SATELLITE RADAR INTERFEROMETRY FOR RISK MANAGEMENT OF GAS PIPELINE NETWORKS

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ABSTRACT

InSAR time series analyses can be fine-tuned for specific applications, yielding a potential increase in benchmark density, precision and reliability. Here we demonstrate the algorithms developed for gas pipeline monitoring, enabling operators to precisely pinpoint unstable locations. This helps asset management in planning, prioritizing and focusing in-situ inspections, thus reducing maintenance costs. In unconsolidated Quaternary soils, ground settlement contributes to possible failure of brittle cast iron gas pipes and their connections to houses. Other risk factors include the age and material of the pipe. The soil dynamics have led to a catastrophic explosion in the city of Amsterdam, which triggered an increased awareness for the significance of this problem. As the extent of the networks can be very wide, InSAR is shown to be a valuable source of information for identifying the hazard regions. We monitor subsidence affecting an urban gas transportation network in the Netherlands using both medium and high resolution SAR data. Results for the 2003-2010 period provide clear insights on the differential subsidence rates in the area. This enables characterization of underground motion that affects the integrity of the pipeline. High resolution SAR data add extra detail of door-to-door pipeline connections, which are vulnerable due to different settlements between house connections and main pipelines. The rates which we measure represent important input in planning of maintenance works. Managers can decide the priority and timing for inspecting the pipelines. The service helps manage the risk and reduce operational cost in gas transportation networks.

1. PROBLEM BACKGROUND

An adequate supervision of the integrity of gas transportation networks is required and known to be a cumbersome task for network operators. We are facing serious challenges when it comes to safety management of gas distribution. Differential settlements between ground and buildings produce strain on connecting pipes. For brittle cast iron gas pipes this could possibly lead to breakage with undesirable consequences as occurred in a gas explosion in Amsterdam in 2008 [1]. A proper risk assessment strategy is therefore needed to prevent occurrence of accidents. As preventive measures, old brittle pipes will be replaced entirely and the status of connections between the distribution pipes and individual houses should be timely and precisely monitored.

Persistent Scatterer Interferometry (PSI) is a proven differential interferometric technique which involves processing large series of multi-temporal Synthetic Aperture Radar (SAR) data to identify networks of persistently reflecting surface features, against which measurements of motion are made with millimeter precision. High density and accurate PSI-derived deformation measurements are acquired over wide areas and long time periods [2]. This qualifies the technique for demanding applications, such as risk management for gas distribution networks.

Here we show how ground motion analysis from space becomes a solution for gas network operators. To meet gas regulations and safety policies, about 10.000 km of brittle gas distribution pipeline will be replaced in the Netherlands in the next 25 years [1]. Planning and prioritizing the replacement of brittle pipes is done based on input derived from satellite radar measurements. In addition to identifying the locations for most urgent replacement, the replacement materials for the pipes can be chosen based on observed subsidence rates.

2. APPROACH

PSI is a powerful technique when it comes to accurately monitor deformation of the terrain especially over long time scales [3]. If the Line of Sight (LOS) deformations are known at millimeter level, knowledge over the precise location of the reflecting objects/surface is a challenging task. Position accuracies in the order of meters [4] make it difficult to distinguish from where the reflections stem. It is not straightforward at all to be able to determine whether the illuminated targets are buildings, grounds or other man-made structures. For pipeline monitoring, differential motions between buildings and ground are of paramount importance.

Classification and characterization of persistent scatterers (PS) in terms of ground or building reflections has been applied using different strategies ([5], [6]). We use here an approach based on the estimated heights resulted from the PSI processing chain. Using deformation and height values of all phase coherent pixels, we derive the representative height of ground level in the area of interest and we define a threshold above which PS points will be classified as buildings. Remaining points in the dataset are attributed to ground

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level. This separation is decisive for determining differential settlements as for the motion of buildings versus ground.
Subsequently, custom PSI products are needed to address the challenges that pipeline network operators are facing in their maintenance and risk management tasks.
For long-term planning and prioritizing of pipe replacement, medium resolution SAR imagery is of added value. For this application, we first divide the area of interest in administrative units that network operators are working with (e.g., postal codes, neighborhoods). For each polygon we give a representative value of the linear deformation rate using as input the rates of all ground points inside (available after the PS classification step). Using a statistical approach, representative numbers are then given by percentiles (10^{th}, 20^{th} or 30^{th}, depending on the case). The percentile chosen is typically found to relate well to the subsidence levels that users experience as representative.
For day to day maintenance and risk assessment, higher resolution satellite data is mandatory (both in time and spatial extent). This type of imagery is available nowadays from TerraSAR-X, Radarsat-2 or COSMO-SkyMed satellite missions, enabling estimation of highly accurate deformation time series at building level. Thus, we can implement a proper monitoring system with alarm triggering capabilities once a pre-defined threshold is exceeded.
A different strategy of analyzing and interpreting the data consists of averaging ground deformation measurements at the location of the pipelines. A weighted average of points within a couple of tens of meters of the pipes is performed for points spaced at regular intervals along the gas pipeline route. This gives a better overview and interpretation of motion along the lines.

3. RESULTS

To determine the feasibility of gas pipeline monitoring by InSAR and using this type of input for maintenance planning, we analyze two datasets from two different satellite missions: Envisat and TerraSAR-X. The first dataset operates with a 5.6 cm wavelength and has a 4 x 20 m image pixel size yielding medium resolution deformation map products. We use for this study descending data over the Netherlands from July 2003 - September 2010. The second dataset consists of high resolution (3 x 3 m) TerraSAR-X images acquired in Stripmap mode and descending orbit. This set adds a significant amount of information and detail in terms of point density with respect to the previous one (Fig. 1 is an indication). We obtain hundreds up to thousand PS points per km^2 in urbanized areas by using this imagery. The analyzed period is April 2009 - September 2012.

Figure 1. Envisat versus TerraSAR-X point density. On average, a tenfold increase in point density is obtained by switching from medium (Envisat) to high resolution (TerraSAR-X) satellite data.

A first step after the estimation of PS height and deformation rate is the PS classification in two groups, ground and buildings. This is being done according to the specifications described in Section 2. Fig. 2 shows such analysis, while Fig. 3 reveals the results of this separation on a small region. This provides a better understanding of differential settlements occurring in the area of interest.

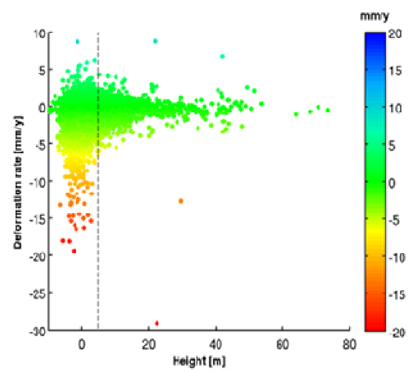

Figure 2. Ground/building separation based on estimated heights of persistent scatterers (Envisat,2003-2010). A threshold of 3 m above ground level was chosen to distinguish between high and low points.

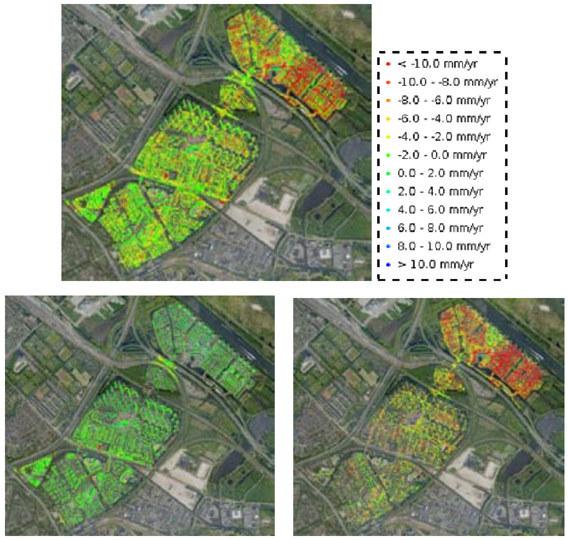

Figure 3. Linear deformation rates (TerraSAR-X, 2009-2012). Upper panel: all PS; Lower left: PS on buildings with a deep foundation, resulting in stability. Lower right: ground level. The difference with the left image shows the differential motion of the top soil layer adding stress to pipelines.

Once differential motion is known, an extra analysis is done to address the challenges of pipeline network operators. To this extent, we have used the linear deformation rates from the historical analysis of the Envisat data. The area is split in polygons corresponding to postal code 4 administrative division units. These regions are characterized afterwards by the 10th percentile of the deformation rates.

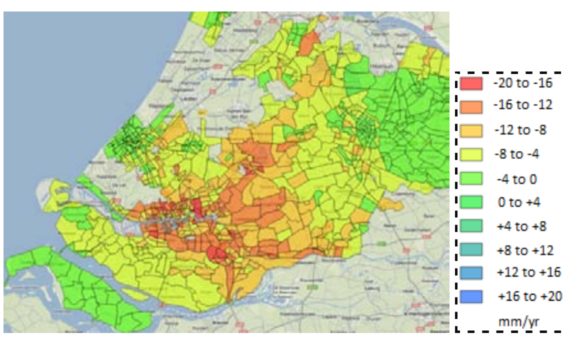

Figure 4. Wide area differential subsidence rates (Envisat, 2003-2010). Polygon boundaries correspond to the Dutch postal codes. Colors denote the representative value for the linear deformation rate. The 10th percentile is used in this case. Only ground points are included in the analysis.

The TerraSAR-X dataset proves to be useful especially from a monitoring point a view. A higher repeat frequency and increased resolution intimately linked to the increase of point density in the area qualify these data for monitoring.

An important input for this type of application is information on subsidence along pipeline routes. The procedure for retrieving it is briefly described in Section 2. We select representative points along the trajectory of the pipes spaced 10 or 20 m apart, depending also on the length of the pipeline. For each of these points, we include deformation information over a 25 m buffer around that location. We apply a weighted average over distance to the deformation rates of the PSs we encounter and thus one value gets assigned at each location. Results are shown in Fig. 5. This illustrates how our initial PSI deformation map becomes a custom-made product for a specific application.

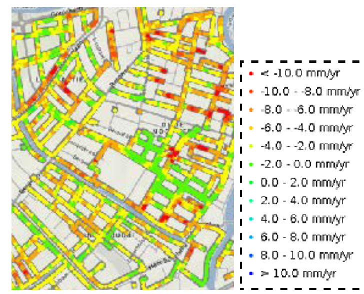

Figure 5. Deformation analysis along pipeline routes. Colors denote estimates of averaged linear deformation rates (in mm/yr). Results are presented for points 10 m spaced along the pipelines. Weighted averaging of points within 25 m of the pipes is performed.

4. CONCLUSIONS

We show the application of InSAR for the gas distribution sector. Using medium resolution ESA imagery over a 7-year time span we monitor differential settlements in gas networks. The polygon analysis proves to be of relevance in tasks such as planning, prioritizing and focusing the in-situ inspections by guiding the field engineers towards the unstable locations. InSAR-derived subsidence rates give also an indication on what type of material should be used for the pipes at different locations. Therefore, InSAR presents itself as a cost-effective tool for asset management. With high resolution SAR data we can obtain information at a door-to-door level. The monitoring approach aims at minimizing the number of breakages in the network, ensuring as much as possible the safety in operations.

5. REFERENCES

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