TERRESTRIAL AND SATELLITE RADAR INTERFEROMETRY APPLICATIONS FOR
GROUND DEFORMATION INVESTIGATIONS IN URBAN SUBSIDENCE
DETECTION, LANDSLIDE VELOCITY MONITORING,
AND NOVEL FAILURE DISCOVERY

by

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Geology)

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ABSTRACT

The projects present interferometric radar measurements at high temporal resolutions and fine spatial precisions that allow new insights about ground deformation dynamics. The work is organized into three studies: (1) A ground-based interferometric radar (GBIR) monitoring campaign conducted on a slow-moving, translational failure landslide in Granby, Grand County, Colorado, USA. (2) A terrestrial radar interferometry (TRI) monitoring campaign for detecting ground settlement analysis within an urban setting in Seattle, Washington, USA. (3) A case study of novel landslide activity recognition related to a very slow creep landslide using satellite ALOS-1 radar interferometry. The research presents methods of survey planning, line of sight measurement, spatial and temporal filtering, uncertainty and error budgeting, scene geocoding, and spatial frame correction.

Results of these studies inform hazard assessment and mitigation activities, novel landslide detection and feature recognition, and sub millimeter velocity monitoring of ground deformation dynamics. Independent datasets of deformation for verification and comparison of movement monitoring with discussion regarding the capabilities and limitations of radar measurements to characterize deformation in these environments. Results are used to create radar-supported workflows for achieving geotechnical engineering objectives including submillimeter velocity tracking, near real time processing and results, and unsupervised reconnaissance campaigns for novel landslide detection.
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To my amazing family, Sasha, Zeke and Colette,

I could not have done this without you.

Thank you
Interferometric radar analysis has become an increasingly effective method in investigating ground deformations remotely. Spaceborne, airborne, and terrestrial radar sensor platforms allow for measurements of ground deformation with high precision and millimeter-level detection limits. These remote platforms allow investigators to gather data continuously over much wider areas by using scanning techniques that collect grids of measurements, while traditional field measurements can only collect point-based measurements where instruments were installed. However, the datasets generated through remote methods have their own limitations, blind spots, and challenges in usage within geotechnical workflows, and require verification with alternative measurements. The geotechnical engineering community has instilled rigorous standards and usage conventions for any measurement or instrument in the field, while the standards for radar remote sensing techniques and platforms are still being established.

1.1 Interferometric Radar Remote Sensing

Interferometric radar remote sensing as an Earth observation (EO) technique began in early 1990’s with the launch of the European Remote Sensing (ERS) constellation, the Japanese Earth Resources Satellite (JERS-1), and Canadian RADARSAT-1 platforms [1,2]. These spaceborne platforms focused on repeat pass, narrowly defined orbits that were capable of creating sets of images that were capable of interferometric analysis. Spaceborne platforms actively pulse radar wavelengths at an incident angle and create images derived from the pulse returns using a synthetic aperture of the track of a satellite orbit, hence giving the name of the method Interferometric Synthetic Aperture Radar (InSAR). Early success in geoscience applications involved pre and post event pairs for seismic displacement [3,4]. Moving beyond simple pairs, studies using a stack of spaceborne InSAR images conducted time-series of measurements capable of measurement of features that evolve over time, such as subsidence [5,6], coseismal creep [7], volcanic activity [8], and landslide monitoring [9,10]. Advanced InSAR processing technique of
persistent scatterers (PS) which uses a statistically stable subset of targets in the image allowing analysis across greater temporal and spatial baselines[11,12]. As processing techniques evolved, the platforms evolved from satellite to airborne [13,14], as well as the development of ground based interferometric radar (GBIR) sensors [15–17]. The term “terrestrial radar interferometry (TRI)” is also adopted and used in this thesis to distinguish radar sensors operated from structures that are elevated from ground positions, but not airborne or spaceborne [18–20].

1.2 Radar Remote Sensing in Deformation Measurements

The benefit of mass collection of deformation measurements has been established before radar interferometry ever made its way into geotechnical projects. In his guide “Geotechnical Monitoring for Field Performance”, Dunniciiff (1993) identified deformation as the “most reliable and least ambiguous” measurement of geotechnical parameters. However, he also acknowledged limitations of deformation sensors: “They are essentially point measurements, subject to any variability in geologic or other characteristics, and may therefore not represent conditions on a larger scale. When this is the case, a large number of measurement points may be required before confidence can be placed in the data.” [21]. Radar remote sensing and interferometric techniques present exactly the kind of en masse collection of deformation measurements. However, another voice of geotechnical authority reminds us of the pitfalls of adoption of novel techniques of instrumentation: “The results of instrumentation do not in themselves make for improved understanding or better practice. The emphasis should be on observation[…] rather than instrumentation [22].

This research seeks to answer Peck’s call to improved understanding of radar observation platforms and methods within the context of geotechnical workflows of landslide monitoring, and urban subsidence due to tunneling through recognition of ground deformations. The objective of this work as a whole is to increase the applicability of radar remote sensing methods to the usage within traditional ground instrumentation practices. This work extends a simple presentation of displacement results to the general implications of radar remote sensing in the fields geo-engineering and geoscience.
1.3 Thesis Organization

This thesis is comprised of three investigations within radar interferometry: Chapters 2, 3, and 4 present three independent papers or manuscripts prepared for submission, or already published within peer reviewed journals.

Chapter 2 presents an application of ground based interferometric radar technique (GBIR) for monitoring an active landslide in Granby, Colorado, USA. Two GBIR surveys were conducted in June, and August 2012 respectively. The GBIR results were compared to displacements derived from global positioning system (GPS) measurements. We discuss the strengths and limitations of GBIR displacement monitoring with a variety of available sensors, and place this monitoring platform, sensor, and workflow into context of previous slope stability monitoring. The methods presented focus on measurement advantages and constraints to augment investigation techniques from GPS measurements. We present displacement imagery conducted from two separate deployments and compare the monitoring campaigns with the dynamic conditions of the landslide causative factors. Using the unique capabilities of a ground based sensor and scanning position, landslide velocities are monitored at the sub millimeter scale with near real time processing capabilities. Spatial modeling of displacement is used to verify conceptual models of landslide movement, providing greater confidence for mitigation planning.

Chapter 3 presents another “terrestrial” radar interferometry (TRI) deployment for a tunnel construction activity monitoring project in Seattle, Washington, USA. The study focuses on survey planning and scan position selection through geospatial modeling with available high resolution elevation datasets. Optimal scanning position was established on top of a building in downtown Seattle to monitor the effects of dewatering on ground subsidence due to tunneling activities. A workflow for optimizing urban radar monitoring was created to iteratively adjust radar survey for measurement interval, noise reduction, diurnal cycling, and radar obliquity. In this case, a combination of spatial filtering and PS methods are used to uniquely track targets within an urban context, including critical infrastructure like the Alaska Way Viaduct. This workflow is unique to an urban environment and can be readily adapted to
TRI monitoring in other similar study areas.

Chapter 4 presents a satellite-based case study of landslide activity using ALOS-1 Radar imagery. This study demonstrates the use of L-Band radar imagery for landslide recognition, classification, monitoring, and hazard assessment. We present velocity mapping that detects a novel zone of creep landslide movement at order of magnitude larger than previously recognized. We discuss the implication of L-Band radar imagery within the literature of landslide characterization and especially in the recognition of new features as discovered in this study. The manuscript concludes with a discussion of the implications the new activity in terms of mass wasting dynamics and geomorphic development.
CHAPTER 2 HIGH RESOLUTION DISPLACEMENT MONITORING OF A SLOW VELOCITY LANDSLIDE USING GROUND BASED RADAR INTERFEROMETRY

This paper has been published in *Engineering Geology* and reprinted with permission.

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2.4 Abstract

Ground-based interferometric radar (GBIR) monitoring was conducted on a slow-moving, translational failure landslide in Granby, Grand County, Colorado, USA. Radar monitoring was completed over two separate surveys in 2011 using a tripod mounted real aperture sensor. The purpose of this work is to evaluate GBIR as a temporally dense monitoring technique for monitoring landslide displacement and compare the monitoring results to ongoing GPS based surveying methods to verify measured displacements. We discuss the strengths and limitations of GBIR displacement monitoring with a variety of available sensors, and place this monitoring platform, sensor, and workflow into context of previous slope stability monitoring with GBIR. For both surveys, displacement time series were created through a small temporal baseline stacking to reduce noise and maintain high temporal resolution. The results of the displacement time series were compared to average displacement rates derived from GPS based surveying. An overall verification of radar and GPS derived displacement rates was achieved, and recognizes important differences relating to the precision and uncertainty of the two techniques. This work demonstrates GBIR monitoring capability of establishing high temporal resolution on tracking variable rates of landslide movements. Spatial modeling of total observed displacements was completed for both surveys verifying a conceptual model of uniform translational landslide movement, providing greater confidence for mitigation planning.
2.5 Introduction

The use of ground-based interferometric radar (GBIR) sensors has become increasingly valuable to the monitoring of displacements of landslides and unstable slopes. These sensors join a geodetic toolset used to monitor landslides alongside laser-based Light Detection and Ranging (LiDAR), global positioning systems (GPS), and photogrammetric imaging. GBIR monitoring enables imaging of ground surface deformation across large areas (<10 km$^2$) with high spatial (<1 mm) and temporal (<1 hr. scan frequency) resolutions. GBIR systems have been successfully implemented for landslide monitoring with good examples presented in literature across a range of sensor types [9,15,23–26]. Table 2.1 summarizes these works by slope failure type, spatial and temporal resolution, sensor type, and analytical method.

The use of GBIR monitoring has been accelerated by the adaptation of satellite-based interferometry software and analysis techniques. Using these advanced algorithms, and with more control over the platform scanning position, GBIR monitoring has distinct advantages for landslide monitoring applications. However, GBIR monitoring must be conducted with knowledge of limitations and integrated with traditional displacement monitoring to become a reliable and useful landslide monitoring tool. This paper presents a high resolution displacement monitoring application of a slow moving [27] landslide using GBIR verified with GPS surveying techniques. The landslide is located near Granby, Grand County, Colorado, USA (Granby landslide hereafter). Radar monitoring was conducted with a Gamma Portable Radar Interferometer (GPRI), a tripod-mounted, rotational scanning radar system with three-antenna real aperture imaging (Figure 2.1). This sensor uses one antenna to transmit and two receiver antennas, which can be configured for polarimetry or from multiple baselines to subtract topographic effects. The Gamma GPRI sensor is formally described in [16] which addresses issues of instrument sensitivity and specific hardware configuration. This sensor differs from other platforms used to monitor landslides in its use of a real (as opposed to synthetic) aperture, a tripod mount, and rotational scanning action (as opposed to track-based), creating a platform-specific set of considerations for conducting displacement measurement monitoring.
### Table 2.1: Examples of GBIR monitoring of landslides by sensor and analysis method

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Failure Type</th>
<th>Range Resolution</th>
<th>Azimuth Resolution at 1000 m</th>
<th>Temporal Resolution (approx.)</th>
<th>Sensor</th>
<th>Analysis Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Leva et al., 2003)[28]</td>
<td>Schwaz, Austria</td>
<td>Debris Flow</td>
<td>2 m</td>
<td>4 m</td>
<td>30 min</td>
<td>Linear SAR-LISA</td>
<td>Interferogram Stacking</td>
</tr>
<tr>
<td>(Tarchi et al., 2003)[29]</td>
<td>NE Italy</td>
<td>Tessina landslide Roto-translational</td>
<td>2 m</td>
<td>4 m</td>
<td>50 min</td>
<td>Linear SAR-LISA</td>
<td>Interferogram Stacking</td>
</tr>
<tr>
<td>(Noferini et al., 2007)[30]</td>
<td>NE Italy</td>
<td>Rotational rock block slide</td>
<td>5 m</td>
<td>15 m</td>
<td>30 min</td>
<td>Linear SAR-LISA</td>
<td>GB-InSAR Permanent Scatterers</td>
</tr>
<tr>
<td>(Barla et al., 2010)[24]</td>
<td>NW Italy</td>
<td>Deep seated gravitational slope deformation (DSGD)</td>
<td>0.5 m</td>
<td>4.5 m</td>
<td>20 min</td>
<td>GB-InSAR</td>
<td>Permanent Scatterers</td>
</tr>
<tr>
<td>(Casagli et al., 2010)[31]</td>
<td>Italy</td>
<td>Reunion Landslide, Stromboli Volcano</td>
<td>2 m</td>
<td>2 m</td>
<td>10 min</td>
<td>Linear SAR-LISA</td>
<td>Spatial averaging</td>
</tr>
<tr>
<td>(Schulz et al., 2012)[26]</td>
<td>Lake City, Colorado, USA</td>
<td>Slumgullion landslide complex</td>
<td>0.75 m</td>
<td>4.37 m</td>
<td>10 min</td>
<td>Linear SAR-LISA</td>
<td>IBIS-L GB-InSAR Permanent Scatterers</td>
</tr>
<tr>
<td>This work</td>
<td>Granby, Colorado, USA</td>
<td>Translational landslide</td>
<td>0.75 m</td>
<td>7 m</td>
<td>7.5 minutes – 15 minutes</td>
<td>Gamma GPRI Real Aperture</td>
<td>Interferogram stacking using temporal baseline</td>
</tr>
</tbody>
</table>
Two sets of scans were carried out in the summer of 2011; in June for a 24-hour span and in August for a 36-hour span. Scans were carried out non-disruptively and independently from existing construction activities such as vehicle movement on the landslide, meaning that some imagery would not be useable for generating landslide displacements. Radar interferometry measurement of displacement is necessarily conducted within the sensor line of sight (LOS), requiring geometric adjustment into a corrected displacement model for use in characterizing landslide kinematics, facilitated in this application by survey data. Specifically, this paper presents a case study of a particular sensor combination of GBIR and GPS monitoring on an active slow moving landslide. Generally, this work adds to the large range of application types and sensors as well as addresses how methods of analysis contribute to greater understanding of the use of GBIR in unstable slope and landslide monitoring. GBIR imaging provides a continuous field of displacement measurement serving to fill in the gaps between survey monuments, but
measurements are subject to issues with image quality, line of sight correction, phase aliasing, and the specific configuration of the GBIR sensor used to acquire the imagery. This paper addresses these issues specific to a landslide monitoring context using a newly available sensor and presents a comparison with GPS surveying to verify the sensor displacement measurements and suitability of the platform for landslide monitoring. We discuss analytical approaches to optimizing the use of the imaging and processing tools to image the landslide, as well as the implications of the large increase in data collection capacity and temporal granularity provided by this remote sensing platform.

2.6 Background: Landslide monitoring radar interferometry from terrestrial platforms

The technique of radar interferometry relies on comparison of the phase differences between the backscatter of repeated radar scans. This technique allows for measurement of millimeter scale displacement with radio wavelengths within the radar band (approx. 1 mm - 30 cm), making the technique particularly suitable for tracking active landslides over a range of velocities. While success in landslide monitoring using spaceborne differential interferometric synthetic aperture radar (D-InSAR) has been demonstrated [10,12], satellite-based monitoring in general suffers fundamental challenges with non-zero baselines and sensor LOS obliquity to downslope landslide movements [32]. The fixed orbital periodicities of satellite platforms range from days to weeks, preventing fine temporal scale (<1 hour) monitoring of dynamically moving landslides. Other challenges in spaceborne investigations arise from variable spatial baselines between satellite positions, unresolvable phase ambiguities, and temporal decorrelation of signal in the target terrain [33].

In ground based platforms, the radar scanning location can be positioned to reduce effects resulting from the obliquity between the radar’s LOS and landslide displacement direction. Imagery acquired from the same platform location effectively becomes a zero spatial baseline set of radar images, simplifying the workflow to monitor temporal changes from scan to scan. Small scan intervals (< 1 hour) and a zero spatial baseline across scans allow for significantly improved control over interferogram quality by reducing temporal decorrelation and providing real time data acquisition.
Joint GBIR and GPS based monitoring enable the measurement of fascinating behaviors: Schulz et al. 2009 [34] presented GPS and geotechnical monitoring data that revealed displacement rate sensitivity to atmospheric tides within the Slumgullion landslide. Follow-up monitoring with a ground based synthetic aperture radar (GB-InSAR) further verified displacement measurements by correlating kinematic elements a variety of displacement datasets collected over decades of investigation[26]. The Slumgullion project is a good example of how high resolution techniques can be used to characterize a spatially variable landslide with many sources of corresponding displacement monitoring methods on long time scales. Further integration of GBIR imaging workflows with GPS displacement monitoring is important to more understanding of spatial and temporal landslide dynamics as well as provide models for integrating GBIR into typical geotechnical investigations.

2.7 Existing displacement monitoring challenges

Information about the Granby landslide has been gathered in an effort to assess stabilization options under a Request for Proposal document issued by Grand County in late 2011, which presents preliminary geotechnical investigation details[35]. The Granby landslide has a surface area of approximately 160,000 m² (40 acres) and is moving in a southwesterly direction. Traditional GPS based surveying performed at this landslide was collected independently by engineering consultants and is conducted on bi-weekly or monthly schedules, limiting the temporal resolution to the average velocity occurring between these visits. These visits require a full day of the surveyor’s time to collect all the points of interest in the project area. Without significant additional instrumentation, this GPS based surveying prevents efficient measurement of daily movement of the landslide and can only resolve displacements that exceed the sensitivity of the GPS device. Furthermore, GPS surveying methods only tracks a limited number of points on the landslide mass that are vulnerable to destruction during mitigation activities and result in a point based dataset that requires interpolation of displacement values across measurements. Subsurface monitoring can be conducted from boreholes, but this monitoring is necessarily limited to short term monitoring due to casing shearing from landslide movements. The RTK measurements represent
averages of 3 GPS measurements taken over 180 second epochs which was deemed to be repeatable and reliable for this survey site. However, GPS accuracy is dependent on a host of different factors including atmospheric delay, systematic errors, post processing and accuracy is commonly accepted at 1-5 cm under ideal conditions[36–38]. The spatial extent and direction of the landslide movement is illustrated by the vector plot shown in Figure 2.2.

![Figure 2.2: Layout of radar scan location and independently mapped landslide block extent with geotechnical instrumentation including groundwater monitoring points, survey monuments](image)

The vectors represent displacement during the month of June 2011 derived from the GPS-based survey. The subsurface investigation revealed a translational slip plane at a maximum depth of approximately 27 m illustrated in an interpreted cross section in Figure 2.3. Evidence of multiple remnant slip planes was found in the boring logs, consistent with landslide footprint being located in a mapped landslide deposit [39]. The slip planes consist of weak clay layers that lie within the Middle Park Formation of Eocene-Paleocene (depicted in grey in Figure 2.3), a unit of Tertiary Period composed of sandstone and shale. The sliding mass is made up of intermingled Middlepark, colluvium, and the reactivated sliding surface has progressed into the landfill material. Monitoring of boreholes indicated an active slip plane both through removable inclinometers and eventual shearing of the borehole at this
depth. While additional work is ongoing, no evidence of reactivation on multiple slip surfaces have been identified, indicating that the landslide movement was constrained to a single failure surface at the time of the radar monitoring.

Figure 2.3: Interpreted cross section showing boreholes, geologic units, slip plane, and groundwater elevation. Surface movement monuments monitored with GPS are shown, including MM-H.

Landslide movement was first observed in spring 2007 with a displacement rate of approximately 0.01 m/day. The rate of movement has been monitored via traditional survey on a monthly basis since 2007 and on a weekly basis during 2011. The velocities have been calculated using repeated surveys 7-30 days apart and do not resolve diurnal changes in the displacement field. The GPS surveying tracks displacements using real time kinematic GPS, relying on a stable base station off the landslide to resolve monument movements on the landslide. These velocities are calculated in three-dimensions (3D), but are tracked in this paper as horizontal displacements, as the contribution from the vertical settlement is negligible due to shallow dipping (5 degrees) translational failure. A total of 66 survey monuments have
been installed during the initial investigation; 21 of those monuments were destroyed due to landslide or construction activity.

Landslide movement varies seasonally, with peak movements coincident with groundwater Table (GWT) rise from snowmelt. Landslide movement reached peak velocities of 0.015-0.20 m/day in spring 2011. Landslide velocity has varied seasonally each year in correlation with seasonal variation in the GWT. Figure 2.4 presents the range of survey-derived displacement velocities (m/day) and the change in GWT (m) of select monuments for a 12 month cycle. These measurements indicate a generally uniform flow field of displacements, indicating a primarily translational failure, with a ratio of depth of rupture to length of rupture ($D_r/L_r$) in 0.1, typical of translational failures[40]. Mapping of slide boundaries have been conducted by field identification of surface shear zone indicators on translational boundaries, tension cracks and scarp features at landslide crown, and heaved or overriding soils at the landslide toe.

![Figure 2.4: Average GWT change and average survey monument displacement rate.](image-url)
2.8 Methods: Line of sight measurements and radar displacement measurement

Radar interferometry is conducted by comparing the phase and amplitude components of two or more radar images to detect and monitor small changes (mm-scale) in the Earth’s surface that are undetectable by typical optical imaging [41]. Analysis of the phase difference between two or more images provides a measurement of the change of distance to the ground surface between the two images, and the phase shift between image measurements reflects changes in the distance between the sensor and the ground surface, i.e., displacement in the LOS direction. The relationship between phase difference and displacement is given by: $\delta_{\text{line of sight}} = \frac{-\lambda \delta \phi}{4\pi}$. The sensitivity of interferometric radar to displacement is therefore determined by the wavelength $\lambda$ of the radar since the phase change $\phi$ can only be measured between a $2\pi$ change given 2-way travel of the radar pulse. As displacement measurements are made in LOS, positioning of radar site in terrestrial platforms is a critical part of planning an effective monitoring program. In the case of the Granby landslide, information about landslide movement and direction was available from existing geotechnical investigation, allowing LOS sensitivity to be anticipated before radar imagery was collected. Given the mobility of the GBIR platform though, monitoring could also be conducted in a reconnaissance mode, deployed without a priori information to constrain movements from multiple scan position at the cost of temporal continuity.

2.9 Methods: Radar system configuration

The radar was deployed across a valley from the Granby landslide with a field of view looking due east (Figure 2.2). The LOS displacement from this angle is oblique to the landslide’s motion by about $45^\circ$ at the center of the landslide block with obliquity angles varying through the radar image due to rotational scanning action of the GPRI platform. This obliquity is compensated for in post-processing. The GPRI system was equipped with a Ku band antenna capable of resolving mm movement using a wavelength of 1.76 cm [16]. Further system configuration and instrumental parameters are summarized in Table 2.2.
Table 2.2: Radar system configuration

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type:</strong></td>
<td>Real aperture FMCW</td>
</tr>
<tr>
<td><strong>Manufacturer:</strong></td>
<td>Gamma RS</td>
</tr>
<tr>
<td><strong>Antenna Length:</strong></td>
<td>2 m</td>
</tr>
<tr>
<td><strong>Frequency:</strong></td>
<td>1.72 GHz (Ku Band)</td>
</tr>
<tr>
<td><strong>Wavelength:</strong></td>
<td>1.76 cm</td>
</tr>
<tr>
<td><strong>Range resolution:</strong></td>
<td>75 cm</td>
</tr>
<tr>
<td><strong>Azimuth resolution:</strong></td>
<td>Range dependent:</td>
</tr>
<tr>
<td></td>
<td>7 m@1 km,</td>
</tr>
<tr>
<td></td>
<td>14 m@2 km</td>
</tr>
<tr>
<td><strong>Displacement Sensitivity:</strong></td>
<td>&lt;1 mm LOS [16]</td>
</tr>
<tr>
<td><strong>Temporal Resolution:</strong></td>
<td>7 - 15 Minutes</td>
</tr>
<tr>
<td><strong>Deployment time:</strong></td>
<td>15 Minutes</td>
</tr>
</tbody>
</table>

The GPRI sensor has a range resolution of 75 m and a range dependent azimuth resolution of about 7 m at 1 km. The range of the scan position to the landslide varies between 350 m and 800 m or an azimuth resolution that varies from 2.5 m to 5.6 m. Two time-lapse radar surveys were conducted in June and August 2011, respectively, from the same monumented position. An 80° field of view with a 2.5 km range limit was selected to encompass the full view of the mapped landslide boundaries (Figure 2.2) established from previous mapping. Individual scan times were approximately 15 seconds and repeated with a minimum interval of 7.5 minute to maximum 15 minute interval between scans. Antenna incidence angle was set at horizontal to maximize the detection of horizontal (translational) displacement, the primary motion in this landslide.

Beyond physical configuration, processing of the acquired radar imagery requires a number of steps to properly conduct the differential interferometry and calculate LOS displacements. The specific combination and parameterization of these separate steps are accomplished with a combination GAMMA provided software, geospatial calculations, and file processing, resulting in a customized workflow that is suited for landslide monitoring with objectives in temporal continuity.
2.10 Methods: Imagery processing and interferogram generation

All images were co-registered with the first scene in the time series, and offsets were calculated using cross-correlation matching of small sub-image chips distributed throughout the radar images. Offsets in radar images were corrected with 1st order polynomial resampling to ensure proper coregistration of the collected SLC image stack. Interferograms were created from a network of temporally adjacent scene acquisitions within the June and August surveys, respectively. For each scan, offset-corrected, single look complexes (SLCs) or scenes were interfered in the phase spectrum of the imagery to generate interferograms. A temporal network of interferograms was created by interfering coregistered SLCs from 3 scenes before and 3 scenes after each 15 minute SLC acquisition. This approach is functionally similar to an SBAS-type algorithm [42], though spatial baseline in our case is zero. While interferometry could theoretically be conducted for every SLC pair, temporally adjacent SLCs provide the least decorrelation. Some noise reduction is useful in filtering scene-to-scene atmospheric noise. For the interferometry network for a single scene, a small temporal baseline limit of <60 minutes establishes a network of 6 interferograms. When this set is stacked through averaging, the resulting image provides a sufficient reduction in interferogram noise while preserving efficient processing. The analysis approach used during both surveys is illustrated in Figure 2.5. Interferograms spanning the two radar surveys were not created due to the large time span and large movement and phase decorrelation of the landslides between these two time periods.

2.11 Methods: Phase unwrapping and displacement inversion

Individual interferograms were filtered using a slope-adaptive filter to improve unwrapping to displacements. Phase unwrapping was accomplished using a minimum-cost flow algorithm [43,44]. After phase unwrapping, some interferograms contained a linear phase ramp that most likely represents a tropospheric path delay rather than a true offset. Such atmospheric effects are likely due to variable humidity levels during a scanning survey, and these correlate with the humidity log for the August survey. We modeled a linear atmospheric phase ramp and subtracted it from the interferogram after [45].
2.12 Methods: Phase unwrapping and displacement inversion

Individual interferograms were filtered using a slope-adaptive filter to improve unwrapping to displacements. Phase unwrapping was accomplished using a minimum-cost flow algorithm [43,44]. After phase unwrapping, some interferograms contained a linear phase ramp that most likely represents a tropospheric path delay rather than a true offset. Such atmospheric effects are likely due to variable humidity levels during a scanning survey, and these correlate well with the humidity log for the August survey. We removed the atmospheric phase by modeling a linear phase ramp and subtracting it from the interferogram after [45].

![Diagram of interferogram generation and time series displacement dataflow]

Figure 2.5: Interferogram generation and time series displacement dataflow

A time series was interpolated using the individual interferogram in an over-determined, linearized least-squares inversion [6]. Displacement inversion requires consistently high coherence imagery. The aim of this step was to produce a time series of interferometric phase for each image acquisition time. Using each radar image in multiple interferograms reduced the noise in the resulting time series. The
resulting time series of interferometric phase was then converted to LOS displacements based on the radar wavelength (0.0176 m) and the viewing geometry. Sources of error in the interferograms include system noise which can be smoothed and averaged out through stacking and unwrapping errors due to improper phase ambiguity resolution, which can be recognized easily by jumps in the displacement by half the wavelength.

GPS survey measurements show a uniform velocity field that can be used to correct LOS obliquity using the geometry of the radar scan and topographic aspect calculated from the radar derived digital elevation model (DEM). Also, the imagery was collected in a horizontal LOS, making the interferometry sensitive only to horizontal displacement and insensitive to changes in elevation.

Displacement maps were geocoded using a high-resolution DEM derived from airborne LiDAR collected through the USGS CLICK as part of the National Elevation Dataset [46,47]. The radar results were then integrated into a geographical information system (GIS) that allowed for cross referencing of the image to known features on the landslide slope and comparison to previous mapping efforts including independently mapped landslide block boundaries and surveying monuments. Low angle shadowing of the radar field of view allowed for verification geocoding of the radar imagery with topographic shadowing and feature matching.

2.13 Results: Imagery and Interferogram Quality

The radar surveys successfully imaged the majority of the landslide from this field of view, with moderate topographic shadowing. Some strong-returning signals associated with structures on the landslide are present in the imagery near the landslide, such as the fence lines near the toe of the landslide and running longitudinally in the imagery near the center of the scene Figure 2.6.
Figure 2.6: Typical radar imagery showing amplitude component collected during the June 2011 radar survey. Amplitude component image is scaled from high power (white) to low power Although the imagery was generated entirely from a single scan position, a functional zero baseline, some offsets did exist and were corrected within the imagery. Low coherence imagery resulted in a gap of 5 hours in the collected imagery in the June 2011 survey. This gap of low coherence or total scene-to-scene decorrelation was due to construction activities like regarding, a challenge with non-disruptive radar interferometry, though other sources of decorrelation could be present. Overall, images generated from scanning were of sufficient quality to generate interferograms that could be used to derive displacements for 11.5 non-continuous hours in the June survey and 36 continuous hours in the August 2011 survey. In June, displacements were calculated between 7:30 to 13:00 on June 10, 2011 and between 4:00 am and 9:00 am on June 11th, 2011. On August 14, 2011, coherent imagery was used to create displacement maps from the hours of 20:00 to approximately 10:00 on August 16th. A typical amplitude image of a radar scan is shown in Figure 2.6, illustrating topographic shadowing and the strength of signal return in various parts of the scene. Pixel size footprints on the surface vary with range; but are generally about 2 m (azimuth) by 0.75 m (range) at the toe and about 4 m (azimuth) by 0.75 m (range) near the crown.
2.14 Results: Radar measured displacements and survey comparison

Importantly, the GPS surveying was conducted independently as part of ongoing stabilization activities. GBIR monitoring was not coordinated with ongoing construction activities resulting in staggering of dates for GPS survey and radar monitoring. This results in limitations in the temporal coincidence of the GPS-radar comparison. This compounds the disparity in measurement sensitivity and temporal sampling differences between the RTK based GPS measurements and radar interferometry. Therefore, the goal of the comparison is to verify the average velocities of the radar monitoring against GPS based surveying. This comparison allows for confirmation of the general accuracy of the technique, as well as facilitates a discussion of strengths and limitations of GBIR being applied to landslide investigations with typically available methods.

After unwrapping and filtering, LOS radar displacements were observed in both surveys. This discussion focuses on analysis of LOS displacements due to the goal of evaluating the performance of GBIR against more traditional methods which are measured in actual displacements. Quantitative verification of GBIR is best suited to a discussion of LOS observations as GBIR is necessarily conducted with the sensors reference frame. Figure 2.7 presents processed displacements over both surveys at 1 and at 5 hours. Faint displacements are apparent after one hour and clearly identifiable in June, but August monitoring does not reveal the landslide bounds till further into monitoring due to the decelerated rate. Figure 2.8 presents stacked displacements in terms of daily displacement rate from both surveys. Orthorectified radar imagery clearly maps the landslide boundaries, with contrasts between zones of horizontal displacement and stable ground.

Maximum LOS displacements of 0.018 m and 0.09 m were observed during the 11.5 hour June and 36 hour August surveys, respectively. These images, especially from the June survey, resolve clear features of the landslide, including a translational shear boundary on the northern landslide boundary, horizontal displacement at the toe, and even a clear boundary between and slide block and crown at the upper part of the landslide block. The southern boundary is diffuse, indicating more of a shear zone than
Figure 2.7: Typical interferometry from June and August 2011 surveys. Note the increase displacement after 5 h in June 2011 survey compared to the slower displacement rate in August 2011.
Figure 2.8: Average total displacement rate from stacked, unwrapped displacements. Note clearly identifiable displacement boundaries, at translational shear zones, block separation at crown, and overriding toe.

a shear plane, though this zone is somewhat obscured by terrain shadowing. Also, this zone may be exhibiting displacements in the vertical that are only revealed by the change in LOS horizontal component by the radar images, implying the need for multiple scan positions in the future. Comparisons with GPS were conducted by selecting the pixel on unwrapped interferogram where the monument was located. Four monuments visible by the radar and centrally located on the slide, MM-H, MM-J, MM-M, and MM-O, were selected to compare daily average velocities from the period of radar monitoring to the GPS derived velocities in both June and August are included in Table 2.3. Radar and GPS derived line of sight displacement rate estimate comparison. Other monuments were selected for comparison when visible by the radar and are included in the bulk comparison, discussed below.
<table>
<thead>
<tr>
<th>Monument</th>
<th>Radar derived mean displacement rate</th>
<th>Survey derived mean displacement rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>6/4/11 over 5 hrs</td>
<td>6/7/11-6/14/11</td>
</tr>
<tr>
<td>MM-H</td>
<td>0.0132 m/day</td>
<td>0.0122 m/day</td>
</tr>
<tr>
<td>MM-J</td>
<td>0.0146 m/day</td>
<td>0.0134 m/day</td>
</tr>
<tr>
<td>MM-M</td>
<td>0.0143 m/day</td>
<td>0.0139 m/day</td>
</tr>
<tr>
<td>August</td>
<td>8/14/11 over 13 hrs</td>
<td>8/2/11-8/14/11</td>
</tr>
<tr>
<td>MM-H</td>
<td>0.0040 m/day</td>
<td>0.0060 m/day</td>
</tr>
<tr>
<td>MM-J</td>
<td>0.0043 m/day</td>
<td>0.0074 m/day</td>
</tr>
<tr>
<td>MM-M</td>
<td>0.0039 m/day</td>
<td>0.0073 m/day</td>
</tr>
</tbody>
</table>

Displacements generally increased linearly with time, with some observable scatter. Figure 2.9 presents a comparison of radar derived displacement rate versus the LOS component of the traditional survey derived displacement rate. Mean daily displacement rates were estimated from the linear trend lines through the time series displacement data. Despite the difference in timing of GPS surveys and radar monitoring, the average radar and survey derived velocities are well correlated. Scatter and offset in these data are due to differences in survey period, local variation due to model smoothing after phase unwrapping, and topographic shadowing that under-sample the terrain in the radar survey. General agreement between radar and GPS-survey derived velocities verify the overall approach of this platform and workflow to monitor displacement rates on a slow moving landslide. The comparison shows general agreement and clearly indicates the higher displacement rate of the landslide in June and the lower displacement rate in August. The deviation from unity in the August survey indicates a faster displacement rate measured by the GPS survey which occur before the radar survey. The GPS survey averages displacement rates over a 2 week period during the overall seasonal deceleration of the landslide and so are expected to measure faster rates of displacement than the 36 hour radar survey. The standard
error of the mean of the time-series interpolation was 0.0035 m for the June 2011 survey and 0.004 m for the August 2011 survey, established statistically through processing of the interferograms, both smaller than the apparent limit of detection for both surveys. This error represents the statistical error of the modeled inversion of LOS displacement unwrapping for the entire time series. This error is therefore specific to the spatial and temporal quality of the imagery for both surveys. Survey measurement error in the August case begins to show the limitation of GPS error for small displacements. Although the RTK method is repeatable at less than 1 cm displacements, positional error may be contributing to the offset of GPS displacement rates in Figure 2.9.

![Figure 2.9: Comparison of radar and GPS derived displacement rate estimates along LOS of radar system.](image)
Finally, time series displacements of single image locations were created for the selected monuments MM-H, MM-J, MM-M and MM-O, which had continuous uninterrupted imagery and consistently high coherence resulting in a finely resolved, tightly constrained measure of displacement at these locations (Figure 2.10). Though the displacements are generally consistent with the rates observed through GPS, there are nonlinear changes in velocity observed in the August survey. These changes in velocity are slight but nonetheless represent dynamic displacement conditions that vary on different locations across the slide. The changes could be caused by a variety of sources such as localized groundwater fluctuations, changing loading forces, or even atmospheric tides as observed in [34]. However, the radar deployments are limited to less than 2 full days, preventing inference to the presence of consistent diurnal fluctuation. Also, no other instrumentation on the landslide was collecting measurements at the temporal density of the radar measurements (7-15 minute intervals) meaning that no confirmatory data can be used to verify the observed fluctuations at this fine of a timescale. Further investigation with high density measurements must be deployed to confirm the variation in displacement rate as well as longer radar occupations to confirm the observed behavior over multiple days.

2.15 Horizontal Displacement Modeling

Correction of radar measurements to LOS displacement requires a global correction to the displacements or simultaneous capture from multiple instruments to correct obliquity of scan angle compared to horizontal displacement direction. Since the GBIR system is a rotational scanner, the LOS obliquity varies azimuthally across the scene. Using an average movement direction from previous surveys monument movements, a final displacement was transformed from LOS to horizontal displacement. To complete the displacement modeling, low coherence zones and topographic shadowing were interpolated through to create a continuous field of landslide surface displacement for both the July and August surveys. These interpolations are presented in Figure 2.11.
Figure 2.10: Time series of radar derived displacements near survey monuments for the June 2011 (top) and August 2011 (bottom) scans. Locations of these monuments are presented on Figure 2.6 and velocities are presented in comparison to survey derived displacement rates in Table 2.3.
Figure 2.11: Radar derived daily horizontal displacement rate models; 24 h of non-continuous monitoring on June 11th, 2011 (top) and 36 h from a survey begun on August 14th 2011 (bottom). Gray background represents stable ground and is displayed as a hill shade of existing topography. Vectors represent scaled monument movement with displacement rates.
While translational uniform failure appears to be primary mode of failure, actual horizontal displacement interpolation indicates at least some differential displacement is occurring across the landslide mass, with fastest displacement rates observed in the northern portion of the landslide near the head. The change in displacement rate changes smoothly across the block, indicating uniform displacement field. Abrupt changes indicative of kinematic heterogeneity would be resolved in stacked radar displacement imagery with boundaries and shear zones internal to the block, but none are apparent. Therefore, we conclude that no complex failure activity existed at the time of the survey within the main landslide mass, consistent with the accepted conceptual model of a landslide with primarily translational failure. The radar imagery and displacement modeling verify the conceptual model and allows decisions to be made with less uncertainty. Because of its continuous spatial field and fine scaled temporal granularity, the GBIR monitoring data confirm the lack of kinematic landslide elements that might have existed between GPS survey measurement points.

Due to primary objective of tracking horizontal displacements, this investigation did not resolve vertical displacement measurements. While toe heave and block head settlement are obvious from site investigations, a second survey location will need to be established in the future to monitor displacement in the vertical direction and generate 3D displacements. For example, a scanning position below the landslide south east of the current position conducted with angled aperture would be expected to detect such displacements, though topographic shadowing from this location would be more prevalent. Alternatively, the ground based investigation could be supplemented by satellite based imaging which is more natively suited to vertical movements.

2.16 Conclusion and future applications

Landslide displacement using the GPRI platform is capable of detecting and monitoring displacement in mm-scale and useful in resolving small scale temporal variation in slip rates. By leveraging the zero spatial baseline, this interferometry collection and processing methodology reveals a high level of temporal resolution of the displacements. The measurements of GBIR is compared and in
good agreement with measurements made by traditional GPS surveys. The major goal of establishing GBIR with the GAMMA GPRI sensor as a spatially and temporally dense landslide monitoring technique was achieved. Now, as mitigation measures are implemented, this sensor can be relied upon to provide near real-time displacement data, allowing for more integrated use in evaluation of stabilization effectiveness.

The specific combination of the GPRI sensor for this monitoring application is overall well suited to this monitoring application. Some assumptions about actual horizontal displacement must be made due to the rotational nature of the scanner, but our work demonstrates that LOS correction is not problematic in this case. GBIR monitoring may be improved by the application of different sensors or different methods, such as permanent scatterer analysis applied in [24,26]. Although this landslide investigation was well established at time of GBIR deployment, the GPRI sensor has a number of significant advantages to reconnaissance and early stage evaluation of incipient slope movements. Evidence of nonlinear changes in displacement rates across the slides also indicate the need to deploy for longer multiday occupations with continuous measurement and similarly densely recording geotechnical instrumentation to observe diurnal fluctuations or other temporal dynamics of the landslide. Opportunities for multiple scan locations, with concurrent deployment of two radar sensors are interesting variations of this simplified case and could be used by investigators to ask questions of landslide kinematics which were impossible to ask before, such as anchor placement effectiveness or evaluation of dewatering pumping on displacement. Also, future analysis and combination with other geodetic tools, such as LiDAR, high rate GPS, and geotechnical data ensures more research on GBIR which will benefit the understanding of this and other landslides.

2.17 Acknowledgements

This work was carried out under multiple NSF grants including MRI equipment award 0923086 and NSF IGERT awards 0801692 as well as collaboration with Grand County authorities and associated consultants. Thanks also to UNAVCO for field assistance and technical consultation.
CHAPTER 3 TERRESTRIAL RADAR INTERFEROMETRIC DISPLACEMENT MONITORING AND PLANNING IN AN URBAN ENVIRONMENT IN SEATTLE, WASHINGTON

This chapter is in manuscript to be submitted to the *Journal of Applied Remote Sensing*.

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3.1 Abstract

A Terrestrial Real Aperture Sensor was used to conduct high rate radar interferometric deformation analysis ground subsidence coincident with excavation related dewatering and known settlement activity for the Alaska Way Viaduct and Seawall Replacement Program (AWVSRP) in Seattle, Washington, USA. To optimize placement of the sensor advanced geometric line of sight (LOS) preplanning and measurement modeling was conducted using Lidar point clouds and geospatial analysis. Radar measurements were rectified into vertical displacement mapping using this same geospatial framework. A workflow for optimizing urban radar monitoring was created to adjust radar survey for measurement interval, noise reduction, diurnal cycling and radar obliquity. This workflow is unique to an urban environment and can be readily adapted to TRI monitoring in other similar study areas.

3.2 Introduction

A pilot deployment of urban ground displacement monitoring using terrestrial radar interferometry (TRI) imaging was conducted in 2015 jointly by Seattle Public Utilities (SPU), Trimble, and Solid Ground Geoscience LLC. The study was conducted during a well characterized period of ground settlement related to the tunneling project of the Alaska Viaduct and Seawall Replacement Program (AWVSRP) in downtown Seattle, Washington, USA[48]. This paper presents the methods of survey planning, radar imagery acquisition, spatial filtering and temporal unwrapping of phase displacements. We also convert of these LOS data into settlement displacements for comparison against other settlement monitoring programs conducted contemporaneously to this study. We conclude with an evaluation of the
limitations and challenges of applying TRI within an urban context for ground displacement monitoring.

Terrestrial radar interferometric analysis is conducted by generating multiple radar images through time with both amplitude and phase pixels of the scene. After some processing, images are differenced in the phase component and “unwrapped” in phase to create a high resolution displacement monitoring of the line of sight (LOS) range displacement between the radar and the target. TRI studies have been used to monitor a variety of contexts in natural slopes, engineered slopes, and civil structures [17,18,49,50]. While the processing approach is derived from the same principle as spaceborne applications [3,51,52], TRI monitoring differs as it allows increased freedom of scan position selection and look angle as well as increased measurement frequency intervals not limited by orbital periods. In Tomas et al. 2004 an acknowledgement of these traits is summarized:

“The acquisition time of terrestrial sensors (Ground based SAR-GBSAR), which is selected by the user, allows to define the time between successive acquisitions as much as few minutes. However, although radar sensors can be strategically placed in prominent locations to get an optimal LOS they are generally limited by the high incidence angle (Pipia et al. 2007, 2008; Monserrat 2012”).[53]

Urban monitoring with TRI benefits from the opportunity of nearby elevated positions on structures to lower the incidence angle of scanning positions. This advantage can be confounded by shadowing, building sway, and decreasing measurement sensitivity due to obliquity. A single scan position using TRI is a line of sight measurement and requires geometric modeling or multiple scan positions to separate displacement into horizontal and vertical components. However, building sway of tall buildings can prevent stable scanning positions that must be masked in the observation record or corrected with onboard instruments[54,55]. Atmospheric and thermal effects on the displacement of structural material are important to understand diurnal displacement variations against longer term trends [20,56,57].

The general objective of this work is to evaluate the effectiveness and capabilities of TRI based monitoring of structures and ground in an urban environment. TRI offers specific technical capabilities attractive to urban monitoring including wide area, reflector-less, non-contact measurements that provide
high precision displacement tracking of structures within the field of view of the scan position. These capabilities fulfill a unique set of strengths that augment more typical monitoring programs reliant on Global Navigation Satellite Systems (GNSS), total station survey, leveling survey, and geotechnical instrumentation (Table 3.1). The Seattle area has been extensively monitored by satellite radar interferometry investigations[58–60]. We include a comparison of one of these studies, Samsanov et al. 2016, for comparison of trend detection to verify the measurements from the TRI sensor[59].

The specific objectives of this pilot deployment are to deploy a TRI sensor to establish a monitoring time series of ground movement and evaluate suitability to detect long term trends related to tunneling and dewatering activities. This work evaluates TRI measurement performance, selection of optimal scanning positions, and integration with other monitoring methods.

This paper is organized into sections describing the objectives and methods of TRI in the context of other monitoring techniques, the creation of the geospatial framework for position selection, characteristics of the observed radar imagery and raw measurements, post-processing steps within taken to suppress noise and rectify measurements into ground settlement displacements. We conclude with a discussion of results, comparison to spaceborne interferometry and generalized lessons for TRI campaigns in urban environments. This paper is an expansion of preliminary results presented in Werner et al., 2016 IGARSS conference proceeding[61].

3.3 Methods: Radar Instrumentation

TRI leverages phase difference of active radar pulses to make measurements of non-moving and displacing targets. This means that the technique has measurement precision based on the order of the radar wavelength, making its precision within the fractions of millimeters for most TRI sensors. This high precision is capable of detecting phenomena that would require significantly longer measurement intervals using other technologies. Radar imaging was conducted with the GPRI-II sensor by Gamma RS, a tribracl mounted, rotational, real-aperture TRI sensor (Figure 3.1) from GAMMA Remote Sensing and Consulting AG. The GPRI-2 is an FM-CW radar operating at Ku-Band 17.1 to 17.3 GHz with an
Table 3.1: Generalized comparison of GPRI-II TRI Sensor to alternate monitoring methods for Pioneer Square Monitoring

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Coverage Type</th>
<th>Measurement Precision</th>
<th>Interval Capability</th>
<th>Data availability</th>
<th>Automation potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital Level Survey</td>
<td>Local</td>
<td>mm</td>
<td>Minutes</td>
<td>Real Time</td>
<td>Low</td>
</tr>
<tr>
<td>Robotic Total</td>
<td>Local to Wide Area</td>
<td>cm</td>
<td>Real Time</td>
<td>Real Time</td>
<td>High</td>
</tr>
<tr>
<td>Stations</td>
<td>Area</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GNSS Network</td>
<td>Wide Area to Regional</td>
<td>cm</td>
<td>Daily</td>
<td>1 day</td>
<td>Low</td>
</tr>
<tr>
<td>Terrestrial</td>
<td>Local to Wide Area</td>
<td>cm</td>
<td>Daily</td>
<td>Days to Weeks</td>
<td>Low</td>
</tr>
<tr>
<td>Lidar Survey</td>
<td>Regional</td>
<td>cm</td>
<td>Weekly</td>
<td>6-12 days</td>
<td>Low</td>
</tr>
<tr>
<td>Satellite InSAR</td>
<td>Regional</td>
<td>cm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

operational range of 20 meters to 16 km. 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. 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 on buildings and mount are relevant.

3.4 Measurement principle of Terrestrial Interferometry

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

$$C(r, \theta) = ae^{-ia\pi r/\lambda}$$
where \( r \) is the surveyor’s range and the phase are given by \(-4\pi r/\lambda\) and \( \lambda \) 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 \( 2\pi \) is equivalent to a change in propagation path distance of half a wavelength (8.72 millimeters). This sensor been deployed in a variety of monitoring environments around the world\([18,62,63]\), and has specific advantages suitable for urban monitoring deployments:

- Lightweight and portable
- Rapid set-up (< 30 minutes)
- Tribrach mounted sensor for tripod, pedestal, or custom deployments
- Wide field of view (up to 360°)
- Rapid scanning (180° in <20 seconds)
• High line of sight measurement sensitivity (< 0.01 m)

Urban monitoring using TRI presents some unique challenges and must be evaluated through modeling and deployment to determine the functional value as a monitoring method for achieving SPU objectives. The most important limitations that must be evaluated are listed in order of importance here:

• Scanning view shed and objective visibility

• Measurement continuity with street traffic and cultural noise

• Line of sight measurement and sensitivity to settlement measurements

• Coherence of radar imagery through time. This coherence is related to platform stability, weather conditions, and target reflectivity

3.5 Position selection and survey planning

As this area of Seattle is amid the downtown district, a number of skyscrapers exist that provide favorable scanning positions for the radar. Smith Tower on 2nd Ave. was chosen for an initial deployment of the pilot monitoring, a 24th story rooftop scan position with good viewshed of Pioneer Square area and tunneling activities. Smith Tower was also not within any known of deformation effects, important consideration in the relative monitoring method of TRI. It also offers a superior view shed and angle of elevation for line-of-sight measurement. A model of the view shed from the Smith Tower was calculated using a top surface LiDAR digital elevation model (DEM) from the Puget Sound LiDAR Consortium[64]. It should be noted that this top surface elevation map has some holes in areas of vegetation, which were not incorporated into the view shed modeling. These view sheds are valuable proxies for assessing shadowing from buildings, roadway visibility and deriving subsequent radar sensitivity maps. Figure 3.2 illustrates modeled visibility of the Pioneer Square area of interest, with good visibility of buildings,
roadway surfaces, and the Alaska Way Viaduct structure in 2015. This model also incorporates a -40 degree elevation pointing of the GPRI-II antennas. While this is a modeled approximation of the view shed, the photographs in Figure 3.5 present the actual visibility from that position.

Figure 3.3 presents the range of the look angle varying from near vertical of about 5 degrees to about 75 degrees within the view shed. This indicates that the measurement sensitivity between scenes could vary between sub-millimeter (approx. 0.15 mm) at the vertical look angles to near millimeters (~1.2 mm) at the outer edges of the images. Another consideration beyond measurement sensitivity is pixel resolution, which expands azimuthally with distance from the radar. Figure 3.3 presents the variance in range from the Smith Tower scanning position showing ranges between 400 ft. to 3000 ft. within the view shed. For the GPRI-II, this translates roughly to radar resolutions of 0.75 cm x 0.75 m (range vs. azimuthal) in the near field at 100 m to 0.75 m by 7.5 m in the far-field at 2000 m.

The radar was installed on the roof location of the Smith Tower in late February of 2015. The GPRI-II system was mounted with radome on top of a steel quad-pod mount provided by the City of Seattle. This mount accommodated an enhanced view shed with a standoff distance from roof edge and was mounted nondestructively on the rooftop of the building (Figure 3.4) and secured with sandbags.

The radar deployment lasted approximately six weeks and collected measurements continuously from March 1, 2015 to April 15, 2015. Measurement stability and coherence imagery was created from initial imagery. During the deployment, data was continuously recorded into a cloud computing environment for rapid analysis. The deployment of the radar on Smith Tower resulted in a clear view of the Pioneer Square area. The radar was placed with a centerline measurement at 195 degrees. Scan parameters are summarized in Table 3.2.
Figure 3.2 Radar look angle, and viewshed and shadowing modeled with 2003 Lidar data.
Figure 3.3: Radar range and radar pixel size
Figure 3.4: GPRI-II installation on Smith Tower lower roof with radome installed.

Figure 3.5: Photographic view shed from Smith Tower potential scanning position (From SE to W)
Table 3.2: Radar scan parameters

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Gamma GPRI-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range Samples</td>
<td>1,868</td>
</tr>
<tr>
<td>Azimuth Samples</td>
<td>1,681</td>
</tr>
<tr>
<td>Radar scan angles</td>
<td>150° to 315°</td>
</tr>
<tr>
<td>Antenna elevation angle</td>
<td>40°</td>
</tr>
<tr>
<td>Radar frequency</td>
<td>Ku Band, 17.2 GHz</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1.78 cm</td>
</tr>
<tr>
<td>Stacked images per day</td>
<td>12</td>
</tr>
<tr>
<td>Total measurement points</td>
<td>3,140,108</td>
</tr>
<tr>
<td>Total number of point scatterers selected for time series analysis (minimum mean/sigma ratio &gt; 1.6)</td>
<td>104,507</td>
</tr>
</tbody>
</table>

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 were resampled to the DEM sample spacing for ease of analysis. The scanning position access on the roof was eliminated in mid-April as building construction activities expanded into the area where the radar was installed.

Radar scenes were acquired every 2 hours for approximately 45 days during March and April of 2015. This approach resulted in minimized unwrapping errors and limited disk usage during the campaign. The resulting datasets used in this analysis are summarized in Table 3.3 and statistical summaries presented in Figure 3.6. Point scatterers (PS) were selected through a minimum mean/sigma ratio (MSR) of 1.6 pixel intensity ratio to the standard deviation (Figure 3.7) between 0.8 and 2.0 (Figure 3.8). This approach resulted in 104,507 PS, each containing 474 measurements over 43 days tracked every 2 hours. The use of PS methods mean that error estimates can be created from each temporal unwrapping through tracking the standard deviation of the phase residual for each point.
Figure 3.6: Aerial Photograph and radar scatterer amplitude brightness.
Importantly, this approach of PS selection selects only for a continuity of temporal measurement but does so without consideration of the targets in the monitoring objective, so displacements can be low magnitude ground settlements, or higher magnitude displacements from thermal effects on metal roofs, loaded parking structures, or swaying streetlamps in the field of view, so long as the temporal continuity is statistically within the selection criteria. This makes the georeferencing of any single point scatterer is necessary to interpret the displacement observed in the time series.

### 3.6 Mitigation of Atmospheric Phase and Mount Instability

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 variation up to approximately one phase cycle in the data. Scan position mounting might also be subject to movement, which translates to a phase ramp across the entire scene. To mitigate phase aliasing of the atmosphere and mount movement, an estimate of the atmospheric phase and mount displacement 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 displacement along
with small-scale atmospheric variations. Displacement in regions on the order of the filter radius/2 or
smaller is preserved by this filtering operation. Figure 3.9 and Figure 3.10 present the result of spatial
filtering to mitigate atmospheric or incidental scan monument motion.

3.7 Temporal Phase Unwrapping

Since the displacement signals may be highly spatially variable, especially in a complex urban
environment, unwrapping the phase in time is preferred. The phase $\phi$ for each point $i$ at time interval
$\Delta t_j$ in the coregistered interferogram stack is given by:

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

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, evaluated by observance of radar
stability as well as structural and geotechnical context. All radar motion relative to the reference point is
subtracted to normalize the phase offset introduced by systemic noise from the mount, instrument, and
atmospheric phase offsets. 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 $\pi$ from open epoch to the next. This
assumption is generally fulfilled in the imagery 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 displacement is close to or exceeds $\frac{\lambda}{4}$. 

43
Figure 3.8: Mean/sigma ratio (MSR) of intensity between 0.8 and 2.0 used to select PS candidates.
3.8 Establishing a Customized Workflow for Urban Monitoring

It is important to note that urban monitoring requires dynamic, customized workflows to properly detect displacements with TRI. This is accomplished by tuning the acquisition parameters and processing workflows into displacements that best reflect the settlement activity on the ground. Figure 3.11 presents a schematic of this customized workflow. This architecture emphasizes modularity, from which updated components can be generated and upgraded as higher quality lidar scans or stereographic point clouds are established from aerial or terrestrial survey.

3.9 Results and Discussion

Radar imagery reveals clearly identifiable features and structures within the radar field of view. Buildings are the brightest objects in the scene and clear reflections are most prominent on building corners and edges. Some vertical sides of the building are seen and are especially apparent on Yesler Avenue. City streets can be resolved in the image but lack coherence over time due to street traffic, parked cars, and low-reflectivity asphalt. Other features that can be resolved are building HVAC infrastructure, tunnel boring machine repair shaft gantry, shipping docks and container yard, and ferry building with incoming ferries.

The fundamental measure of TRI image quality is coherence, which is the scan-to-scan stability in phase measurement of individual scatterers in the scene. Figure 3.12 presents a radar coordinate image showing the scene-to-scene coherence in a single comparison. This Figure also indicates some of the radar artifacts that were processed out of the imagery later including saturation lines and resultant sidelobes from strong reflectors that saturate the radar sensor.
Figure 3.9: Unfiltered Interferograms exhibiting phase ramps due to large scale atmospheric phase delay
Figure 3.10: Filtered interferograms indicating higher scene to scene stability with phase ramps removed from phase displacements
Figure 3.11: Customized workflow for urban monitoring with terrestrial radar interferometry. Inset refers to MSR PS collection in Figure 3.8: Mean/sigma ratio (MSR) of intensity between 0.8 and 2.0 used to select PS candidates.
These time series are zeroed arbitrarily near the middle of the collection around March 20. All collected time series indicate high measurement fidelity in line-of-sight displacement tracking. In this study, these motions were low magnitude, being characterized by a diurnal cycle of displacement on the order of about 1-2 mm. Temperature fluctuations based on material expansion and contraction has been established in other studies[56]. Mount instability would also translate to the entire scene and is therefore mitigated in the spatial filtering described in the methods section. These measurements establish 1-1.5 mm of displacement noise within most measurement points, allowing settlement displacement detection between 3 and 4 mm over multiple days to verify the trend separate from the diurnal temperature induced variation.

Approximately 100,000 measurement points were established the Mean sigma ratio to standard deviation of phase residual. Selected time series have been selected and labeled and are presented in Figure 3.13 and identified by location on Figure 3.15. Some artifacts can be seen in the time series, most prominently in Figure 3.13 TS1, which present unwrapping errors of the phase “skipping” outside of temporal continuity. These skips are seen as discontinuities in the time series where the temporal unwrapping algorithm incorrectly models the displacement and can be identified and manually processed to a more continuous phase. These monitoring errors can be modeled out of the time series with moving outlier filters but are left in for this analysis to detect rapid movements as an indication of incipient failures. Approximately 100,000 measurement points were analyzed for trends of total displacement over the survey. Overall uncertainty in unwrapped LOS in the measurements is low, near 0.1 cm/year for most LOS measurement rates.

Overall, the LOS measurements measured show low magnitudes of total displacement during the pilot deployment, consistent with results of the existing ground program seen by SPU survey leveling programs.
Figure 3.12: Radar Coordinates of typical scene to scene coherence index.
Figure 3.13: Line of Sight displacement time series from selected points of time series (Figure 3.15). Displacement zero reference is near the middle of the series at March 15, 2015 00:00. Error envelopes shown in grey are the unwrapped standard deviation of phase residual.
These displacements can be modeled an estimate of maximum vertical displacement into a Z-
rectified by using the lidar height and obliquity maps from survey planning activities. Without multiple 
simultaneous scan imagery, 3 dimensional modeling of LOS is not possible. Z-rectified maximum 
estimate is useful for monitoring objectives, as utility thresholds for damage are most vulnerable in the 
vertical direction from ground settlement motions[65]. Samsonov et al. 2016 analysis does indicate some 
limited horizontal motion apparent in the scene according to InSAR, and therefore this modeling could be 
overestimate of the actual vertical displacement. Our metric here serves as a useful maximum 
displacement estimate, rather than an absolute measurement of ground deformation.

Selected points summarized in Table 3.3 for P11 and P12 agree with the InSAR based analysis from 
Samsonov work but show major differences in measured and modeled rate at P10. P10 time series in the 
LOS TRI measurements was a single scatterer isolated from many neighbors near the laydown yard of the 
crane and construction area, so may not be indicative of ground settlement. P10 is relatively more distal 
and has higher line of sight obliquity so the estimate of maximum displacement trend is less reliable. The 
settlement measurements near TS2 Viaduct are numerous (>50 PS) on the viaduct are strongly correlated 
and consistent with the known motion vulnerability from the Nisqually Earthquake in 2001[66]. Figure 
3.14 presents a view of individual scatterers near the viaduct structure showing positive line of sight 
displacement of multiple point scatterers, a clear indication of a spatial trend of vertical settlement. 
Vertical viaduct supports are even visible in these PS images, further evidence of correct geolocation and 
expected difference in displacement behavior. These displacement maps can be indicators of hotspots of 
motion activity but should not be tied to settlement ground deformation behavior without additional 
ground truth verification or investigation. Co-located corner reflectors, GNSS monitoring, or survey 
prisms would be useful as cross validation and geolocation on specific structures in future studies.
An interpolated grid of displacements is presented in Figure 3.15. These rates are kriged datasets for
with limits of 40 meters neighborhood with at least 12 neighbors to prevent interpolation at isolated
points. This grid represents a method for sifting through the datasets and identifying spatial trends of the
data rather than a strict representation of ground deformation.

<table>
<thead>
<tr>
<th>Persistent Scatterer</th>
<th>LOS Annual Displacement Rate*</th>
<th>standard deviation of residual phase (unwrapped into LOS units)</th>
<th>Maximum Vertical Rate using Z-rectification model from LOS measurements</th>
<th>Vertical Rate from Satellite InSAR (Samsonov et al., 2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1</td>
<td>+1.01 cm/year</td>
<td>+/- 0.09 cm/year</td>
<td>-1.48 cm/year</td>
<td>not available</td>
</tr>
<tr>
<td>TS2 Viaduct</td>
<td>+2.29 cm/year</td>
<td>+/- 0.06 cm/year</td>
<td>-4.6 cm/year</td>
<td>not available</td>
</tr>
<tr>
<td>P10</td>
<td>+0.90 cm/year</td>
<td>+/- 0.01 cm/year</td>
<td>-5.5 cm/year</td>
<td>+3.22 cm/year</td>
</tr>
<tr>
<td>P11</td>
<td>+0.82 cm/year</td>
<td>+/- 0.013 cm/year</td>
<td>-0.04 cm/year</td>
<td>+0.36 cm/year</td>
</tr>
<tr>
<td>P12</td>
<td>-0.64 cm/year</td>
<td>+/- 0.06 cm/year</td>
<td>+0.4 cm/year</td>
<td>+0.12 cm/year</td>
</tr>
<tr>
<td>P13</td>
<td>+0.23 cm/year</td>
<td>+/- 0.06 cm/year</td>
<td>-1.48 cm/year</td>
<td>-0.95 cm/year</td>
</tr>
</tbody>
</table>

*(positive = away from radar LOS, negative = towards radar LOS)
Figure 3.14: Time Series view of individual PS as collected on the viaduct raised roadway indicating roadway settlement. Vertical supports indicated through negative LOS displacement.
Figure 3.15: Kriging result of maximum estimate of vertical displacement rates. Kriging parameters include neighborhood limit of 40 meters with at least 12 neighbors.
3.10 Conclusions

The pilot deployment successfully demonstrated the ability to achieve the three monitoring objectives of urban TRI monitoring. (1) Wide area, standoff, reflectorless monitoring, (2) reliable sub-millimeter precision for a large number of permanent scatterers, and (3) Near real-time processing and ground settlement detection capabilities using a consolidated workflow presented in this work. Although this monitoring program was deployed during periods of low settlement or ground deformation, the technique for monitoring was provable with sub-millimeter precision even with slope angle rectification at more distant targets. The necessary conditions for reliable radar monitoring were also demonstrated:

- Platform visibility and stability
- High-coherence imagery allowing for reliable phase difference measurements
- Retention of high-precision measurements after slope angle corrections

The technique can be used for early warning hotpot detection and used to prioritize, verify, and measure ground movement dynamics with high fidelity and wide coverage. The technique suffers in urban environments from strong reflections of the built environment, making selection of a single terrain monitoring objective such as ground deformation difficult to distinguish from other reflectors. The technique is limited to line of sight measurements and would be augmented by multiple scan positions cycled on a daily basis, rather than the estimates of vertical displacement presented here. Multiple acquisition positions would allow true geometric decomposition of vertical and horizontal components. Scan interval collections can be increased to eliminate phase aliasing artifacts, at the cost of additional computation resources and size of collected datasets. TRI presents a unique offering of parameter detections for urban displacement monitoring, and this pilot deployment will allow for rapid understanding of processing requirements and can allow rapid assimilation of data into real-time monitoring and operational decision making. The modular workflow presented allows for incremental updates and improvements in the model as newer datasets become available.
Future work to refine TRI collections in urban environments includes collocating corner reflectors for geolocation and structure specific monitoring as well as cross validation against contemporaneous survey and remote sensing datasets.
4.1 Abstract:

This paper presents a case study of novel landslide activity recognition related to the East Muddy Creek Landslide in Gunnison County Colorado, USA using satellite ALOS-1 radar interferometry. ALOS-1 interferometric analysis allows interpretation of newly detected ground displacement at a greatly increased spatial extent with very slow to extremely slow velocities. We compare the application of radar imagery to landslide recognition tasks with traditional field methods for ground motions at a watershed scale. Line of sight velocity mapping is used to characterize displacement zonation, failure modes, and hazard assessment activities. Mass wasting estimates using previous geological modeling are discussed in terms of potential of landslide element dynamics. The implications of expanded displacement activity in the context of landslide geomorphologies, mountain denudation, exhumation, and future monitoring efforts for hazard and risk assessment are also examined.

The “East Muddy Creek Landslide Complex” is located on the western flanks of the Ragged Mountains in Gunnison County, Colorado (Figure 3.16). The complex has been investigated[1–4] over decades during different periods of reactivation. Previous studies identified the spatial extent of three slow velocity landslides[70–73] that destroyed Highway 133 in 1986-1987. The three active landslides form part of a larger hillslope with geomorphic features indicative of historical landslide activity. Previous geological mapping of this larger hillslope noted hummocky terrain, truncated drainage
networks, and sag ponds[68,74,75]. These studies did not classify temporal characteristics with regard to activity or dormancy. Such a temporal classification using field mapping is difficult, especially when deformation activity is slow and over large regions of spatial extent.

This paper presents a case study of previously unknown landslide activity within the western hillslope of the Ragged Mountains using ALOS-1 radar imagery between 2007 and 2011. We describe the expanded spatial extent of very slow, creep style deformation observed through interferometric analysis[76]. Using high definition velocity mapping of the hillslope, we describe new geomorphological features detected with the radar imagery and present the advantages and limitations of InSAR imagery in landslide recognition tasks. We conclude with a discussion of the implications of this newly recognized activity to the geomorphic development of the Ragged Mountain Range.

Figure 3.16: a) Western hillslope below the Ragged Mountains, Gunnison County, Colorado, USA, looking northeast. Photo by L. Weyers b) East Muddy Creek Landslide investigation area from Lowry 2010.
4.2 Landslide recognition and radar remote sensing

Earth observation (EO) methods of radar interferometry, lidar remote sensing, and advanced image processing are increasingly successful in identifying and characterizing active slope deformations both in spatial scale and magnitude of displacement [52,77–80]. Radar interferometric measurements provide landslide scientists with a precision that rivals in-situ geotechnical instrumentation[81]. However, a successful instrumentation campaigns requires initial recognition of landslide activity to design a campaign to monitor critical zones and can be limited by not siting instrumentation correctly[49]. InSAR imagery can play a vital role in assisting this initial detection of spatial extents through the creation of continuous field of measurements identifying active and inactive zones for better instrumentation installation. The tasks of landslide “recognition” comprises of 3 main categories: (From Scaoni et al. 2014) [78].

1. Reconnaissance, Recognition, and Classification
2. Monitoring and Characterization
3. Hazard and Risk Assessment

Scaoini’s framework emphasizes the need for feature detection in spatial extents, displacement magnitude, movement seasonality. Using InSAR methods to detect slow landslide movement on the Ragged Mountains western hillslope presents a unique opportunity to examine a case of EO based landslide recognition. We contrast this approach with previous investigations and other methods to monitor the ground displacement on the hillslope. This study area was selected based on InSAR analysis of an area of previously known landslide activity in the East Muddy Creek Landslide Complex.

4.3 Geological Setting

The southwestern flanks of the Ragged Mountains in Gunnison County, Colorado contain a number of active and historical slope disturbances that have been investigated with a range of studies[70,71,74]. These slopes are mapped as “inactive” landslide deposits of reworked glacial till[74,75] or simply labeled “ancient” landslide deposits[75]. Natural hazard and transportation risk studies were completed on three
spatially distinct active landslides: “North,” “Central,” and “South” after reactivations events in 1986 and 1987 [82]. The landslide materials rest upon the surficial Wasatch Formation (Tw) that overlies the Ohio Creek Sandstone (Koc). The sedimentary rocks in the area of the landslide complex are gently folded into a N-S trending syncline. The contact between the Tw and the Koc is unconformable and has been recognized as a likely mechanism for “dip slip” landslide slip planes[68,71,75]. The Ragged Mountain Lacolith (Tqmp) that abuts the hillslope of the complex, is interpreted Eocene age possibly coeval with the Wasatch formation.

The Muddy Creek landslides caused significant damage to Colorado State Highway 133 in 1986-1987[73]. The landslide complex is recognized by state and federal agencies as a significant hazard, endangering both transportation routes as well as the nearby Paonia Reservoir, located immediately downstream of the East Muddy Creek. The reservoir is vulnerable to impacts from sedimentation, landslide damming, back flooding and overtopping seiches[72].

Particular concerns from increased reactivation are damage to the highway, the formation of landslide dams, and channel sedimentation[67,69,73]. Three dimensional subsurface modeling and geological investigation of the three reactivations were conducted to create a framework for further study. Modeling efforts included determining the relative thicknesses of the landslide masses[68]. The landslides have been periodically monitored by the US Bureau of Reclamation using a prism-based survey measurement through 2007. Previous studies all note the high likelihood of uncharacterized zones of landslide activity within the “Apron” of landslide deposits covering the hillslope below the Ragged Mountains (Figure 3.17).

Residences and occupied structures exist on the slope above the known active landslides. Energy infrastructure including natural gas wells have been established in the area as recently as 2011 [83] including pipeline infrastructure and LNG gathering stations[84]. Even “extremely slow” displacement velocities are hazardous to linear structures that penetrate slip planes in the subsurface or shear zones on surficial installations.
4.4 Methods

Very Slow or “creep” scale ground displacement velocities (< 10 cm per year) are difficult to discern compared to higher activity features like shear zones, sag ponds, and scarp formations. Such large, slow moving landslides are difficult to detect without displaced linear features like fence posts or roads. Statistical weights of evidence methods carried out over the Ragged Mountain hillslope area failed to recognize or inventory the previously known active landslides, and mistakenly classified areas of known activity as “low susceptibility” to landslide activity[85].

Satellite remote sensing, where suitable, has a significant advantage for mapping slow landslide features because of its superior viewshed. The large footprint of satellite images allows for efficient analysis of slope movements at a watershed scale. This study presents satellite InSAR measurements from the ALOS-1 platform in 2007-2011 (Table 3.4). The ALOS-1 Platform operated an L-Band Microwave sensor called the Phased Array Type-L Synthetic Aperture Radar (PALSAR); characteristics are summarized in Table 3.5. The platform stopped operation in 2011 due to loss of communication with the satellite, affording landslide monitoring during a short window from 2007-2011. Interferograms were
created with a modified SBAS algorithm, which focuses on temporal rather than spatial unwrapping of measurements, important for monitoring time variable displacement of landslides rather than single events such as an earthquake. The ALOS radar dataset has been recognized as a superior platform for detection of slow landslide activity[86,87] due to the ability to create stable interferograms over long temporal and spatial baselines. Persistent scatterer interferometry (PSI) was not attempted in this study due to the low number of total scenes, 10, not meeting the PS suitability criteria of >25 in Ferreti 2001[11]. Lack of scatterers within the Muddy Creek hillslope may require advanced computer vision techniques such as sub pixel offset tracking[88] or deployment of corner reflectors [88,89] for PSI to be effective on the vegetated slopes such as those in the Muddy Creek complex. ALOS-1 InSAR analyses all suffer from the shortened imagery availability from 2006-2011. Other platforms such as Sentinel and Radarsat scenes are decorrelated even in 12 day pairs due to the vegetated montane conditions of the terrain, highlighting the capabilities of ALOS-1 L-Band capabilities of maintaining coherence over long spatial and temporal baselines. Recent work with the Sentinel platform notes the challenges of C-Band interferometry for landslides in the “Very Slow” and “Extremely Slow” Velocity Class[90] despite having more continuous monitoring campaigns.

Initial displacements were detected in long period <1 year interferograms of in the L-Band based imagery from ALOS 1. Scene wide phase ramps were removed. Some DEM error can be observed in steep gullies or ridges but are generally coherent and stable on hillslope areas. InSAR processing was completed using a modified Short Baseline Subset (SBAS)[42,91] time series processing algorithm.

Table 3.4: ALOS PALSAR Sensor platform characteristics, adapted from [25]

<table>
<thead>
<tr>
<th>Feature</th>
<th>Mode used for this study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Mode</td>
<td>Single Polarization</td>
</tr>
<tr>
<td>Center Frequency and Wavelength</td>
<td>L-Band (1.27 GHz, 23.6 cm)</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>~10 m</td>
</tr>
<tr>
<td>Swath Width</td>
<td>250-350km</td>
</tr>
<tr>
<td>Off-Nadir Angle</td>
<td>27.1° (default)</td>
</tr>
</tbody>
</table>
SBAS velocity tracking relies solely on temporal unwrapping with no spatial unwrapping considerations. This is an important method for landslide reconnaissance investigations which increases capability in detecting new displacement features as the unwrapping process imparts no neighborhood effects upon the slope motion estimates. This technique works well for uniform velocity landslides but may introduce unwrapping errors at faster velocity displacements or temporally sparse scenes. Scaioni et al. 2014, and Zhao et al. 2012, [78,86] note that SBAS processed L-Band imagery is particularly useful for landslide recognition and monitoring of wide area, slow moving landslides. As only a single track of ascending scenes was available during snow-off conditions, line of sight (LOS) velocities are presented. Results are discussed with relation to landslide recognition tasks of detection, characterization and hazard assessment. The sparse imagery coverage cannot resolve seasonal variations, so velocities are analyzed as averaged annual rates of displacement.
4.5 Landslide Geomorphology InSAR, and Mass Wasting Estimates

Landslide size and velocity characteristics are important to estimate denudation and sediment transport, a vital task in understanding geomorphic evolution of montane landscapes [92]. Mass wasting estimates for landslide movement are typically deployed using topographic change analysis with differential Digital Elevation Models (DDEM) with lidar, photogrammetric, or Structure from Motion models [93–95]. These techniques can identify depletion and accumulation zones before and after reactivation events or by integrating elevations over time with a time series of DDEM measurements [96,97]. DDEM based methods derive mass displacement through mass balance modeling[96]. Material displacement rates must then be modeled and are sensitive to the accuracy of the derived DEM products[98]. ALOS platform has been used in landslide mass wasting studies as by Chen et al., 2018 [99] tracking the post seismic deformation field of a giant landslide, which uses DEM based analysis of pre and post event topographies to constrain volumetric estimates of mass displacement. Schlogel et al. 2015 present typical radar-based signatures of “Morpho-structures” for different types of landslide types (Figure 3.20).

Without descending orbit scenes to create a true 3D decomposition of displacement[100,101], we have made some assumptions that can adjust displacements into reasonable spatial constraints that better estimate the actual downslope displacement. The phase change in scenes were negative, meaning a decreasing range to the sensor implying that translational E-W motion is predominant. With the ascending imagery of the right looking satellite, we can assume that the deformation is sensing LOS movements in predominate deformation as translational movement, indicated by previous interpretations of sliding mechanisms [68] (Figure 3.18 and Figure 3.19).

4.6 Results

Interferograms of the area display a visible deformation phase shift clearly indicating a moving landslide mass (Figure 3.21). Displacements are visible in most interferogram pairs and defined through SBAS phase unwrapping. Some phase anomalies are present in deeper values and likely DEM error.
Table 3.5: ALOS-1 Scene characteristics and suitability

<table>
<thead>
<tr>
<th>Satellite Platform</th>
<th>Scene Acquisition Date</th>
<th>Snow cover present</th>
<th>Used in Analysis</th>
<th>Temporal Baseline in SBAS in Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALOS-1</td>
<td>2006-12-25</td>
<td>Yes</td>
<td>No</td>
<td>Not Used</td>
</tr>
<tr>
<td>ALOS-1</td>
<td>2007-06-27</td>
<td>None</td>
<td>Yes</td>
<td>Not Used</td>
</tr>
<tr>
<td>ALOS-1</td>
<td>2007-09-27*</td>
<td>None</td>
<td>Yes</td>
<td>92</td>
</tr>
<tr>
<td>ALOS-1</td>
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1 ALOS-1 scenes are relative orbit 194, frame 770, Fine Beam Mode
Figure 3.19: SBAS Network with Perpendicular Baselines and Delaunay Pairs from Table 3.5
Figure 3.20: Displacement patterns, morpho-structures, and associated interferometric phase for 3 landslide types. (Adapted from Schlogel et al. 2015)
Figure 3.21: Stacked Interferogram generated from 2007-2011 (inset see Figure 3.22)
Figure 3.22: ALOS-1 Stacked deformation between 2007 and 2011 indicating clear displacements beyond previously mapped landslide activity.
Figure 3.23: Map classified by LOS Velocity by SBAS InSAR greater than 0 cm/year
Figure 3.24: Selected time series of SBAS displacements with least square fit for velocity in m/year.

Figure 3.25: Manually unwrapped Time series at C (South Landslide) with phase manual unwrapping vs. SBAS unwrapping

Velocity maps (Figure 3.23) of the unwrapped displacements illustrate the rate of movement over the entire time frame of the ALOS-1 Imagery available to this study. Time Series were selected at points within the moving landslide (Figure 3.24) show the SBAS derived velocities ranging between 1 cm per year (Time Series I) and 5.5 cm per year (Time Series E).

Areas of scene to scene decorrelation are coincident with water bodies like Tomahawk reservoir,
Paonia Reservoir, and previous mapped landslide zones. Of particular note is the decorrelation near the VOLK #12-89-21 #1, which underwent construction during the acquisition period[83]. Movements of the previously known active landslide areas are well correlated spatially indicating adequate geocoding of the ALOS imagery to the topography of the terrain without radar image artifacts of overlay or foreshortening within the hillslope.

4.7 Mass Displacement Estimates

The hillslope topography is characterized by hummocky terrain with an interrupted drainage pattern and immature fluvial mass wasting regime. Here, we are estimating mass wasting of the internal to the hillslope only by mass displacement (landslide activity), which is then removed through fluvial erosion at the toe of the higher active landslides. Displacement mapping measures a continuous rate without evidence of strong seasonality, mass transfer is calculated in a per year rate (Table 3.6). The LOS velocity is likely an underestimate of translational displacement so rates are adjusted with off-nadir right look angle to along slope direction angles as outlined in Zhao 2012[86]. Azimuthal component of velocity vector is applied uniformly to average downslope direction. 30 m resolution SRTM us used to generate the DEM for topographic calculations.

<table>
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<th>Landslide Element</th>
<th>Area (m²)</th>
<th>Average Annual Rate Mass Displacement 2005-2007 (m³ per year)</th>
<th>Annual Mass Displacement with adjusted velocities 2007 - 2011 (m³ per year)</th>
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<td>8.38E+05</td>
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<td>Western Hillslope</td>
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4.8 Discussion

The recognition of the novel zone of landslide creep on with ALOS-1 Archives has important implications in both practical and methodological considerations for landslide investigators of this hillslope. These results enhance our understanding of the specific dynamics between different elements of the landslide complex and their relation to previously assumed dormant materials. Instead of considering the three landslides as separate distinct entities with episodic behavior, investigations must now consider the interdependence of these elements as a whole hillslope in constant interaction with one another. Given the slow velocity scale of displacement, the absence of previous recognition through other field methods is understandable.

Estimated velocities of downslope motion are consistent with rates seen in prism monitoring from 2005-2007. Rates seen during the 1986-1987 reactivations are not seen anywhere in this time period of InSAR imagery. Velocity profiles indicate distinct areas of activity on each landslide including interesting phenomena not previously recognized upslope from the known active zones. Velocity profile mapping indicate faster velocities measured above these areas, indicating landslide progression upslope (Figure 3.26). Patterns of velocity profiles and comparison with morpho-structures from Schlogel 2015 [102], indicate that the translational regime of landslide motion is validated, with some evidence of complex movement in the upper reaches of the 2500 m distance from the valley bottom. As the landslide mass narrows downslope in the areas of depletion, the velocity increases rapidly indicating zones of mass translation. Finally, the landslide transitions to lower LOS velocities near a spreading toe or accumulation zone, which is in turn carried away from by fluvial erosion.

Evaluating uncertainty within the velocity rates calculated in this paper are difficult to calculate due to the presence of only a single track of satellite acquisition. Here, the absolute magnitudes of displacements are difficult to resolve against a model of landslide without contemporaneous, independent measurements. Studies with earthquakes or groundwater subsidence can be modeled geomechanically and cross validated against InSAR rates. The use of InSAR in this case is more valuable as qualitative and
pattern recognition than absolute measurements of displacement the landslide. Overall, the LOS velocity mapping invalidates the model of simple reactivation and dormancy and instead indicates dynamically linked elements of acceleration, deformation accommodation, and mass transport. Punctuated events of reactivation expected throughout the slope depending on the geotechnical properties of the soil.

4.9 Landslide Geomorphology System and Mass Wasting Dynamics

Crozier 2009[103] presents the “Landslide geomorphology systems” framework for discussing how landslide processes contribute to geomorphological development of different types of terrain. The Ragged Mountain western hillslope exhibits similarity to the “stratigraphically controlled hill country” identified in the New Zealand based study by Crozier. The larger zones of mass transfer, if persistent over periods at 5 year and 10 year and multi decade period will contribute to a much larger component of mass transfer and denudation than the episodic reactivations more widely studied and characterized in the literature. While sedimentation loading events will be increased with episodic reactivation, more investigation of the dynamic between zonal transitions needs evaluation and monitoring. Treating mass wasting events as those seen in 1986-1987 from landslides as alternately “active” and “dormant” ignores the watershed scale of denudation and geomorphic development [93,97].

The spatiotemporal evolution of the Ragged Mountains western hillslope is more complex than simple alternating active and dormancy of landslide deposits. This study indicates a more continuous signal of mass movement which would manifest in different parts of the hillslope at different periods of relative reactivation and relative inactivity. As the spatially larger creeping zone of movement provides landslide materials to catchment of the narrower, steeper paleo incised channels where episodic reactivations of the North, Central, and South landslide elements are seen. The episodic nature of the movement in these paleo valleys may therefore be controlled by this supply from the larger hillslope mass above moving at much slower rates. This is compatible and evidence of a theorized direct relationship between mountain formation and landslide rates in work by Roering[104–106] and Larsen and Montgomery[107]. Specifically here in the Ragged Mountains, the landslide geomorphology system
Figure 3.26: LOS Velocity Profiles of Extended North, Central, and South Landslide extending beyond known boundaries of activity into Western Hillslope of Ragged Mountains
appears directly connected with recently studies that high differential exhumation rates of 108-870 m/Ma in the Neogene [108–110], which would be partially explanatory of such a large landslide complex system to be located on the western flank. Karlstrom et al., [108] uses fluvial incision rates to correlate denudation with tectonism, but this study implies that denudation might be better represented with a combination of fluvial and landslide mass wasting as suggested by Crozier’s [103] model of landslide geomorphologies. Mass balance analysis of mass transfer and orogenic exhumation rates is therefore an important next step in understanding the dynamics of geomorphic evolution for the Ragged Mountains.

4.10 Hazard and Risk Implications

Expansion of the recognized area of active slides means that field mapping and damage assessments are necessary to verify remote sensing results with ground truth instrumentation. The landslide masses as detected in this study would most certainly damage penetrating structures like natural gas wells and pipelines, known to exist within the bounds of the Ragged Mountain western hillslope footprint. Valuable subsurface information could be attained during structure damage assessments in the identification of slip plane depths. More granular understanding of local site or borehole deformation could also prevent possible leaks and spills related to energy production in this basin.

This case study shows the success of combining historical field investigations with EO methods, and we acknowledge that InSAR archives were explored with previous knowledge of displacements in the area. The prospect of unsupervised campaigns detecting and recognizing landslide activity without a priori knowledge. InSAR monitoring campaigns with L-Band wavelengths that could reveal landslide features as imagery is acquired in a valuable addition to the EO capabilities of landslide science. Additional monitoring campaigns with L-Band wavelengths will contribute to both the ability to recognize landslide patterns in radar imagery and to contribute to the growing understanding of hillslope evolution.
CHAPTER 5 GENERAL CONCLUSION

5.1 Research Themes and Conclusions

Radar-based remote sensing technique has proved to be effective for monitoring slow landslide velocities and ground subsidence in an urban environment. The three case studies presented in this thesis carry a similar theme of radar images collected over time for the purposes of monitoring deformation with interferometric analysis. Each of these investigations focuses on the acquisition and transformation of deformation measurements into spatial reference frames relevant to comparison with alternative datasets, which enable the uncovering of new information. By using Ground Based Interferometric Technique (GBIR) technique, chapter 2 focuses on converting the displacement into downslope velocities at millimeter-scale of an active landslide in Granby, Colorado, USA. The GBIR results were compared to GPS based survey of 3D velocities. The precision and coverage of measurement and reliability of scene to scene tracking allow for better understanding of kinematic dynamics of the landslide’s causative factors. Chapter 3 presents a case of terrestrial radar interferometric (TRI) data application in ground subsidence measurements in an urban environment. The investigation collects high fidelity measurements of a key transportation asset from an optimal scanning position hundreds of feet off the ground. This study uses advanced persistent scatterers (PS) TRI techniques to overcome the unique challenges of date interpretation in an urban environment. Chapter 4 makes use of classical L-Band satellite InSAR techniques to discover new information about a re-active landslide complex. The InSAR results reveal that the reactive landslide area is much larger than previously recognized. This study demonstrates the advantages of L-Band InSAR in landslide hazard assessment.

5.2 Future Research

Despite the order of magnitude increase in measurements in both temporal and spatial domains with radar remote sensing methods presented in this research, all these investigations are limited by the quantity of scenes and sensors available for analysis. Multiple, long term scanning positions for ground
based interferometry studies are required to eliminate measurement ambiguity from the dataset transformation into a common spatial reference frame. Co-located GNSS or geotechnical instruments will benefit urban monitoring TRI studies the most, but advanced temporal filtering may be able to separate the measurements of interest too. While the ALOS-1 L-Band platform was uniquely qualified for new landslide activity detection, no platform exists today with similar campaign-based continuity is available to pick up the measurements to watch the landslide dynamics evolve. With the motivation of great geotechnical researchers like Dunnicliff (1993) and Peck (1972), this research pushed the envelope of what can be considered a “standard” measurement and evolves the thinking of how to design future investigations with the tools of radar remote sensing.
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