NASA DEVELOP National Program
Georgia – Athens

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Unalakleet Climate
Analyzing Permafrost Degradation and Drainage Networks in Unalakleet, Alaska

DEVELOP Technical Report
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1) **The Tech Paper page limit is 10 to 12 pages**. This excludes the cover page, references, and appendices.

2) If your team is interested in publishing your project in a specific publication outlet (like an academic journal), you can write your tech paper using the style guide for that publication. Contact the Project Coordination Team first and gain approval to do so. You must have identified a journal you would like to submit to before notifying the PC Team.

3) Write in past tense and use **active voice** as much as possible. There are some instances where you can only write in passive voice – that is okay, but it's DEVELOP's preference to write in active voice whenever possible.

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1. Abstract

The coastal community of Unalakleet is currently the eighth most at-risk community in Alaska to the adverse effects of climate change that include permafrost degradation, severe coastal erosion, and flood inundation from increasingly frequency of storm surges and sea level rise. In response, the community has started a managed relocation with support from the Native Village of Unalakleet (NVU) and the National Renewable Energy Lab (NREL)'s Fairbanks, Alaska campus. The Unalakleet Climate NASA DEVELOP team has partnered with the NREL's Alaska Campus to provide analysis for resilience planning in Unalakleet, supporting their ongoing relocation efforts and guiding future expansion. The team used Sentinel-1 C-Synthetic Aperture Radar (SAR), WorldView-2, and WorldView-3 datasets from 2017 – 2023 to analyze permafrost degradation and used a 2014 Ancillary USGS 5 m Alaska DEM to perform drainage network analyses including watershed delineation and Height Above Nearest Drainage (HAND) analysis. The team's end products included maps containing permafrost degradation and drainage zones information at and surrounding the designated relocation site. The team's work provides NREL with seasonal subsidence data and drainage information surrounding the community, in order to better assist Unalakleet's managed relocation. The data helps Unalakleet adapt to the catastrophic effects of climate change and build resilience in a community on the front lines of climate change.

Key Terms

Alaska, permafrost degradation, subsidence, InSAR, drainage networks, HAND, remote sensing, resilience planning

2. Introduction

2.1 Background Information

Climate change poses unique challenges to remote coastal communities, such as the Native Village of Unalakleet (NVU). NVU is situated in Western Alaska, bordered by Norton Sound to the west, and the Unalakleet river to the southeast. Due to its location, it is experiencing increasingly frequent, intense impacts of climate change including permafrost degradation, melting-induced flooding, coastal erosion, and sea level rise (USACE, 2019). The city is located on a 4-mile-long gravel spit, situated approximately 14 ft above sea level. However, the current rate of erosion of ~2 feet per year from the Unalakleet River poses a significant threat to the longevity of NVU's existing infrastructure (USACE, 2019). This has forced the community to plan and carry out a relocation ~1.5 miles northeast to a prospective location at the base of the Nulato Hills (shown in Figure 1.). For centuries, the people of Unalakleet, which currently number ~800 permanent residents, have relied on the ecosystem for their subsistence due to an abundance of hunting, fishing, and gathering opportunities in the region. The Unalakleet River is known for the multitude of salmon species that spawn there and the caribou, ptarmigan, oogruk (bearded seal), and various bird species that are vital for recreation and subsistence hunting. The native residents of Unalakleet also rely on gathering salmon berries, blackberries, sour dock, duck eggs, and many others from the surrounding landscape (USGS, 2004). This ecosystem, and thus its availability of resources, have been severely impacted by permafrost degradation, and coastal and riverine erosion, as habitats are degraded along with loss of access to hunting grounds. Furthermore, the indigenous people of Unalakleet heavily rely on their existing infrastructure like roads and runways, primary means of transportation in and out of the village.

Melting permafrost poses a dire threat to the livelihood of Unalakleet's residents. Alaska's surface terrain is ~85% permafrost, consisting primarily of rock, soil, and sediments that have been continuously frozen for at least two or more years (Alaska Department of Natural Resources, 2023). Permafrost is the thickest and most expansive in the northern region of Alaska, gradually thinning and becoming more discontinuous moving south until eventually becoming absent (Jorgenson et al., 2008). Permafrost degradation in the Arctic regions has long

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1) What NASA Earth observations were involved
2) The partner organization(s) with whom you partnered
3) Who the decision makers are and what the decision being made is
3) What the problem was
4) What you did in response
5) What the benefits or outcomes are/will be
6) What were your results

Be concise. Give only high-level information. Write in active voice in simple past tense: www.englishpractice.com/improve/active-passive-voice-simple-tense/

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Commented [CM13]: cite map instead of referencing a figure (quality is too poor and we should just say where we got the information) been partially attributed to an increase in air temperature and snow thickness. However, localized studies in discontinuous, low-land regions of permafrost such as the Unalakleet region suggest that this degradation has been associated with the formation of taliks and excess ground ice (Strozzi et al., 2018, Farquharson et al., 2022). Low-land permafrost areas with abundant ground ice have been found to be more vulnerable to the extreme seasonal freezing and thawing cycles, leading to increased slope instabilities and damage to the infrastructure (Strozzi et al., 2018). A rapidly growing number of studies are using Sentinel-1 Interferometric Synthetic Aperture Radar (InSAR) to analyze, monitor, and develop subsidence models influenced by changing environmental conditions in high-land and low-land permafrost (Liu et al., 2009, Strozzi et al., 2018), based on the changes in the phase of radar signals reflected from the Earth's surface over time. InSAR allows the detection of very fine centimeter-scale changes common in permafrost degradation. These minute changes can cause catastrophic shifts in the ground capable of severely damaging or even destroying infrastructure. In addition to quantifying shifts in subsidence due to permafrost degradation, Zwieback and Meyer (2021) used InSAR subsidence observations to characterize ice-rich and ice-poor areas. In particular, the interannual variability of late-season subsidence was found to be largest for ice-rich regions, while the late-season subsidence for ice-poor regions was conversely smaller than the observational uncertainty. The significant variability in permafrost subsidence highlights the problem complexity and the value of high-resolution temporal and spatial permafrost subsidence information.

In addition to permafrost degradation, extreme erosion impacting the banks of the Unalakleet River, southeast of the village, compounds the urgency of the community's planned relocation. To better understand the impacts of riverine erosion on the Unalakleet region, the team created drainage network maps derived from quantitative analyses to provide information about river characteristics like flow accumulation, direction, stream networks and watershed extent (Tarboton, 1997). Surface hydrology derived from the high-resolution Digital Elevation Models (DEMs) have also played an important role in the development of hydrological models such as Height Above Nearest Drainage (HAND) - HAND uses the relative vertical distance to the drainage to display a highly accurate representation of soil water environments and soil draining potential derived from the local topography (Nobre et al., 2011, Rennó et al., 2008). HAND provides an effective method for flood inundation mapping and modeling due to its high accuracy and accessibility (Li et al., 2023).

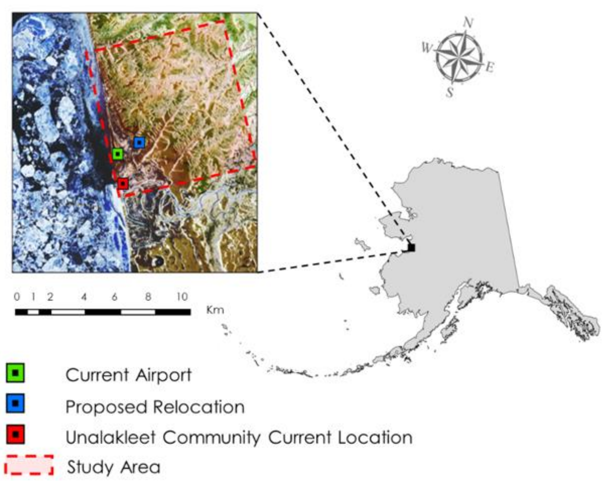

Figure 1. Location of the Unalakleet community in Alaska. The study area is highlighted in the dashed red box overlain over a false-colored image. Data source: PlanetScope, May 10, 2023.

2.2 Project Partners & Objectives

This project partnered with the National Renewable Energy Lab (NREL)'s Alaska campus, who provides the NVU with policy recommendations to support their managed relocation of the village. NVU has explored relocating their village further inland since 2003, and the first phase of the move started in 2020 when the location at the foot of the Nulato Hills was selected - a small preliminary subdivision has also already been constructed at the relocation site. The partner's objectives are to support NVU's ongoing relocation and to provide NVU with a more proactive response to the changing climate. To support the partner's objectives, the team's project has two primary objectives: 1) Analyze seasonal subsidence and drainage networks at and surrounding the relocation site, 2) create maps that highlight subsidence and drainage zones at and surrounding the relocation site.

NREL and NVU are bound by different legislation in their decision-making process. NVU operates under the Alaskan Native Claims Settlement Act (ANCSA) of 1971. NREL's decision-making process is governed by the U.S. Interagency Arctic Research Policy Committee (IARPC)'s 2018 Principles for Conducting Research in the Arctic. Under these principles NREL strives to remain accountable, establish effective communication, respect the Indigenous knowledge and cultures, build and sustain relationships, and pursue responsible environmental stewardship. End products provided by the NASA DEVELOP Unalakleet Climate team will help NREL determine favorable locations and appropriate foundation systems for building new infrastructure, such as buildings and roads. NREL's guidance of NVU will enable the community to make better-informed decisions as they navigate ongoing challenges of relocation while ensuring that long-term health and community resilience continue to remain at the center of the project.

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3. Methodology

The project study area (Figure 1) was an 8 km x 8 km square area that encompassed the relocation site and landscape located on the north side of the Unalakleet River delta, beginning along the coast and moving in a northeast direction. This wide coverage ensures that the drainage network and permafrost degradation analysis cover a significant amount of the surrounding watershed, including highlands and lowlands. It also covered the existing infrastructure, including roads, the current Unalakleet community location, and the Foothills Subdivision.

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3.1 Data Acquisition

The data and imagery for the drainage network analysis was extracted from the Alaska 5 m mid-accuracy Digital Elevation Model (DEM) obtained from the United States Geological Survey (USGS) 3D Elevation data portal (USGS, 2014). While USGS DEMs of the contiguous United States are derived from LiDAR, the Alaska DEMs were instead created using InSAR, which was part of the Alaska Mapping Initiative meant to improve the existing DEM resolution from 60 m to 5 m.

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Data product names are often found on satellite/sensor websites or sorted by NASA Distributed Active Archive Centers (DAACs) here!

Citations for these data products are also required. See the linked document in the **References** section for guidance on how to properly cite data.

Data for InSAR permafrost degradation time series analyses came from Sentinel-1 SAR C-band collected from Sentinel-1A and Sentinel-1B satellites deployed by the European Space Agency (ESA). The team's methodology used the Single Look Complex (SLC), retaining the amplitude and phase information useful for interferometric analysis. Data scenes were acquired through the Alaska Satellite Facility (ASF) Vertex portal and included imagery from 2017-2023 covering the summer thaw season from the middle of May to the middle of September. Products ordered and extracted from the ASF Vertex portal included ascending and descending looks of vertical transmit and vertical receive (VV) interferograms that overlapped with the study area.

To corroborate the observations made in their drainage network and permafrost degradation analyses, the team used WorldView-2 and WorldView-3 high-resolution (~40 cm) optical imagery from the NASA Commercial Small Sat Data Acquisition Program. The WorldView images are from 2017 to 2023 and were used to identify key features like areas of prominent vegetation, drainage networks, topography, and existing infrastructure. The WorldView images were also used to identify reference points for permafrost degradation analysis time series, such as rock outcrops and other long-stable features helpful for interferometric analysis. Furthermore, the WorldView images were used to create shapefiles for roads, current community location, and the Foothills Subdivision. A list of the team's Earth observations used is shown in Table 1.

Platform & Sensor	Parameter(s)	Use
InSAR-derived USGS 5 m Alaska Digital Elevation Model (DEM)	Relative elevation and slope	Served as inputs to perform watershed delineation and HAND analysis
Sentinel 1 C-SAR	Vertical displacement	Derived interferograms were used to assess vertical displacement in land surface, which can show permafrost degradation and ground subsidence
WorldView-2	Surface reflectance	This dataset provided high-resolution imagery that was used to locate a reference point as well as current infrastructure such as roads to compare with drainage networks and permafrost degradation
WorldView-3	Surface reflectance	This dataset provided high-resolution imagery that was used to locate a reference point as well as current infrastructure such as roads to compare with drainage networks and permafrost degradation

Table 1. Earth observations and datasets used for the drainage networks and permafrost degradation analysis

3.2 Data Processing

3.2.1 Drainage Networks

Drainage network maps help visualize and reproduce hydrological features based on local topography derived from Digital Elevation Models (DEMs). The team utilized the Hydrology toolset in ArcGIS Pro 3.1.1, and the HydroSAR-notebook in ASF OpenSARlab to extract hydrologic information from the study area watershed, subsequently applying the data to a HAND calculation (Figure A1). After obtaining multiple DEM tiles covering the study area, the team mosaiced and clipped them to a smaller area, and then projected them in ArcGIS Pro 3.1.1 as part of the pre-processing for the analysis. After pre-processing the ancillary DEM, the first procedure was to create a hydrologically conditioned, or filled, DEM, which was vital to the accuracy of the flow direction estimations (Grimaldi et. al, 2007). To prepare the necessary inputs for the drainage network analysis, the team calculated flow direction (indicating the direction of runoff) using the D8 flow algorithm. The D8 method was designed to model the flow direction from each cell to the closes neighboring cell in eight directions (O'Callaghan and Mark, 1984). Based on the flow direction raster, flow accumulation was calculated

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What did you do to the data to make it 'readable'? Were there conversions needed in order to analyze it? Did you have to mosaic images or use a cloud filter? Did you have to normalize anything to fit other datasets? Did you run an NDVI calculation, change detection, etc.? Remember to properly cite any models or tools you are utilizing from other authors, including DEVELOP projects.

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to highlight the areas of the network with higher concentrated flow. Flow direction, flow accumulation, and the filled DEM acted as major inputs for the drainage network analysis.

A similar process was adopted using the HydroSAR interactive code in the Alaska Satellite Facility's (ASF) OpenSARlab. HydroSAR is a notebook designed to easily run hydrological processes and analyses, such as HAND. Due to the number of dependencies & packages needed, OpenSARlab runs in JupyterHub with built-in customizable environments that users can easily access. To begin, the team activated the HydroSAR environment provided by ASF. The team's mosaiced and clipped DEM was utilized to reduce error; however, all data inputs were projected to WGS 1984 to prevent projection conflicts during data processing. The workflow for the data processing in HydroSAR followed these steps: 1) Load the DEM data, 2) extract a grid from the DEM raster to read the data, 3) fill the depressions to produce a conditioned DEM, 4) generate a flow direction grid, and 5) generate a flow accumulation grid. These hydrologic analyses were acquired using an open-source library called Pysheds and were used within the HydroSAR notebook to produce a HAND calculation as seen in Meyer et. al., 2020.

3.2.2 Permafrost Degradation

In a similar way to the HydroSAR HAND analysis, the team processed the InSAR data collected for the permafrost degradation in ASF's OpenSARlab. InSAR data were ordered from the ASF Vertex portal and directly extracted, unzipped, and stacked on Alaska Satellite Facility's Hybrid Pluggable Processing Pipeline (HyP3) (Hogenson et al., 2020). HyP3 is a service used to process Synthetic Aperture Radar (SAR) imagery that addresses the common issues of preprocessing, such as distortion, when starting out with the raw SAR data. SAR processing is computationally intensive, complicated, and prohibitively expensive, and in response, ASF provides a persistent, cloud-based, customizable computing service in OpenSARlab to run HyP3 and subsequent processing software (MintPy). The workflow for HyP3 involved 1) loading the data stack into the notebook, 2) filtering for date range (2015 – 2023), flight path (44), and orbit direction (descending and ascending), 3) downloading and unzipping the data, and finally 4) confirming the presence of a DEM, azimuth angle map, and incidence angle map for subsequent analysis. All InSAR images that overlapped with our study area were included.

After HyP3 processing, the team proceeded to the MintPy Time-Series Notebook for Short Baseline Subset (SBAS) InSAR analysis. In this notebook, the team created multiple InSAR time series for analysis with the prepared ASF HyP3 InSAR data stack. The time series enabled the team to map the surface deformation, assess the quality of the stack inversion, temporal coherence, and velocity errors. Stack inversion involves backpropagation of network data into displacement results, temporal coherence is the measure of the available SAR data in consecutive temporal baselines, and velocity errors represent the uncertainty in the rate of subsidence. The MintPy processing workflow was derived from Yunjun et al., 2019 as shown in Figure 2 and was run in OpenSARlab.

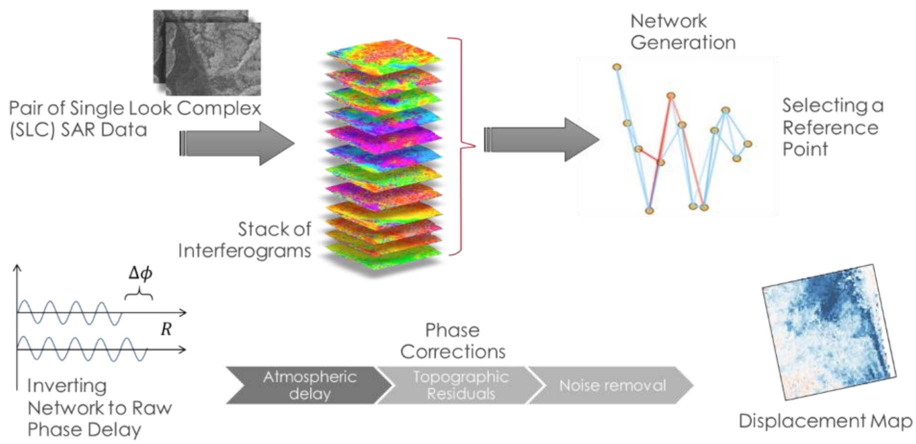

Figure 2. The MintPy processing workflow the team used to invert a stack of unwrapped interferograms and apply different corrections to obtain the ground displacement time series. An interferogram is formed using two scenes in Single Look Complex format. All pairs are stacked for the study area and used to generate a network of interferograms.

MintPy applies a network inversion to calculate the phase change, $\Delta\phi$ for each of the pairs. The phase change, as shown in Figure 2, is simply the difference between wave phase of the received signal for the first pass and second pass. The phase change is as described by Ferretti et al. (2001) and occurs because of land deformation, atmospheric delay, topographic errors, orbit error, and random noise. Orbit error can be ignored for well-engineered satellite systems such as Sentinel 1. This relationship is described in equation 1 (Ferretti et al., 2001):

$$\Delta\phi = W\left\{\frac{4\pi}{\lambda}\frac{B_{\perp}}{R\ \times \sin{(\theta)}}h_{err} + \frac{4\pi}{\lambda}v \times \Delta t + \phi_{atmo} + \phi_{orbit} + \phi_{noise}\right\} \quad (1)$$

Where $\Delta\phi$ is the change in phase of the radar signals from reference scene to the secondary scene wrapped from $-\pi$ to π. Wrapped means the values are in terms of wave phase instead of wavelength. R is the range distance calculated based on travel time. θ is the incident angle. λ is the radar signal wavelength. $B_{\perp}$ is the perpendicular baseline: the distance between location of the satellite for first and second pass. h_{err} is the residual topographic height error caused because of the imperfection of the DEM used and the fact the topography seen by radar might not be the same as the one defined by DEM. The DEM might refer to the land surface, but radar can see the top of the vegetation or snow or even a few centimeters into the ground. v is the velocity of earth surface deformation in line of sight of the radar readings, which for the team's purpose is the rate of land subsidence due to permafrost degradation. Vertical displacement velocities can be calculated assuming horizontal displacements are negligible. Δt is the temporal baseline or the time between the first pass and the second pass. ϕ_{atmo} is the atmospheric delay of the radar phase. ϕ_{orbit} is the phase change caused by satellite orbit error. For Sentinel satellite, this error is negligible. ϕ_{noise} is the random noise in phase change can be calculated and removed. The noise component is random in both time and space.

The beginning of Equation 2 accounts for phase change due to topography, with the source and received signals being incoherent, and can be calculated using the DEM. However, due to the errors in DEMs the topographical residue h_{err} needs to be corrected. The team used the method of Fattahi and Amelung (2013), which operates in the time domain after inversion of the network of interferograms for the displacement time series, to correct residual topographic errors. The atmospheric delay is primarily caused by inhomogeneities in temperature, pressure, water content in the troposphere and variation of electron density ion ionosphere (Mayer and Nicoll, 2008). For this study, electron density variation was insignificant. For the remaining factors, (temperature, water vapor, and pressure) the effects of their variations were simulated using ERA5 climate reanalysis pressure data in the MintPy Jupyter notebook based on Global Atmospheric Models (GAMs) data (Jolivet et al. 2011; 2014). Other options to correct for these three factors were height correlation models such as in Doin et al. (2009) and iterative tropospheric decomposition model described in Yu et al. (2018) but were not used for this study. The ERA5 data have a horizontal resolution of 0.25° x 0.25°. Each interferometric pair has two unknowns, the topographic error h_{err} and velocity of displacement v (the rate at which displacement/subsidence occurs). The team used MintPy SBAS timeseries analysis to do the network inversion and solve for these parameters using all pairs with a temporal baseline ≤ 24 days and spatial baseline ≤ 300m. The process of network inversion into time-series was done using weighted least square (WLS) estimator as described in Barardino et al. (2002). Interferogram coherency maps were also created in MintPy and displayed the accuracy of the phase information – the lower coherence values meant noisier data and made interpretation of the displacement more challenging. The spatial coherency for each pair was calculated using equation 2 which was based on Prati et al. (1994), creating a complex variable γ between 0 and 1:

$$\gamma = \frac{\langle s_1 s_2^* \rangle}{\sqrt{\langle s_1 s_1^* \rangle \langle s_2 s_2^* \rangle}} \tag{2}$$

Average spatial coherency was calculated over all pairs within the study area and is shown in Figure B1, with a pixel value that was closer to 1 being more reliable for use in time series analysis. A threshold of 0.4 was applied to filter out pairs with too low/unreliable spatial coherencies. Pairs with average coherency above this threshold were kept and used for analysis.

The team then set a reference point which all deformation within the analysis region was relative to. The team chose two spots in Unalakleet that would be relatively stable through the entire study period. The first reference point was the Unalakleet airport runway (latitude: 63.883°, longitude: -160.797°) which was relatively stable for decades and is situated next to the original site. As a corroboration of the runway's stability, the second reference point was a rock outcrop (latitude: x°, longitude: y°) to ensure the runway reference point was indeed stable.

3.3 Data Analysis

3.3.1 Drainage Networks

To begin the drainage network analysis, flow direction, flow accumulation, and the filled DEM were used as inputs for several calculations. The team started by extracting stream network values from the flow accumulation layer. Flow accumulation thresholds are highly sensitive to the local topography, and it can be difficult to determine an appropriate value that accurately represents the input for the drainage network (McMaster, 2002). To determine the appropriate threshold for the stream network, the team explored various thresholds, including 500, 1,000, 10,000 and 100,000 (Figure A2). Based on the derived stream networks, the

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team was able to locate, and place, outlet points at the mouth of the Unalakleet River and Powers Creek, a small creek ~8 km north of the Unalakleet River. To delineate the watershed, the team then snapped the outlet points to the raster grid of the flow accumulation layer, and utilized the watershed tool in ArcGIS Pro to calculate the upslope area that contributes water flowing into the two outlets (Figure A3). To authenticate the location of the streams, outlet points, and drainage basins, a visual inspection of the landscape was implemented by comparing (cm-scale) various WorldView-2 and WorldView-3 images. After visually inspecting the topography, HAND was calculated utilizing the following inputs: 1) 500, 1,000, 10,000, and 100,000 flow accumulation thresholds, 2) the conditioned DEM, and 3) the flow direction raster. The team calculated the vertical flow distance from the lowest point in the drainage utilizing these four different thresholds for comparison with each other and the local topography.

Similarly, HAND was calculated in the HydroSAR-notebook with a series of steps. To compute HAND, the team began by locating the drainage basins that intersected with the pre-processed DEM. The team loaded the basins, reprojected the basins to the DEM projection, and ran the code that combined the DEM with the basin database. The basin code identified all polygons that intersected with the DEM. To calculate HAND, the code looped over and extracted elevation data for each polygon basin and calculated the height from the lowest point in the drainage. The inputs for this calculation were the same as the analysis done in ArcGIS Pro, and included flow accumulation thresholds of 500, 1,000, 10,000 and 100,000, the conditioned DEM, and flow direction. Once the HAND was calculated, the team ran a land mask to fill over the nearby ocean and performed a final check for "Not a Number" (NaN) values. The remaining land cells returning NaN values were labeled and filled. The four different HAND images were exported as .tiff files for comparison with the other values previously created.

3.3.2 Permafrost Degradation

To evaluate the quality of the MintPy outputs, which include coherence, velocity, and surface displacement, the team initially inspected the results for the 2019 summer. This summer was identified as exceptionally warm, based on thawing degree days (TDD) estimated from ERA5 air temperature (Zwieback and Meyer, 2019). The 2019 data available from the ASF Vertex portal consisted of 12 interferometric scene pairs, which range from 05/03/2019 - 09/24/2019. Two temporal baselines were used (12 and 24 days) to avoid any broken connections between consecutive scenes. This helped particularly when there were scenes which had too sharp of a gradient in phase change, such as going from $+\pi$ to $-\pi$ over a short distance or vice versa. The orbit flight path was 44 with a descending look.

The team began by looking at the average spatial coherence. Inspecting the interferogram network in Figure B2, it was found that the scenes had perpendicular baselines within ~100 m and an average spatial coherence ~0.6, which is considered significant (spatial coherence value ≥ 0.4, as suggested in Jian and Lohman, 2021). The spatial coherence map in Figure B1 showed the pixel-wise coherence (corresponding pixels in a scene pair show strong phase similarity and thus signals), and the team observed coherence "hot spots" with values close to 1.0 that indicated bare ground, along with a stretch of area close to zero values that corresponded to the Norton Sound. These high and lows were interspersed by a range of values that corresponded to vegetation and bare ground close together – the short wavelengths used by the InSAR satellites have difficulty penetrating dense vegetation and can lead to the observed incoherence. Comparisons were made with high-resolution (cm-scale) WorldView-2 and 3 images.

The team also inspected the temporal coherence, which represents the consistency of the timeseries with the network of interferograms and varies from 0 to 1 for each individual pixel (a higher value indicates better reliability for timeseries analysis). A temporal coherence value above 0.7 is considered significantly appropriate (Yunjun et al, 2019). For the 2019 analysis the temporal coherency of all the pixels within the study area was 1. Temporal coherence was calculated using equation 4 based on Pepe and Lanari, 2006:

$$\gamma_{temp} = \frac{1}{M} |H^T \exp\,[j(\Delta\varphi - \mathbf{A}\widehat{\varphi}]| \tag{4}$$

where j is the imaginary unit, M is the number if interferogram used in the network, H is an $\boldsymbol{M \times 1}$ all-ones column vector. $\Delta\varphi$ is the interferometric phase vector for each interferogram. $\boldsymbol{A}$ is an $M \times (N-1)$ 2D matrix indicating acquisition pairs used for interferometric analysis. The matrix is filled with -1, 1, and 0 for each row with -1 if the scene is a reference sense, 1 if the scene is a secondary scene and 0 if the none.

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4. Results & Discussion

4.1 Analysis of Results

Commented [BRC(ED35]: Remember, “negative” results should still be reported! It’s important to keep a record of what was not feasible or just simply did not work within the scope of the project.

4.1.1 Drainage Networks

Flow accumulation thresholds of 500, 1,000, 10,000 and 100,000 yielded varying results due to the highly sensitive nature of drainage network stream density. Stream networks were a vital parameter in calculating HAND, acting as the lowest point in the drainage, and the team used the different thresholds in an exploratory study to most accurately describe the landscape. The smallest threshold of 1000 displayed dense stream networks reflecting the local topography and indentations of the drainage basins when compared to larger thresholds. As the team increased the threshold, stream density and extent decreased, however, larger streams were useful in identifying the larger drainage basins for input into the HAND calculation (Figure A2). The lowest thresholds in the HAND calculation output a rough surface raster due to the immense number of pixels being input as “drainage” and were therefore determined to be too finite. Similarly, the largest threshold tested was not able to calculate the height from the smaller drainages, and the results did not reflect gradient shifts seen in the local topography. These calculations were dismissed, and the team determined that, in reference to multiple studies and the team’s visual inspection, the 10,000-threshold HAND calculation displayed a shaded relief of the study area that most accurately represented visual changes in the environment. Furthermore, the 10,000 HAND calculation highlighted local relative variations in height and more pronounced drainages when compared to the original DEM as discussed in Rennó et. al., 2008 (Figure A4).

When analyzing the location of the drainages in comparison to local roads, it was found that several large drainages in the center of the study area crossed over one of the main roads while some were located at the highest points above the drainage (Figure A5). Overlapping this data and locating the roads that interacted with large and small drainage networks provided valuable information about current and future infrastructure for the partners. Infrastructure located within the drainages risk damage from flooding and erosion due to the winter runoff and unprecedented flooding events. As you move away from the drainage, there is less potential damage and instability for roads and future buildings because they would not be directly impacted by mass runoff and inputs into the major drainages. This information is valuable for the NVU as they continue relocation construction and combining this data with summer subsidence data would further inform decision making in regards to housing plans and future infrastructure. (insert)

Commented [CM36]: Write about classified map and how that can help inform infrastructure-higher risk for these environments and wetter soil-refer to some sources

4.1.2 Permafrost Degradation

In addition to validation of landscape features through visual inspection, the team also looked at the net displacement over the 2019 study period. Over approximately 4 months, the team observed a maximum displacement ~5 – 6 cm which is within the range of observed late-season (Aug. 10 – Sept. 10) permafrost subsidence in Zwieback and Meyer (2019) in Kivalina in NW Alaska (4 – 8 cm in ice-rich areas, -1 – 2 cm in ice-poor areas, with a ±0.6 cm uncertainty) which is ~280 mi from Unalakleet. The physically reasonable output of the MintPy time series for 2019 summer gave confidence to apply the workflow to the InSAR data for 2017 – 2022. Displacement patterns for study areas reveal a generally S-shaped curve for years 2017-2019, transitioning to a degraded shape for subsequent years. This shift aligns with the significant climatic influence exerted by record-setting air temperature of 2019.

What can you tell from your graphs, images, etc.? What does the data tell you? What does this mean for your project?

What factors could you not account for? What are potential holes or problems with your methodology? Include an error analysis. What things didn't work out like you expected they would, etc.?

Table 3
Interannual periods used to create persistence maps

Persistence Year Range	Interannual Periods Aggregated for Persistence
2000-2005	2000-2001, 2001-2002, 2002-2003, 2003-2004, 2004-2005
2005-2011*	2005-2006, 2006-2007, 2007-2009, 2009-2010, 2010-2011
2010-2016*	2010-2011, 2011-2013, 2013-2014, 2014-2015, 2015-2016

The "*" indicates ranges with gaps due to missing interannual periods from Landsat for 2008 and 2012.

Add table or image for coherency analysis:

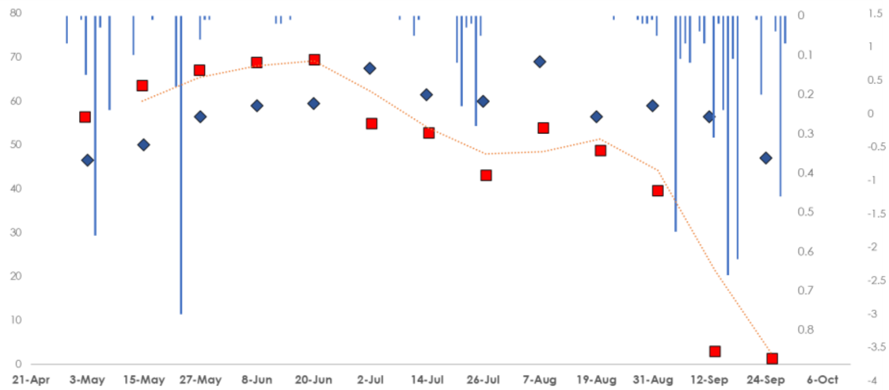

Figure ??. Comparison of weather rainfall, temperature and calculated subsidence for the period of May 01 to October 01. Weather data are based on ?? station. The red boxes are the subsidence values in cm obtained from SBAS analysis. Blue diamonds are the mean temperature in degree F, and blue bars are the rainfall in inches.

4.2 Feasibility Assessment

Evaluate the methodology your team has created using Earth observations and speak to the feasibility of addressing or enhancing the end user's decision-making needs using Earth observations in this instance. Did your project find that the partner could utilize the methods you employed? This section is partner-centric and should speak to the feasibility of applying your methods to the end user's issues.

4.2.1 Drainage Networks

A series of limitations hindered the HAND calculation within OpenSARlab. To properly calculate the flow direction for HAND, the entirety of the relevant watershed needed to be included in the DEM, and due to the 5-m high resolution of the imagery, the HAND calculation averaged 30 hours. In addition, when the team was able to produce results, there were large gaps in the data, possibly due to the coastal nature of the study area, which can produce NaN values in low-lying cells. For future studies, the team suggests focusing on a smaller watershed or utilizing a 30-m DEM to avoid the errors experienced throughout this study.

Commented [BRC(ED37]: Table labels, descriptions, and notes differ in format from figures.

Commented [BRC(ED38]: If you need a note to explain your table, it goes here. Don't italicize.

Commented [JN39]: Add table for coherency for each pair, mean coherency value

4.2.2 Permafrost Degradation

Phase unwrapping errors, phase decorrelations, phase inconsistency of the data impact the quality if the inversion.

4.3 Future Work

Speak about what steps your partners could take to further the methods or better integrate them into their decision-making practices. If (and only if) there is another term planned, how should that team proceed?

5. Conclusions

Word count: 200 to 600, about a page.

Synthesize your results here – what are the main takeaways of your research and how do they compare to your original hypothesis? How do they relate to your community concerns, how will your partners benefit from the project results, etc.? What are the main takeaways of the results of your research and how do they compare to your initial hypothesis?

The team found that seasonal subsidence was evident in

6. Acknowledgements

Keep to a concise paragraph or bullets of names. End with the following sentences:

This material contains modified Copernicus Sentinel data (insert year), processed by ESA.

This work utilized data made available through the NASA Commercial Smallsat Data Acquisition (CSDA) program.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration.

This material is based upon work supported by NASA through contract NNL16AA05C.

7. Glossary

Define field-specific terms and acronyms, but not only acronyms. When the body is complete, re-read your paper and identify the scientific jargon words to add to the glossary. The goal of this section is to help the reader better understand the work presented in the paper. Include vocabulary that the reader may not be familiar with, in addition to defining the acronyms in your paper. Write this section as if someone who isn't familiar with your application area is reading your paper!

Earth observations – Satellites and sensors that collect information about the Earth's physical, chemical, and biological systems over space and time
MODIS – Moderate Resolution Imaging Spectroradiometer
Raster Pixel Cell – A pixel of a raster

Commented [BRC(ED40]: Conclusions should summarize the main findings and major implications of the study. Statements like "we made a map of *x*" are not proper conclusions. What does the map show and what does that mean for the partners and broader community?

Commented [BRC(ED41]: From here down does not count against the 12-page max.

Commented [BRC(ED42]: Include the ESA acknowledgement statement only if you used Sentinel data.

If any other private data is used like DigitalGlobe/Maxar or PlanetScope, confirm proper acknowledgments with your Fellow and be sure to include the CSDA statement.

If you used Maxar data, this sentence should also go in the acknowledgements:
"DigitalGlobe/Maxar data were provided by NASA's Commercial Archive Data for NASA investigators (cad4nasa.gsfc.nasa.gov) under the National Geospatial-Intelligence Agency's NextView license agreement."

If you used raw Planet data, this sentence should go in the acknowledgements: "© Planet Labs PBC {Year}. All rights reserved."
If you used derived Planet data, write: "Includes copyrighted material of Planet Labs PBC. All rights reserved."

Commented [IL43R42]: Remember to cite the proper Planet data you used: raw or derived!

Commented [BRC(ED44]: The two NASA legal statements are *required*!

Commented [BRC(ED45]: The goal of this section is to help the reader better understand jargon and terms introduced in the paper. Include vocabulary the reader may not be familiar with, in addition to defining the acronyms in your paper.

8. References

Start your alphabetized list of references on a new page and use APA 7 formatting. Please review the separate References template document to learn more! You should be able to copy-paste the example citations into this document with formatting intact. Then, just replace with your source's information!

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9. Appendices

Begin each appendix on a **new page** (insert a Page Break rather than hitting 'enter') with the word appendix in the top center. Use an identifying capital letter (e.g., Appendix A, Appendix B, etc.) if you have more than one appendix.

Label tables and figures in the appendix as you would in the text of your manuscript, using the letter A before the number to clarify that the table or figure is found in the appendix (e.g., Figure A1, Table B2, etc.)

Don't forget to refer to all appendix figures in the body text of the paper. If an appendix consists entirely of a single table or figure, the title of the table or figure should serve as the title of the appendix.

The appendix is <u>not</u> the place to stick every map/graph/figure that you want to send to your partners! The purpose of the appendix is to supplement your tech paper, not add copious amount of new information; therefore, the appendices have a page limit of 10. If you want to put 10 or more pages of appendices or supplementary information, it should be submitted as an extra, optional deliverable. This deliverable can mimic how the appendices are set up in the tech paper.

Commented [BRC(ED47]: Each appendix (not each individual image) goes on a separate page. Be sure to group similar images, graphs, etc. into correct appendix groupings.

Commented [BRC(ED48]: Example: 'Figure A1' refers to the first figure in Appendix A, 'Table B2' refers to the second table in Appendix B, etc.

Appendix A: Drainage Networks

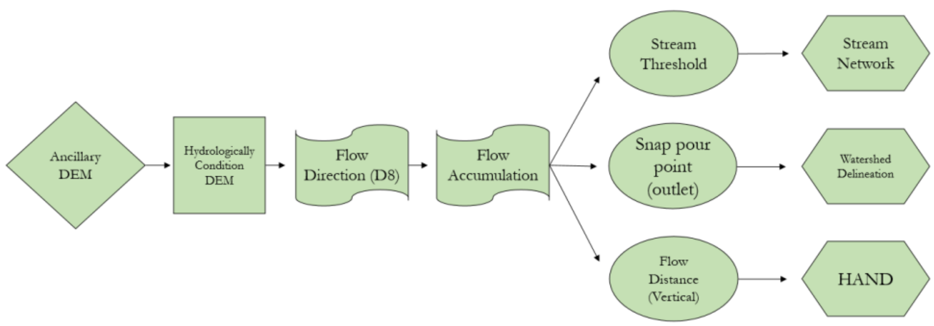

Figure A1. Workflow for watershed delineation and HAND. The diamond and the square display the first procedure of the analysis, where the team filled the depressions in the original DEM to create the conditioned DEM. The flags represent original raster layers derived from the conditioned DEM. The ovals were derived from the flow direction and flow accumulation raster layers and acted as inputs for the final analysis of products visualized as polygons.

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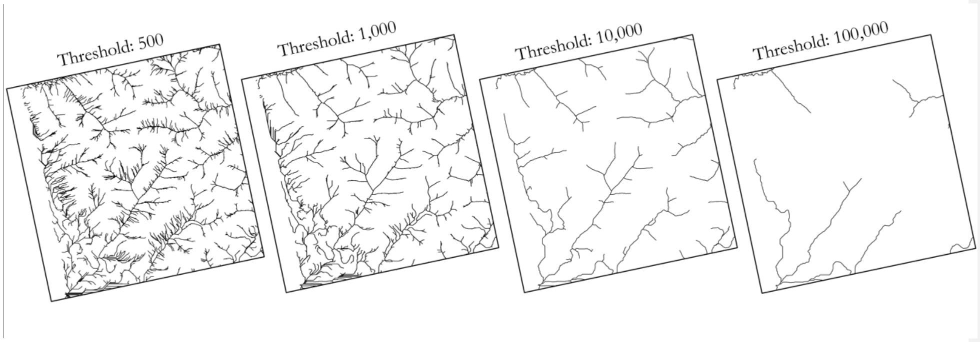

Figure A2. To calculate the stream networks, thresholds of 500, 1,000, 10,000, and 100,000 were applied to the flow accumulation layer and compared to high resolution imagery in order to locate and verify the location of small streams and larger drainage networks throughout the study area.

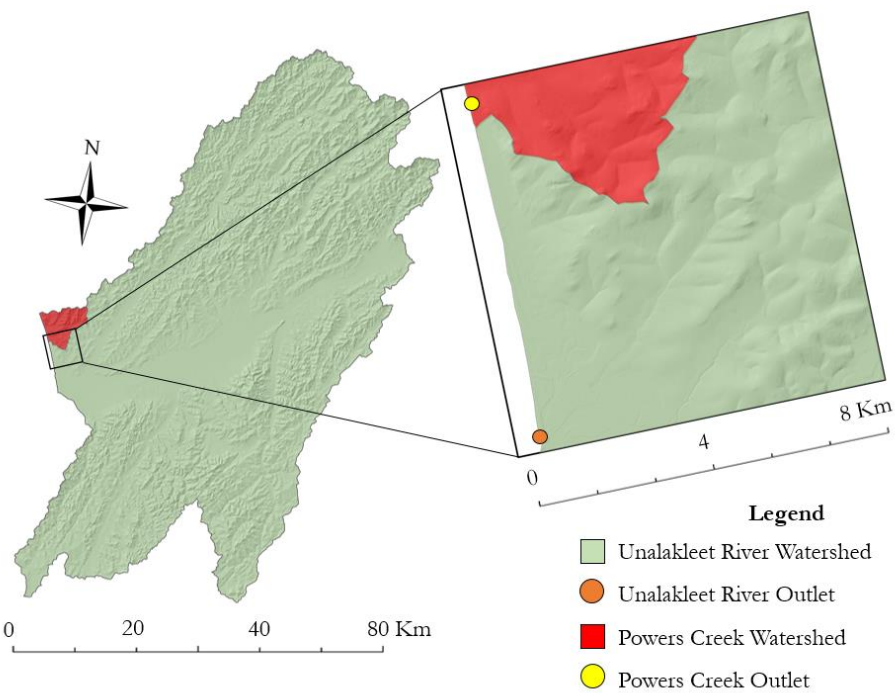

Figure A3. Map displaying the watershed delineation, including the Unalakleet River and Powers Creek watersheds, and their corresponding outlets.

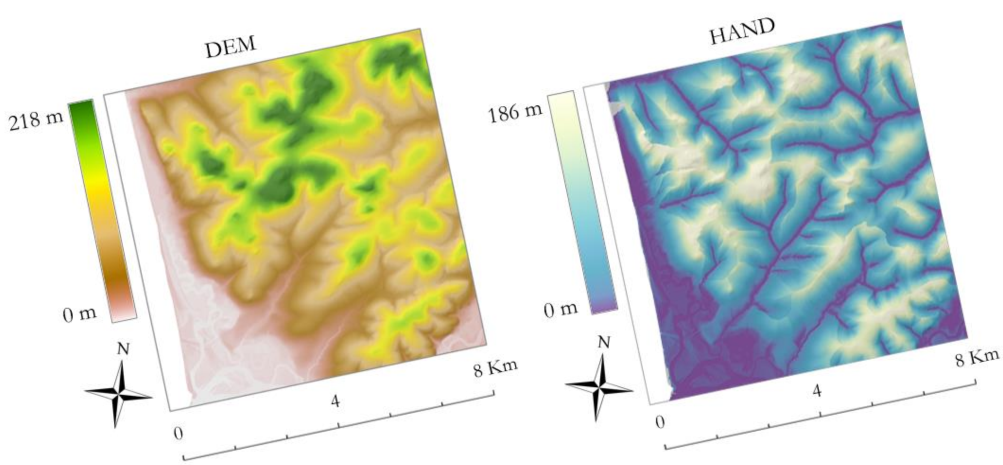

Figure A4. Results of HAND-compared to the ancillary DEM. Rennó et. al., 2008 discussed the visual and applicable difference between HAND and ancillary DEMs.

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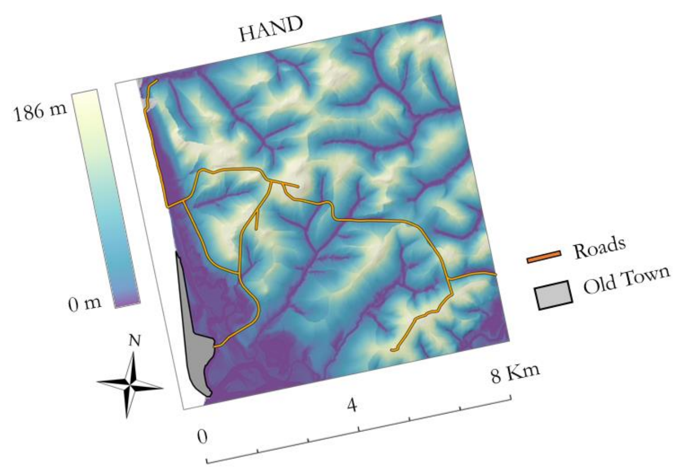

Figure A5. Results of HAND with roads and old town, and results of HAND flood vulnerability classification

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Appendix B: Permafrost Degradation

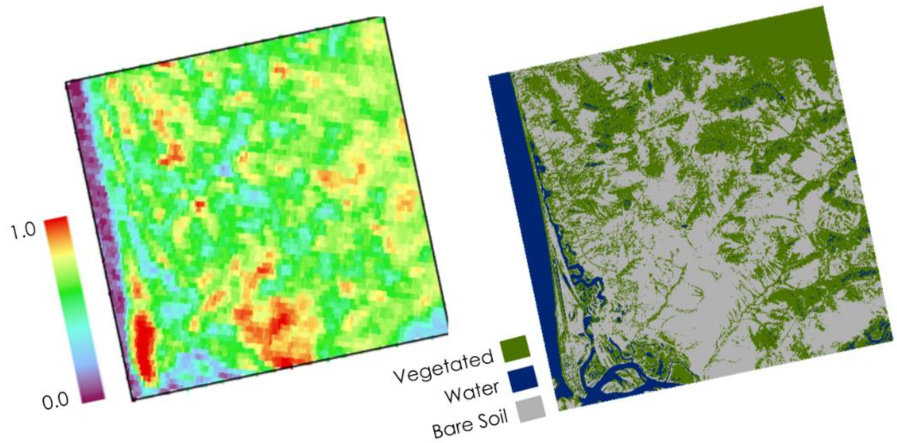

Figure B1. Spatial coherence map for the team's 5 mi x 5 mi study area (left) and an unsupervised land cover classification using Maxar image of the same area (right). The hot spots in red in the coherence map correspond to bare ground on the Maxar image, and areas with green and yellow spatial coherence correspond to closely interspersed vegetation and bare ground with more incoherence. The darker blue areas correspond to water from the Norton Sound, which absorbs the InSAR wavelength.

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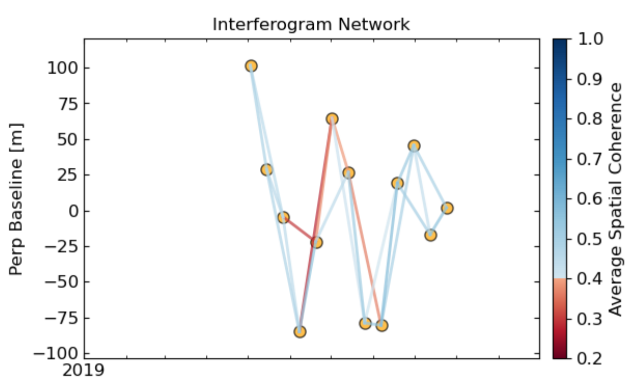

Figure B2. Interferogram network for summer 2019 at the study area. Each point refers to an interferometric scene pair, and each point is connected to adjacent points 12 and 24 days away.

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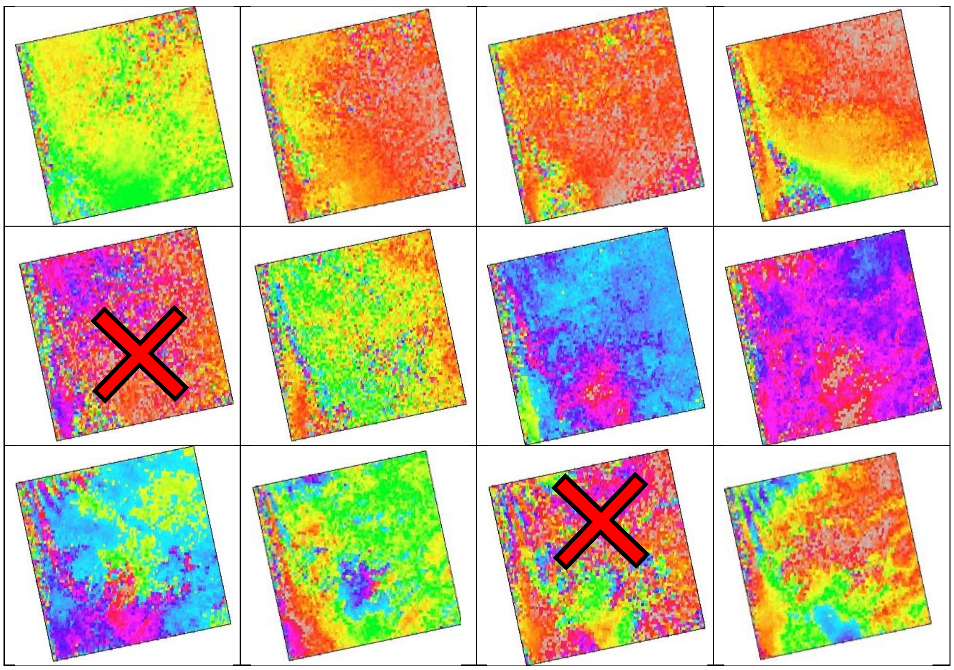

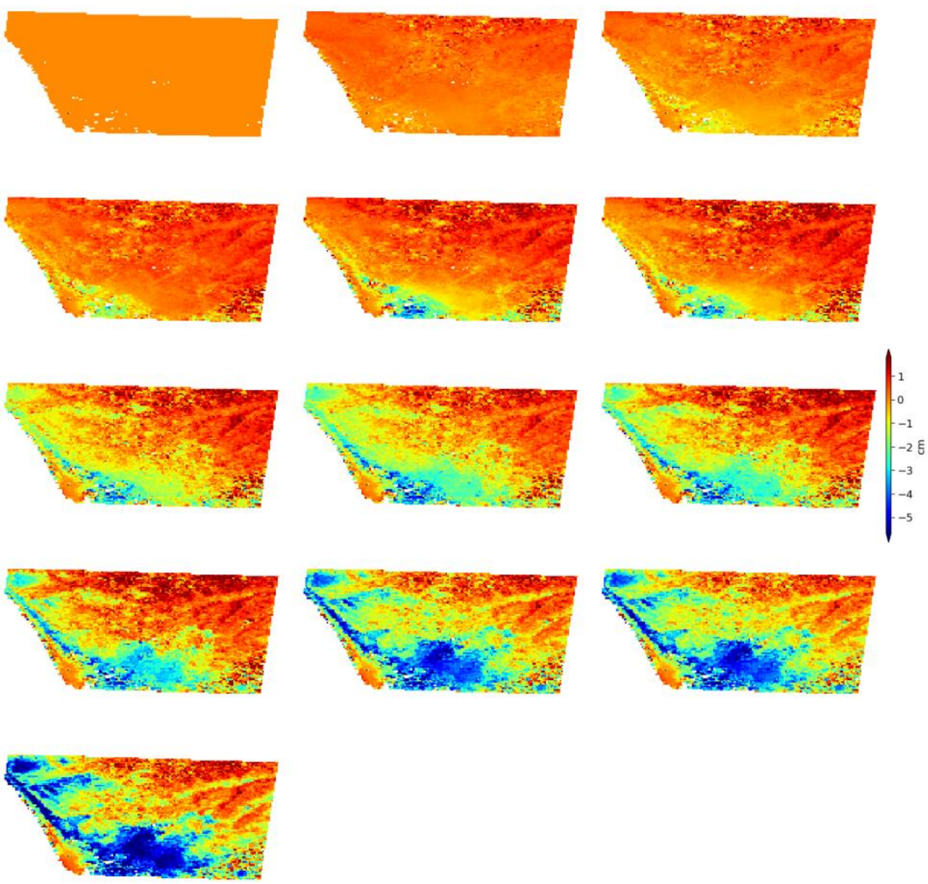
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