DEFORMATION TIME-SERIES DERIVED FROM TERRESTRIAL RADAR OBSERVATIONS USING PERSISTENT SCATTERER INTERFEROMETRY IN SEATTLE, WASHINGTON

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ABSTRACT

The GPRI2 Ground-Based Real-Aperture radar was deployed in Seattle over a 6-week period during March and April 2015 to measure sub-millimeter scale subsidence related to construction of the Alaskan Way Viaduct and Seawall Replacement Program (AWVSRP). The radar was located on the mid-level roof of the Smith Tower overlooking Pioneer Square at an altitude of about 75 meters above street level. Radar images at 2 hour intervals were processed to obtain Line-of-Sight (LOS) deformation maps. Point target analysis was used to identify stable targets and to mitigate variations in propagation path length due to atmospheric changes. Geo-location and rectification of the more than 100,000 monitored points was carried out using a LiDAR DEM.

Index Terms — Terrestrial Radar, Differential Interferometry, Subsidence, Deformation Mapping, Urban Mapping

1. INTRODUCTION

Ground-Based radar interferometry has the potential to rapidly map deformation over large areas with sub-millimeter precision without the need to install reflectors. We describe one of the first deployments of a ground-based radar in an urban environment. This environment is challenging for several reasons including identification of points in the scene that can be measured, determining the best observation geometry, and mitigation of variations in path length due to atmosphere. This paper is organized to first describe the motivation and selection of the observation site, followed by a description of the instrument and the point based processing approach, and concludes with a discussion of the results.

2. MOTIVATION AND SITE SELECTION

The Alaskan Way Viaduct is an elevated highway in Seattle built in the mid-1950s. Due to concerns about earthquake safety, especially after damage caused by the 2001 Nisqually earthquake, the Viaduct is being replaced by a tunnel. There has been significant subsidence in the Pioneer Square area possibly due to tunnel construction and extensive repairs to the tunnel boring machine [1]. The Gamma Portable Radar

Figure 1 Deployment of the radar interferometer on the Smith Tower above Pioneer Square in Seattle

Interferometer (GPRI-2) was deployed to monitor possible further deformation of buildings, roadways, and urban infrastructure in and around Pioneer Square. In order to get a good view of the area and to have a look direction with significant vertical component, the radar was mounted in a radome on the mid-level roof of the Smith Tower overlooking the Square at the 75-meter level, see Figure 1. The radar measures displacement along the Line of Sight (LOS), hence it critical to this application is that look vector from the radar to the region of interest is aligned with the displacement direction to get the best sensitivity. Since the deformation is primarily vertical, a relatively steep look angle ($20 \le \theta \le 60$) degrees is preferred, predicated upon having sufficient spatial resolution on the ground. Figure 2 shows the viewshed and look angle of the radar for the Pioneer Square area derived from a LiDAR DEM in geographic coordinates with a posting of 2.042×10^{-5} degrees (~2.27 meters).

3. RADAR INSTRUMENT

The GPRI-2 is an FM-CW radar operating at Ku-Band 17.1 to 17.3 GHz with an operational range of 20 meters

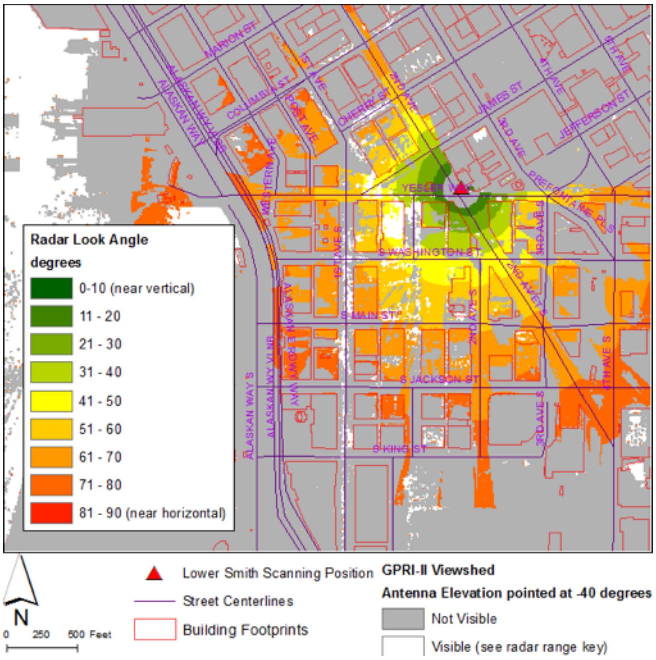

Figure 2 Pioneer Square district viewshed and incidence angle

to 16 km [2][3]. Range resolution is 90 cm along the LOS. The instrument operates in real-aperture mode using 0.385-degree wide azimuth fan-beam antenna pattern. During data acquisition, the radar performs a rotary scan of the scene at a programmable rate between 0.5 and 15 degrees/s. This radar geometry is ideal for wide-angular scans as required for urban deformation mapping. The GPRI is phase coherent and capable of acquiring data suitable for differential interferometry with a precision for measuring changes in the LOS distance better than 0.1 mm. Primary limiting factors in the accuracy of LOS displacement time series are interferometric phase coherence and variations in path delay due to atmosphere. Furthermore, thermal effects are relevant.

The images produced by the GPRI are complex-valued radar backscatter as a function of slant range r and rotational azimuth angle coordinate θ. The complex image samples $C(r,\theta)$ include both amplitude and phase information:

$$C(r,\theta) = ae^{-i4\pi r/\lambda}$$

where r is the slant range and the phase is given by $-4\pi r/\lambda$ and λ is the radar wavelength. The phase of individual persistent scatterers (PS) in the scene can be tracked over the entire observational campaign. A change in scatterer phase of 2π is equivalent to a change in propagation path distance of half a wavelength (8.72 millimeters).

Interferometric processing is carried out in the radar geometry and the results are then geocoded using a specified map projection or geographic coordinates. Figures 3 shows

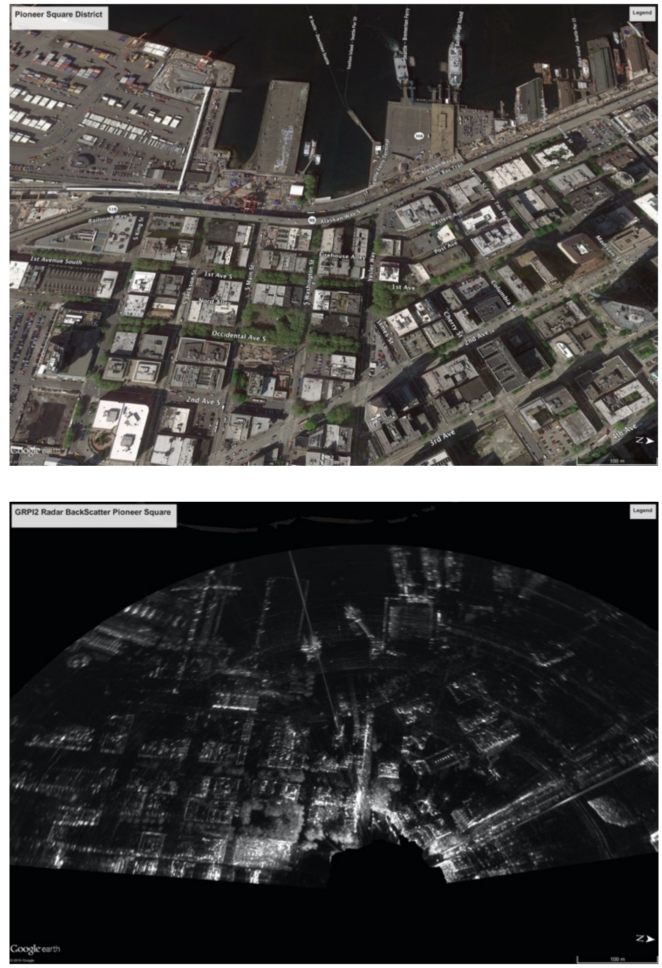

Figure 3 Google Earth view of the Pioneer Square District (upper) and geocoded radar backscatter (lower)

the Pioneer Square district from Google Earth along with the radar backscatter after geocoding.

4. INTEFEROMETRIC TIME SERIES PROCESSING

A total of 474 scenes spanning the period from 1-March-2015 to 11-April-2015 were used for the time-series analysis. The time interval between scenes for most days is 2 hours. However, there are missing acquisitions resulting in longer gaps apparent in the time-series.

The radar images cover an angular scan of 168 degrees in azimuth and have a starting slant range of 100 meters extending out to 700 meters. Pixel spacing is 0.75 meters in range and 0.1 degrees in azimuth. Azimuth resolution varies from approximately 1 meter in near range to 4.7 meters at far-range. The geocoded data are resampled to the DEM sample spacing.

In an urban setting there are many point target scatterers, but only a subset of these are from fixed structures that can

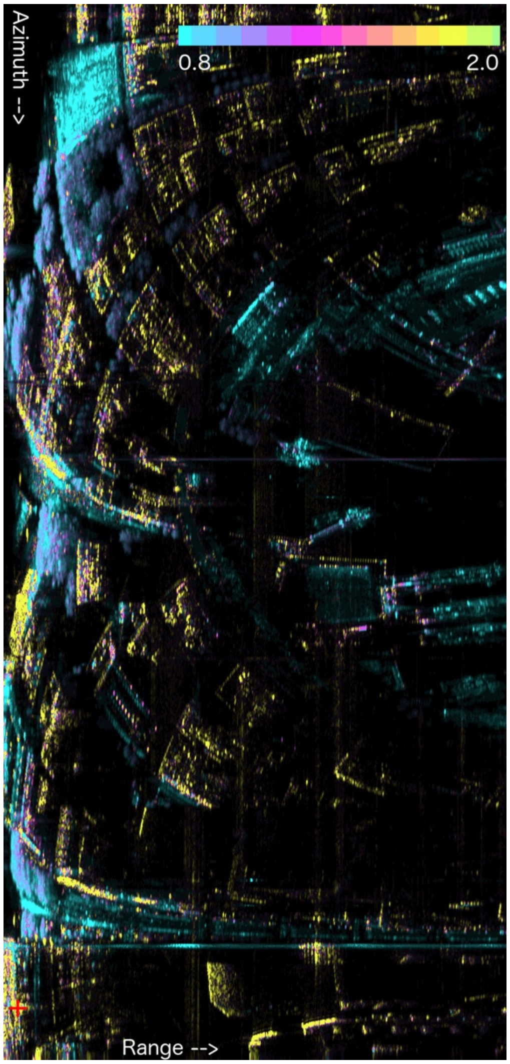

Figure 4 Mean/sigma ratio (MSR) of intensity between 0.8 and 2.0 used to select PS candidates. Note that the trees and parking lot in the upper left corner have low MSR values. The phase reference point is located at the red cross, lower left.

be used to monitor deformation. These stable targets are called Persistent Scatterers or PS. The approach used in our analysis is to evaluate for each pixel the ratio of the mean intensity to the standard deviation of the intensity using the entire image set. Because hundreds of images are available, for analysis, an accurate statistic can be calculated. A minimum mean to sigma ratio threshold of 1.6 was set to select points resulting in 104,507 PS.

A single-reference scene approach was used to estimate the deformation time-series [4][5]. In this approach all phase differences are relative to a single reference scene, in this case acquired at 1245 UTC on 22-Mar-2015. An interferogram with the reference scene is calculated for every scene in the ensemble.

4.1 Mitigation of Atmospheric Phase

The path delay through the atmosphere is a function of local temperature, pressure and humidity. At Ku-Band (17.2 GHz) this leads to significant phase up to approximately one phase cycle in the data.

To mitigate the effect of the atmosphere, an estimate of the atmospheric phase is calculated for each interferogram by applying a radial smoothing filter with a radius of 180 samples (135 meters). The filter is adapted for use with GPRI data by taking into account the variable azimuth resolution of the radar geometry. The filter output is an estimate of the large scale atmospheric phase in the image. Each of the filtered interferograms is spatially unwrapped using a minimum cost-flow unwrapping algorithm. The unwrapped phase is then subtracted from the original interferogram. What remains is phase due to a combination of the deformation along with some small-scale atmospheric variations. Deformation in regions on the order of the filter radius/2 or smaller is preserved by this filtering operation.

4.2 Temporal Phase Unwrapping

Since the deformation signals may be highly spatially variable, unwrapping the the phase in time is preferred [4]. The phase ϕ for each point i at time interval Δt_j in the coregistered interferogram stack is given by:

$$\delta\phi_{i,j} = \frac{-4\pi}{\lambda}\left(v_j\Delta t_j + \phi_{i,j}^{atm}\right) + \phi_{i,j}^{n}$$

where j is the index of the interferogram in the stack, v_j is the average velocity of the scatterer for the interferogram time interval, and $\phi_{i,j}^{n}$ is phase noise due to decorrelation or thermal noise. A stable reference point is chosen in the scene in a region known to be stable (see Figure 4). All radar motion relative to the reference point is subtracted. The phase history of each point relative to the reference point is unwrapped in time using the assumption that the changes in phase are less than π from open epoch to the next. This assumption is generally fulfilled given the dense temporal sampling of the image acquisitions and high coherence of the PS. Phase unwrapping errors may occur when there are gaps in the data acquisitions or rapid motion, such that the LOS deformation is close to or exceeds $\lambda/4$. The PS may also just be disturbed or disappear.

5. RESULTS AND CONCLUSIONS

The deformation time series is obtained from the unwrapped phase by scaling the unwrapped phase by $-\lambda/4\pi$. A linear fit of the unwrapped phase gives an estimate of the average deformation rates. The average LOS deformation rate of the PS can be geocoded using the DEM as shown in Figure 5. The color scale cycle is 4 cm/year.

A section of the Alaskan Viaduct near the center of the image appears to be subsiding at a rate of approximately 2.38 cm/year as shown by the time series in Figure 6. The total deformation is positive denoting motion away from the radar.

The average deformation rate scaled to vertical deformation/month can be calculated by scaling the LOS deformation cos θ_l where θ_l is the radar look angle as shown in Figure 7.

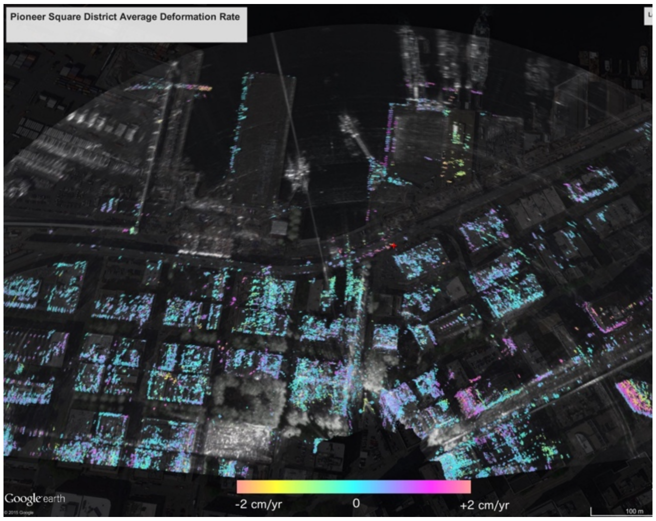

Figure 5 Linear Deformation Rate for the Pioneer Square District 1-Mar-2015 to 11-Apr-2015. The time-series in Figure 6 is evaluated at the red cross near the image center

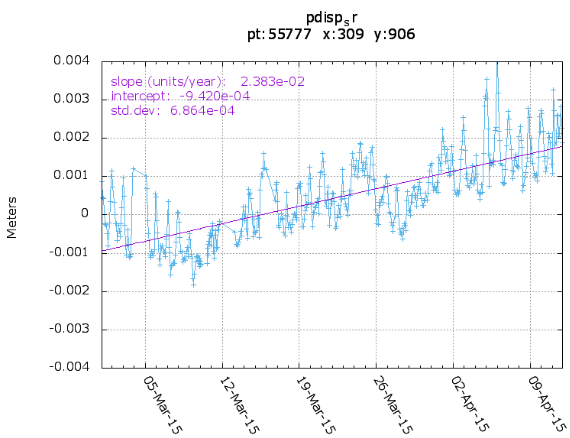

Figure 6 Time-series deformation of a point on the Alaskan Viaduct subsiding at a rate of 2.4 cm/year.

Note the strong diurnal motions of the point time-series. Previous work with TerraSAR-X data acquired over Barcelona, Spain strongly suggests that this is due to diurnal thermal expansion and contraction of the structures [6]. Different structures in the scene show this effect to different degrees suggesting that it is not related to motion of the radar itself in the building. Further work includes estimation and modelling of the diurnal phase to improve the deformation estimates. We have demonstrated deformation mapping in an urban environment using a ground-based radar with precision better than 1mm.

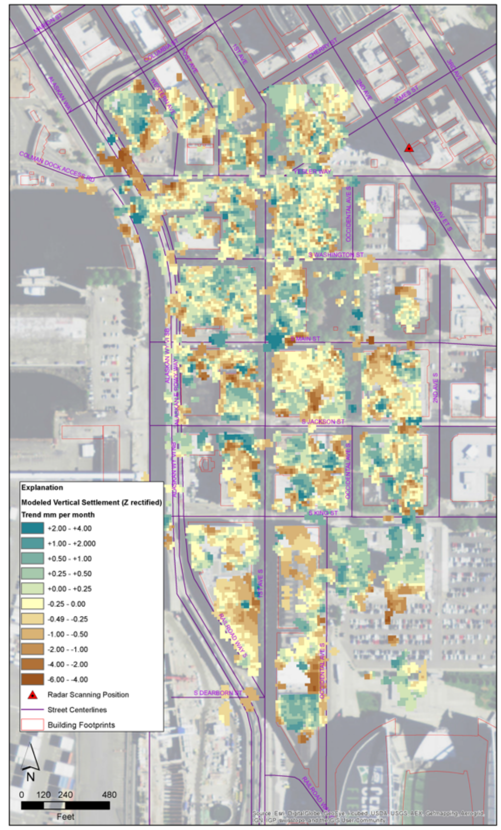

Figure 7 Pioneer Square District modeled vertical settlement (Z-rectified) mm/month

REFERENCES

[1] Johnson, Kirk (December 9, 2014). "In Seattle, a Sinking Feeling About a Troubled Tunnel". The New York Times.

[2] Werner, Charles, A. Wiesmann, T. Strozzi, A. Kos, R. Caduff, and U. Wegmüller (2012), "The GPRI multi-mode differential interferometric radar for ground-based observations", 9th European Conference on Synthetic Aperture Radar, EUSAR, 23–26 April, Nuremberg, Germany.

[3] Caduff, Rafael, et al. "A review of terrestrial radar interferometry for measuring surface change in the geosciences", Earth Surf. Process. Landforms 40, 208–228 (2015)

[4] C. Werner, U. Wegmüller, T. Strozzi, and A. Wiesmann, "Interferometric point target analysis for deformation mapping," in Proc. IGARSS, Toulouse, France, 2003, pp. 4362-4364.

[5] Wegmüller U., D. Walter, V. Spreckels, and C. Werner, "Nonuniform ground motion monitoring with TerraSAR-X persistent scatterer interferometry", IEEE Trans. Geosci. Remote Sensing, Vol. 48, 2, pp. 895-904, 2010.

[6] Wegmüller U. and C. Werner, "Mitigation of Thermal Expansion Phase in Persistent Scatterer Interferometry in an Urban Environment", Proceedings Joint Urban Remote Sensing Event JURSE 2015, Lausanne, Switzerland, 30.3.-1.4. 2015