On the use of VR for improved interpretation of InSAR results

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On the use of VR for improved interpretation of InSAR results

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TU Delft

Preface

This report in front of you is the master's thesis "On the use of VR for improved interpretation of InSAR results" by Wouter Niessen. This thesis was part of the master's program of Applied Earth Sciences with the Earth Observation track at TU Delft. It introduced me to the challenges in current analysis methods for InSAR and specifically Persistent Scatterer Interferometry and gave me the opportunity to work on this and improve the current analysis methods. I developed a Virtual Reality application, which aids in the analysis of InSAR data.

I would like to thank CGI for giving me the opportunity to do this research in collaboration with them. Specifically, Pavithra Raghunathan who advised me throughout the project and Robert Voûte who lead a group of interns within CGI, including me, which fostered a collaborative environment in which we could deliver engaging studies and help one another achieve our goals. Their encouragement and insight have been invaluable to the successful completion of this work.

From the University I would like to thank my supervisors, Ramon Hanssen, Martijn Meijers and Roderik Lindenbergh, for their time and effort in providing me guidance and including me in active research activities performed within their teams. I learned a lot from these. And Antonio Napolitano, who created the BIM model for the Wilhelmina tower, and who together with Lina Hagenah and Maurits van Galen joined me in multiple discussions regarding the use of VR/3D and integration of conceptual data for the analysis of InSAR. Also, I would like to thank Freek van Leijen, for explaining the processing methodology of DePSI and discussing unique findings from the VR visualizations.

Finally I would like to thank SkyGEO and CGI for providing datasets needed for my research and participating in the expert interviews during my thesis.

Wouter Niessen
Delft, July 2025

[0] In this thesis AI has been used to improve spelling and readability.

Abstract

Understanding surface deformation is critical for monitoring and maintaining urban structures and environments. Persistent Scatterer Interferometry (PSI) plays an important role in this, it can give insight regarding the stability and deformation of both anthropogenic and natural structures. Despite its utility, the interpretation is a difficult process, representing a four-dimensional problem with multiple sources of uncertainty. Current two-dimensional visualization methods are lacking in conveying all information inherent to PSI data, which lead to the aim of this research, which was to develop and design a prototype Virtual Reality (VR) application that can enhance the interpretation of PSI data by integrating the visualization of PSI data with contextual 3D geometric data. A Unity based VR prototype was developed that visualizes sub-pixel and pixel-level PSI datasets alongside LiDAR point clouds, 3D Models, Building Information Models (BIM) and 3D geometric properties inherent to InSAR. Three diverse case studies, a subsiding railway (Betuwelijn), a collapsed tower surrounded by forests and hills (Wilhelminatower) and a suburban environment (TU Delft Campus), were selected to visualize in VR. In the application users can navigate freely, select individual scatterers, visualize their 2σ confidence intervals, their geometric properties and view time-series in situ in an environment visualized by the 3D geometric datasets. Six domain experts evaluated the system through open exploration and structured interviews. Results showed that the enhanced depth perception and interactive environment improved the user's ability to link deformation signals to real-world features, identify anomalies and assess uncertainty. Despite it's current usability limitations and limited functionality, VR proved a powerful platform for multi-dimensional data exploration, offering new opportunities for monitoring infrastructure. It was concluded that through the integration of geometric datasets, such as LiDAR, 3D models and geometric properties, the interpretation of PSI data is enhanced by accessing the data in a higher dimension and linking it to the environment.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
BIM	Building Information Model
BLUE	Best Linear Unbiased Estimator
DS	Distributed Scatters
DSM	Digital Surface Model
GIS	Geographic Information Systems
InSAR	Synthetic Aperture Radar Interferometry
LEO	Low Earth Orbit
LoD	Level of Detail
LOS	Line of Sight
NMAD	Normalized Median Absolute Deviation
PS	Point Scatters
PSI	Persistent Scatterer Interferometry
PDF	Probability Density Function
VR	Virtual Reality

1 Introduction

In this chapter the background of this research, the research questions and the research scope will be described. Finally the last section will describe the outline of this thesis.

1.1. Background

Understanding ground deformation is critical for monitoring natural hazards like land slides and subsidence, as well as for monitoring and maintaining urban structures and environments. However, interpreting satellite data remains complex and inaccessible for many end-users. Synthetic Aperture Radar Interferometry (InSAR) plays an important role in monitoring deformation on a large scale [51], large scale meaning across a large area at once. InSAR can give insight regarding the stability and deformation of both anthropogenic and natural structures.
Despite its utility, interpreting InSAR results is still a difficult process with several sources of uncertainty. These include processing errors, phase-unwrapping ambiguities, interferometric de-correlation and uncertainties in the origin of radar reflections [24]. This is particularly true for Persistent Scatterer Interferometry (PSI), where datasets consists of thousands to millions of data points in 3D space, with each point consisting of time series extending up to hundreds of epochs. These datasets represent a four-dimensional problem in which it is difficult to analyze all dimensions simultaneously. Furthermore, the complex 3D radar reflections have a position in 3D space that is not necessarily physically relatable and/or visible, which makes it difficult to geo-reference these points in relation to their physical environment.
Currently these datasets are mostly viewed through a two dimensional perspective using Geographic Information Systems (GIS) such as QGIS and ArcGIS or other methods. However, this results in significant information loss, with respect to the origin and orientation of point scatterers, given the reduced dimensionality when viewing the data. In these 2D visualizations often the elevation component of the position and positional uncertainty are ignored during the analysis and in the visualization. To solve this problem, it would be ideal to be able to view the data in a higher dimension and in context to the actual environment from which the data originates. A way to do this is through the use of Virtual Reality (VR). VR is a three-dimensional digital environment in which there are multiple degrees of freedom available, that allow a user to interact and engage with an environment [30]. VR can enable higher-dimensional data exploration, trough it's intuitive spatial navigation and increased depth perception with respect to ordinary visualization methods. At the moment multiple applications are developed which try to integrate GIS with VR, these GIS systems are used to visualize different 3D geometric data sources, for example LiDAR, 3D Building Information Models (BIM) and Digital Surface Models (DSM). Examples of these are: software developed by the Environmental Systems Research Institute (Esri), recognized for its GIS application, ArcGIS, which integrates digital elevation models with a map layer in VR [34], but also Google Earth VR [23], which allows one to fly through a map of different landscapes. And GeaVR which allows one to make measurements, use topographic models and access GNSS data in VR [21]. While these applications demonstrate the feasibility of VR-GIS integration, they primarily operate with raster data, such as land cover maps and do not offer high levels of interactivity or support

for complex InSAR datasets. A 3D visualization of PSI data in combination with LiDAR data has been done by van Natijne [49], however this was limited to the position of scatterer with respect to a LiDAR point clouds and it allowed for limited interaction with the data. It used a potree web-viewer, to project 3D visualization, but did not allow for the use of VR.
Furthermore, while InSAR is widely used for large- and regional-scale deformation studies, it remains difficult to identify displacements in small features, such as independent parts of the same observation object. According to Yang et al. [53] to correctly interpret estimated displacements in InSAR point clouds they need to be linked to real-world structures. To achieve this 2 things are needed:

1. Accurate and precise 3D positioning of each point.
2. An 3D environment to which the data can be linked.

With the availability of data from Low Earth Orbit (LEO) satellites using X band radar, high resolution SAR images can be created and with the advances in sub-pixel positioning processing methods an accurate and precise location can be estimated for point scatterers ($< 0.3\,\mathrm{m}$ in azimuth and range [14]). Which leaves us with a 3D environment to which the data can be linked.
The aim of this research is to enhance the interpretation of PSI results by integrating them into a VR environment. This integration allows for immersive, spatially accurate visualization of PSI results with respect to 3D geometric data and facilitates a more intuitive and precise interpretation of deformation patterns by allowing users to interact with PSI point clouds in their true spatial context.

1.2. Research Objective

The objective of this research is to create an application which can visualize PSI data in Virtual Reality and determine whether it improves the interpretation of InSAR data. In chapter 2 the theoretical background elaborates on the different visualization methods that are available to visualize data in 3D, the currently used visualization methods and the physical principles on which InSAR works. Using this knowledge the following main research question was formulated:

> *”How can 3D contextual information be effectively integrated with InSAR in Virtual Reality to develop a dynamic 3D visualization that enhances the interpretation of InSAR results?”*

In this context, the term *dynamic* means that the visualization can be explored from multiple perspectives in three-dimensional space, as well as to be interactively engaged with by the user.

To answer the research question it has been divided in a multiple sub-questions, which are either answered through literature research or through the experimental phase of this research.

1. What contextual 3D geometric information contribute to an improved interpretation of PSI data?
2. What attributes of InSAR data convey important insights for the interpretation of InSAR data?
3. How can we combine and interpret InSAR datasets in a 3D environment, while taking account of the uncertainties in the data?
4. What functionalities are required in a 3D environment to interact with and interpret the data?
5. To what extent does visualization in Virtual Reality enhance the comprehension of PSI results?

1.3. Research Scope

As stated the objective of this research is to create an application which can visualize PSI data in VR. The primary contribution of this research for this reason lies in the design and development of a VR prototype for visualizing and interacting with PSI data and while the broader motivation involves improving the interpretation of InSAR results, the main focus is on creating a functional interactive VR environment that integrates PSI data with 3D contextual information.

1.3.1. Area of Interest

This research focuses on three case studies, these are selected to provide a diverse set of land cover types and infrastructure characteristics, while maintaining the focus on the development of the VR application. The selected sites are a section of the Betuwelijn, a important railway line from the harbor of Rotterdam to the border with Germany for freight transport, the recently collapsed Wilhelminatower in Valkenburg and the campus of the Delft University of Technology (TU Delft).

The Betuwelijn is known to exhibit deformation and with each day approximately 100 trains passing over it is critical to closely monitor the infrastructure and evaluate it's condition to guarantee safe usage. The deformation of railways can have diverse causes, ranging from subsidence of the soil, animals settling near the railway (e.g. badger den's) or deformations due to thermal expansion and contraction. Monitoring railway displacement with high spatial and temporal resolution is therefore essential and the ability to interpret such data in visually complex environments with small structures, makes this location suitable for this research. Figure 1.1 shows the area of interest and clearly indicates sections where subsidence occurs in orange and heave in blue in the line of sight (LOS) direction. The Wilhelmina tower has recently collapsed and is currently extensively studied to understand the reason's for it's collapse, additionally it is located in a forested and hilly area, which can interfere with InSAR techniques. The visualization of this tower in VR can give additional insight into the process of it's collapse and makes it therefore an interesting case study to visualize in VR. Figure 1.2 shows a map with the LOS displacement rates in the area and also images of the tower before and after it's collapse. This shows the importance of deformation monitoring to avoid/circumvent future collapses. Finally the TU Delft is a sub-urban area with both high-rise and low building with vegetation interspersed in between, it is representative for typical sub-urban area's as can be seen in Figure 1.3.

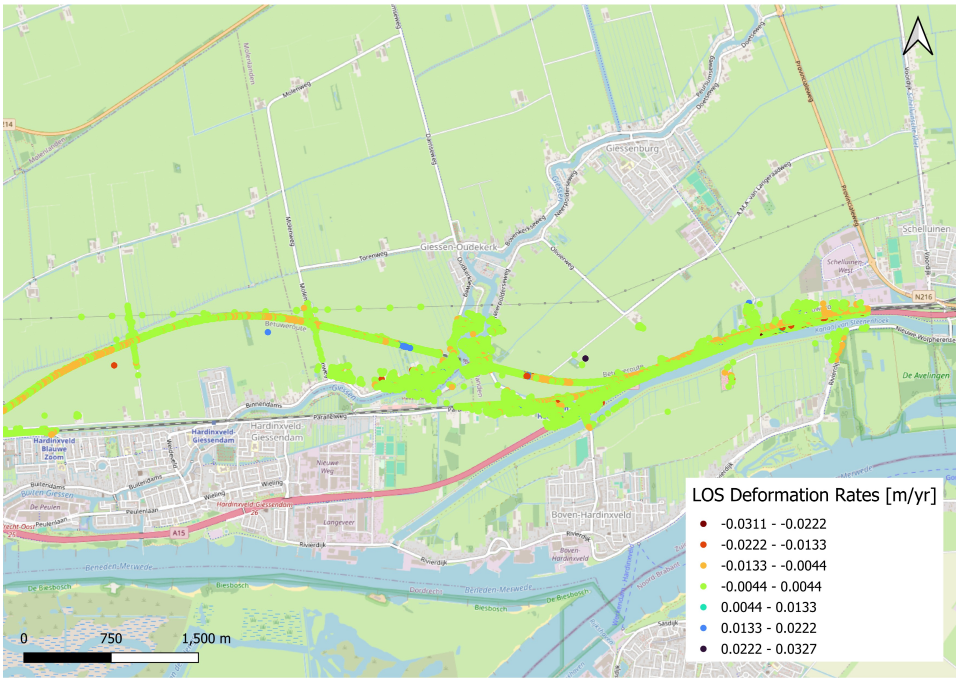
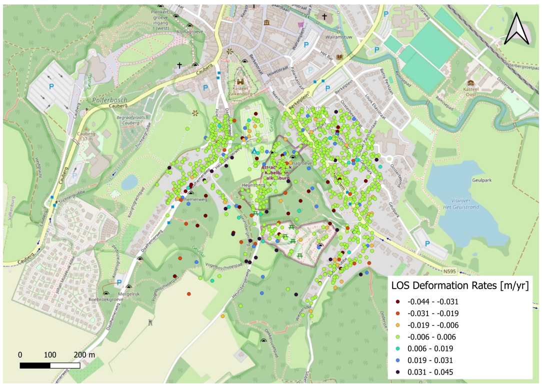


Figure 1.1: Area of Interest No.1: this map shows a section of the Betuwelijn, a railroad for freight transport, which corresponds to the area of interest. It indicate LOS displacement rates measured using InSAR. It shows multiple sections in orange, blue and red along the track, where displacement occurs.

1.3.2. Content

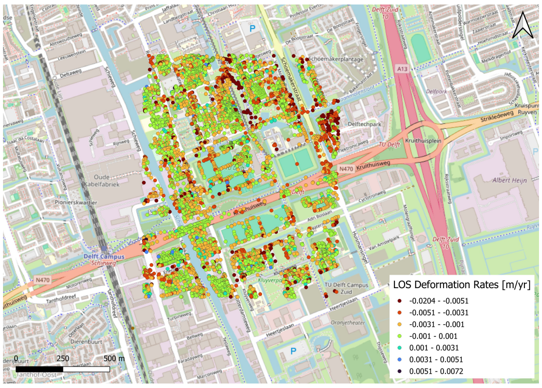
In terms of content the main focus of this research is the development of a Virtual Reality application in which InSAR data will be visualized with respect to a 3D environment. It will not concern itself with the different techniques used to generate 3D geometric data and neither will data be manually processed specifically for this research. The data used will be supplied trough external sources and assumed to be correct.



(a) Map of the Wilhelmina tower indicating LOS displacement rates measured using InSAR.

(b) Before and after photo of the Wilhelmina tower and it's collapse [50].

Figure 1.2: Area of Interest No.2: The Wilhelmina tower



(a) Map of the TU Delft indicating LOS displacement rates measured using InSAR.

(b) Aerial view of the TU Delft campus, it shows the complex urban environment with both low and high rise buildings combined with vegetation.

Figure 1.3: Area of Interest No.3: TU Delft Campus

1.4. Outline

This thesis is structured in 7 chapters, each contributing to answering the central research question: ”How can 3D contextual information be effectively integrated with InSAR in Virtual Reality to develop a dynamic 3D visualization that enhances the interpretation of InSAR results?”.

Chapter 1 introduces the topic, outlines the motivation and background of the research, and defines the research objective and scope, finally it concludes with this outline of the thesis structure. Chapter 2 presents the theoretical background for this thesis, discussing the principles of InSAR, different visualization methods and techniques, and multiple 3D geometric data forms.

In chapter 3, the methodology for the development of the VR prototype is described. This includes the data acquisition, data preparation, system design and implementation and finally the evaluation method used to evaluate the application and it's use. Aside from this the limitations of the methodology will also be briefly discussed.

After this the research results will be described in chapter 4. It starts with an overview of the functionalities, which has been added to the application in the end, before describing the results from the evaluation of the application with expert in InSAR form the scientific field and industry and personal observations made using the developed application.

In chapter 5 a reflection on the research results will be provided, before in chapter 6 a conclusion for the research will be provided. Answering the research questions and describing the contributions of this research.

Finally chapter 7 gives suggestions regarding the usage of the developed VR application, before recommending technical improvements to the application and suggesting future research directions based on this thesis.

2

Theoretical Background

This chapter outlines the theoretical background relevant to this research. It begins with the principles of InSAR, followed by an overview of various visualization methods that can be used to visualize and interpret 3D data. Finally, a brief section introduces different sources of 3D geometric data.

2.1. Principles of Synthetic Aperture Radar Interferometry

Rosen et al. [40] describe Synthetic Aperture Radar Interferometry (InSAR) as a remote sensing technique used to measure surface topography, detect surface changes over time, and capture subtle variations in surface characteristics. InSAR achieves this by analyzing the phase differences between radar signals acquired at different times.

Before exploring how three-dimensional contextual information can be integrated with InSAR in VR, it is important to understand the fundamental principles behind InSAR, particularly PSInSAR, which is the focus of this study. This includes how point scatterers (PS) are geolocated and what types of uncertainties are inherent in their positioning. This section first outlines the basic principles of InSAR, followed by a discussion of its geometric considerations and the associated positional uncertainties.

2.1.1. InSAR Principles

The fundamental concepts of InSAR have been extensively documented by sources such as Rosen et al. [40], Hanssen [24], and van Leijen [48]. Therefore, only a concise overview is provided here.

InSAR involves an active radar system, typically mounted on a satellite or airborne platform, which transmits radio pulses toward the Earth's surface and records the returned signals. The resulting data contains information on the intensity of reflections and the travel time to the Earth's surface , which are stored as complex values (phasors) on a regular grid [24].

By aligning and resampling one radar image y_2 to match the grid of a reference image y_1, an interferogram can be generated by multiplying y_1 with the complex conjugate of y_2. This operation isolates the phase differences, which encode information about the Earth's surface, including elevation and deformation. For a single pixel, the interferometric phase φ^{ms} is given by, [48]

$$\begin{aligned} \varphi^{ms} &= \psi^m - \psi^s \\ &= -2\pi\alpha - \varphi_{\text{flat}} + \varphi_{\text{topo}} + \varphi_{\text{defo}} + \varphi_{\text{atmo}} + \varphi_{\text{scat}} + \varphi_{\text{noise}}, \end{aligned} \tag{2.1}$$

where φ_{flat}, φ_{topo}, φ_{defo}, φ_{atmo}, φ_{scat} and φ_{noise} are the flat Earth, topographic, deformation, atmospheric, scattering and noise phase contributions to the interferometric phase.

By leveraging the repeated orbital passes of radar satellites, multiple acquisitions can be made over the same area. These allow for the generation of a series of interferograms using a common reference (mother) image. Through this time-series approach, PSI algorithms aims to isolate the displacement signal φ_{defo} from other phase components, such as those due to topography, atmospheric effects, or noise.

The result is a displacement time series for strongly reflecting objects, PS, or small scattering objects, Distributed Scatterers (DS), which exhibit stable phase responses over time [12]. These time series enable the detection of surface displacements with millimeter-level accuracy per year.

Several processing approaches exist for PSI. The original algorithm was proposed by Ferretti et al. [19], followed by alternative methods such as the Small Baseline Subset (SBAS) technique described by Lanari et al. [31] and the geodetic estimation method outlined by van Leijen [48]. An overview of various processing strategies is provided in Crosetto et al. [12].

Depending on the processing algorithm used, the position of each scatterer can be estimated either at the pixel level or at a higher sub-pixel resolution. Sub-pixel estimation is typically achieved by oversampling the radar image and fitting a 2D polynomial function to identify the peak response within a resolution cell. If only pixel-level resolution is used, the coordinates of the resolution cell are taken as the scatterers position, and the height (cross-range) is estimated accordingly.

2.1.2. PSInSAR Geometry

Understanding the three-dimensional radar geometry underlying InSAR is essential for correctly processing and interpreting the data. This geometry is illustrated in Figure 2.1. InSAR measures displacement along the radar Line of Sight (LOS), which defines the range direction. As the radar sensor acquires an image, the position of each pixel in the range direction corresponds to the round-trip travel time of the radar pulse. Consequently, all radar returns located within a 3D resolution cell at a distance R from the satellite are aggregated into a single pixel, as illustrated in Figure 2.2.

Due to this three dimensional nature, localizing the precise position of a PS within a resolution cell becomes non-trivial. The challenge arises because multiple objects may lie at the same slant-range distance from the radar. This is evident in Figure 2.3, where both point P and point P' are located at the same range R_1 from the satellite during Orbit 1. As a result, both targets contribute to the same pixel in the SAR image, making it difficult to determine their individual locations in 3D space.

To resolve this, the cross-range component of the scatterer's position must be estimated, which will be addressed in more detail in section 2.1.3. If an inaccurate Digital Elevation Model (DEM) is used during PSI processing to remove the topographic phase component φ_{topo}, it can lead to a miss estimation of the cross-range position. In such cases, a point scatterer may be incorrectly geolocated within the 3D resolution cell. For example, point P could be erroneously projected elsewhere in space if the wrong topographic phase estimate (φ_{topo}), based on a DEM, is subtracted.

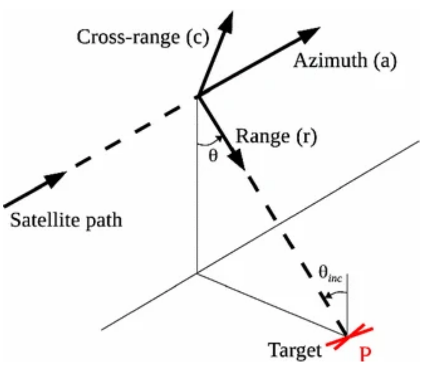


Figure 2.1: 3D radar geometry: range (r), azimuth (a), and cross-range (c) dimensions [14].

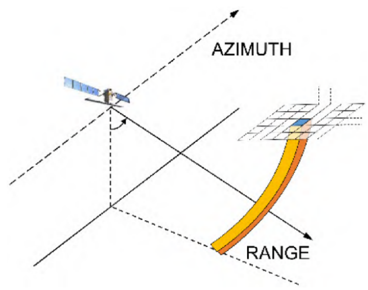


Figure 2.2: Diagram of a resolution cell in 3D space [52]. In orange it indicates the volume in which all reflections contributes to same pixel in a SAR image.

2.1.3. PS Positioning

To determine the three-dimensional position of point scatterers (PS) in a terrestrial reference frame, a process known as geocoding is employed [14]. This process relies on the range, Doppler, and ellipsoid equations [41]. Initially, the scatterer's position is estimated in radar coordinates, range, azimuth, and cross-range, and then transformed into a geographic or cartesian coordinate system.

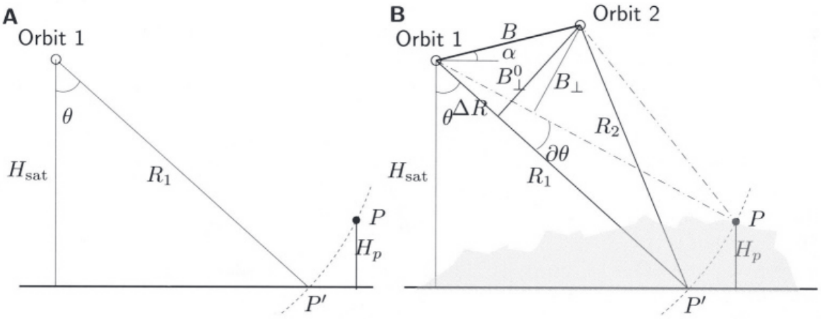


Figure 2.3: Interferometric configuration: two SAR acquisitions observe the same scene from slightly different positions, separated by a baseline B. Both points P and P' are located at the same range R_1 from the satellite in Orbit 1 [24].

The standard deviations in range (σ_r) and azimuth (σ_a) are typically obtained through error propagation during PSI processing. However, estimating the uncertainty in the cross-range direction ($\sigma_{\hat{c}p}$) requires additional steps.

Cross-Range

The cross-range position ($\underline{c}_p$) and its associated uncertainty ($\sigma_{\hat{c}p}$) are derived using baseline information and variations in look angle ($\underline{\theta}_{PR}$) and slant range ($\underline{r}_p$). These are computed as:

$$\underline{c}_p = \underline{r}_p \cdot \underline{\theta}_{PR} \tag{2.2}$$

$$\sigma^2_{\hat{c}p} = \underline{r}_p^2 \cdot \sigma^2_\theta \tag{2.3}$$

To estimate σ^2_θ, we begin by expressing the interferometric phase (φ^{ms}) in terms of the range difference (ΔR) between two acquisitions, assuming consistent scattering behavior:

$$\varphi^{ms} = -\frac{4\pi\Delta R}{\lambda} \tag{2.4}$$

$$\partial\varphi = -\frac{4\pi}{\lambda} \cdot \partial\Delta R \tag{2.5}$$

Using the far-field approximation from Zebker and Goldstein [55], $\partial\Delta R$ can be expressed as a function of the perpendicular baseline ($B_\perp$) and the angle difference ($\partial\theta$):

$$\partial\varphi = -\frac{4\pi}{\lambda} B\cos(\theta^0 - \alpha) \cdot \partial\theta \tag{2.6}$$

$$\partial\varphi = -\frac{4\pi}{\lambda} B_\perp \cdot \partial\theta \tag{2.7}$$

This linear relationship allows for the estimation of $\partial\theta$ and its variance using the Best Linear Unbiased Estimator (BLUE) framework [45]. The linear observation model obtained is shown in Eqs. (2.8)-(2.11), where $k = -\frac{4\pi}{\lambda}$.

$$E\left\{\underbrace{\begin{bmatrix} \partial\varphi_1 \\ \partial\varphi_2 \\ \vdots \\ \partial\varphi_{m-1} \end{bmatrix}}_{\underline{y}}\right\} = \underbrace{\begin{bmatrix} kB_{\perp_1} & 0 & \cdots & 0 \\ 0 & kB_{\perp_2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & kB_{\perp_{m-1}} \end{bmatrix}}_{G} \cdot \underbrace{\partial\theta}_{x} \tag{2.8}$$

$$\hat{\underline{x}} = (G^T Q_y^{-1} G)^{-1} G^T Q_y^{-1} \underline{y} \tag{2.9}$$

$$\sigma_\theta^2 = \sigma_{\hat{x}}^2 = (G^T Q_y^{-1} G)^{-1} \tag{2.10}$$

$$Q_y = \sigma_\varphi^2 \cdot I \tag{2.11}$$

The phase variance σ_φ^2 is estimated using the Normalized Median Absolute Deviation (NMAD), shown in Eq. (2.13), as proposed by Brouwer and Hanssen [8]. Here A represent the amplitude time series vector.

$$\mathrm{MAD} = \mathrm{med}(|A - \mathrm{med}(A)|) \tag{2.12}$$

$$M_A = \frac{\mathrm{MAD}}{\mathrm{med}(A)} \tag{2.13}$$

Then σ_φ is approximated by,

$$\sigma_\varphi = 1.3 M_A + 1.9 M_A^2 + 11.6 M_A^3, \tag{2.14}$$

then combining Eqs. (2.3), (2.8), and (2.14) results in the final expression for $\sigma_{\hat{c}p}^2$ given here:

$$\sigma_{\hat{c}p}^2 = \underline{r}_p^2 \cdot k^{-2} \cdot \frac{\sigma_\varphi^2}{\sum_{i=1}^{m-1} B_{\perp,i}^2} \tag{2.15}$$

Azimuth and Range

When range and azimuth variances are missing from the dataset, they can be approximated using the following relationship described by Eineder et al. [17]:

$$\sigma_{\mathrm{r/a}} \approx \frac{0.55}{\sqrt{\mathrm{SCR}}} \cdot \Delta_{\mathrm{r/a}}, \tag{2.16}$$

where, $\Delta_{\mathrm{r/a}}$ represents the pixel size in range or azimuth, and SCR is the Signal-to-Clutter Ratio, estimated via the inverse of the NMAD.

$$\mathrm{SCR} = \frac{1}{M_A} \tag{2.17}$$

Note that this method approximates variance from temporal signal quality and does not account for oversampling in the spatial domain, which influences the actual uncertainty in σ_r and σ_a.

Covariance Matrix

Finally the positional uncertainty of a scatterer in radar coordinates can be expressed with the covariance matrix Q_{rac}:

$$Q_{rac} = \begin{bmatrix} \sigma_r^2 & 0 & 0 \\ 0 & \sigma_a^2 & 0 \\ 0 & 0 & \sigma_{\hat{c}p}^2 \end{bmatrix} \tag{2.18}$$

For scatterers estimated at sub-pixel precision, the matrix components represent statistical confidence in each dimension. For those estimated only at pixel resolution, the uncertainty in range and azimuth is uniform across the resolution cell, while $\sigma_{\hat{c}p}$ remains determined by the baseline configuration.

2.2. Visualization Methods

This section discusses the methods used to present and interpret PSI and spatial data. It begins with an overview of visualization environments. It then outlines key visualization techniques such as color mapping, transparency, and the use of vague objects. Together, these approaches support effective spatial data interpretation in immersive contexts.

2.2.1. Visualization Interfaces and Environments

This section outlines the environments and platforms available for presenting 3D spatial data. While the decision to use VR for this research has already been made, it is important to understand the broader landscape of visualization technologies and their respective capabilities for spatial data interpretation.

Virtual Reality

Virtual reality enables users to enter immersive environments through head-mounted displays such as the Meta Quest or HTC Vive. In these environments, users can interact with spatial data and experience its scale and depth in a way that closely resembles real-world perception. Unlike 2D screens, VR provides stereoscopic views and spatial awareness, reducing distortions in geometric interpretation and enabling a more natural understanding of three-dimensional data.

VR offers several key strengths, it's spatial immersion, intuitive exploration and the higher dimensionality of it. Regarding the spatial immersion, the stereoscopic view offered by VR headsets enables a more accurate perception of depth and geometry. This allows users to better comprehend spatial relationships as VR leverages how the human brain naturally processes spatial information [39]. Aside from that it allows for an intuitive exploration of data, which is embodied by the experience of being ”inside” the data, allowing users to navigate and examine spatial datasets from multiple angles in an intuitive manner and in turn improving the interpretability. Finally, it's higher dimensionality facilitates the perception of complex relationships in the data by leveraging the third spatial dimension, making it easier to identify patterns or anomalies that may be less apparent in traditional 2D representations.

However, VR also comes with multiple limitations, mainly it's accessibility and the motion sickness it can cause. VR requires specialized hardware, which may not be readily available to all users. Moreover, there is currently limited support for VR in standard data visualizations software, as the technology is still predominantly associated with entertainment applications. These reduce the accessibility of the technology. Aside from that some users may experience discomfort or motion sickness, commonly referred to as ”cyber sickness”, when using VR, particularly in poorly optimized environments or prolonged usage [28].

Augmented Reality

Augmented Reality can be implemented in two main ways. The first approach is through head-mounted displays, similarly to VR , which use outward-facing cameras to capture the real world and overlay virtual information onto this view within the headset. The second method involves handheld devices, such as smartphones or tablets, where virtual elements are superimposed on the live camera feed.

AR offers several key strengths, mainly real-time visualizations, it's spatial immersion and the higher dimensionality of it. AR enables the overlay of virtual information onto the real world, allowing real-time comparisons of spatial data with physical environments. This supports on-site analysis of data and immediate contextualization. Regarding spatial immersion, AR is similar to VR, AR is delivered through head-mounted displays that can offer high degrees of immersion. This enhances the understanding of spatial relationships due to the way the brain processes 3D information [39]. Finally, regarding the higher dimensionality of AR is is again similar to VR and allows users to intuitively perceive more relationships and patterns within spatial data by leveraging the third dimension.

While AR shares many strengths with VR, it also introduces some unique limitations regarding the alignment accuracy of visualizations and the limited field of view. AR requires precise registration of virtual elements with the physical world. Without the use of additional hardware and or physical markers in addition to GNSS, this alignment may be imprecise, potentially leading to misinterpretations [27]. Aside from the alignment accuracy AR, AR headsets typically restrict the user's visible area compared to natural human vision. This reduced field of view can impair spatial awareness and, in some cases, pose safety risks.

Stereoscopic Displays

Stereoscopic displays create the illusion of depth by presenting two slightly different images to each eye, thereby mimicking natural binocular vision. This method enhances the perception of three-dimensional structures without requiring full immersion. A common example of such a system is the PluraView stereo monitor [1], which uses dual displays and a semi-transparent mirror in combination with passive polarized glasses to generate a convincing 3D effect.

Stereoscopic displays offer several key strengths, it is a mature and proven technology and allows for a shared viewing experience. Stereoscopic visualization has a long history of use in geo-spatial and scientific applications. It is supported by various professional software packages, including ArcGIS Pro, which provides built-in stereoscopic viewing functionality. Aside from that these systems support wide viewing angles, making it possible for multiple users to simultaneously view and interpret 3D spatial data. This feature facilitates collaborative analysis and discussion, which is more difficult to achieve in individual VR or AR setups.

Despite these advantages, stereoscopic displays also have notable limitations, it can cause eye strain and fatigue, compared to VR and AR it offers limited depth immersion and it has strict hardware dependencies. Prolonged use of stereoscopic displays may lead to visual discomfort, particularly due to the continuous binocular focus and the use of specialized glasses [54]. Secondly, while they provide a sense of depth, the level of immersion is considerably lower than in VR or AR environments. The user remains in a fixed position and cannot navigate around objects in real time. Finally, similar to VR and AR systems, stereoscopic displays require dedicated hardware, including specific monitors, graphics cards and driver support, which can limit accessibility.

2.2.2. Visualization Techniques

Visualization techniques serve as a bridge between raw data and user understanding. The effective use of properties such as color, transparency, and vague representations allows users to explore large and detailed datasets without cognitive overload, particularly in three-dimensional or immersive environments.

Color Mapping

The human perception of color is both psychological and physiological [43], but its application in data visualization is difficult to quantify. As a result, many proposed color mappings fail to effectively convey information. There is little agreement on the optimal use of color for encoding quantitative data [42], and conventions often vary by scientific discipline.

Brewer [7] provides a widely accepted set of guidelines for color use in mapping and visualization. Two types of color schemes described are particularly applicable to PSI data, mainly diverging color schemes and sequential color schemes. Diverging color schemes are used to show variation outward from a critical midpoint. In PSI visualizations, this is often employed to represent displacement rates, typically a rainbow color-map is standard for PSI visualizations within the InSAR domain. This map diverges from green (no displacement) to blue (positive displacement) and red (negative displacement), see Figure 2.4. However, the rainbow color map is perceptually non-uniform and can introduce interpretation errors, as changes in hue and intensity do not linearly correspond to changes in displacement velocity [11]. An example of a perceptually uniform color map is the roma color-map shown in Figure 2.5. Differing from the diverging color schemes, sequential color schemes are better suited for unidirectional data, such as PSI point quality scores, ranging from 0 to 1. These schemes change hue and intensity in a perceptually uniform way, allowing for more accurate visual estimation of values and allows people with color deficiencies in their sight to interpret it as well [11].

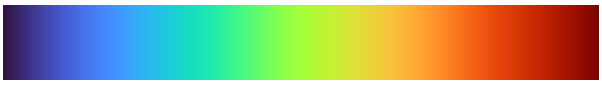


Figure 2.4: Rainbow color-map, which is standardly used to visualize linear displacement rates of PSI data.

Vague Objects and Soft Boundaries

Vagueness is an inherent property of many spatial phenomena. An object is considered vague when it cannot be definitively classified as one category or another, representing a gradual transition rather

Figure 2.5: Roma, a diverging perceptually uniform color-map [10], which can be a better alternative for the rainbow color-map.

than a crisp boundary [15].

This concept is particularly relevant to PSI data, where uncertainty in the position of point scatterers is often modeled as a normally distributed probability density function (PDF). Such distributions describe uncertainty as a gradient, ranging from high to low probability, rather than discrete boundaries. This can be visually encoded through vague regions, where either the intensity or transparency of a pixel fades gradually to represent the probabilistic boundary of the scatterer.

Transparency

In dense spatial datasets, transparency can be an effective tool for managing visual clutter and occlusion, especially in 3D visualizations [18]. It allows for the layering of multiple spatial features, such as geometric structures, zero-Doppler planes, or PSI scatterer plots, without overwhelming the user. However, the addition of transparent surfaces add visual complexity and may have negative impact on task performances. It is important to evaluate its impact on user experience.

Transparency can also encode uncertainty or attribute quality. For example, varying transparency levels can indicate standard deviation, coherence, or point quality. As described in section 2.2.2, this technique can complement vague object representations to more intuitively communicate confidence levels or probability and is according to Korporaal et al. [29] is one of the most effective ways to indicate uncertainty in decision making.

2.3. 3D Geometric Data

3D geometric data forms the spatial context in which other geo-spatial information, such as the object of this research PSI data, is interpreted. It consists of representations of terrain, infrastructure, and buildings, in the form of meshes, point clouds, or textured surfaces. These datasets can be obtained through various methods such as LiDAR scanning, photogrammetry, or existing 3D city models [4], such as Google's photo realistic 3D Tiles and 3DNL from Cyclomedia [13].

In immersive environments such as VR, 3D geometric data enhances spatial cognition by anchoring abstract data (e.g. point scatterers) to familiar spatial references. It allows users to perceive the scale, shape, and layout of physical features, thereby improving interpretation of geo-spatial phenomena [32].

The level of detail (LoD) of 3D models also plays a role in perception and performance. Highly detailed models can increase realism but may cause visual clutter or computational inefficiencies. Therefore, a balance between geometric fidelity and performance must be considered when integrating 3D data into spatial visualizations [5]. Also the scale on which an analysis is performed plays an important role in the LoD wanted, when investigating on a small scale, individual buildings for example, a high LoD BIM model can improve the interpretation of PSI data, due too the enhanced spatial context.

3 Research Methodology

This chapter outlines the methodology used to design, develop and evaluate a VR application for visualizing PSI data to finally answer the research question as stated in chapter 1.

3.1. Overview

The research is structured into four sequential phases, as visualized in Figure 3.1.

In the first phase, *data acquisition*, relevant 3D geometric data sources that contribute contextual and spatial information are identified and described.

In the second phase, *data preparation*, these datasets are processed, transformed, and converted into formats suitable for integration with the VR application.

The third phase, *System Design and Implementation*, outlines the tools and technologies used in the development process. It also describes the architecture of the application, including the individual components and how they interact.

Finally, the fourth phase, *evaluation method*, details the procedures used to assess the system's functionality and the effectiveness of the VR approach for interpreting InSAR data.

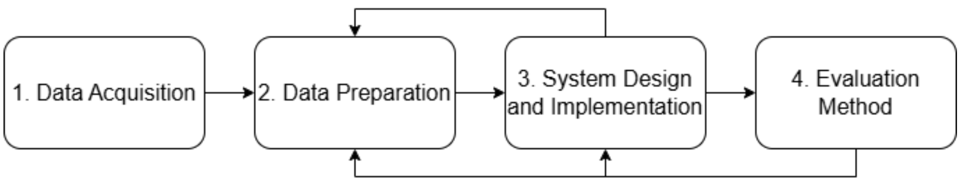


Figure 3.1: Flowchart of the research design, using an iterative approach.

3.2. Data Acquisition

The data used in this research can be split in 2 groups. The first group consists of 3D geometric data, which can enrich the visualization of InSAR data with conceptual information. And the second group consists of different PSI data sets visualized in the process.

3.2.1. Case Studies

To support data acquisition, relevant data was gathered for specific case studies. In total, three case studies are visualized in this thesis, as described in chapter 1. These case studies were selected to represent a diverse range of land cover types and infrastructural characteristics.

- **Case Study 1: Betuwelijn**
  This case involves a section of the Betuwelijn railway. The area is primarily composed of railway

tracks and a railway tunnel surrounded by agricultural fields. As vegetated areas typically yield few persistent scatterers, this case is expected to show point scatterers predominantly along the railway track. This makes it well-suited to evaluate both the visualization accuracy and the potential of VR to highlight relevant infrastructure.

- **Case Study 2: Wilhelmina Tower, Valkenburg**
  The second case involves the site of the recently collapsed Wilhelmina Tower, located in a complex, forested, and hilly environment. This presents a challenging test case due to reduced coherence in vegetated and uneven terrain, but it offers an opportunity to explore how VR may assist in interpreting PSI data in such settings.
- **Case Study 3: TU Delft Campus**
  The final case study focuses on the TU Delft campus, a suburban area characterized by a mix of high-rise and low-rise buildings interspersed with vegetation. This environment allows for evaluation of PSI visualization in a typical urban setting.

Through these three case studies, a comprehensive assessment of the utility of VR for interpreting PSI data can be conducted.

3.2.2. Identification of 3D Geometric Data

To identify 3D geometric data sets, a survey was performed of available 3D geometric data sources. The goal was to identify datasets that could serve as contextual backdrops for interpreting InSAR displacement measurements in a 3D environment. For this there were a few selection criteria, mainly the geographic coverage, the spatial resolution and accuracy, the data availability and format compatibility. Regarding the geographic coverage it is important that the dataset overlaps with areas of interest from the case studies. Secondly a high spatial resolution and accuracy are needed to effectively geo-locate the datasets with respect to the InSAR data and give meaningful information regarding the scene given thge resolution is high enough. Aside from that the datasets needed to be openly accessible to effectively use them and finally the format of the 3D geometric datasets needed to be compatible with Unity or they have to be covertible to compatible data formats.

Based on these criteria three data sources were identified, LiDAR point clouds, digital surface and elevation models (DSM/DEM) and 3D models. Multiple LiDAR point clouds are freely available through AHN and ProRail, they contain point clouds of the environment scanned using light detection and ranging. DSM's and DEM's correspond to 3D models that offer general terrain context and finally high resolution 3D models can be created manually or generated from point clouds to have accurate representations of structures in the area of interest.

Aside from the identified data sources another data format was identified during the progress of this research, which was Building Information Models (BIM). BIM is the process of creating and managing information for a built asset. It integrates structured, multi-disciplinary data to produce a digital representation of an asset across its life cycle. Which due to it's inherent nature of integrating multi-disciplinary data, can give access to a greater amount of conceptual information.

3.2.3. Identification of PSInSAR Data

As discussed in section 2.1, there are multiple methods for generating InSAR data. These methods differ in the spatial precision with which scatterer positions are estimated. For the purpose of this research, the datasets can be divided into two categories, sub-pixel precision methods and pixel-level methods. Sub-pixel precision methods estimate scatterer locations within a resolution cell and provide uncertainty metrics in range, azimuth and cross-range direction, while pixel-level methods assign scatterers to resolution cells without specifying their location within the cell. They only have a normally distributed uncertainty in the cross-range direction and have uniform uncertainty distributions in the range and azimuth directions.

A total of four PSI datasets were acquired for this study. Originating from two different satellites, RADARSAT-2 and TerraSARx. Three of them were processed using sub-pixel estimation techniques and were provided by SkyGeo. The fourth dataset, provided by CGI, contains pixel-level InSAR measurements without sub-pixel accuracy. Two of these datasets consists of both descending as ascending tracks, while the other two only cover a descending track.

Table 3.1 provides an overview of these datasets, including their satellite source, format, coordinate reference system (CRS), and spatial precision. The parameters $\bar{\sigma_a}$, $\bar{\sigma_r}$, and $\bar{\sigma_c}$ represent the average uncertainty in azimuth, range, and cross-range directions respectively, where available.

The fact that different satellites are used also effects the visualizations due to the differences between them. The radar sensor from TerraSAR-X uses X-band and RADARSAT-2 uses C-band. X-band has a higher frequency and thus a shorter wavelength ($\lambda \approx 3.1$ cm) with respect to RADARSAT-2 ($\lambda \approx 5.5$ cm). As seen in Eq. (2.15), $\bar{\sigma}_c$ is dependent on the wavelength and increases as the wavelength increases. Furthermore the differences in antenna length (L) for both satellites result in differences in the azimuth resolution, given that $\Delta_a \approx L/2$ [3]. TerraSAR-X has a shorter antenna (4.8 m) with respect to RADARSAT-2 (15 m), resulting in a better azimuth resolution. Finally, the range resolution is dependent on the bandwidth (B) of the signal following the formula $\Delta_r = c/(2B)$ [24], due to the larger bandwidth of TerraSAR-X (300 MHz) versus the smaller bandwidth of RADARSAT-2 (100 MHz) this results in a better range resolution for TerraSAR-X. As seen in Eq. (2.16) the uncertainty in the range and azimuth direction, directly relate to the resolution. Thus generally TerraSAR-X data will have a lower uncertainty than RADARSAT-2 as seen in Table 3.1.

Table 3.1: Overview of datasets used in this study. Precision values for PSI datasets represent average spatial uncertainty in azimuth ($\bar{\sigma_a}$), range ($\bar{\sigma_r}$), and cross-range ($\bar{\sigma_c}$) directions, where available. LiDAR and BIM entries include positional bias and standard deviation where applicable.

Dataset	Satellite	Format	CRS	Accuracy			Source
				$\bar{\sigma_a}$ [m]	$\bar{\sigma_r}$ [m]	$\bar{\sigma_c}$ [m]	
PSI - Wilhelmina tower	TerraSAR-X	.csv	EPSG:4326	0.256	0.128	2.816	SkyGEO (2025)
PSI - TU Campus	RADARSAT-2	.csv	EPSG:7415	0.53	0.97	4.14	SkyGEO (2025)
PSI - Betuwelijn	TerraSAR-X	.csv	EPSG:4326	n/a	n/a	n/a	SkyGEO (2025)
PSI - Betuwelijn	RADARSAT-2	.csv	EPSG:4326	-	-	3.43	CGI (2025)
				Bias [m]	**σ [m]**		
LiDAR	Airborne	.LAZ	EPSG:7415	0.05	0.05	-	AHN [2]
LiDAR	Airborne	.laz	EPSG:7415	n/a	n/a	-	Prorail [38]
3D BIM	-	.ifc	EPSG:7415	-	≈ 0.1	-	Napolitano, A. (2025)
3DBAG	-	.obj	EPSG:7415	-	≈ 0.15 [1]	-	3DBAG [37]

3.3. Data Preparation

To enable integration into the VR application, all datasets underwent a structured preparation process. This included aligning coordinate reference systems, converting data into Unity-compatible formats, and enriching the PSInSAR datasets with additional metadata required for visualization.

3.3.1. Coordinate Transformation

The first step in harmonizing the datasets was selecting a common coordinate system. Amersfoort / RD New (EPSG:7415) was chosen due to its Cartesian nature, making it compatible with Unity's coordinate framework, and because it is widely used in the Netherlands, where the areas of interest are located. Several of the datasets were already provided in this coordinate system.

The PSInSAR datasets, originally in geographic coordinates (EPSG:4326), were reprojected to EPSG:7415 using the `pyproj` Python library. The transformation results were visually validated in QGIS. Although Unity uses a Cartesian system, it employs a left-handed coordinate system with a Y-up orientation, in contrast to the Z-up convention typically used in GIS and LiDAR tools. Therefore, a coordinate axis transformation was necessary for the LiDAR data. This transformation was applied using CloudCompare and is defined by the matrix in Eq. (3.1), which reorders the axes to match Unity's internal coordinate system. For the BIM model and 3DBAG dataset, the models needed to be rotated around the x-axis by 90 degrees and mirrored in the x- and z-axis to be properly positioned in Unity. This was done within Unity itself.

[1] 3DBAG is described with an accuracy of 30 cm [37], which was the standard it had to conform to, the exact uncertainty is however unknown, here this accuracy is interpreted as the 95% confidence bound. This conforms to 2σ.

$$T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.1)$$

3.3.2. Format Conversion

Following coordinate alignment, data formats were converted to ensure compatibility with Unity. The LiDAR point clouds, originally in LAZ format, were converted to PLY format using CloudCompare, enabling them to be loaded into Unity. At the same time, the LiDAR data originating from ProRail were merged together and subsequently split into files with a size of approximately 4 GB, due to the small area each pointcloud covered in the initial files. The BIM model was provided in the Industry Foundation Classes (.ifc) format, an open standard that facilitates interoperability in construction and design. The conversion to this format had already been completed before the dataset was obtained. The 3DBAG dataset did not need to be converted.

3.3.3. PSInSAR Preparation

The PSInSAR datasets were enriched with metadata to support accurate 3D visualization and analysis. Specifically, three attributes were added to the data, the satellite heading, the incidence angle (where missing) and the estimated positional uncertainty in azimuth, range and cross-range directions.

Satellite heading and incidence angles were derived from the metadata accompanying the datasets. For the first dataset, positional uncertainty in each direction was calculated using Eq. (2.18). The second dataset only provided average uncertainty values, based on Dheenathayalan et al. [14], which were uniformly applied to all points. The third dataset lacked sufficient metadata to estimate uncertainty; therefore, average values from the second dataset, which is based on similar satellite and acquisition parameters were used. The fourth dataset, processed at the resolution-cell level rather than sub-pixel level, only included a normally distributed uncertainty in the cross-range direction. In this case, no azimuth or range uncertainty was estimated, as the positional error is assumed constant across the resolution cell in azimuth and range.

Table 3.2: Summary of data preparation steps, including format conversions, coordinate transformations, and tools used.

Dataset	Format	Coordinate System	Tools
AHN LiDAR	LAZ → PLY	EPSG:7415 → Unity	CloudCompare
ProRail LiDAR	LAZ → PLY	EPSG:7415 → Unity	CloudCompare
PSInSAR	CSV → CSV (Unity-ready)	EPSG:4326 → EPSG:7415	Python (pyproj)
3DBAG	n/a	EPSG:7415 → Unity	Unity
BIM	n/a	EPSG:7415 → Unity	Unity

3.4. System Design and Implementation

The development of the VR application followed an iterative and incremental approach, as described by Bittner and Spence [6]. To do this the application is divided into smaller subsystems, whose functionality are continuously evaluated. The overall system was gradually constructed, by focusing constantly on a single subsystem, which were added to the application incrementally. As the added subsystems are evaluated, they might be reiterated as further functionalities are implemented. This approach also informed adjustments to the data preparation pipeline described in section 3.3, which evolved alongside the system components.

This section is structured around five key components: Environment Setup, System Architecture, Data Integration Workflow, VR Interaction Design, and Rendering and Visualization.

3.4.1. Environment Setup

Unity [46] was selected as the development platform for the VR application. Unity is a widely used game engine capable of rendering immersive virtual reality applications. The decision was based on several factors: its extensive documentation, adoption by CGI, and the availability of Unity expertise at TU Delft. Unity is also widely adopted in the scientific community for VR-based data visualizations. For example, Morales-Vega et al. [33] developed a VR tool for visualizing dimensionality reduction methods, Donalek et al. [16] used Unity to visualize 3D graphs and create an immersive Martian landscape, and Kingsley et al. [25] created a VR application for interacting with chemical and macromolecular structures.

The selection of a game engine for PSI data visualization was based on several requirements: the engine had to support 3D and VR development, offer comprehensive documentation, present a manageable learning curve (given the limited time frame of the research project), and preferably be open source. Based on these criteria, three engines were considered: Unity, Unreal Engine, and Godot. Of these, only Godot is fully open source, while Unity and Unreal Engine offer free access through educational licenses.

Godot was quickly ruled out due to limited VR optimization and a relatively small community, which translated into sparse documentation and a scarce third-party plugin library. Unreal Engine, while known for high-quality rendering and used in scientific contexts such as medical data visualization [20], was deemed less suitable due to its steeper learning curve. Given that high-resolution rendering was not critical for this project, because of limitations in the resolution of the PSI data itself, Unity emerged as the most practical and efficient choice.

Although Unreal Engine [47] and Godot [22] are viable alternatives, Unity was ultimately selected for its robust ecosystem, extensive support, and relatively low barrier to entry.

Development was carried out using Unity version 6000.040f1, employing the VR Core template. Additional tools and plugins included PCX [44] for point cloud data loading and the IFC Unity Editor Plugin [26] for importing Building Information Modeling (BIM) models.

3.4.2. System Architecture

The VR application consists of several modular components within Unity, each responsible for specific tasks such as data loading, visualization, and user interaction. Figure 3.2 provides an overview of these modules and their interactions.

The process begins with the VR Settings, where the user selects the datasets and configures scene parameters, including the area of interest, scaling, and visualization method. Based on these inputs, the SceneSetup object loads the PSI and LiDAR data and visualizes it in the VR scene. It also communicates with the MoveModelInScene object to correctly position BIM and 3D models.

The MoveModelInScene object applies spatial adjustments to these models based on user-defined settings.

User interaction is handled through the Point_UI_Controller, which reads data objects within the VR scene and manages input from the VR user. It generates time-series graphs using the TimeSeriesGraph script and passes them to the graphCanvas for display. The Point_UI_Canvas listens for user actions and relays these commands to the controller for processing.

3.4.3. Data Integration

To integrate the various datasets into the VR scene, each dataset is imported using appropriate plugins and loaders.

For the LiDAR datasets, the PCX plugin automatically converts the point clouds into a single 3D mesh when imported, containing the colored point cloud. This reduces system load and allows the mesh to be visualized using the `PointVisualizer` script.

For the BIM models, the IFC Unity Editor Plugin is used. It parses the IFC files and generates compatible 3D objects for Unity. The 3D models from 3DBAG can be added directly into the project without additional data loaders. Once loaded, the `ShiftModel` script rotates, scales, and positions the BIM and 3D models correctly, based on the parameters set in the `SceneSetup`.

The PSI data is imported using the `CSVLoader` script, which reads each line of the CSV file and generates a component containing all relevant attributes for a given point. These components are attached

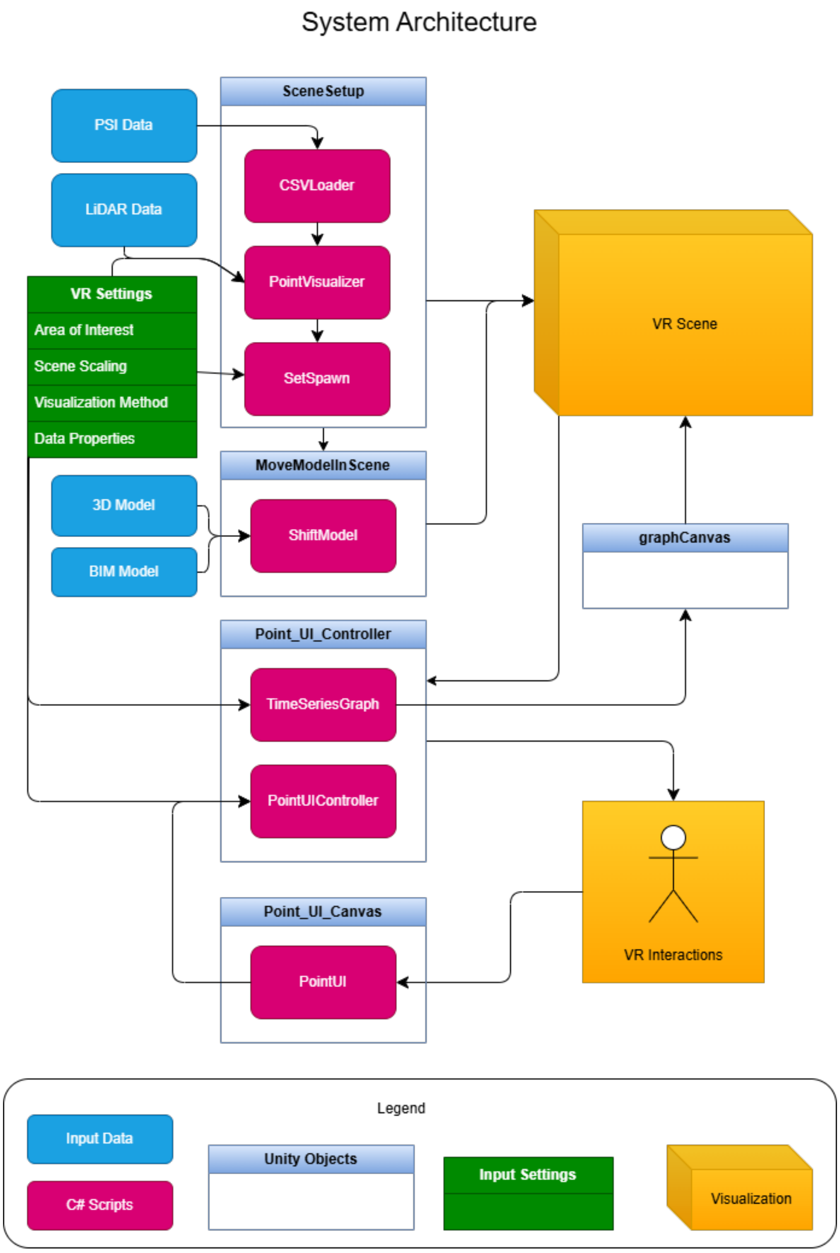


Figure 3.2: System architecture of the Unity-based VR application. The diagram illustrates how input data sources and VR settings are processed through dedicated Unity GameObjects and their associated C# scripts. Arrows indicate the flow of data and logic, from initialization in `SceneSetup`, through model positioning in `MoveModelInScene`, to user interaction and data visualization via `Point_UI_Controller`, `Point_UI_Canvas`, and `graphCanvas`. The system culminates in a dynamic VR scene where users can explore PSI data interactively.

to visual objects representing each PS point, which are created by the `PointVisualizer`. Based on the `VRSettings` and the attached data, the points are visualized and positioned in the VR scene.

If required data is missing or settings are incorrect, the system logs warnings in the Unity console to help identify issues such as missing files or misnamed columns.

3.4.4. VR Interaction Design

The VR interactions are designed to facilitate intuitive and effective interpretation of PSI data in a 3D spatial context. They support spatial and temporal analysis and exploratory data interaction. The following five interaction types are initially planned for implementation: selection and inspection, spatial analysis tools, visualization management tools, data correction tools and data storage and removal.

Regarding selection and inspection, users should be able too select individual point scatterers using a pointer mechanism linked to the VR controller. Upon selection, a UI panel provides access to available actions and data. For the spatial analysis tools, users should be able to define a spatial region of interest using a bounding box or polygon to select multiple point scatterers. A UI panel then displays statistical information, such as mean displacement, standard deviations and trend comparisons across the selected group. With respect to visualization management, users should be able to toggle visibility of contextual elements (e.g. Zero-Doppler planes, 3D resolution cells and point scatterers) to highlight specific data relationships. After analyzing data relationships, users can adjust the positions of selected point scatterers within logical restraints (e.g. limiting movement to the cross-range direction as discussed in section section 2.1) for data correction. Finally, users can remove point scatterers from the scene or mark and store them as "Points of Interest". These sets can subsequently be exported for further analysis outside of Unity.

All interactions are implemented using Unity's XR Interaction Toolkit, in combination with custom C# scripts.

3.4.5. Rendering and Visualization

To convert the PSI and 3D geometric data into an immersive and interpretable VR visualization, several design and performance decisions were implemented.

PSI Data

The spatial accuracy of each PS point is visualized using its 2σ confidence interval.

Two geometry types are used in the visualization of point scatterers. For sub-pixel data, the PDF is normally distributed across azimuth, range and cross-range directions, resulting in an ellipsoid shape. For pixel-level data however, the PDF is uniform in azimuth and range, forming a rectangular base, and normally distributed in the cross-range direction. Resulting in a cuboid shape.

Each point is colored based on its estimated relative linear LOS displacement using the rainbow color-map Figure 2.4 instead of a uniform color-map, such as roma Figure 2.5, this color-map is chosen since it is the standard color-map used to visualize PSI data by most experts in the field. To emphasize high-confidence points, transparency is applied to the points. Fully opaque for high-confidence and increasingly translucent for lower confidence. Given that points with a higher uncertainty are larger in the visualization, the transparency reduces the occlusion caused by the large, uncertain points.

Contextual Geometries

To contextualize the point scatterers two geometries are used: The Zero-Doppler plane and the 3D representation of a SAR resolution cell. The Zero-Doppler plane is visualized through a vertical plane, perpendicular to the satellite heading and intersects all point scatterer with the same azimuth coordinate. A semi-transparent surface is rendered at each scatterer's location. For the 3D representation of the SAR resolution cell a semi-transparent volume beam is rendered perpendicular to the LOS direction. Its width and height match the SAR image pixel size, and its length spans several hundred meters. Although true SAR beams are slightly curved, a straight beam is used due to the minimal curvature. For TerraSAR-x at 514 km altitude [9] this corresponds to $\approx 0.01°$.

Other different geometries that were considered were arrows, indicating the LOS and displacement directions or the standard deviations in the azimuth, range and cross-range directions. These are however not planned, due to time constraints and that these properties can be inferred from the other visualizations already planned(e.g. 3D resolution cell and confidence intervals).

UI Elements

Two main UI panels are created for the VR application, the main menu panel and the timeseries panel. The main menu provides toggles for rendering components (e.g. the Zero-Doppler plane, 3D resolution cell and point scatterers), it displays the colorbar legend and offers options to store, remove and export the PSI data. The timeseries panel, displays a graph showing relative height over time for the selected point scatterers. The panel is accessible from the main menu after selecting a point in the environment.

Rendering

The PCX plugin requires a custom shader to render point clouds in VR, as VR shaders are not included by default. To improve performance, all scene objects are shifted so that the center of the area of interest aligns with Unity's origin. Without this, positioning objects >100 km from the origin causes rendering instability due to floating-point precision errors.

3.5. Evaluation Method

To assess the developed VR application's usability, interpretative effectiveness, and overall user experience, a qualitative expert evaluation was conducted, which is inline with common practices for software development as stated by Paz and Pow-Sang [36]. The goal was to validate whether the application supports the interpretation of InSAR data, and to identify its strengths, limitations, and potential use cases. Aside from the user evaluation, the researchers own observations and experience with the application are also included as part of the evaluation. Given the extensive practice with the application and knowledge of the case studies, he can capture insights into the datasets, which may not be apparent to participants in the short time they can experiment with the application. This results in a more comprehensive assessment of how a 3D visualization can enhance the interpretation of InSAR results.

Participants

Six domain experts participated in the evaluation: three Phd candidates specialized in InSAR and three industry professionals working with PSI data in practice. These participants were selected for their experience in both interpreting InSAR outputs and applying them to real-world geospatial or engineering problems.

Evaluation Setup

The evaluations were conducted on-site using a Meta Quest 3 VR headset connected to a VR-capable laptop. Each session took place in a quiet environment with sufficient space for standing and moving within the VR setup.

The evaluation was structured into three stages:

1. **Pre-exploration Interview**
   Each session began with a short semi-structured interview to establish a baseline understanding of how the expert currently processes, visualizes, and interprets InSAR data. Participants were also asked about their expectations for how a VR environment could potentially support or improve these tasks.
2. **Exploration Phase**
   Participants were then invited to freely explore the three case studies, defined in chapter 1, within the application. No predefined tasks were assigned; instead, participants were encouraged to use the available interaction tools to investigate the PSI data and accompanying contextual geometries as they saw fit. During the exploration they were free to ask questions about usage or give impromptu feedback on their experiences.
3. **Post-exploration Discussion**
   After exploring the application, a guided discussion was held focusing on the usefulness of the application, the relevance of its interaction design and its potential use cases. Participants were also asked to comment on any limitations or missing features, and to suggest improvements based on their domain expertise.

Data Collection and Analysis

All feedback was collected through note-taking during the interview and discussion stages. The data was analyzed qualitatively to identify common themes, recurring challenges, and suggestions for improvement. No quantitative scores were assigned, as the purpose of this evaluation was not to measure performance, but rather to understand expert perceptions and validate the application's utility in real-world contexts.

3.6. Limitations

Several limitations were encountered during the development and evaluation of the VR application. These limitations relate to technical challenges, feature implementation, visualization design, and the evaluation approach.

One major technical constraint involved the conversion of point clouds into meshes. The generated meshes often contained significant artifacts unless extensive manual clean-up was performed, making the approach impractical, as seen in Figure 3.3. As a result, point clouds were not visualized using

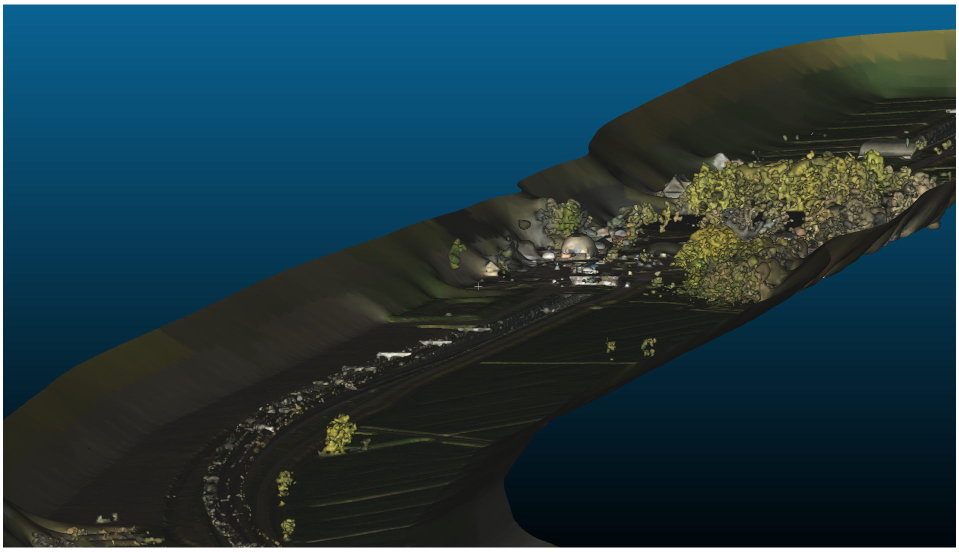


Figure 3.3: Here a mesh generated from the point cloud of the Betuwelijn is shown, it is generated using poisson surface reconstruction, which is a mesh creation function in CloudCompare. It contains significant artifacts, which will need to be processed extensively to create a usable mesh.

mesh representations. Additionally, the plugin FastPoints [35] was initially selected for point cloud rendering due to its built-in support for level-of-detail (LOD) management, which could have improved performance and enabled the use of larger datasets. However, installation and compatibility issues prevented its use in the final application.

A further limitation arose from file size restrictions. When loading point cloud files larger than 4 GB, Unity encountered errors that halted the loading process. This constrained the maximum dataset size that could be visualized at one time and required limiting the spatial extent of scenes.

There were also challenges in aligning BIM and 3D models within the VR environment. Depending on the software used to export the models (e.g., Civil3D vs. Revit), coordinate metadata was handled inconsistently. In some cases, objects were correctly positioned upon import, while in others, manual translation and alignment were required. This inconsistency reduced the automation and reproducibility of scene setup.

In terms of visualization, the initially selected rainbow color-map caused visibility issues in the immersive environment, as PSI scatterers blended with similarly colored surroundings. To address this, the color-map was changed to the perceptually uniform plasma color-map, which provided better contrast and visibility for the relative LOS displacement rate.

Some proposed interaction features could not be implemented due to time constraints and complexity.

Specifically, spatial analysis tools and data correction tools were not included in the final prototype. This limited the analytical capabilities of the application.

Finally, the evaluation was qualitative and involved a small group of expert participants, which restricts the generalization of findings. Furthermore, the researcher's dual role as both developer and evaluator introduces the potential for bias in interpreting feedback and usability outcomes. While efforts were made to prioritize expert perspectives, complete objectivity cannot be guaranteed.

4
Results

This chapter presents the results of the thesis. It begins with an overview of the functionalities implemented in the VR application, followed by the outcomes of the expert evaluation.

Some of the figures in this section have a corresponding video, Table 4.1 contains a list of these figures and hyperlinks to these videos.

Table 4.1: Index of VR video links corresponding to figures in the Results section, these videos were created within the VR application.

Video No.	Corresponding Figure	Brief Description	Video Link
1	Figure 4.10	Video showing the user interactions within the VR environment	Link
2	Figure 4.13	Video showing the resolution cell intersecting two buildings on the TU Delft campus.	Link
3	Figure 4.14	Video showing floating point scatterers around the Wilhelmina tower.	Link
4	Figure 4.15	Video showing systematic elevation errors in RADARSAT-2 data for the Betuwelijn.	Link

4.1. Application Functionalities

This section describes the functionalities added to the application. It covers the application setup, 3D visualizations, VR interactions, and analysis tools.

4.1.1. Application Overview

Before using the VR application, each scene must be configured within Unity. Figure 4.1 provides an overview of the Unity interface used during scene preparation. Six main windows are used in this setup:

1. **Scene View**
   Displays the current scene, allowing navigation and positioning of objects. It also supports switching to the Game View, which mirrors what the VR user sees—useful for observers.
2. **Hierarchy Window**
   Lists all objects loaded into the scene, including assets and scripts controlling the application.
3. **Project Window**
   Contains the project's file system. New data is added here, organized into appropriate folders depending on type.
4. **Inspector Window**
   Shows properties of the selected object from the Hierarchy Window, allowing for configuration and fine-tuning.
5. **Global Settings Window**
   A custom window developed for this project. It lets users define the visualized area, adjust scale, set data-specific parameters, modify the color-map range, and reload all scene data with a single click.

6. **Console Window**
   Logs system messages, including error notifications (e.g., problematic data imports) and user interactions such as point selection or data export.

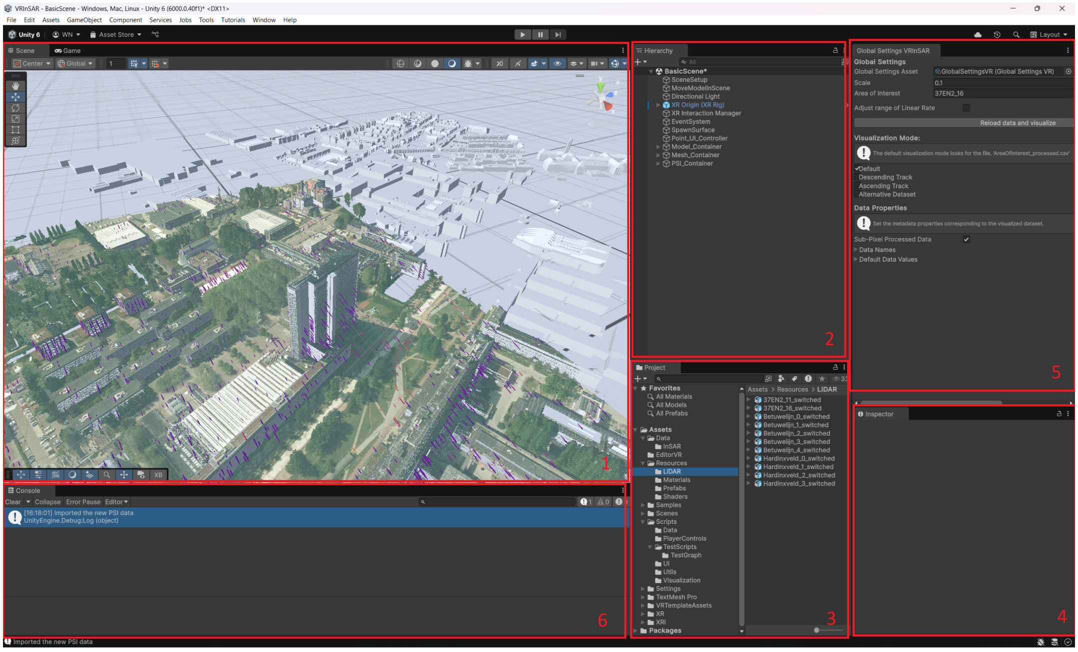


Figure 4.1: Unity interface during scene preparation. In the red squares the different application windows are indicated with numbers, described in section 4.1.1.

4.1.2. 3D Visualizations

This section outlines the visual representation of contextual datasets and PSI data in the VR environment.

3D Contextual Geometries

Figures 4.2 and 4.3 show visualizations of LiDAR point clouds. It can be seen that the point cloud of the Betuwelijn (ProRail) is denser than the AHN dataset, but due to the higher density only a smaller area can be visualized at once. Figures 4.4 and 4.5 illustrate two 3D model types: the 3DBAG dataset with simple geometric building representations, and a detailed BIM model of the Wilhelmina tower. While 3DBAG offers nationwide coverage for buildings, it lacks infrastructure elements like bridges or tunnels, which can be included through BIM models.

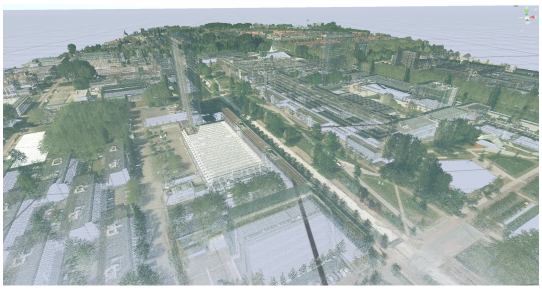


Figure 4.2: AHN LiDAR point cloud of TU Delft campus, it is a relatively low density point cloud, covering a relatively larger area.

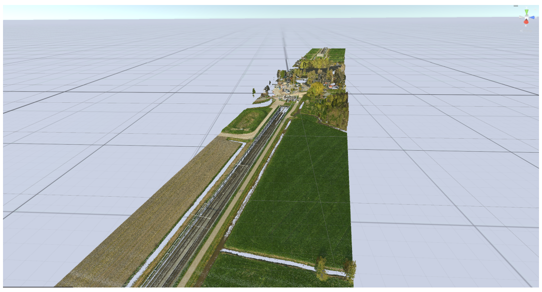


Figure 4.3: LiDAR point cloud of the Betuwelijn from ProRail, a relatively high density point cloud, covering a relatively small area.

3D PSI Data

Point scatterers are visualized in two ways depending on positional accuracy. Sub-pixel estimations are represented as ellipses indicating 2σ confidence intervals assuming normal distributed PDF's in

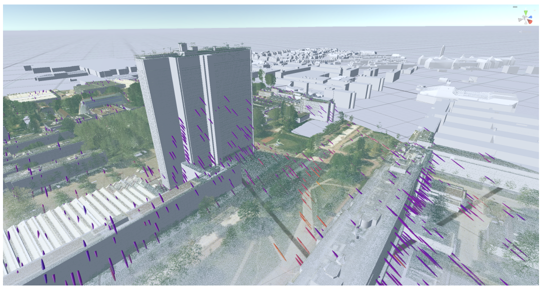


Figure 4.4: 3D BAG data representing Dutch buildings.

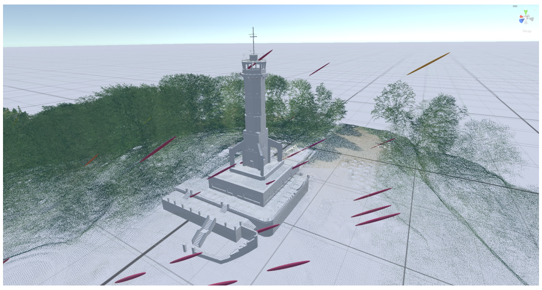


Figure 4.5: High-resolution BIM model of the Wilhelmina tower.

the azimuth, range and cross-range direction as can be seen in Figure 4.6. The pixel level estimations are visualized as cubes indicating 2σ confidence intervals, given uniformly distributed PDF's accross the resolution cell in azimuth and range, and a normally distributed PDF in the cross-range direction, as seen in Figure 4.7.

Based on the final size of the confidence interval, the scatterer is made more transparent when the uncertainty is higher. Additionally, the 3D resolution cell for each scatter is visualized, Figure 4.9, along with the Zero-Doppler plane, Figure 4.8, aiding in spatial understanding.

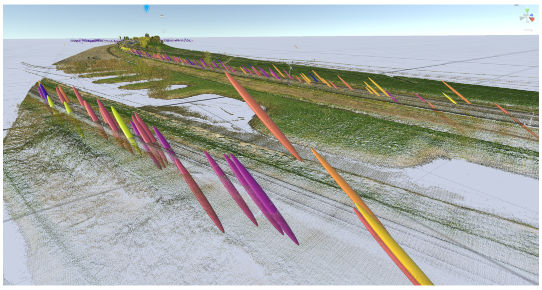


Figure 4.6: Confidence interval, subpixel position estimation.

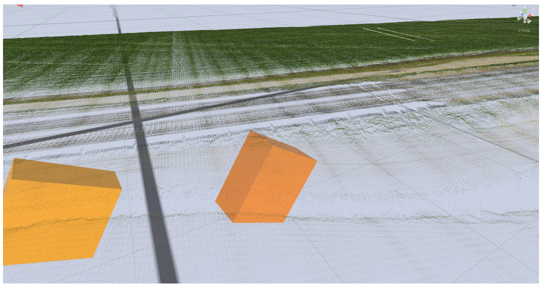


Figure 4.7: Confidence interval, pixel level position estimation.

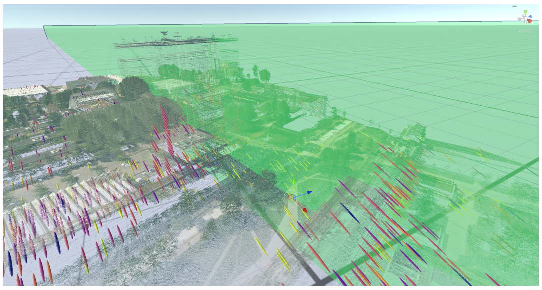


Figure 4.8: Zero-Doppler plane, perpendicular to satellite azimuth in transparent green color.

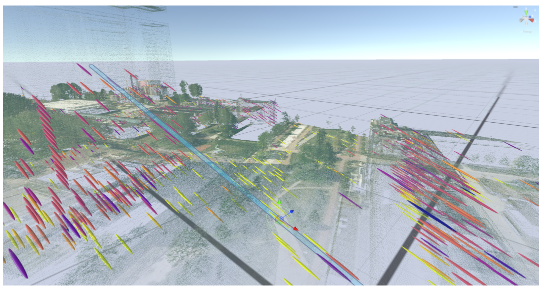


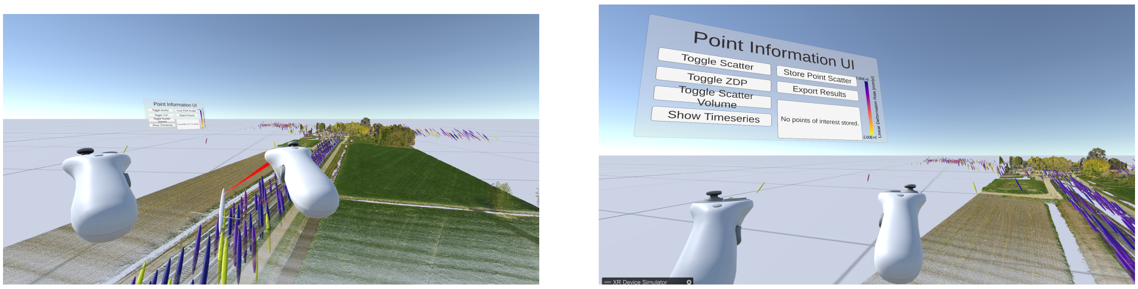
Figure 4.9: 3D resolution cell of a point scatterer in transparent blue color.

4.1.3. VR Interactions

The application includes multiple interaction methods in VR: Free navigation, point selection and an interaction menu. In the application users are able to fly freely through the scene using a VR controller. For the point selections, user can aim and select a point scatterer using the controller. These points are subsequently highlighted in white as seen in Figure 4.10a. Finally for the interaction menu a floating UI can be called after selecting a scatterer, see Figure 4.10b, offering six different options.

The first option, Toggle Scatter, enables the removal of selected points from the scene. The second option, Toggle ZDP, visualizes the Zero-Doppler plane for the selected scatterer. The third option, Toggle Scatter Volume, visualized the 3D representation of the SAR resolution cell. The fourth option, Store Point Scatter, saves selected points for further analysis and finally the sixth option, Export Results, exports the removed points and the saved points of interest in two separate CSV files containing the information corresponding to each point.

Finally the interface also includes a colorbar, corresponding to the linear estimated displacement rates and a list of stored points.



(a) Highlighted selected point. **(b)** UI menu for scatterer interaction.

Figure 4.10: User interactions within the VR environment, click here for a video.

4.1.4. Analysis Tools

The application includes two basic analysis tools, a time seriees visualization and a data export function. For the timeseries visualization a graph is created that displays the relative displacement over time for the selected scatterer as seen in Figure 4.11. Regarding the data export function, users are allowed to export points of interest or deleted points in CSV format for further analysis.

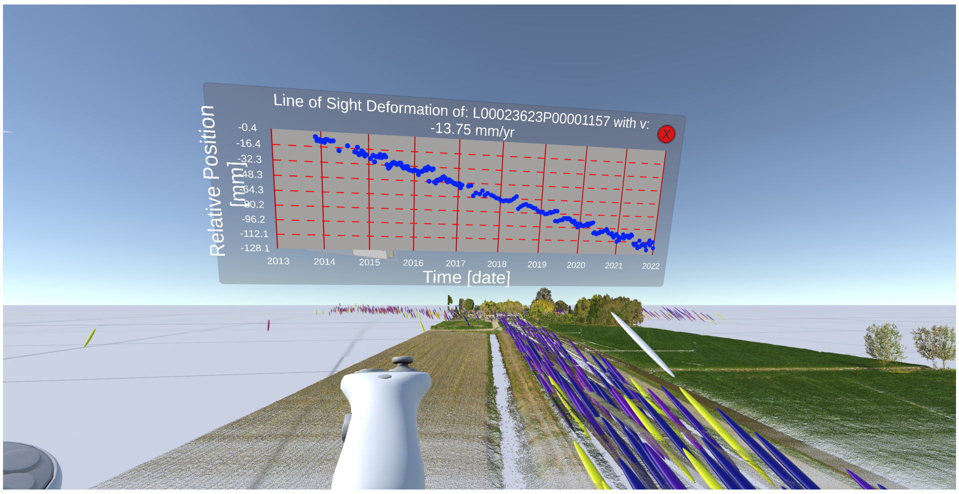


Figure 4.11: Time series of relative LOS displacement for a selected scatterer.

4.2. Evaluation Results

This section presents the evaluation results based on the expert interviews. It follows the order of the evaluation structure: First analysis methods and expectations from the pre-exploration interviews, secondly usability and interaction feedback, thirdly data interpretation and potential use cases, fourthly limitations and suggested improvements, fifthly observed differences between expert groups, and finally the researcher's own observations.

4.2.1. Analysis Methods and Expectations

The academic experts primarily focus on advancing InSAR processing methods and, as such, rarely engage in applied case studies. Consequently, they do not follow a standardized InSAR data interpretation workflow.

In contrast, industry professionals described workflows that vary depending on the project. Typically, their analysis begins with 2D color maps indicating linear displacement velocities across a broader area. They first scan for general displacement trends before zooming in on specific areas of interest. At this stage, individual time series are examined, often in rapid succession, and spatial analysis tools are used to average values across a region or compare scatterers. Two of the professionals used integrated online viewers for this process, which provided built-in tools for interpretation.

When scatterer position is critical, such as distinguishing between measurements from building tops versus ground level, analysts separate high and low points to infer the likely origin. This type of interpretation was often described as an iterative process, combining technical analysis with discussions with clients to assess the validity of observed deformation patterns. All experts indicated that reliance on 2D visualizations causes ambiguity in scatterer position and struggle to verify 3D locations. Experts also noted the importance of analyzing changes at multiple time scales.

Several experts emphasized that when the precise origin of scatterers is important, additional analysis is required, such as investigating reflection amplitudes related to specific surface materials. In contrast, in scenarios involving isolated structures within vegetated areas (e.g., towers in forests), the precise positioning of scatterers was considered less critical, since any detectable points were assumed to originate from the object of interest.

Despite differences in background, several shared expectations regarding a VR application emerged across the domain experts. The ability to perform quality control by identifying systematic errors in the datasets, the desire to mark anomaly prior to visualizing the data to quickly inspect these irregularities within the scene and finally tools for exporting selected points of interest after scene analysis. Specifically, the ability to mark anomalies in VR is important, since this allows the analysis of these anomalies in 3D with respect to the environment and enable the determination of whether they are anomalies or if there is a real problem in these locations.

One of the academic experts however, indicated skepticism regarding VR's added value, particular for more abstract, non-visual method development task, which they were working on.

4.2.2. Usability and Interactions

Most experts, four out of six, adapted to the application's user interface, controls, and navigation within 5 to 10 minutes. One expert with experience using game controllers adjusted especially quickly, describing the controls as intuitive.

However, two experts experienced motion sickness during or shortly after use. One reported immediate symptoms, while the other experienced discomfort after approximately 30 minutes, which significantly limited their willingness to use the tool. One person indicated it seemed to be linked to the flickering of the LiDAR point cloud.

Participants generally found it easy to select and interact with points. Difficulties arose only when scatterers were densely clustered or positioned slightly behind one another, making it challenging to select the intended point, which was indicated by two different experts. Aside from that, one expert found it specifically helpful that the controller gives haptic feedback when hovering over different scatterers.

Regarding the experience of using the application, two problems were identified by multiple experts. Three experts reported an issue, where due to shadow, the back side of scatterers were visualized in black, hampering the point selection. For the time series visualization, four experts indicated preferences for a millimeter scale and a symmetric color-map centered on 0 mm. The issue with shadows and millimeter scale, have been addressed in subsequent iterations of the VR application.

4.2.3. Data Interpretation and Use Cases

The application was regarded as a valuable tool for quality control by 3 experts. Two of the industry professionals, in particular, found it effective for identifying systematic errors, such as shifts in scatterer positions or unrealistic placement due to environmental constraints. Visualization tools such as the zero-Doppler plane and 3D resolution cells played a crucial role in understanding these issues, indicating the unrealistic placement of certain scatterers. One of the industry professionals immediately recognized faulty points in the TU Delft campus scene, where points were positioned at a location that was obscured by a large building from the satellite, shown in Figure 4.12.

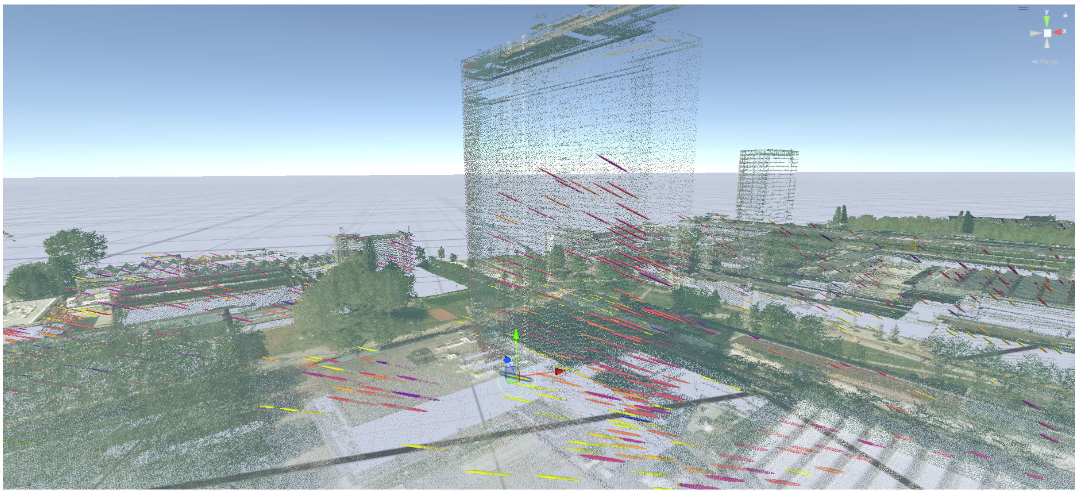


Figure 4.12: Unrealistic positioned scatterer, indicated by the blue, red and green arrows. It is obscured by the building from the LOS of the satellite and is therefore in an unrealistic position.

All experts agreed that being able to inspect individual scatterers in a 3D environment significantly improved their understanding of scatterer origin and behavior. The 3D resolution cell representations provided insight into which objects contribute to each pixel's reflection, helping experts evaluate whether multiple objects were contributing to noise.

One notable comment came from an industry expert analyzing the Wilhelmina Tower scene: the 3D resolution cells helped clearly identify cases where vegetation was interfering with InSAR measurements.

As for use cases, all experts agreed the application is particularly well-suited for small-scale investigations, such as studies focused on individual buildings, bridges, or quay walls. For larger areas, experts emphasized its value for internal quality control and exploratory analysis. However, three industry experts mentioned they would not use the tool directly with clients. Instead, they would extract visuals or recordings from the scene to communicate findings more effectively.

4.2.4. Limitations and Suggested Improvements

The most significant limitation identified was the application's ease of use. Several experts expressed that unless this improves, they would be unlikely to incorporate it into their workflow.

A key technical limitation is the current method of loading data into the application, which must be done manually. One industry expert recommended enabling direct streaming from a connected data server. Additionally, they requested the ability to load a standard metadata file to automatically adjust global visualization settings to suit each dataset.

Another major limitation is the absence of built-in spatial analysis capabilities, such as statistical tools for grouped selections or group comparisons. This was mentioned by three of the interviewees and noted as a critical gap, which would limit the applications use as a replacement for current analysis methods, though it was understood that time constraints prevented its implementation.

Based on the use of the application and their expectations, the interviewed experts suggested a number of improvements and additions to the application. For improvement, it was suggested that the rainbow color-map option would be provided by three experts, that the time series graphs would be automatically updates when different point scatterers were selected by two experts and to provide the ability to switch between grayscale and RGB for LiDAR point cloud colors by one expert.

Finally, additions that were requested were: the addition of ambiguity values to the time series graph by three experts, the ability to load in additional data subsets and highlight them in the scene by three experts, adjustable filter (e.g. by point quality) to refine data visualization by four experts, indications of the mother image in the time series and highlighting of the dataset's reference point in space by 2 experts, two experts requested the ability to switch between different environmental models at runtime (e.g. AHN 1 to AHN 5) and lastly two experts requested the ability to manually adjust scatterer positions to correct for systematic or processing errors.

4.2.5. Differences Between Expert Groups

A number of differences were observed between academic and industry experts.

Academic experts focused more on individual PS analysis and understanding the underlying causes of scatterer behavior. Their feedback emphasized technical clarity, methodological accuracy, and per-point analysis capabilities.

In contrast, industry experts prioritized workflow efficiency, ease of use, and practical communication with clients. They often viewed the tool as a means to support their own interpretation and then convey findings externally, favoring features that enhance speed, clarity, and data visualization over granular methodological tools.

These distinctions align with each group's working context: academic researchers typically work on a single case study at a time, while industry professionals handle many varied projects and client interactions.

4.2.6. Researcher's Observations

Several insights were gained during prolonged use of the VR application. The combination of the 3DBAG dataset and the AHN LiDAR point cloud proved to be complementary. While the 3DBAG model provides watertight and clean building geometries, particularly on vertical surfaces where AHN is often sparse, the AHN dataset captures detailed environmental features such as terrain and vegetation. This complementary relationship is illustrated in Figure 4.13.

For the LiDAR dataset from ProRail, no such sparsity was observed. Due to its high density and different acquisition method, it contained sufficient points even on building facades.

Throughout extended usage of the application, several scenarios were encountered in which the 3D visualization clarified the spatial positioning of point scatterers, insights that would have been difficult or impossible to obtain from traditional 2D visualizations.

For example, in the TU Delft campus scene, it was noted that a large building exhibited scatterers only up to halfway along its height. On closer inspection, it became apparent that the potential scatterers at the top of this building shared the same resolution cell with a neighboring building. The resolution cell intersected both buildings, and the algorithm assigned the scatterer to the lower building, with higher back scattering properties, as visualized in Figure 4.13.

Another observation was made in the scene containing the Wilhelmina tower, which displayed a noticeable number of point scatterers floating above the surface, as seen in Figure 4.14. These outliers can have multiple different causes, the lower resolution of the RADARSAT-2 data, the larger amount of vegetation in the area and processing errors for example. These outliers could be filtered by applying a quality threshold. However, several of these floating points exhibited high point quality values and would therefore have remained in a traditional 2D-based analysis. The VR interface allowed for intuitive, manual removal of such physically implausible points, thereby improving the accuracy of the interpreted dataset.

A similar advantage was demonstrated in the Betuwelijn case study, which used a RADARSAT-2 dataset provided by CGI. Here, the point cloud revealed a systematic elevation bias, scatterers appeared several meters below the actual ground surface, as shown in Figure 4.15. This type of systematic error is difficult to detect in 2D but became immediately apparent in the immersive 3D environment.

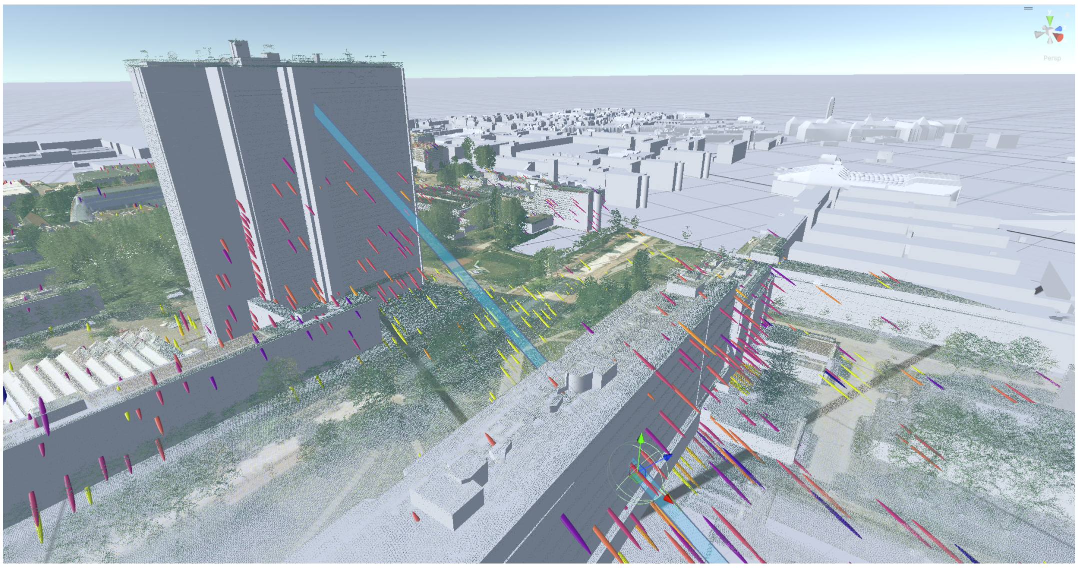


Figure 4.13: Resolution cell intersecting two buildings on the TU Delft campus. Click here to see video.

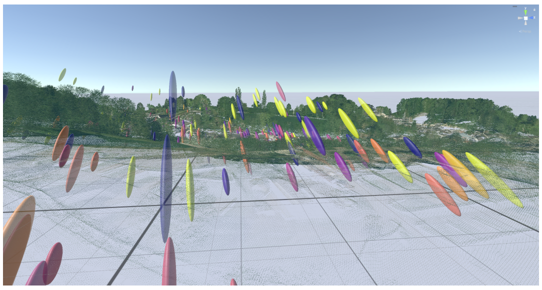


Figure 4.14: Floating point scatterers around the Wilhelmina tower. Click here to see video

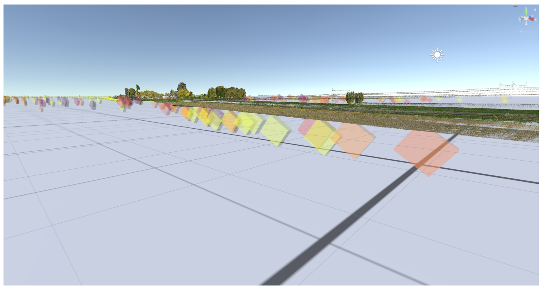


Figure 4.15: Systematic elevation error in RADARSAT-2 data for the Betuwelijn. Click here to see video.

5 Discussion

This chapter discusses the results of the research, focusing on both the development of the VR application and the outcomes of the expert evaluations. The discussion begins with the functionality of the application, followed by the interpretation of the evaluation results. These insights are then integrated into a broader reflection. Finally, the limitations of the research are addressed.

5.1. Application Functionalities

From the application overview, only the global settings window is discussed here, as it was specifically developed for this project. This component functioned effectively for loading data and selecting areas for visualization. However, multiple reviewers noted that manually entering the properties of each dataset is both time-consuming and error-prone. A potential improvement would be to enable the application to read metadata automatically and populate dataset parameters accordingly. When using standardized data formats, this enhancement would make the application easier to use and better suited for integration into existing workflows.

Multiple 3D contextual datasets have been and can be visualized in the VR application, e.g. LiDAR point clouds, 3DBAG and BIM models. They have however different strengths and weaknesses. Regarding the point clouds, there were two different sources used for the pointclouds. The AHN, which is a point cloud covering the whole of the Netherlands and the point cloud from ProRail, which covers almost all the railway tracks in the Netherlands. The AHN point cloud, is really useful due to it's large coverage and that it contains contextual information of both structures and vegetation, giving a clear overall image of an area, but the point cloud is relatively sparse, specifically on the facades of structures, due to the acquisition method. This results in less contextual information, for interpreting point scatterers on facades of structures. The point cloud from ProRail however, is much denser and covers the facades of structures well, but is limited to the area covered by railway tracks and it's immediate surroundings. Due to the density of the point cloud, it is also only possible to load in smaller area's at once. The second dataset, 3DBAG, contains 3D models/geometries for all the buildings in the Netherlands, which is useful, since it also contains simple geometries of the facades of buildings, which is missing/less visible in the AHN pointcloud. However a weakness is that these 3D models do not contain any texture or give information regarding the surroundings of buildings, which can be found in the LiDAR point clouds. Also, the geometries contained in this dataset are relatively simple and are not high resolution models of the buildings. If the LiDAR point cloud is not dense enough in the facades, it is a benefit to visualize it together with the 3DBAG. Then the strengths of both datasets complement each other and reduce their individual weaknesses. Finally, a BIM model only contains the geometry and associate information regarding a single structure. However, depending on the creation it can be a high resolution model of this structure, giving extra insight in the structure and it can also be textured giving information on materials. It is a benefit to use BIM models, when analyzing displacement of singular structures, e.g. the Wilhelmina tower, but it usefulness reduces when there is a need to analyze a larger area. In the future it might be interesting, to visualize photogrammetry datasets. Which contain both geometries as texture. Or the 3DNL dataset from Cyclomedia, which contains geometries and textures for a large part of the Netherlands.

Regarding the 3D visualization of PSI data, several aspects emerged from the evaluations. The use of confidence intervals to define scatterer shape clearly communicates the uncertainty in point location. Additionally, the geometry of the scatterer relative to the satellite is conveyed intuitively through the shape. A color map indicating relative linear LOS displacement velocity effectively highlights anomalous points and reveals deformation trends within a region. Transparency based on uncertainty helps maintain focus on high-confidence points.

Nonetheless, improvements are needed. Points with higher uncertainty and therefore larger confidence intervals can obscure more reliable data, even with transparency applied. A more balanced integration of size and transparency is required. For sub-pixel estimated scatterers, the underlying probability density function is normally distributed in azimuth, range, and cross-range directions. Currently, the 2σ confidence interval is visualized with a color based on velocity. Implementing vague regions using a color gradient, as described in chapter 2, could offer a more accurate spatial representation. The same concept applies to pixel-level visualizations, where a uniform distribution in azimuth and range often results in large, imprecise representations. A color gradient could indicate the locations where the scatterer originates from with the highest chance.

The Zero-Doppler plane visualization proved to be somewhat redundant. While the 3D resolution cell includes the same directionality as the Zero-Doppler plane, it also conveys additional conceptual information, such as incidence angle and scatterer contributions, that enhances interpretation, as seen in Figure 4.13. For example, in this figure, the absence of points on a tall building, despite consistent materials throughout, was initially confusing. Visualization of the resolution cell allowed the formation of two hypotheses: (1) the adjacent building, with superior back scattering characteristics, dominated the reflection; or (2) a low-resolution DEM caused inaccuracies at higher elevations. While data limitations prevented a full analysis, the first hypothesis seems more likely. This could be verified with amplitude data, which were unfortunately unavailable. Consequently, a feature to visualize average scatterer amplitude could be valuable for future versions.

A notable visualization issue is the positioning of the resolution cell. Currently, the scatterer is placed at the center of the cell. In reality, the scatterer is not necessarily centered. To resolve this, the pixel coordinates and the estimated scatterer position should both be maintained. This would allow the resolution cell to be visualized at the correct pixel location, with the scatterer positioned accurately within it. At present, while the scatterer is positioned correctly, the resolution cell is slightly offset.

Overall, the VR interactions were found to be intuitive and required little training. However, point selection remains difficult when points are partially obscured. A key missing feature is the ability to reposition scatterers to correct for systematic errors in processing, as illustrated in Figure 4.15.

Regarding analysis tools, the time series visualization was considered a valuable addition by multiple experts. Nevertheless, it requires improvement to enhance usability and insight. Features such as displaying higher and lower ambiguity time series could assist in identifying unwrapping errors, a common issue in InSAR results. Enabling dynamic updates, where selecting a new point instantly loads its time series, would streamline the analysis process. Although useful in their current form, the tools are still insufficient. Additional features such as spatial averaging, point grouping, and highlighting based on prior knowledge are essential for deeper deformation analysis.

5.2. Data Interpretation

Visualizing PSI data in VR provided significant insights into the origin of scatterers. Compared to traditional 2D or 3D visualizations, VR offers a more intuitive understanding of spatial relationships, depth, and scale. While conventional 3D visualizations projected onto 2D screens lose spatial information, VR allows users to interpret scenes more naturally and accurately.

Based on the evaluations, the application in its current form supports two main use cases: quality control and small-scale investigations of individual structures such as buildings, bridges, and tunnels. However, broader potential exists. As illustrated in the Betuwelijn case study, the tool can also help build confidence among non-experts. InSAR is often viewed with skepticism, as its opportunistic nature means that scatterer locations are not guaranteed. The VR environment can help users understand the spatial accuracy of measurements. In the Betuwelijn case, for instance, the precise alignment of scatterers along the railway and their absence in adjacent fields provided a compelling visual argument for data reliability.

Overall, VR-based PSI visualization facilitates in-depth analysis, cross-domain communication, and the integration of conceptual geospatial data across different scientific disciplines.

5.3. Limitations

While visualization enhances understanding, it is critical to consider the origins and properties of the PSI data. Satellite parameters, processing methods, and data preservation practices significantly influence visualization outcomes. Satellite resolution, incidence angle, and orbital geometry vary by location and acquisition track (ascending vs. descending), and these factors impact how data should be interpreted. Moreover, the shape of confidence intervals, whether cubic or elliptical, depends on the processing method. Using incorrect assumptions or metadata may result in significant misinterpretation.

Even within the datasets used for this thesis, certain assumptions were necessary. The standard deviations in azimuth, range, and cross-range were not preserved during data processing. As a workaround, a relation between baselines and amplitudes was used to approximate uncertainty, as detailed in section 2.1. However, this approximation is temporally dependent and does not accurately capture spatial relationships. Ideally, sub-pixel uncertainty should be derived from spatial relationships with neighboring points.

Usability constraints also exist. Currently, the application is limited in the volume of data it can visualize simultaneously. This is primarily due to the rendering load imposed by LiDAR data. Efficiency could be improved by implementing data structures such as an octree to dynamically adjust level-of-detail based on the user's position and line of sight. This would reduce system load and allow larger areas to be visualized. Another limitation with regard to usability is the ability to orient yourself in the environment. Currently, there is no indication of where in the environment you are located, meaning that unless you are already familiar with the scene it can be difficult to navigate through the scene.

Finally, the current requirement to manually load all data into the application increases the likelihood of user error. A better approach would be to integrate the application with a server capable of streaming data and automatically setting visualization parameters based on metadata. This would reduce errors, simplify the user experience, and allow the application to be compiled and deployed directly to standalone VR headsets, eliminating the need for a PC connection or Unity Editor.

6 Conclusion

As stated in the introduction, understanding ground deformation is critical for monitoring natural hazards, urban structures, and infrastructure. Synthetic Aperture Radar Interferometry (InSAR) plays a key role in this process, particularly through Persistent Scatterer Interferometry (PSI), which enables precise long-term deformation monitoring.

This research explored the potential of Virtual Reality (VR) as a tool for visualizing and interpreting PSI data. The goal was to design, develop, and evaluate a VR application that offers spatial insights into PSI data by integrating 3D contextual geometric information, insights that are difficult to obtain through traditional 2D or desktop-based 3D visualizations.

6.1. Research Question

The main research question to be answered was:

> ***"How can 3D contextual information be effectively integrated with InSAR in Virtual Reality to develop a dynamic 3D visualization that enhances the interpretation of InSAR results?"***

The research demonstrates that VR enables an effective and comprehensive visualization of PSI data by integrating 3D contextual information directly into the analysis environment. This is achieved through the incorporation of 3D geometries associated with PSI data, such as the Zero-Doppler plane and 3D resolution cells, as well as confidence intervals and spatial context provided by geometric data sources, including LiDAR, 3D models, and BIM.

By combining these diverse datasets into a unified VR environment, it results in an enhanced understanding of the spatial positioning of point scatterers, the likely origin of radar reflections, and the confidence associated with each measurement. VR's immersive capabilities provide a true sense of scale and depth, which improves insight into the 3D space in which scatterers exist. In comparison, while the static images included into this thesis effectively illustrate the integrated visualization of InSAR and conceptual data, they cannot fully convey the immersive depth and context that VR provides.

Compared to traditional 2D or screen-based 3D visualizations, this approach leverages more of the inherent spatial information present in InSAR data. For instance, the elevation of a point scatterer, typically underused or simplified in conventional workflows, becomes a key visual and analytical component in VR. This contributes to a more intuitive and holistic interpretation of PSI results. However, in regards to orienting and navigating yourself within the scene it is more difficult in VR without additional information or knowledge about the scene, while in 2D you immediately have an overview of the whole area.

To answer the main research question, several sub-questions were explored as defined in section 1.2.

1. What contextual 3D geometric information contributes to an improved interpretation of PSI data?

Throughout this study, various sources of contextual 3D geometric information were identified that contribute to improved interpretation of PSI data. Their primary role is to provide insight into the physical environment from which a point scatterer originates and the temporal context of the InSAR measurements.

LiDAR point clouds were identified early on as a valuable data source. In the Netherlands, high-resolution LiDAR data is freely available (e.g., AHN1 to AHN5), with coverage over multiple years. Since this LiDAR dataset includes color information, it can indirectly indicate surface materials and vegetation, both of which influence InSAR signal quality. However, due to the aerial acquisition method, LiDAR often lacks adequate coverage of building facades. This limitation was addressed by using denser point clouds provided by ProRail, which was also colored, but these, while freely available, only cover the dutch railway network and it's immediate surroundings.

Other valuable geometric data sources include DSM's and DEM's, which offer watertight surfaces instead of sparse point representations and capture the topography of an area. These were not implemented due to time constraints but offer potential advantages by eliminating gaps in coverage.

Additionally, 3D models such as 3DBAG and BIM's were identified as highly beneficial. 3DBAG is openly available and covers all of the Netherlands, while BIM provides detailed structural models suitable for in-depth analysis of specific individual assets, but needs to be created manually specifically for each structure of interest. Though only geometric elements were visualized in the current application, BIM's can contain metadata such as construction materials and historical modifications. Accessing this information within VR could significantly enhance cross-domain communication and interpretation of PSI data.

2. What attributes of InSAR data convey important insights for the interpretation of PSI data?

InSAR data includes several key attributes that aid in interpretation, which can be broadly grouped into geometric properties and measurement properties.

Geometric properties include the position of the point scatterer, the satellite heading, and the incidence angle. The position is critical for determining the reflection origin. Satellite heading and incidence angle define the observation geometry and are effectively conveyed using visual elements such as the Zero-Doppler plane and 3D resolution cells. These representations help explain scatterer placement and support error identification. Additionally, understanding SAR pixel size, upon which the resolution cell is based, is essential.

Measurement properties include the relative LOS displacement, estimated displacement velocities, point quality indicators, and amplitude values. Initially, focus was placed on the LOS displacement, velocities, and quality. However, during the study, it became clear that amplitude information is also essential, particularly in scenarios involving multiple potential reflection sources within a single resolution cell (e.g., Figure 4.13).

3. How can we combine and interpret InSAR datasets in a 3D environment, while accounting for uncertainties in the data?

A suitable way to incorporate uncertainty in a 3D visualization is through the use of confidence intervals. These intervals represent the spatial region within which a scatterer is likely located with a certain probability (e.g., 95%). Visualizing these intervals provides spatial context for positional uncertainty.

While integrating external datasets, it is important to consider their relative accuracy. In practice, the uncertainties associated with high-resolution 3D geometric datasets such as LiDAR or BIM are typically one to two orders of magnitude smaller than those of InSAR measurements. As a result, these datasets can be assumed to represent ground truth in the visualization context, allowing the focus to remain on InSAR uncertainty.

4. What functionalities are required in a 3D environment to interact with and interpret the data?

For effective interaction and interpretation of InSAR data in a dynamic 3D environment, several key functionalities are required:

- Navigation through the dataset and selection of individual scatterers.

- Access to measurement and geometric properties via visual overlays or interaction panels.
- Analysis tools for grouping points, conducting statistical evaluations, and correcting known processing errors (e.g., systematic offsets).

Equally important is the overall usability of the application. As highlighted in expert interviews, if a tool interferes with the workflow or is too cumbersome to use, it is unlikely to be adopted, regardless of its capabilities.

5. To what extent does visualization in Virtual Reality enhance the comprehension of PSI results?

Although it is challenging to quantify the exact degree to which VR enhances understanding, expert evaluations indicate that VR-based visualization provides unique insights that are difficult to achieve with conventional 2D or screen-based 3D methods. The immersive environment fosters intuitive data exploration and facilitates the identification of spatial patterns, positional errors, and reflection origins.

VR proved particularly useful for small-scale investigations (e.g., buildings, bridges, or tunnels) within a few square kilometers. On a larger scale, the visualization enabled efficient identification of systematic errors and anomalous points, enhancing overall data quality assessment.

For example, VR showed that for TerraSAR-X, most of the scatterers were fixed to physical objects in the environment, indicating accurate positioning, but for RADARSAT-2 data many points are floating in the air, unrelatable to physical objects. Thus the positioning for this satellite is much less precise than thought, which had previously been unseen using 2D visualization methods.

6.2. Research Contributions

This research contributes a novel method for visualizing PSI data that integrates uncertainty, geometry, and conceptual data into an immersive framework. It provides the foundation for a new method of spatial analysis of InSAR data, incorporating geo-spatial understanding with technical analysis. It also demonstrates VR's potential as a medium for cross-disciplinary communication. As stated in chapter 1 3D visualization has been done before, visualizing both LiDAR en PSI data, this research has expanded on this enabling a dynamic and interactive method of PSI analysis in VR, not just a 3D projection, going beyond visualizing the position of point scatterers in space. But accessing the geometric information inherent to InSAR data as well, e.g. 3D SAR resolution cells and Zero-Doppler planes, and allowing the interaction with them.

There are, however, a few limitations, which have been discussed in detail in chapter 5, including the reliance on complete metadata, the manual handling of data, and performance bottlenecks in the current implementation. Additionally, only a small expert group was interviewed regarding the use of VR for interpreting InSAR data, which limits the generalizability of the evaluation.

Despite these limitations, this study lays important groundwork for the future development of VR-based geo-spatial analysis tools. It shows that immersive environments can enrich interpretation by making abstract geometries more tangible, improving user intuition, and bridging the gap between geo-spatial expert and domain specialists. As such, the application developed in this research represents both a functional prototype and a proof of concept for future interdisciplinary tools in geospatial monitoring and analysis.

7 Recommendations

Based on the findings and limitations discussed throughout this thesis several recommendations are proposed to guide future development, research and practical implementations of VR for InSAR data visualization.

7.1. Suggested Usage

Despite the limitations discussed, the current prototype can already be applied in specific use cases. It is specifically well suited for: Small-scale spatial investigations, error identification and expert communication and training.

With regard to small scale spatial investigations, the application allows for detailed inspections of singular objects or small areas (e.g. critical infrastructure or buildings) if high resolution 3D models are available, such as BIM. For error identification, systematic errors and inconsistencies in point scatterer positioning can be visually assessed through the immersive environment, offering insights not easily seen in 2D tools. Finally, regarding expert communication and training, the VR visualization can be used to communicate PSI data to non-specialists or interdisciplinary teams, helping bridge the gap between InSAR analysts and domain experts in various fields, such as civil engineering, geo-technical engineering and earth sciences.

Users are encouraged to use the application in combination with traditional analysis tools for tasks requiring high precision or large-scale statistical comparisons, while leveraging VR for spatial reasoning, contextual awareness, and hypothesis formation. A prior analysis of PSI data can allow one to identify anomalous measurements and specifically visualize those points to verify their authenticity or whether they are outliers.

7.2. Technical Recommendations

To improve the application a number of technical improvements are recommended: Automated meta-data parsing, optimized data handling, data streaming and improvements in the analytical capabilities.

Regarding the automated meta-data parsing, a standard needs to be created for storing meta-data across different InSAR datasets and use this standard to automate the reading and parsing of meta-data to load in InSAR data, thereby minimizing the user error. For the optimization of the data handling, spatial data structures and level-of-detail techniques should be implemented, which would improve performance and scalability when rendering and visualizing large datasets. In regards of data streaming, by implementing the ability to load data directly from a server it will be possible to run the VR application independently from a PC and reduce the manual work required for visualizing data. Finally, regarding improving the analytical capabilities of the application, while the application in the current state supports PSI data interpretation in VR, several functionalities, such as spatial analysis tools (e.g. grouping of data and performing statistical analysis on them), point quality filtering and error correction tools are missing. Implementing these functionalities would aid the interpretation in VR.

7.3. Future Research Directions

To further improve the interpretation of InSAR a few further research directions are suggested: Multi-sensor integration, collaborative environments, workflow integration and augmented reality implementations.

Regarding multi-sensor integration, a more comprehensive analysis can maybe be achieved, by exploring the integration of other geo-spatial and sensor datasets in the current visualization (e.g. GNSS, optical imagery), which is applicable to for example the Integrated Geodetic Reference Stations (IGRS). Secondly, while in the current state, people can view what the user of the VR application does from a screen, to better communicate about results an investigation in multi-user VR environments for joint interpretation and decision making is an important research direction. Regarding workflow integration, a study on how VR tools could be embedded into operational PSI workflows to support real world monitoring and reporting is an important next step. Finally, an augmented reality implementation would allow InSAR to be projected in real-time on an environment and give insight in currently running processes and enable on site investigations with real-time environmental context.

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A

Interviews

In total six interview were held, with both academic and industry experts. Some of the sections in each interview will differ, since the interviews were held in a discussion format and sometimes different topics were discussed. First the academic interview notes will be given, then the notes from the interviews with industry experts.

A.1. Academic Experts

Three academic experts were interviewed in the process of this thesis. Here the notes taken during those interviews can be found.

A.1.1. Interview 1

Data processing

Expert indicated working on the monitoring of quay walls in Amsterdam as a case study, but was mainly focused on the recursive processing method for InSAR data. There was a high requirement in regards of the precision of the location of a point scatter, because normally the position is projected on a 2D map and there is always the uncertainty that the scatter is not a reflection of a quay wall and an inspection in 3D/Virtual Reality would help in understanding the data. Specifically, this expert looked toward a future where it is possible to visit the site in person and use Augmented Reality as a tool to project point scatters in the real world.

Expectations

The ability to mark anomalies in the scene and export them. And visualize points of interest based on prior knowledge, by for example having an notification of anomalies at certain epoch at a certain location and highlighting these anomalies in the scene for easy identification and visualization.

Viewed Scenes

Three scenes were experienced by this expert. The TU Campus, with TerraSAR-X data, for which there was no comments made. The Wilhelmina tower, with RADARSAT-2 data, it was noticed that there were multiple point scatters located in the sky, for which there was no explanation at that point. And finally, the Betuwelijn scene, with TerraSAR-X data, it was noticed by the expert that the mother epoch/image was not at the start of the timeseries. Resulting in the recommendation to add an indicator in the timeseries graph, which corresponds to the mother epoch. Other recommendations based on the scene were to change the unit of the timeseries graph from meters to millimeters, to add the model used to estimate the timeseries to the graph view and make clear how the date is formatted in the label of the x-axis.

VRInSAR Usage

After half an hour, the expert still needed to get further used to the controllers and function usage in VR. The expert however did indicate that the VR visualization gave much more insight in the origin of point scatters and confidence in this position.

Missing features
A number of features were found missing by this expert. The highlighting of points of interest based on prior knowled, by providing a list of points of interest and visualizing them with a marker in the scene. And highlighting points based on their inherent properties.

Other comments
Regarding the accuracy of the 3D resolution cell, if point scatters are processed at sub-pixel level, their position would not be in the center of the 3D resolution cell.

A.1.2. Interview 2

Data processing
This expert mostly does not work on case studies and primarily works on the improvement of processing methods, while applying the methods to individual case studies, no interpretation is done with regards to the results that come from this. It is done to check whether the improved methods can be used. This experts works on improving the stochastic model, functional model and network used to process InSAR data.

Expectations
This expert indicated to be slightly skeptical regarding the use of VR in the interpretation of PSI data. The methods that this expert works on, do not work on sub-pixel level estimates and only calculate cross-range and other variables across the whole resolution cell. It was indicated that before going deeper in the interpretation of the data using VR, more steps are needed. On the other hand the expert expected that for a InSAR product user/analyzer, it would be useful to see the exact position of scatters in 3D/VR for the analysis and instantly seeing some behavioral properties, timeseries and velocities.

VRInSAR Usage
The expert found the ability to visualize both sub-pixel and pixel level estimates very good, with logical shapes used to visualize each. Overall the expert quickly got used to the controls within 5-10 minutes and was impressed by the visualization, indicating the increased spatial insight it gave regarding the data.

The most useful functions in the application according to this expert, were the visualizations of the time series in combination with coloring the different point scatters at their precise location based on their estimated velocities.

Improvements
The expert noticed that due to shadows, one side of each visualized point scatter was fully black. This needed to be fixed, aside from that scatters with a large uncertainty were visualized as larger points, obscuring the smaller point scatters with a higher confidence. Finally, it was noted that the units needed to be changed from meter to millimeter.

Missing features
Three features were named, which the expert missed. The addition of ambiguity in the timeseries visualization, The addition of the fitted model to the timeseries and finally, being able to instantly see differences between 2 scatters through some comparison functionality.

A.1.3. Interview 3

Data processing
This expert mostly worked with Distributed Scatters, but for the processing uses a network of point scatters, which are used for atmospheric correction of the distributed scatterers. Aside from that this expert processes a lot of point scatters, but does not use them or check them for quality. But shares them with colleagues.

Expectations
Being able to correctly see the position of point scatters and able to access it's properties by interacting with them.

VRInSAR Usage
The applications use quickly caused dizziness and nauseousness to the expert, due to the flickering of the LiDAR point cloud in the scene. Aside from that the controls were easy to understand and the expert quickly go used. The expert indicated by being able to see the point scatters in a 3D environment they give a much better understanding about what happens to a specific point scatter.

Improvements
The expert indicated that the units should be changed from meters to millimeters and the colorbar should be centered around 0, using a diverging color-map like rainbow. Aside from that the expert indicated that the shadows on point scatter, caused them to be black, when looking from specific directions. Finally a configuration file should be added for each dataset, which can be read to automatically fill in the global setting of the application.

Missing functionality
The expert indicated that the spatial reference point should be indicated in the visualization and that there should be an option to highlight prior identified points of interest in the scene, by loading them in separately, though a beacon or other methods.

A.2. Industry Experts

Three Industry experts were interviewed in the process of this thesis. Here the notes taken during those interviews can be found.

A.2.1. Interview 1

Data Analysis
This expert indicated to have worked on multiple different projects using InSAR. And that per project there were different requirements, regarding the accuracy of the position of point scatters. But almost always there was a need for a better positioning and current this expert used different methods to pinpoint where a point scatter originated, using back scatter properties of materials to identify the origin of scatters. It however proved difficult sometimes to convince a client of the results, without improved visualizations.

Expectations
The expert expected, that by using VR, it would be possible to move through a scene and view the scene at different times, by changing the environment. That associated geometries, such as a resolution cell, could be viewed and used to identify obstruction and intersections of objects within the same scatterer. To be able to see multiple datasets at the same time, both descending and ascending and identify intersecting scatters of these datasets, which would enable the decomposition of the LOS measurement in multiple directions.

Viewed Scenes
Three scenes were viewed by this expert. The TU Campus, with TerraSAR-X data, for which no comments were made. The Wilhelmina tower, with RADARSAT-2 data, here it was commented that the 3D resolution cell was really usefull. It gave indications on what can be seen in the SAR image in different season, with vegetation growth during the different seasons in the surroundings affecting the InSAR data. This location is surrounded by forests. Finally, the vibration of controller, was useful to indicate whether a point scatter could be selected. In the Betuwelijn scene, both TerraSAR-X and RADARSAT-2 data were visualized. Here it was noticed that the overlapping confidence intervals from different datasets, ascending and descending, gave extra insight in the deformation of specific objects. Allowing the decomposition of the measurements in multiple directions, due to the different viewing geometries.

VRInSAR Usage
After half an hour of use the application started causing dizziness in the user. Aside from that after 10 minutes user got used to the controls in the application. It was indicated that the VR visualization gave increased spatial insight in the InSAR results and was better able to understand the scene. The expert would however not share the application with clients and would prefer to create snapshots from the

scenes to indicate specific information and use those to inform different clients about the result. While the application is limited in it's current form, it was indicated that already it would improve the analysis and if the expert had access, they would use it.

Missing features

A few missing features were indicated as necessary by the expert, the ability to filter the dataset based on point quality, from within the scene and to have a color-map centered around zero for the displacement rates. Aside from that, indications of the mother epoch in the timeseries and the spatial reference point in the scene were requested. Finally, it was wished that different epochs of the dataset could dynamically be removed or added to the dataset and subsequently immediately refitting the model.

A.2.2. Interview 2

Data Analysis

This expert explained his current process of data analysis as an iterative approach. First, together with clients it is determined what data and information is needed to answer their problems using InSAR. Then the timeseries of different scatters in the area of interest are individually analyses and through conceptual information it is attempted to identify the processes behind the movement of scatters. After this initial analysis, higher resolution DTM's are used to separate point from the terrain and identify points on the surface and on top of constructions, for a more detailed analysis. The analysis is performed using a 2D viewer, which has a few functionalities, such as area average of selected sections of the data. Through this viewer, systematic errors are identified in the horizontal plane. The elevation component is then mostly ignored. It was indicated that not always a precise point location was necessary, they had a case, where objects were monitored in the middle of grass fields. This meant that all scatters found in the surrounding area, had to originate from this object, since point scatters cannot be found in vegetation, due to de-correlation. Finally orthophoto's are used to identify changes over time in the scene, in their analysis.

Expectations

The main expectation this expert had, was to be able to use the application for quality control of InSAR datasets, being able to identify systematic errors or processing error and finally moving the point scatters to correct these errors. Not just in the cross-range direction, but also in the azimuth and range direction. Aside from that, it depended on the intended purpose of the tool, whether it should replace 2D viewers or be an additional tool aside from the viewer. If it needs to replace the original viewer, it was expected to have functionalities, such as point aggregation, quick analysis of timeseries etc. Else, as additional tool it was expected to use it in studies where the 3D position has a large impact on the interpretation and again using it for just quality control.

VRInSAR usage

The application allowed the expert to instantly identify incorrect points, validating his expectation regarding tusing it for quality control. Aside from that it was a benefit to be able to recognize whether a point is from a descending or ascending dataset instantly in the visualization, through it orientation. The navigation felt intuitive and was quickly understood. Overall the visualization gave a better spatial understanding of the data.

In the current state the expert indicated he would mostly use the application for quality control purposes and internally for analysis of specific areas. But would not share the application with clients, thinking it might cause confusion for those with less understanding of InSAR.

Improvements

The expert requested a number of improvements of the application, the ability to instantly generate a new timeseries when selecting different point scatters, instead of needing to press show timeseries again. The removal of shadows causing black point scatters, when viewing from certain directions. Addition of a symmetric colorbar centered around 0. Preferably, the rainbow color-map and in millimeters instead of meters. Function to make models transparent, to identify point scatters within them. Increasing the point size of LiDAR points. Adding the ambiguity bands in the timeseries. And finally an option to change the color of the LiDAR point cloud to grayscale, for better visualization of the point scatter colors.

Missing features

Aside from that a number of features were missing, the ability to switch between different LiDAR datasets, such as AHN1 to 5 from within the scene. The ability to filter the data visualization based on point quality or temporal coherence. And to be able to select an area of interest, for which you then can quickly go through the different timeseries and properties and have some statistical analysis performed.

Before being to use the application in more projects, these features and improvements have to be implemented. But then the experts sees a future in which across a large are, problem cases can be identified and then using the VR application to zoom in on these problem locations to analyze them.

A.2.3. Interview 3

Data Analysis

This expert indicated they worked on the 3D analysis of InSAR, but they did that by creating 3D models from DEMs and draping point scatter across the surface, thus through this ignoring the elevation component of the point scatters them selves.

Expectations

This expert indicated not to have any expectations for VR analysis, but was mostly interested in the performance of the application.

VRInSAR Usage

The expert got used to the controls within minutes, but feels that the UI trigger and grab button should be switched. For the visualization, the expert found it very useful to see point scatters intersect each other from different tracks. This gave extra insight into the deformation of these objects that were reflecting, by enabling the decomposition of LOS displacement. The ability to export points of interest and remove data points were appreciated. And he felt using this application, he could increase the confidence of clients in InSAR methods, be being able to show exactly where data is generated from and indicating the origin of scatters. He also indicated that in comparison of snapping to LiDAR method, which is a relatively black box approach to moving scatters. Being able to visualize points and moving them based on geometries and insight gives much more certainty in fixing positioning of InSAR data, even though that is currently not possible.

Missing features

The experts indicated a number of missing features, the ability to filter based on point quality, the ability to create a screenshot from within the application, to generate images for reports and the ability to manually move the position of point scatters. Finally, the application would improve a lot if the data would be streamed through a server, giving access to larger datasets and improving the ease of use.

The expert indicated that to encourage the use of the application, it should be easily accessible and take minimal time to setup. Preferable data access is automated and you only need to wear the headset to instantly have access to all data. Additional steps will reduce the use of the application by analysts, when they have access to other tools that are faster to use and setup. For example an online viewer, even if that would only be in 2D. Finally, it was noted that the highest resoltion LiDAR point cloud is unneeded, meaning the performance can be improved by reducing the point cloud density.

B

User Manual

VRInSAR instruction Manual

This document describes how to install and use VRInSAR. VRInSAR is the current name of the project/application to visualize InSAR data in Virtual Reality.

Requirements

1. PC/Laptop Recommended
    a. 16GB RAM
    b. Windows 10
    c. VR ready graphics card (NVIDIA GeForce GTX 1060 or greater)
        i. This was created with an NVIDIA GeForce RTX 2060 (laptop)
2. VR Headset Recommended
    a. Meta Quest 3
        i. Meta Link Cable
        ii. Controllers
    b. Other VR headsets that support *Open XR* should work, but are not tested.
    c. There is a headset simulator in the application, to test the software without a VR headset.
3. Data Requirements
    a. InSAR data in .csv format
        i. Important column names: [“pnt_id”, “pnt_rdx”, “pnt_rdy”, “pnt_height”, “pnt_linear”] and date columns in the form of “d_yyyymmdd”. For example “d_20150703”. These represent the point id, x, y and z coordinates and the linear estimated Line of Sight deformation rate.
            1. It is possible to use alternative names, the column names need to be set in the global settings window in Unity, usage step 2.g.
    b. LiDAR data in .LAZ , .LAS or .ply format
    c. Different 3D datasets needs to be georeferenced in the correct cartesian coordinate system, for the Netherlands that is EPSG:7415, and be in .obj format.
    d. 3D BIM models need to correctly georeferenced, for the Netherlands that is EPSG:7415, and exported in .ifc format.
        i. It seems that exporting through Civil3D maintains the correct georeferencing when importing the model in Unity. Revit gave problems, other programs were untested.

Installation

1. **Download/Retrieve Files**
    a. Download and store the VRInSAR project folder locally.
        i. This is a .zip file, which needs to be unpacked. Inside is a folder which is loaded into unity in installation step 3.b
    b. Download and store the Python script locally. This script is used to prepare the InSAR data.
        i. Data_preparation_1.ipynb
        ii. Data_preparation_2.ipynb
    c. Create a python environment containing the following packages.
        i. numpy
        ii. pandas
        iii. os
        iv. laspy
        v. pyproj
    d. Download and Install CloudCompare. www.cloudcompare.org
        i. This was done in cloud compare version 2.13.2.

2. **Install Unity Hub.**
    a. To use VRInSAR, Unity hub needs to be installed. Unity Hub can be downloaded from: https://unity.com/download
    b. An educational license can be requested for unity from: https://unity.com/products/unity-student
    c. After installing Unity Hub and logging in, an editor needs to be installed from within Unity Hub. On the left panel click on installs and then press Install Editor on the top right corner. Select the editor version 6000.0.40f1 LTS VRInSAR is created on this version. If it isn't in the list, go to Archive and visit the download archive. Here you can download the version needed and install it.

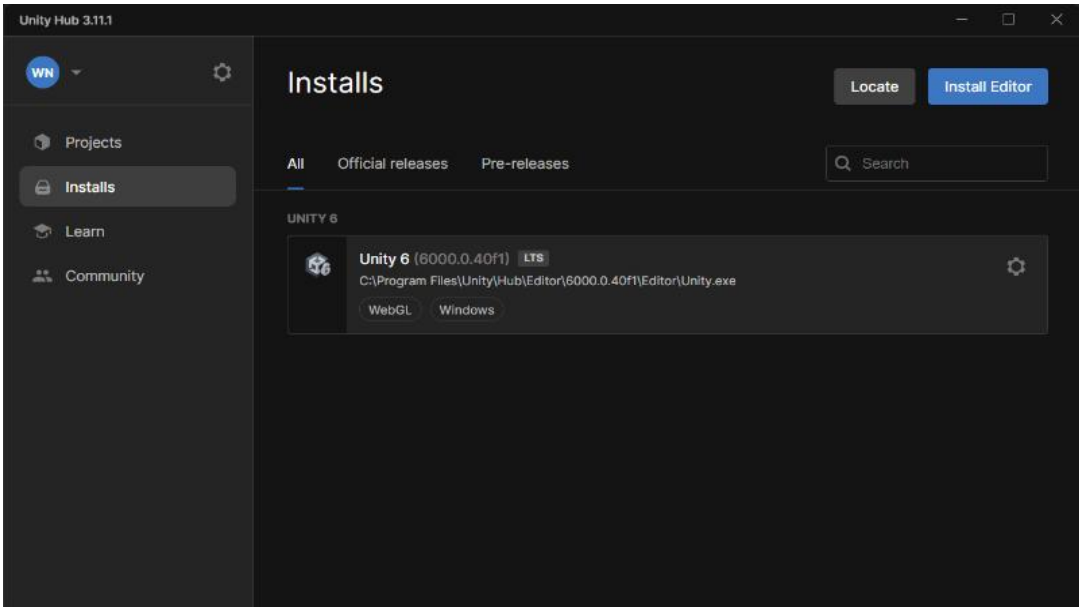

Figure 2

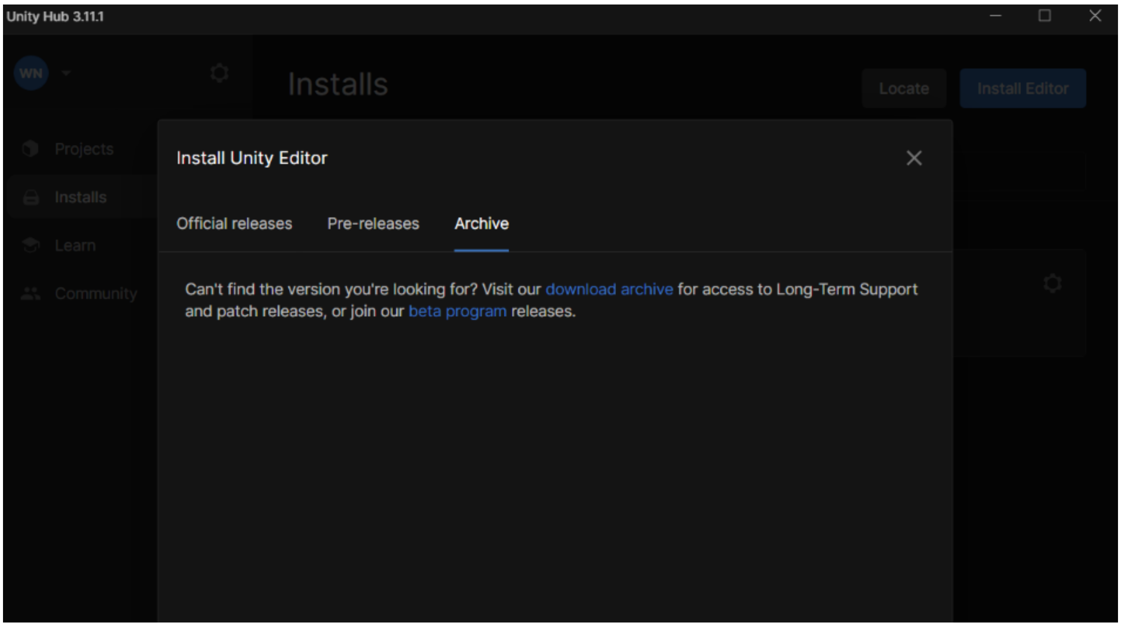

Figure 1

3. **Open VRInSAR project**
    a. After installing the editor, go to Projects in Unity Hub and click on Add → Add project from disk.

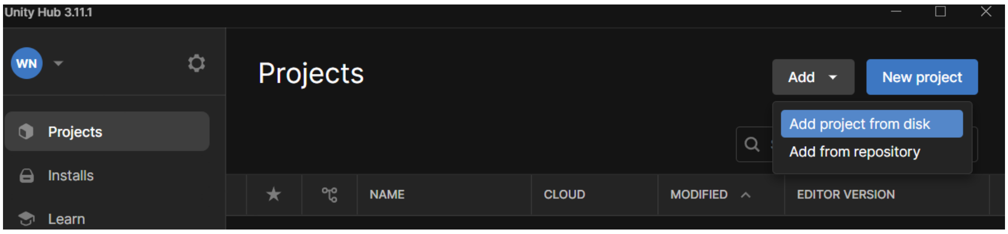

Figure 3

    b. Select the VRInSAR project files and open.
    c. Finally start Unity Editor by double clicking the project in the Unity Hub window.

4. **Install Meta Link and Optionally Steam VR.**
    a. Download the Meta Quest Link application to be able to connect the meta quest headset to your pc and install it, this is needed to connect with the Meta Quest 3 headset. [Getting started with Meta Quest Link App | Meta Help Centre | Meta Store]
    b. *Optionally Install Steam, depending on the computer it works directly with Meta Quest Link.*
        i. Download and install the Steam application. In this application the necessary software can be found to connect the VR headset with Unity. [Steam, The Ultimate Online Game Platform]
        ii. Start up Steam application and search for Steam VR. Install Steam VR. This will allow the VR headset to communicate with Unity.

Usage

1. **Process the data.**
    a. Open the python notebook *Data_prepraration_1.ipynb*
    b. Set the variables *path_insar* and *path_store* to the folder where your InSAR data is stored and where you want to save the modifed data, then run the script. This script will enrich the InSAR data and transform the coordinate system to the same coordinate system as the LiDAR data.
    c. Store the Lidar data (.LAZ) in a folder together with the csv's containing the InSAR data.
    d. Create 2 subfolders, named:
        1. Processed
        2. Switched
    e. Open the python notebook Data_preparation_2.ipynb
    f. Set the path to the insar data and lidar data, this script will clip the InSAR data to the extent of the LiDAR point cloud and name the created files correctly. The results will be stored in the processed subfolder.
    g. Open Cloud Compare and load in the LiDAR point clouds
    h. Select the point cloud and use apply Transformation. Using the following transformation:

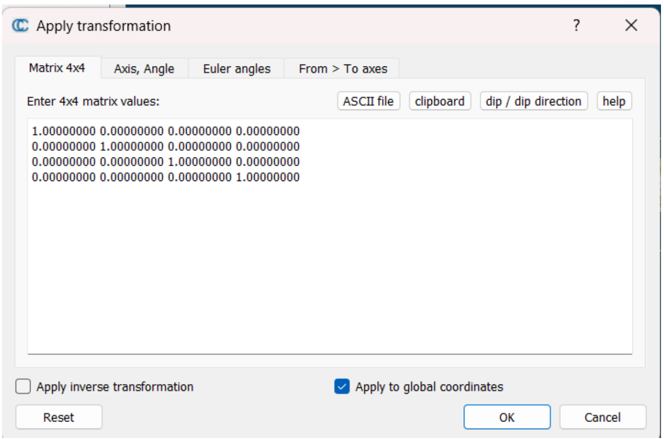

Figure 4. Transformation

    i. Save the file again as type PLY mesh (*.ply). Change the name of the file to: (…*_switched.ply*)

2. **Load the data into Unity.**
    a. Open the VRInSAR project in Unity Hub. It will look similar to this.

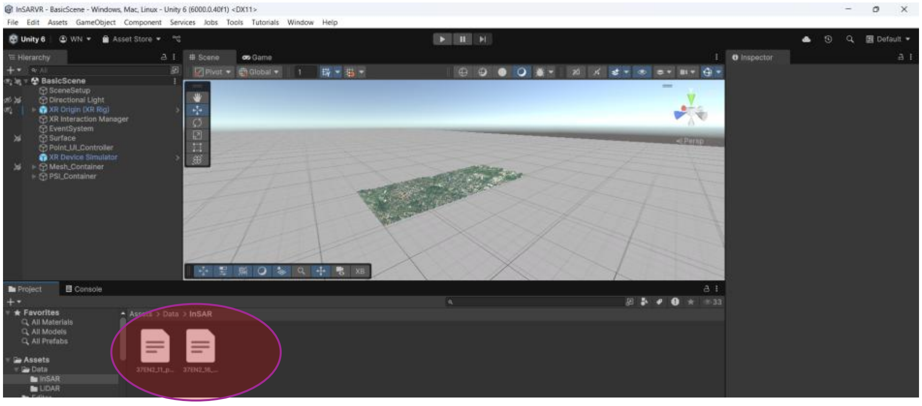

Figure 5

- **b.** In the project folder on your screen, go to Assets→Data→InSAR. And drag the csv files with the processed InSAR data to this folder.
- **c.** Then go to Assets → Resources → LiDAR and drag the …_*switched.ply* file containing the LiDAR data to this folder. This can take a few minutes.
- **d.** In the Hierarchy window click on SceneSetup, this will show additional information in the Inspector window.
- **e.** In the inspector window fill in the Csv File Path, toward the stored InSAR data. As shown in figure 6.
- **f.** In the top bar, click on Tools → Global Setting. Drag the window to the top of the Inspector window and let it snap in place.
- **g.** In the Global Settings window click on Global Settings Asset and select GlobalSettings. As shown in figure 7.
- **h.** In the global settings the scale of the scene can be set. Recommended to be 0.1 or 0.01. And set the original name of the Area of Interest. (The name of the original LiDAR data) This will set the dataset to be loaded into the scene.
- **i.** Then adjust the range of linear rate in the Global Settings window, when not ticked it will take the maximum and minimum displacement rates for the InSAR dataset.
- **j.** Then select the visualization mode, by default it looks for data named AREAOFINTEREST_processed.csv. But if separate datasets for ascending and descending exist, you can tick either one of those and it looks for data named AREAOFINTEREST_dsc_processed.csv or AREAOFINTEREST_asc_processed.csv. Finally, it possible to have an alternative dataset name, which can be set manually when ticking alternative dataset.

k. In the global settings, it has to be indicated whether the dataset is estimated on the sub-pixel level position or only on pixel level position. This will result in different visualizations of the point scatters.

l. Under Data Names, the column names used by the InSAR data for different properties can be filled in, to let Unity find the correct data in the csv files.

m. Under Default Data Values, a number of default values can be filled in to account for missing information in the InSAR data. Here also the pixel spacing of the mother image has to be filled in for each InSAR dataset.

n. Finally click the Reload and Visualize button in the Global Settings window, this will load in the InSAR and LiDAR data.

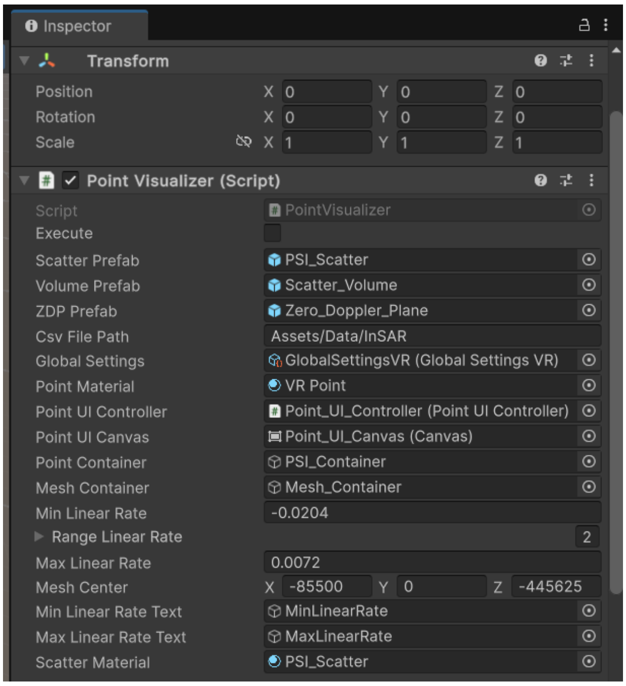

Figure 6. Inspector window

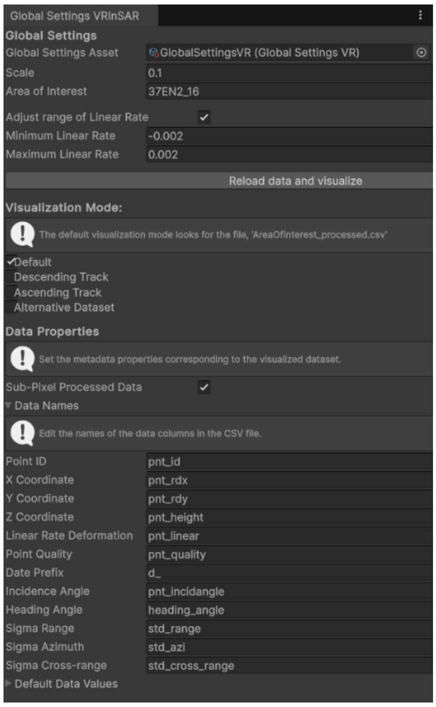

Figure 7. Global Settings

3. **Load the 3D data into Unity.**
   a. For 3D models, drag the model in .obj format to Assets → Data.
   b. Then from this folder drag the object into the Model_Container in the Hierarchy window, as shown in figure 8.
   c. Then to position the object correctly in the scene, select the MoveModelInScene object in the hierarchy window and in the inspector move the 3D object from the hierarchy to the Target Model field, as shown in figure 9.
   d. Then select the Is BIM_IFC flag and click execute. The object will automatically be loaded into the scene.
      1. If incorrectly georeferenced, the model needs to be manually repositioned in the scene. Still use the MovelModelInScene object, to correctly rotate and scale the model.
   e. For BIM models in the .ifc format, after loading the model using the plugin stated in the Notes section, repeat step 3.c and 3.d.
      1. If incorrectly georeferenced, the model needs to be manually repositioned in the scene. Still use the MovelModelInScene object, to correctly rotate and scale the model.

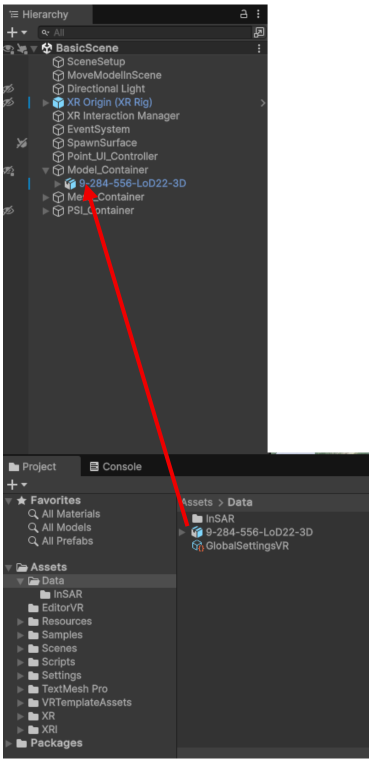

Figure 8

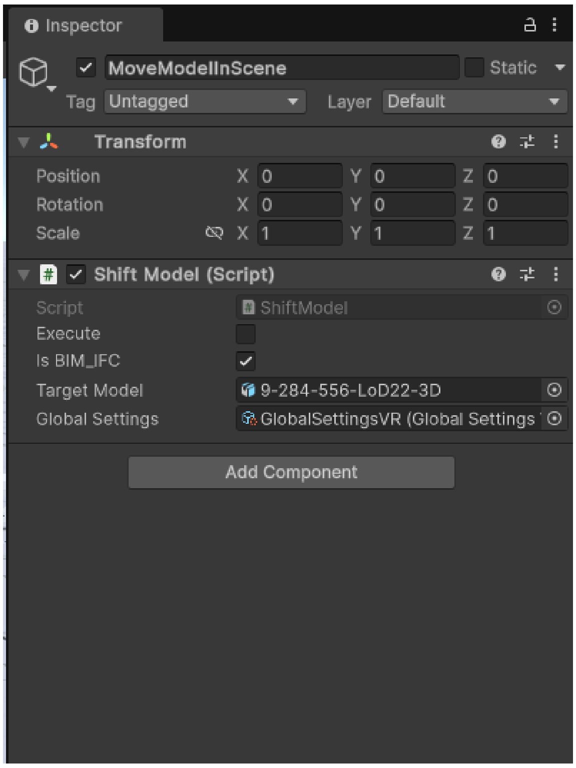

Figure 9

Run it in VR.

1. Start Meta Link application and connect the VR headset to the pc, with the link cable. Optionally: Start Steam VR.
2. When Meta VR recognizes the VR headset you can start up the VRInSAR project in Unity and press the play button at the top of the window in Unity.
3. Use the headset controllers to move around and the buttons to select the point scatters or interact with the UI.

VR Controls

Figure 10. Controller Scheme

Run it without VR headset.

1. In the Unity project window go to Assets → Samples → XR Interaction Toolkit → 3.0.7 → XR Device Simulator. Then drag the XR Device Simulator from the folder to the Hierarchy window. See figure 7.

2. Press the play button at the top of the screen. You can use keyboard and mouse to control the character. In the game view, a small window opens with the controls for the XR device simulator.
3. Maximize the game window, top right of the window, for a better view.

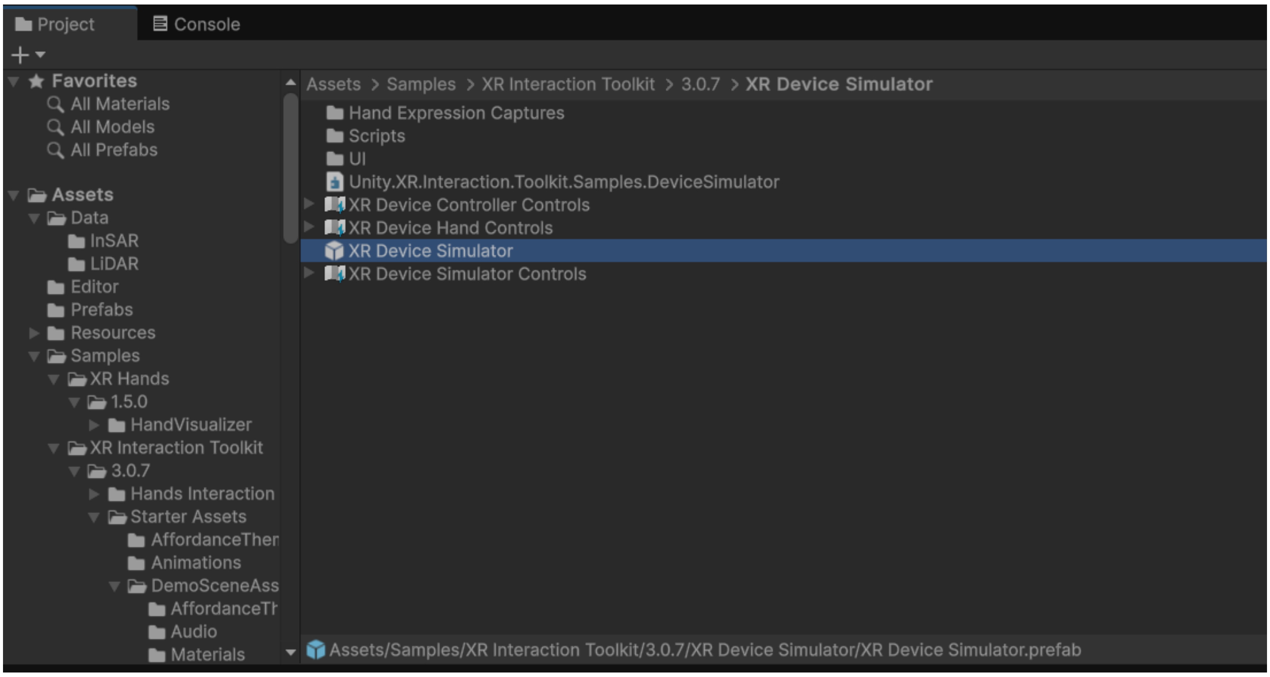

Figure 11

Notes:

1. Currently only LiDAR point clouds and InSAR data with cartesian coordinates can be used it will not work for spherical coordinates such as WGS84.
    a. It works for EPSG 28992, Amersfoort / RD New. But should also work for different cartesian coordinates systems.
2. 3D BIM models in the .ifc format can be imported using the following plugin if they are georeferenced correctly, however if georeferenced incorrectly it will need to be dragged manually.
    a. [Chair-Intelligent-Technical-Design/IFC-Unity-Editor-Plugin: Load IFC files during design time into unity.]
    b. Download LiDAR data for the same area, to check if the BIM overlaps with the LiDAR data. Also since VR InSAR uses the LiDAR mesh for positioning this is needed. In the inspector window you can manually disable the LiDAR mesh after loading it in, which will make it invisible in the scene.