Automated tools to derive short-term glacier velocity from high-resolution commercial satellite imagery

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Abstract

Image feature tracking with medium-resolution optical satellite imagery (e.g., Landsat-8) offers measurements of glacier surface velocity on a global scale. However, for slow-moving glaciers (<0.1 m/day), the larger pixel sizes (˜15-30 m) and longer repeat intervals (minimum of 16 days, assuming no cloud cover) limit temporal sampling, often precluding analysis of sub-annual velocity variability. As a result, detailed records of short-term glacier velocity variations are limited to a subset of glaciers, often from dedicated SAR image tasking and/or field observations. To address these issues, we are leveraging large archives of very-high-resolution (˜0.3-0.5 m) DigitalGlobe WorldView/GeoEye imagery with ˜monthly repeat interval and high-resolution (˜3-5 m) Planet PlanetScope imagery with ˜daily-weekly repeat interval for the period from 2014 to 2019. We are using automated, open-source tools to develop corrections for sensor geometry and image geolocation, and integrating new, high resolution DEMs for improved orthorectification, reducing the uncertainty of short-term (monthly to seasonal) velocity measurements. These temporally dense records will be integrated with other velocity products (e.g., NASA ITS_LIVE), which will allow us to study the evolution of glacier dynamics, and its relationships with local climatology, geomorphology, and hydrology on a regional scale. In this study, we present initial results for surface velocity mapping for glaciers in Khumbu Himalaya, Nepal and Mt. Rainier, USA. We are using high-performance computing environments to scale this analysis to larger glacierized regions in High Mountain Asia and Continental U.S.

Quantifying changes in the dynamic cryosphere with high-resolution satellite imagery

Automated, open-source photogrammetric workflows for sensor correction, DEM generation and glacier velocity

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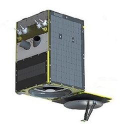
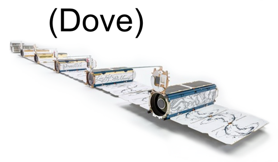
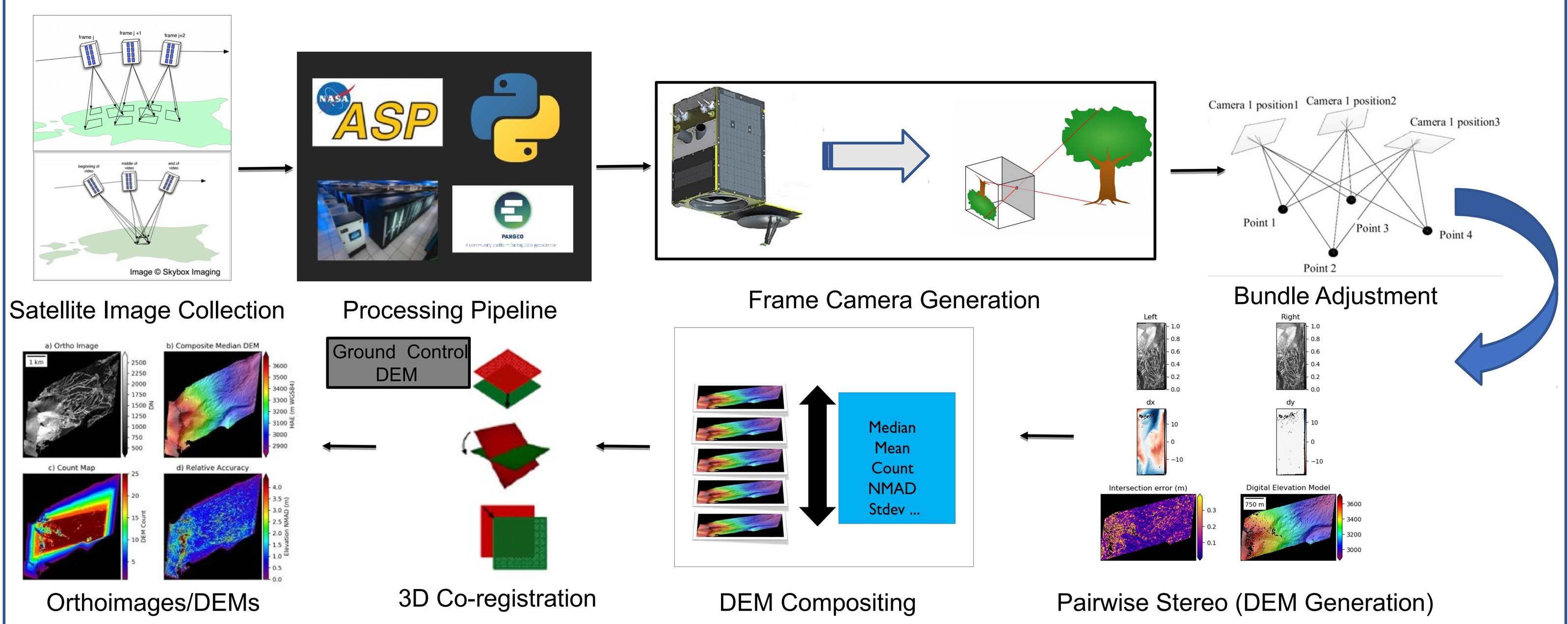
Summary

- We are using high-resolution commercial (DigitalGlobe and Planet) satellite imagery to study geodetic change of snow/ice in complex mountain topography over High-mountain Asia and Western North America.
- Preliminary results for Planet SkySat (0.9 m stereo), PlanetScope (3-5 m).
- Developing sensor model corrections to reduce artifacts, improve accuracy.
- Developing automated, open-source workflows to generate DEMs, orthoimages and derived products (elevation change, surface displacement).
- Applications: seasonal snowpack, monthly glacier velocity evolution.

Sensors

	Opportunities	Challenges
Planet Skysat 	• 13 Satellites in orbit • Less tasking competition • Multiview stereo (triplet, video mode) • 0.7 to 1 m GSD	• Small scene footprint (1-2 km²). • RPC geolocation errors: 10 to 100 m. • Stereo accuracy reduced in terrain with significant relief.
Planet PlanetScope (Dove) 	• ~150 satellites in orbit • Scene footprint (100-200 km²) • Continuous daily coverage • 3 to 5 m GSD • Short-term surface displacement • Potential multi-view stereo	• Saturated visible bands over snow/ice • Poor stereo geometry (small convergence angles) • Poor geolocation L3 orthorectified images • Band-to-band registration (parallax issues over terrain)

Methodology



DEM/Orthoimage Generation

- Create custom frame camera model from satellite/image metadata (RPCs)
- Bundle adjustment to correct relative position and orientation of all cameras
- Identify valid stereopair combinations and run pairwise stereo
- Co-register DEMs to accurate control data (Lidar, ICESat-2 WorldView DEMs)
- Create composite DEM (median, weighted average) and per-pixel statistics (NMAD)
- Generate orthoimages using composite DEM and mosaic

Derived Products: Elev. Change & Velocity

- DEM differencing to quantify elevation and volume change
  - Seasonal snow depth, glacier elevation change and mass balance, response to natural hazard events (landslides, avalanches, volcanic deformation).
- Sub-pixel feature tracking between orthoimage pairs to produce time series of surface velocity observations with short interval (weeks to months).

Skysat Triplet Stereo DEMs

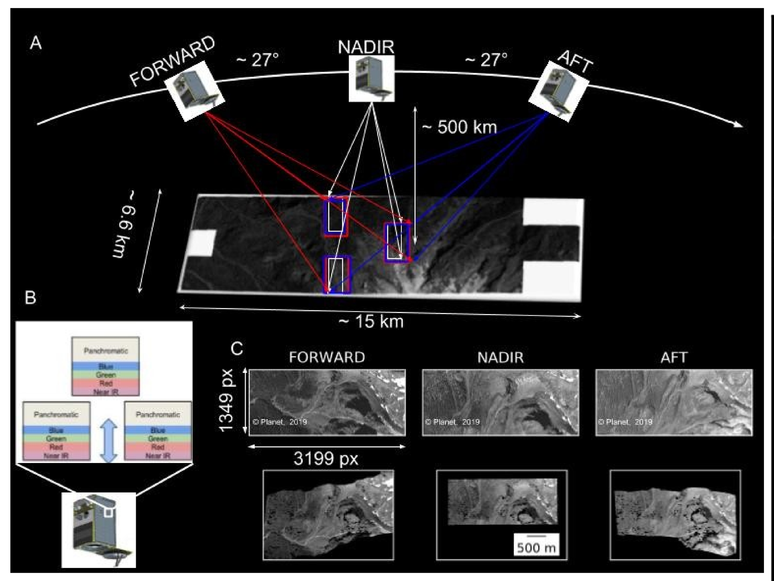
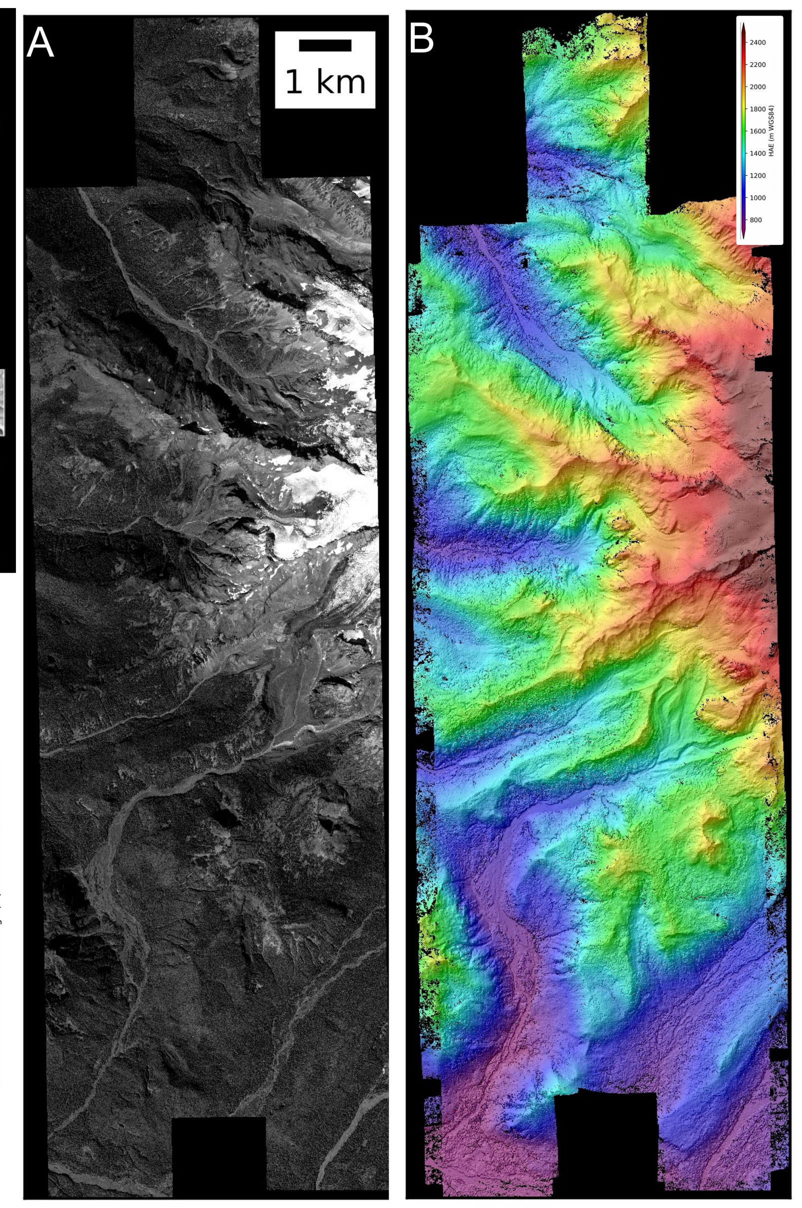


Figure 1: A) Skysat Triplet image acquisition geometry (not to scale). B) SkySat camera 3-CCD focal plane geometry. C) L1B frames and orthoimages. Note the difference in perspective for forward, nadir and aft images.



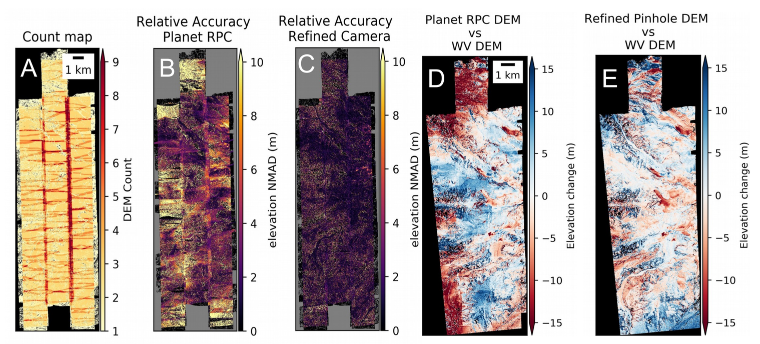


Figure 3: Mt. Rainier SkySat Triplet DEM metrics. A) DEM Count Map, B/C) per-pixel Normalized Median Absolute Difference (NMAD) before and after correction and bundle adjustment, D/E) Elevation difference between WV DEM composite (~2015) and Skysat DEM before and after correction. Refined camera models and relative position/orientation of all frames results in improved relative and absolute accuracy.

Figure 2: Sample Skysat triplet stereo products acquired August 27, 2019 for the western flank of Mt. Rainier, WA. a) Composite orthoimage, b) Composite 4-m DEM from 641 individual DEMs created using all two-scene stereo combinations.

Skysat Video: Multi-View Stereo

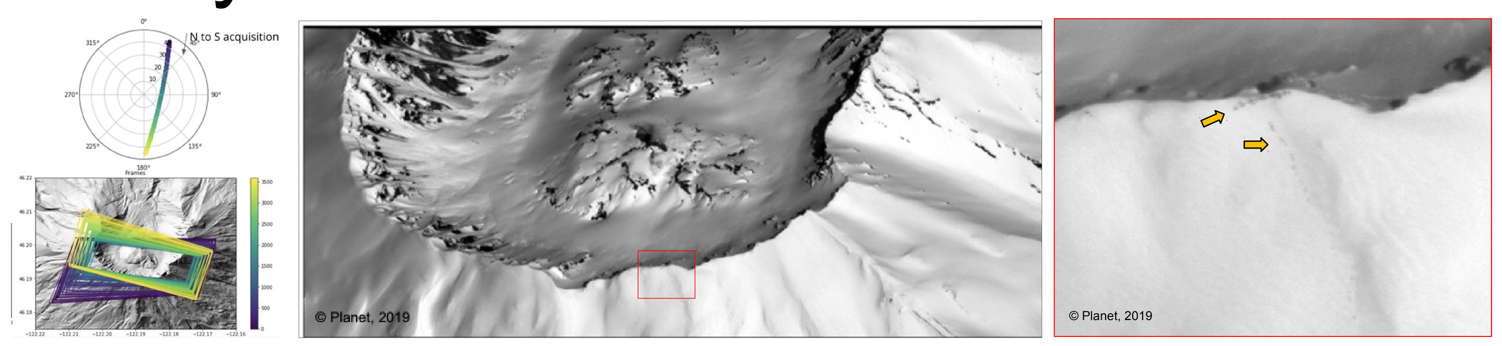


Figure 4: Left) SkySat video acquisition geometry and footprints for video frames 0-3600 of Mt. St. Helen's April 20, 2019 collect. Center) sample off-nadir video frame near the end of the video sequence. Right) Detail showing climbers approaching the summit.

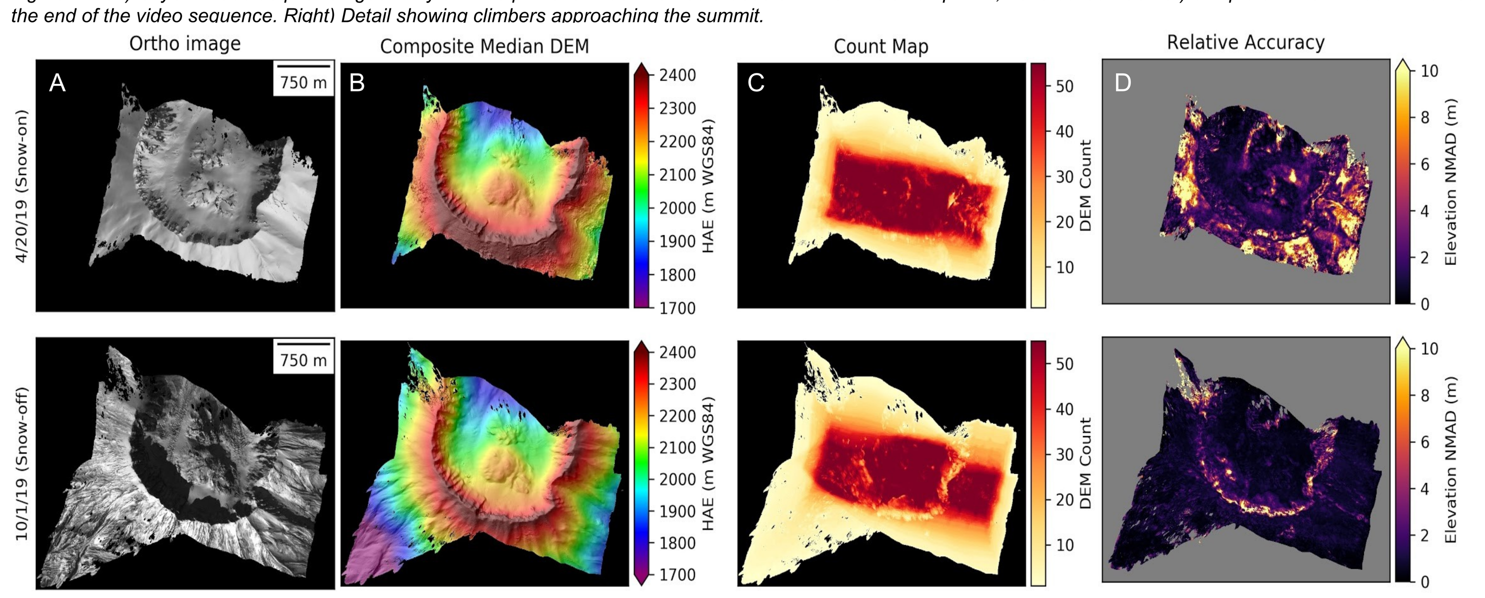


Figure 5: SkySat video products for Mt. St. Helen's crater, acquired April 20, 2019 (near peak SWE, top row) and October 1st (near end of melt season, bottom row): a) Orthorectified image mosaic, b) Composite ASP DSM from 55 stereo pairs, c) per-pixel DSM count, and d) per-pixel Normalized Mean Absolute Difference (NMAD), which provides metric for relative accuracy of composite DSM. Note DSM quality over steep crater wall slopes and <1 m relative accuracy over crater floor.

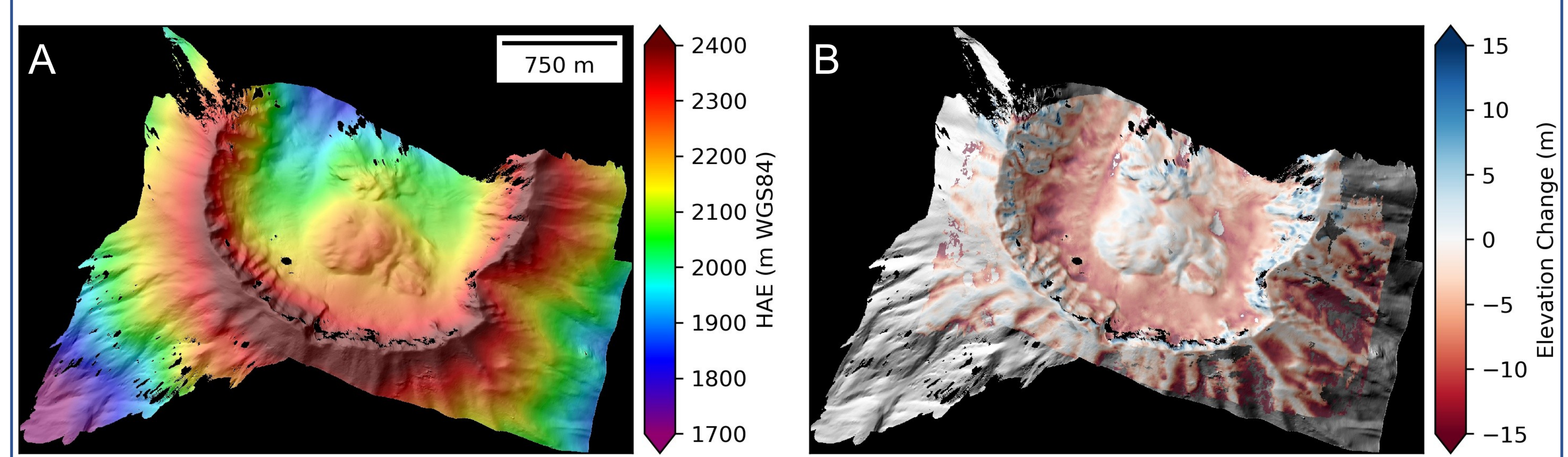


Figure 6: a) Enlarged Oct. 1 DSM. b) Preliminary SkySat elevation difference map, showing snow melt between April and October.

PlanetScope Glacier Velocity

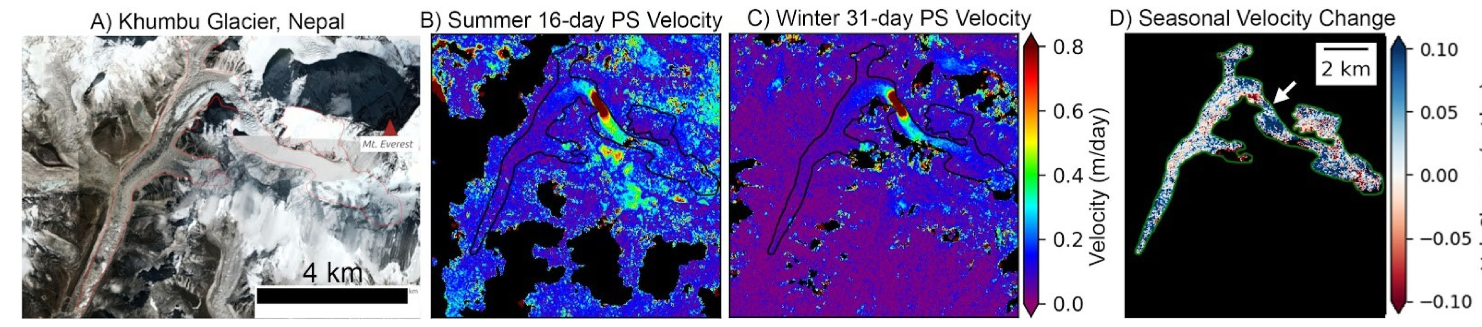


Figure 7: Seasonal velocity for Khumbu Glacier derived from corrected PS 3-m orthoimages with 16-day and 31-day separation for June-July (summer) (B) and October-November (winter) (C), respectively (arrow in D highlights seasonal change below/above fast-flowing region of Khumbu icefall).

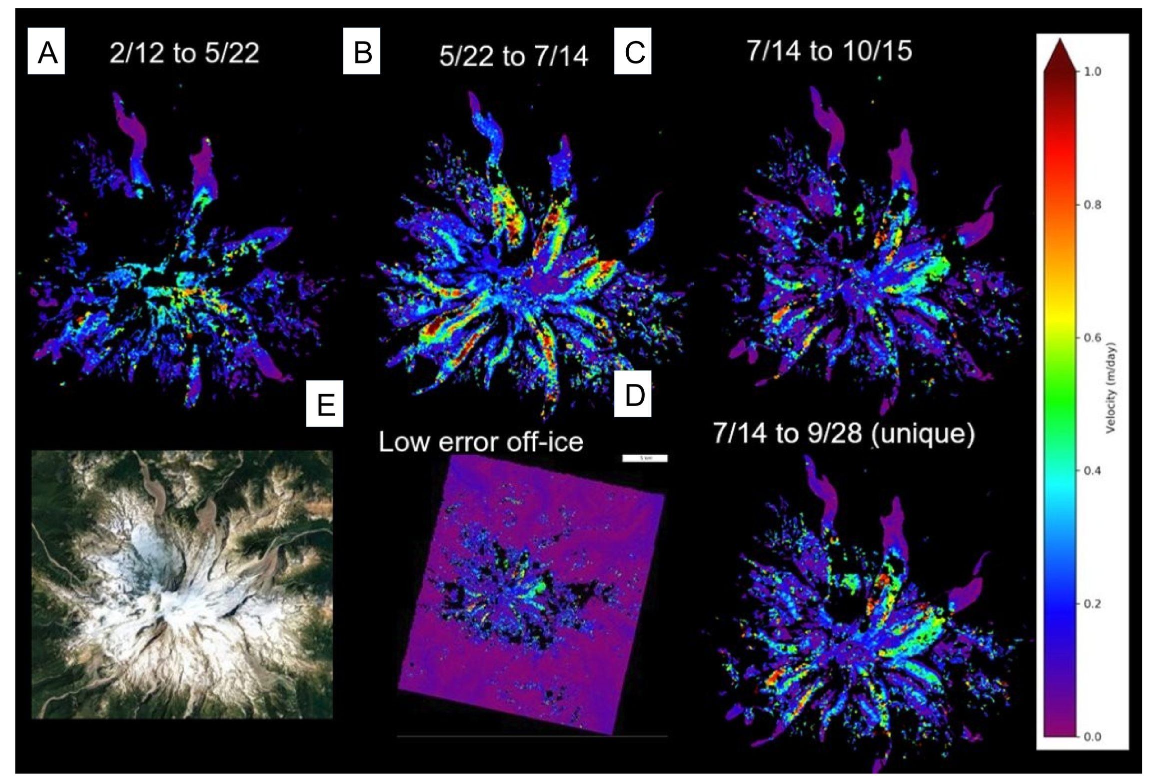


Figure 8: Seasonal Velocity variations for Glaciers at Mt. Rainier, WA derived from correct PS 3-m orthoimages. Note the reactivation of debris-covered lower Carbon and Winthrop Glaciers in late spring and the low error over static surface.

PlanetScope DEM

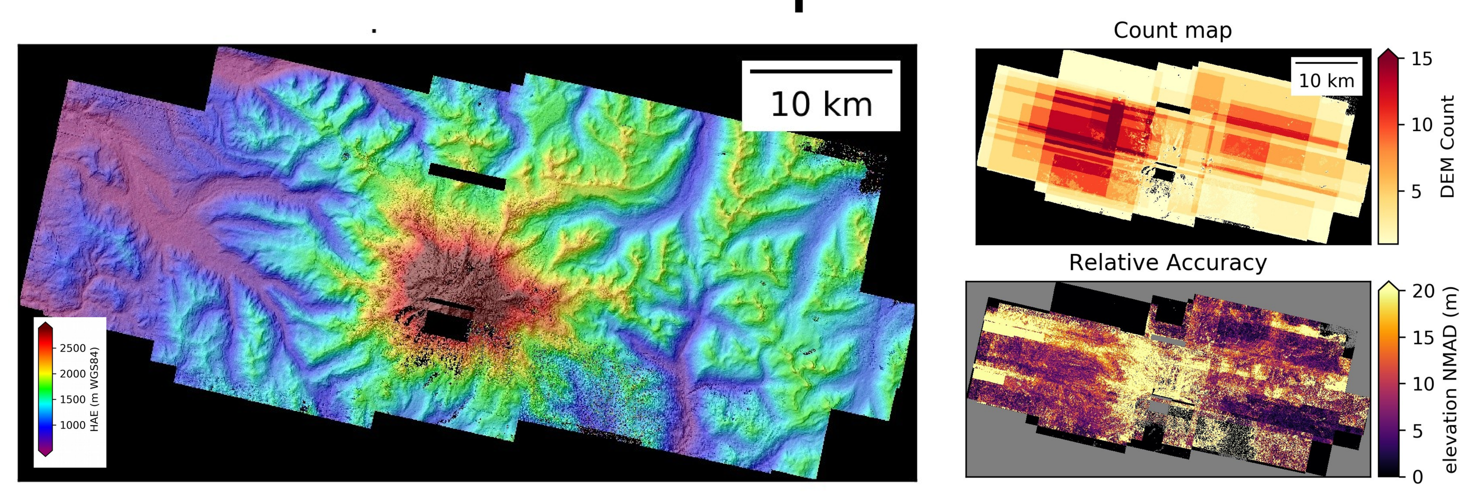


Figure 9: Preliminary Composite PlanetScope DEM (left) , DEM count and NMAD (right) from candidate pairs in Fall 2017 over Mt. Rainier, WA.

PlanetScope Archive

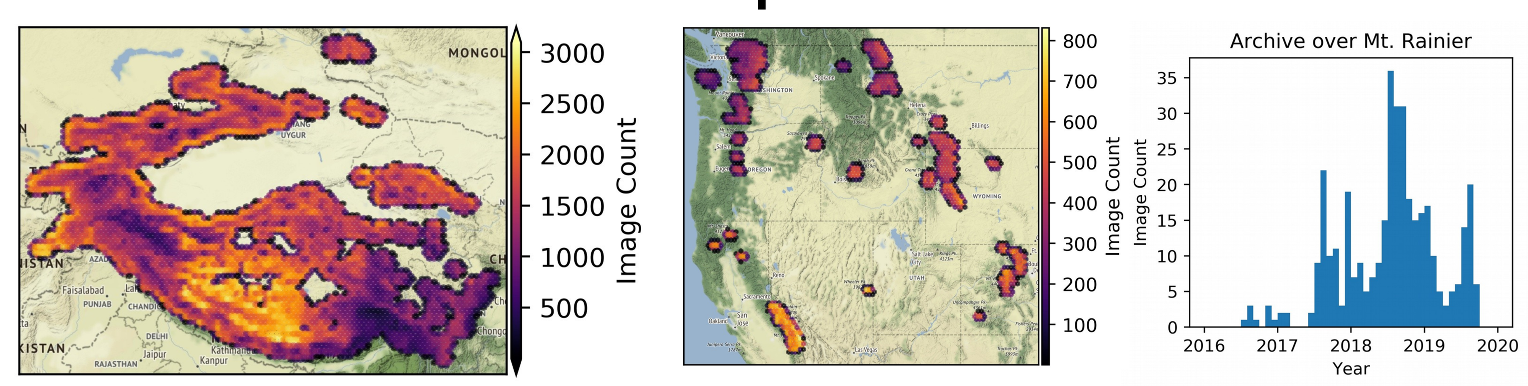


Figure 10: Left) Cloud-free PlanetScope imagery over High-Moutain Asia (<20% cloud cover) and CONUS (<30% cloud cover). Right) Monthly, cloud-free PS coverage over Mt. Rainier, WA, USA.

Future Work

- ❑ Implement refined corrections to further improve Skysat DEM accuracy, reduce uncertainties in PlanetScope Glacier velocity estimates.
- ❑ Improve processing workflow, generate seasonal glacier velocity observations for high-priority sites, integrate velocity measurements from WorldView time-series.
- ❑ Document and release open-source workflows and derived data products.

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