Harnessing Satellite 4D SAR for Glacier Surface Tracking over Khumbu Glacier at Mount Everest

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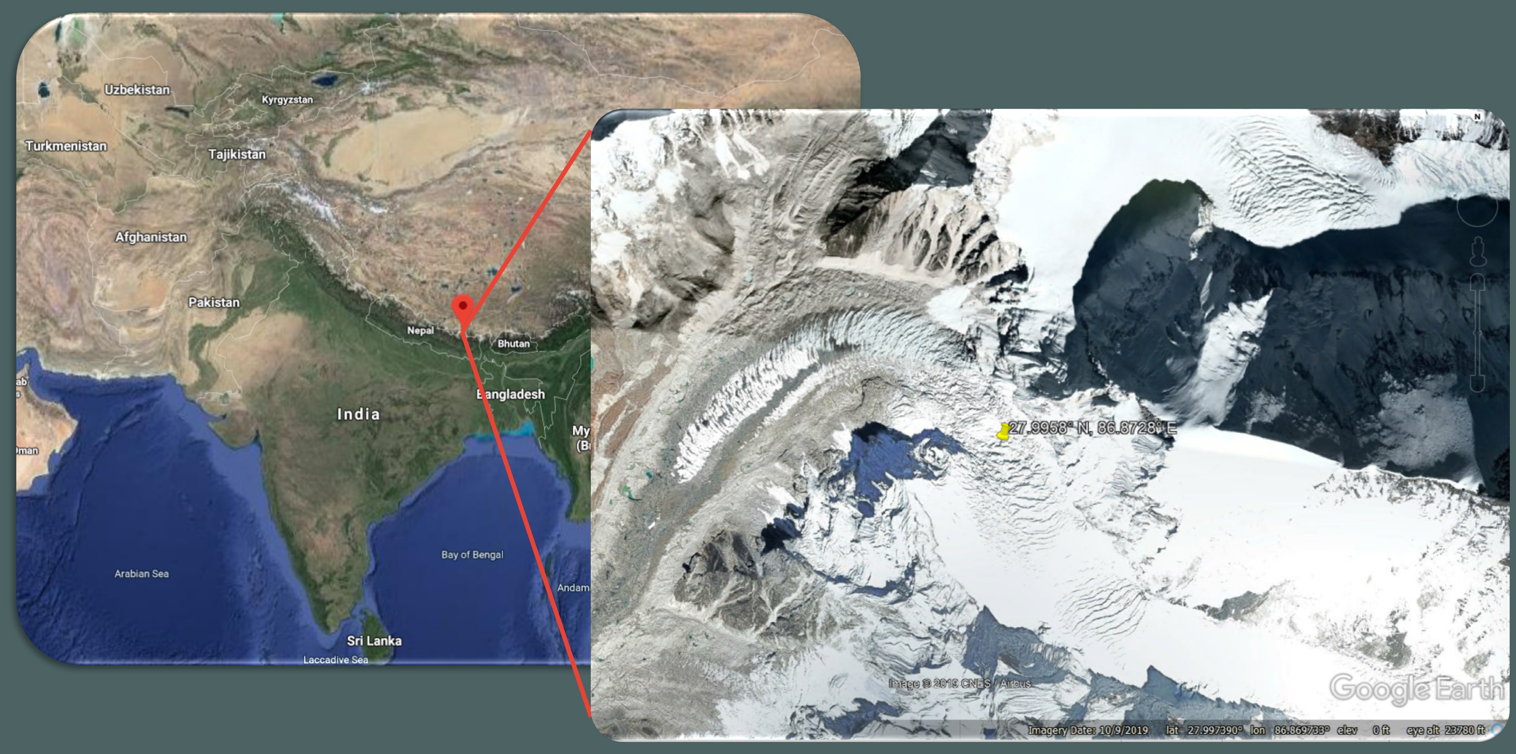
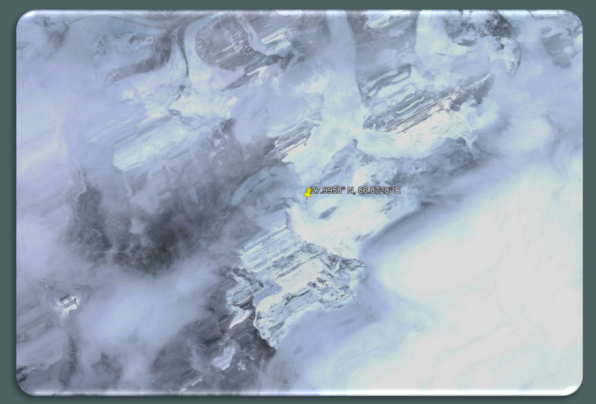
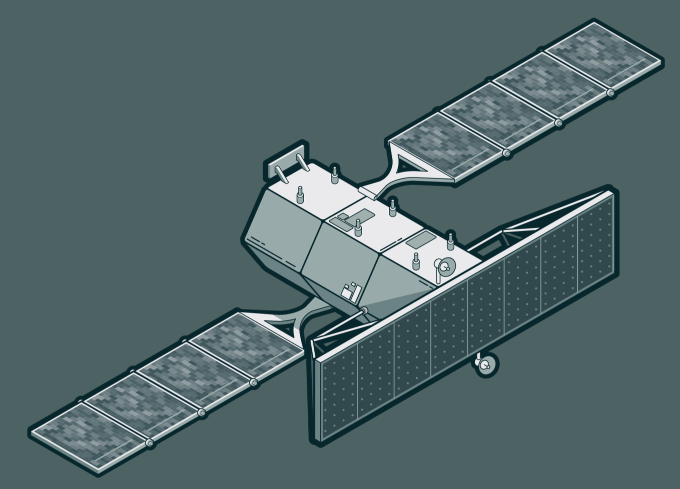
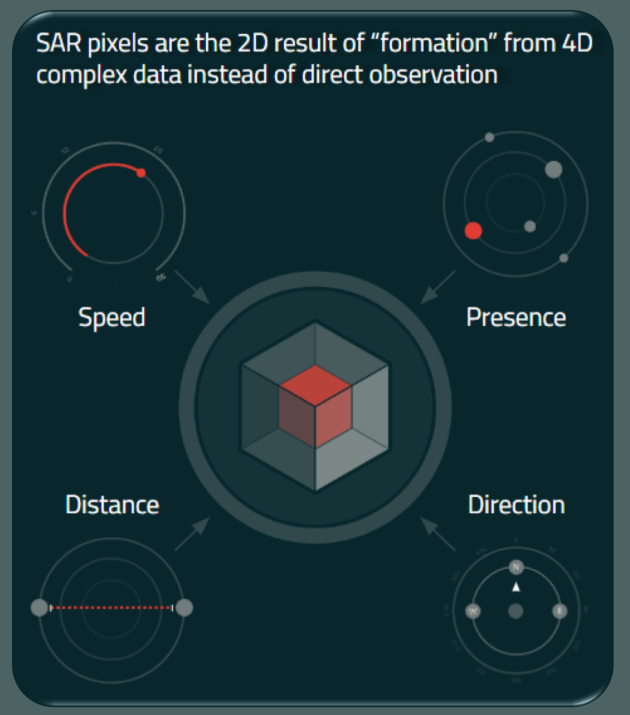




Khumbu Glacier Ice Fall

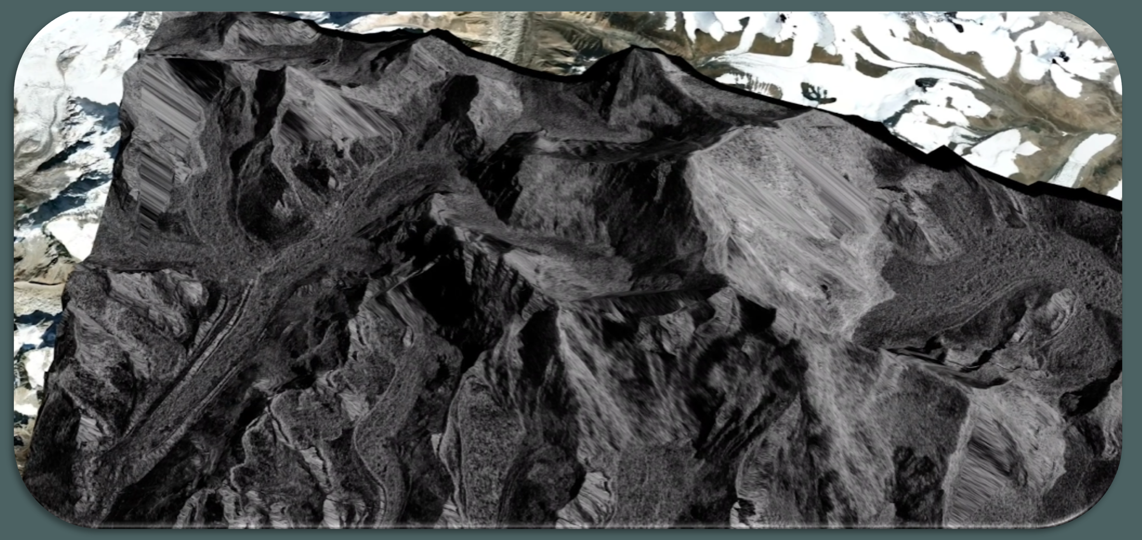
The Khumbu Icefall lies at an approximate altitude of 5,500 meters on the Nepali side of Mt. Everest and is one of the most dangerous stages of the major South Col route to the summit. In the Khumbu Icefall, seracs, or ridges on the surface of a glacier, are known to collapse unexpectedly, displacing massive volumes of ice down the Khumbu Glacier, estimated to advance 0.9 to 1.2 m down the mountain every day. For much of the year, Mt. Everest experiences heavy precipitation in the form of both snow and rainfall, introducing cloud cover within optical satellite imagery. This provides challenges for photography based remote sensing techniques to characterize the geometry and geophysics of the environment.

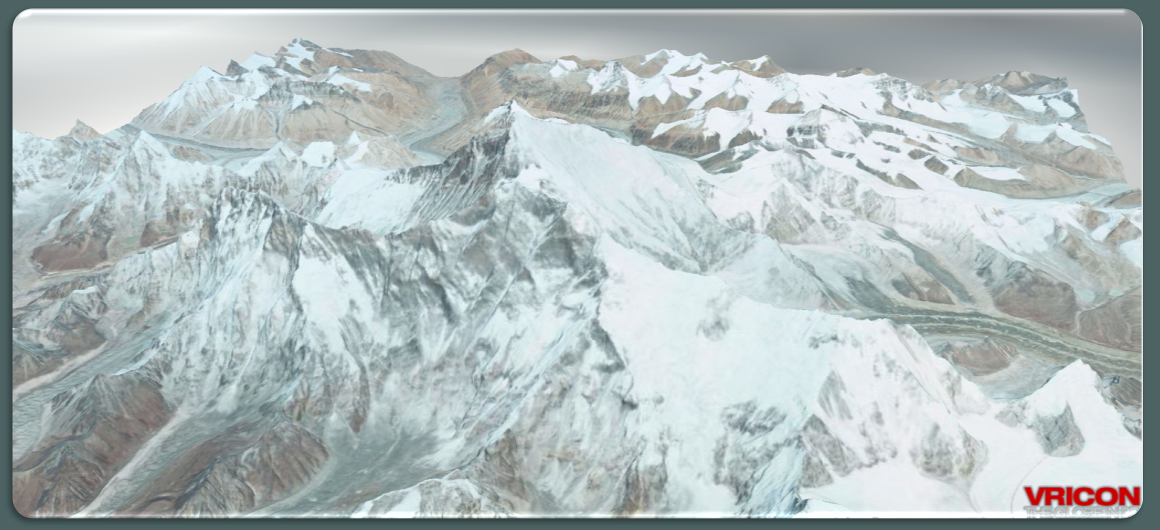




C-Band Satellite SAR through Sentintel-1

Satellite Synthetic Aperture Radar (SAR) uniquely enables a next generation of remote sensing capabilities that offer a persistent, all-weather, day/night, complete characterization of the Earth and its dynamic surface changes. SAR goes beyond the limitations of satellite optical in important ways to offer a more reliable and complete characterization of the Earth. Optical satellites can only collect data when certain lighting conditions are satisfied, where SAR satellites are not limited to these constraints. As more satellites are deployed, additional sensing times during the day will also become available. Using open source C-band (~20 m ground resolution) SAR data from the Sentinel-1 satellite constellation, ice dynamics can be reliably tracked at an approximately bi-monthly cadence (approximately every 12 days) over the past five years. The C-band instrument is nearly unaffected by cloud cover as it is not significantly attenuated by water vapor, making it incredibly useful for time-sensitive and temporal analysis such as tracking ice volumes, especially in regions under heavy cloud cover for over half of the year.



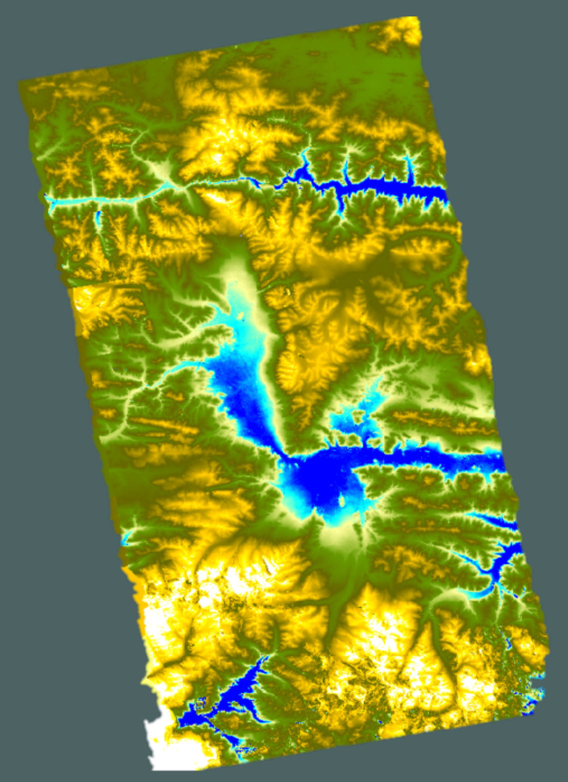


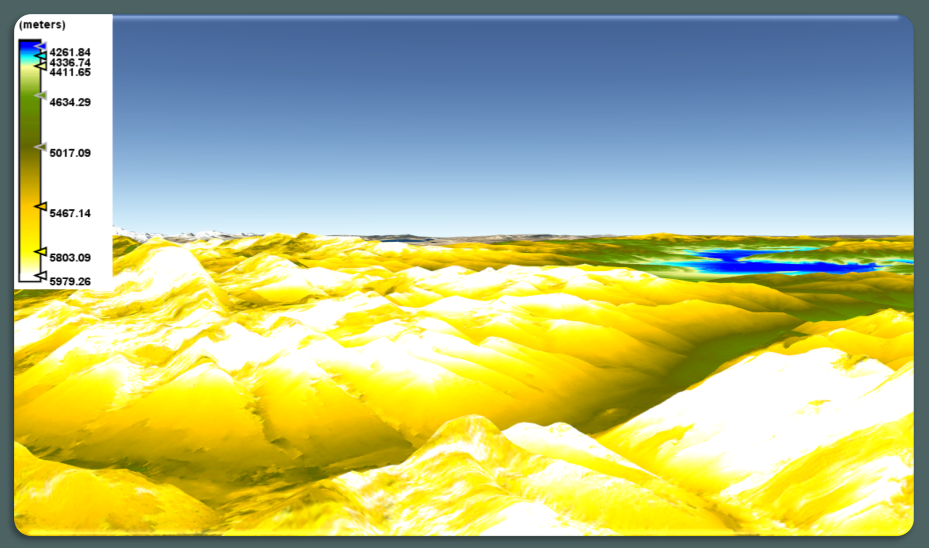
4D SAR for 3D Machine Vision

SAR data is inherently 4D, describing a 3D scene at a time instance. To form an earth observation image, the satellite SAR radar must be processed into an image within the slant plane, which will then be projected, and flattened, to an assumed ground plane. High resolution 3D surface models derived from electro-optical data and 3D Computer Aided Design (CAD) structural models can be used as the backdrop for exploration of surface changes with SAR data. By mapping SAR data directly into 3D through high-fidelity surface models, such as those available through Vricon (on left), typical SAR imaging artifacts, such as layover or foreshortening, can be avoided. In addition, dynamic SAR data can provide model correction diagnoses for 3D surface models, which are static and represent a scene either at an instance in time or averaged over a temporal sequence. Through this enhanced machine vision, we demonstrate a unique approach for enhanced multi-temporal analysis, 3D change detection, and powerful 3D visualization.

InSAR for Detailed Volumetric Tracking

Radar signal can be unwrapped to create phase history data to unlock information about the movement of objects in the scene. This process, known as InSAR (Interferometric SAR), can be used to perform very accurate measurements of 3D change across the glacier. InSAR is a paired product requiring at least two complex images taken from different orbital positions and/or at different times, but from identical satellite flight paths. With the correct pair of complex images, interferometric SAR (InSAR) can be used to generate an explicit 3D representation of the scene in the form of a digital elevation model (DEM). The power of InSAR is the ability to measure dynamic features, e.g. objects in a scene changing volume over time. However, InSAR for mapping glacial ice motion can be challenging due to both temporal and spatial decorrelation, leading to a poor coherence score between SAR collections which would prevent the extraction of height data.



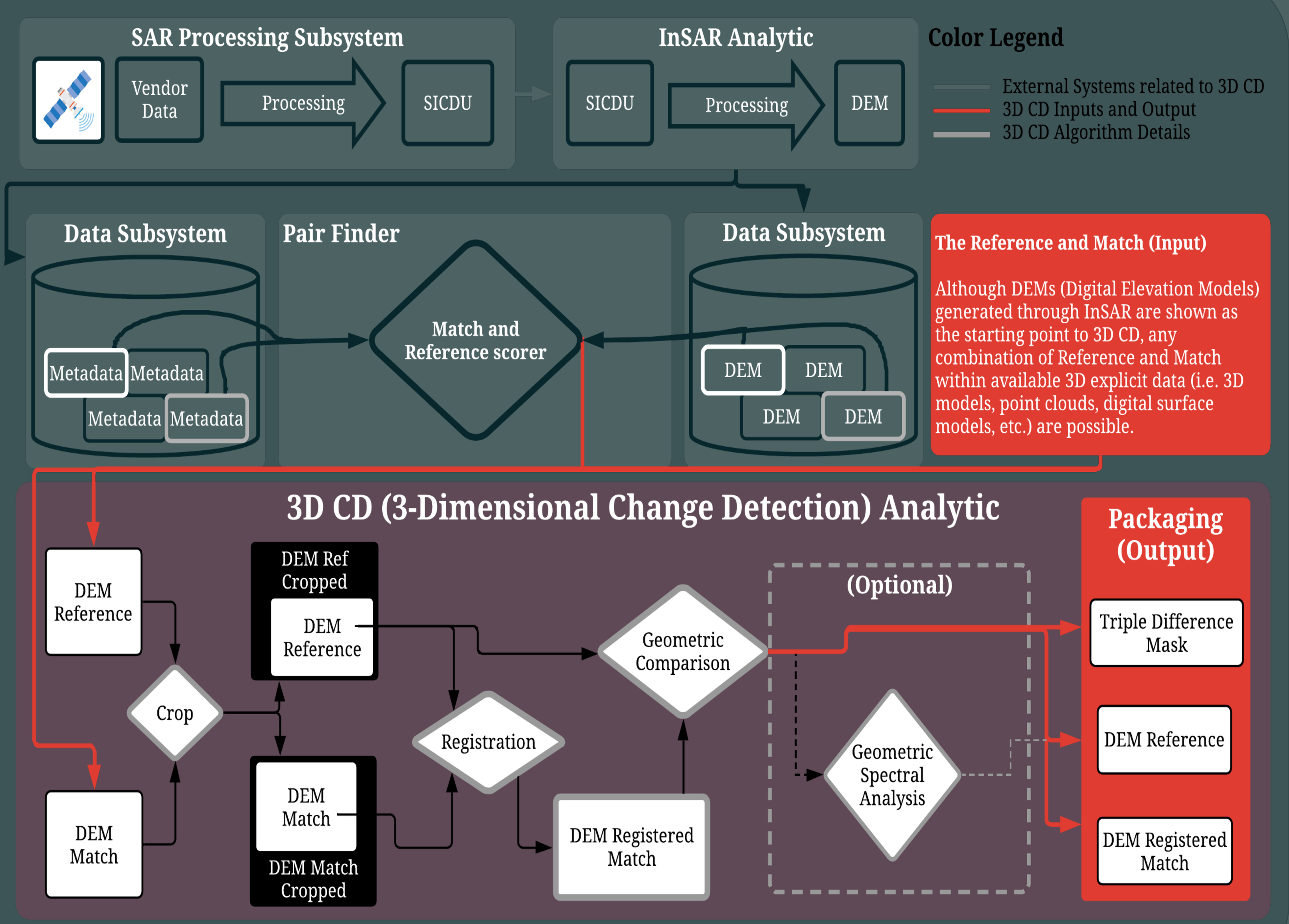


Potential Applications

Ursa's approach to non-traditional 3D data fusion allows the possibility for a multitude of additional applications, including 3D land-cover-land-use (LULC) model generation, 3D anomalous change inference and trend monitoring, and geocoding through automated feature detection and extraction. The latter can further enable geographic object-based imagery analysis and classification, by providing curated inputs to a neural network or other machine learning system and by providing additional training data for inference problems. Specific to cryosphere sciences, these techniques could be applied to studying glacier loss or retreat, ice thinning, or predicting probabilistic ice motion to better prepare expeditions. These algorithms could also be applied to climate change studies, where data-driven surrogate models could be correlated with temperature data for more robust forecasting.

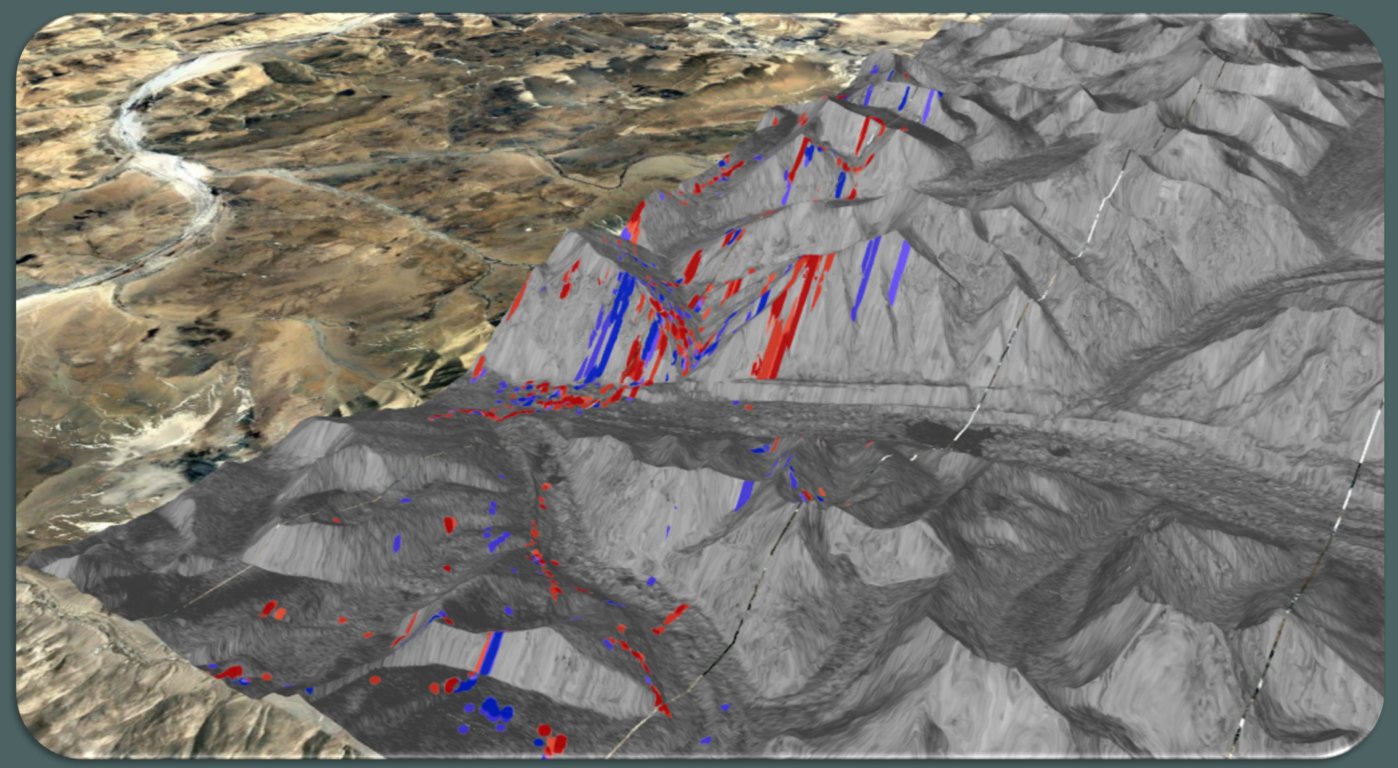
Volumetric (3D) Change Detection

Speckle tracking in the form described to the right can be extended to map two-dimensional glacier surface velocities (azimuth and range directions) and working in tandem with InSAR described to the left, detailed volume tracking is possible. 3-Dimensional Change Detection (3D CD) examines the direct differences between 3-dimensional representations of an AOI instead of SAR imagery. As shown in the analytic workflow below, 3D CD utilizes any form of 3D explicit data (3D CAD models, point clouds, digital surface models), including the output from InSAR, as input for the change detection, and compares scenes on a vertex-level, rather than pixel-level.



Speckle Tracking for Time Series Analysis

Correlation based feature tracking techniques have been applied through coherence and intensity tracking for glacier and ice velocity estimation. By tracking change over an extended time series (as opposed to pair-wise change detection), non-coherent change detection enables a more comprehensive view of evolving volume motion. Where deeper colors indicate a more recent change and lighter colors indicate a detected change further in the past, "smear plots" provide qualitative geospatial trends as well as demarcated areas with frequent change. Focusing on a region of the AOI, here the Khumbu Glacier in Mt. Everest, and choosing snapshots of SAR collections within time windows where the climate is relatively stable (minimal wind or precipitation), broad environmental change can be identified.



References and Acknowledgments

1. SAR imagery provided courtesy of European Space Agency (Sentinel-1).
2. Optical imagery provided courtesy of Airbus and Planet.
3. Surface models provided courtesy of Vricon.
4. Kumar, Vijay, Gopalan Venkataraman, and Y. S. Rao. "SAR interferometry and speckle tracking approach for glacier velocity estimation using ERS-1/2 and TerraSAR-X spotlight high resolution data." *2009 IEEE International Geoscience and Remote Sensing Symposium*. Vol. 5. IEEE, 2009.
5. Qin, Rongjun, Jiaojiao Tian, and Peter Reinartz. "3D change detection–approaches and applications." *ISPRS Journal of Photogrammetry and Remote Sensing* 122 (2016): 41-56