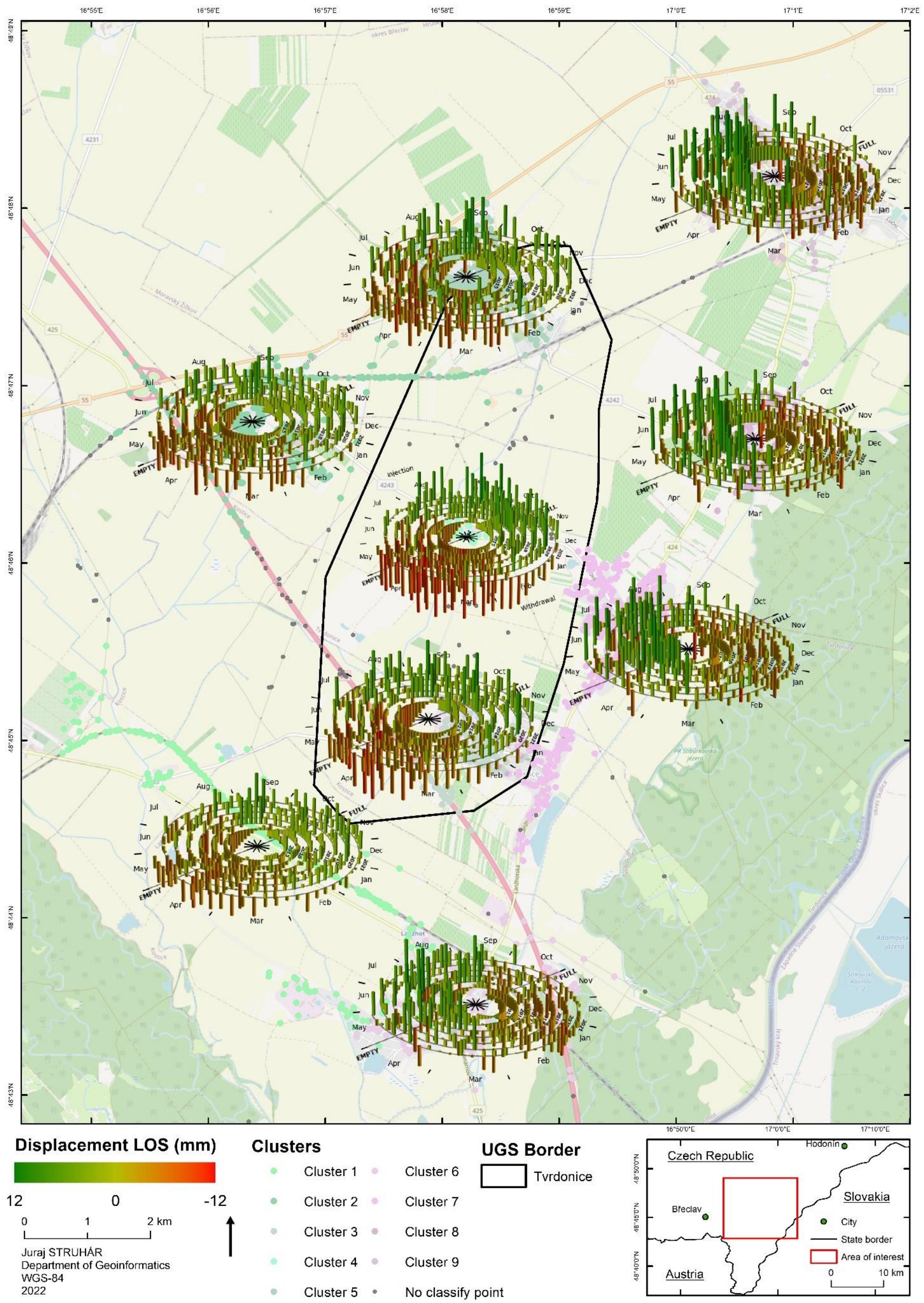


Figure 2 Spiral graphs for individual clusters.

Where r is linear interpolated values from k to k+6.63 (where k=2), it is the length of measurement of years. Bars and their colour in spiral represent measured values.

Finally, a map with spiral graphs for each cluster was created. It also displays points forming individual clusters.

RESULTS

As a test site, we chose the area east of the village of Tvrdonice, the Czech Republic, under which the UGS Tvrdonice is built. We processed data from October 2014 to May 2021. In total, we had 332 measurements. We processed the measurement using the PS InSAR method implemented in SALSIT (www.insar.cz/salsit.html). We obtained time series for 2978 points (permanent scatterers) located inside or up to 4 km outside of the UGS boundary. Due to the high number of points, we had to reduce them for visualisation purposes. We first selected points whose time series showed an annual periodicity close to the gas injection/withdrawal cycle (total 2132 points), and then we cluster them based on the spatial proximity and similarity of the time series.

Figure 1 shows a linear plot and spiral graph for one cluster. Each spiral lap corresponds to one injection/withdrawal cycle and is one year long. From the linear plot, there is a clear periodic course of the time series, and it is possible to deduce from it the existence of a particular trend, but it is difficult to compare the individual cycles with each other. Conversely, the plane spiral graph allows for an easy comparison of individual cycles. Across the laps, we can then compare individual adjacent annual cycles with each other, but the long-term trend is dimed out. The figure shows a significant difference between the period when the UGS is full of natural gas and when it is empty. Figure 2 shows the spiral graphs for the individual clusters above the map. They display diametrically different clusters above the UGS and clusters beyond the south-eastern border of the UGS. This difference was interpreted as a consequence of the geological structure – the existence of a fault at the south-eastern boundary of the UGS (Rapant et al. 2020).

CONCLUSIONS

Visualisation of long periodic space time series is a challenging task. The use of classical line graphs is problematic – they do not allow the comparison of neighbouring cycles of individual time series and do not support the visualisation of spatial relationships between individual time series. Therefore, the use of spiral graphs in the plane or 3D seems most suitable. Displaying a plane spiral in 3D is proving to be a very suitable tool: displaying the development of the monitored attribute perpendicularly to the spiral plane allows one to understand the data better. Moreover, the display of individual spirals above the map also allows one to capture and interpret the evolution of the monitored attribute in space. On the contrary, the spiral graph deems a time trend in time series, so if it is of interest, it must be studied using different visualisation techniques. Another disadvantage is that the data visualised on the spiral partially overlaps, making interpretation difficult.

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