Three summers of high-resolution, high-accuracy velocity data of Helheim Glacier, as measured by an automated terrestrial LiDAR scanner: methods, challenges, and applications

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Background

Measurements of glacier surface velocity are used to inform glacier flow and flux models (Stearns and Hamilton 2007), investigate glacier dynamics such as calving response (Nettles et al., 2008), and estimate mass loss (Howat et al., 2007). Direct measurement of surface velocity with on-ice GNSS receivers produces data with dense temporal resolution, but these data are limited in spatial resolution, spatial coverage, and temporal coverage. Remote sensing, whether by terrestrial, airborne, or spaceborne platforms, can provide surface velocity measurements with better temporal and spatial coverage, but often at the expense of temporal and/or spatial resolution.

As previously reported (Finnegan et al., 2015; Finnegan et al., 2016), the autonomous Terrestrial LiDAR Scanner, ATLAS, was installed south of the Helheim Glacier (Figure 1) in June 2015. This scanner produces three-dimensional data (point clouds) with dense spatial resolution (~10 pts/m^2 at 2km, Figure 4) and good temporal resolution (4 scans per day during the summer, 1 scan per day during the winter). This poster presents the glacier surface velocities as calculated from pairs of ATLAS point clouds, using a relatively new three-dimensional change detection method called Coherent Point Drift (CPD).

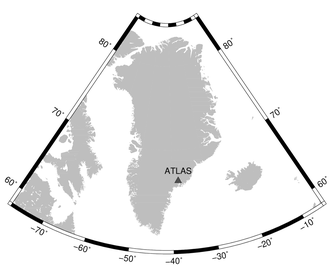


Figure 1: Location of the ATLAS system on the south side of the Helheim Glacier in southeast Greenland.

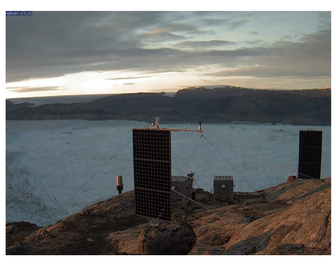


Figure 2: An image from ATLAS_CAM, taken 2017-09-04 21:25:00 UTC. ATLAS_CAM is a remote camera that looks north through the ATLAS site and across the Helheim Glacier.

System detail

The ATLAS system consists of a Riegl VZ-6000 scanner inside of a smart protective housing, with supporting data logger, weather sensors, solar power, and fuel cells. Scanner information and configuration are presented in Table 1. Scan data are stored on the scanner and on a site-local backup hard drive. Due to high data volumes, the scan data themselves must be retrieved in person during yearly site revisits. System status information and environmental data are transmitted via satellite link in hourly "heartbeat" messages, and system status is presented in visual form via http://atlas.lidar.io (Figure 3) and programmatically via http://api.glac.io. We maintain several cameras around Helheim and the Sermilik Fjord (Figure 4), and the two of these autonomous cameras are located near the ATLAS system provide near-realtime visual information about the system (e.g. Figure 2).

LiDAR system manufacturer and model	Riegl VZ-6000
Laser wavelength	1064 nm
Laser pulse repetition rate as configured	50 kHz
Maximum measurement range (ρ ≥ 90%/ρ ≥ 20%)	6km / 3.6km
Manufacturer specified accuracy	15 mm
Manufacturer specified precision	10 mm
Laser beam footprint at 2km	240 mm
Scan frequency	Every 6 hrs until October 1st, then every 24 hrs until winter shutdown.

Table 1: ATLAS system information and configuration.

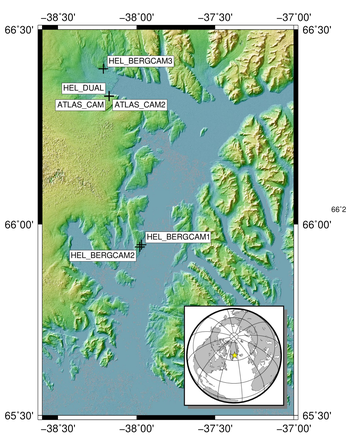


Figure 3: Currently active remote cameras maintained by our group around the Helheim Glacier and Sermilik Fjord.

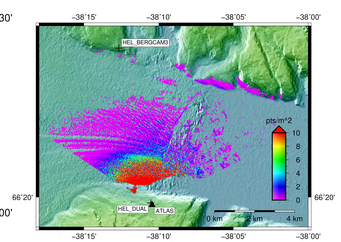


Figure 4: Equipment locations and typical scan data densities captured by the ATLAS system.

Figure 5: The ATLAS status website, http://atlas.lidar.io.

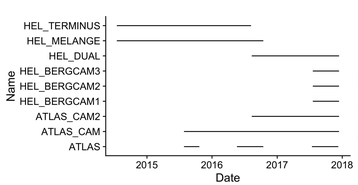


Figure 6 (left): Temporal coverage for all of our equipment at the Helheim Glacier and the Sermilik Fjord. Remote cameras (everything except ATLAS) transmit their images back to servers in CONUS via satellite link. ATLAS stores data locally, and these data are retrieved during yearly site visits.

Results

Figure 7: Image taken by HEL_TERMINUS at 2016-07-08 12:00 UTC. HEL_TERMINUS is a remote camera stationed near the ATLAS system, pointed north across the Helheim Glacier. HEL_TERMINUS was replaced by HEL_DUAL in late July 2016.

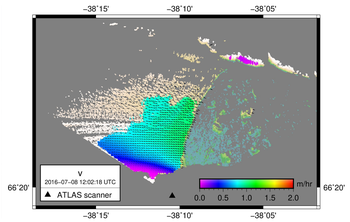


Figure 8: Glacier surface velocity magnitude, in m/hr, as calculated by comparing a scan collected at 2016-07-08 12:02 UTC and another scan collected at 18:02 UTC the same day. Arrows indicate the direction of the x-y component of velocity, and size of the arrow provides relative magnitude of that x-y component. Arrows are located at the center of gravity of each CPD measurement, and background data is a DSM calculated from the ATLAS scan data, colorized by elevation.

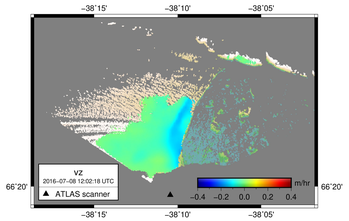


Figure 9: The glacier surface velocity in the z-direction, as calculated from the same pair of scans as referenced in Figure 8. The downward motion, visible in blue, is due to the tidal response of the floating tongue of the glacier. Figures 11-20 will reference z-direction velocities only, as the the z-velocities provide the most visually compelling results.

2015 and 2016 in aggregate

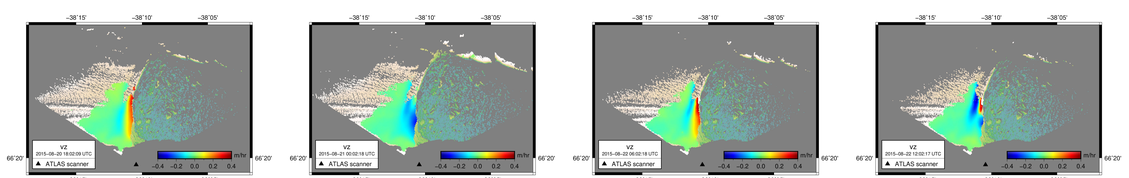
Number of scans	576
Approximate number of points on glacier and melange	More than 6376 million
Number of independent velocity measurements	354337

The ATLAS system shut down for the season on December 10th, 2017, and we look forward to retrieving the 2017 scan data during our 2018 site revisit.

Future work

- A second ATLAS system will be installed on the north side of the Helheim Glacier in summer 2018, near the current site of HEL_BERGCAM3. This second system will provide across-glacier terrestrial LiDAR coverage and, thanks to better solar exposure, a longer scan season than the original site. The original site will continue to operate with upgraded hardware.
- CPD-derived velocities should receive additional validation from coincident on-ice GNSS measurements.
- An improved power system will hopefully get us closer to year-round data collection.
- On-site processing would allow for near-realtime calculation and transmission of glacier velocities, removing the need for expensive site visits to retrieve velocity data.
- CPD should continue to be assessed versus alternatives, such as ICP and particle imaging velocimetry (PIV), for accuracy and computational performance.

Figure 10: Image taken by HEL_TERMINUS at 2015-08-21 12:00 UTC.



Figures 11-14: A sequence of four images of the z component of the glacier surface velocity, beginning at 2015-08-20 18:02 UTC and ending 2015-08-22 12:02 UTC. This sequence illustrates the development of a rotating block at the terminus of the glacier before a calving event.

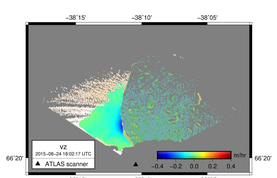
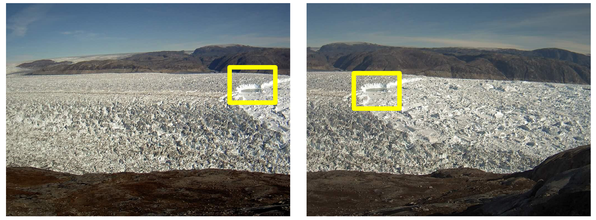
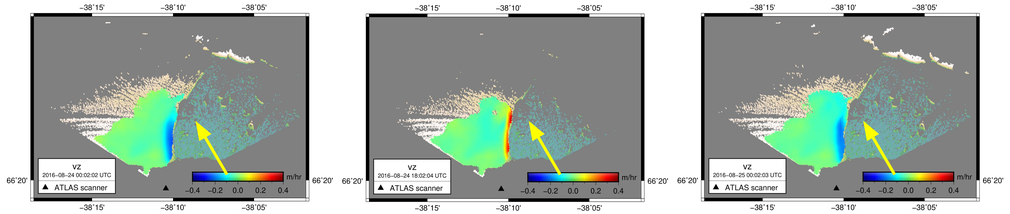


Figure 15: The z-velocity of the glacier post-calving event, as derived from data collected 2015-08-24 18:02 UTC.



Figures 16-17: Two images taken by HEL_DUAL on 2016-08-24 at 12:00 UTC. HEL_DUAL is a dual-camera system that replaced HEL_TERMINUS in late July 2017. A large upwelling is highlighted in both images.



Figures 18-20: Maps of the z-velocities as calculated from three scans collected between 2016-08-24 and 2016-08-25. The same upwelling that was identified in Figures 16-17 is indicated with arrows in Figures 18-20. It appears as though the terminus near the upwelling is *not* descending as tides recede (Figures 18 and 20), but is rising at high tide (Figure 19).

Methods

Data processing takes place in three steps:

1. Georegistration
2. Velocity calculation
3. Interpolation

Georegistration

Georegistration is complicated by diurnal and other motion in the ATLAS scanner (Figure 21), and so takes the following form,

```
GLCS = POP * ADJUSTMENT * SOP * SOCS,
```

where `GLCS` is a point in the global coordinate system, `POP` is the ATLAS's project's own position matrix, `ADJUSTMENT` is a rotation and translation that best aligns the scan data to the reference scan, `SOP` is the scanner's own position matrix for the reference scan, and `SOCS` is the point in the scanner's own coordinate system.

To calculate the adjustment matrix, CPD is to align a 1m sample of the "near field" points, i.e. data collected on rocks and vegetation and *not* on the glacier, with the reference scan. The reference scan was collected during system installation in July 2015, and was georeferenced using GNSS receivers and cylindrical retroreflectors. The resultant rigid transformation is the adjustment matrix.

Velocity calculation

Nonrigid three-dimensional change detection is traditionally done by moving a "rigid" change detection method through the data using a segmented moving window approach, a la Zhang et al, 2015. We copied that approach, but instead of Iterative Closest Point (ICP) (Besl and McKay, 1992) we use Coherent Point Drift (CPD) (Myronenko and Song, 2010). This method has been shown to be more accurate than ICP, as compared to on-ice GNSS measurements at Helheim Glacier (Gadomski, 2016), though additional validation is surely warranted.

Data are divided into 100m grids, with all grid cells smaller than a given threshold (in this case, 250 points) upsized to 200m. CPD is run on grid cells collected six hours apart, and the mean displacement of the grid cell's points is reported as the displacement of that grid cell. The time between the two scans is used to convert this displacement to a velocity measurement

Interpolation

Each grid cell is reduced to its center of gravity (Figure 22), and all centers of gravity with a z coordinate of less than 40m are removed in a crude attempt to report only glacier surface velocities. It should be noted that melange velocities are also produced by this method and could themselves be of scientific interest, but are not discussed in this poster.

The remaining point measurements are interpolated to a 10m grid using inverse distance weighting with a minimum number of neighbors 7 within 200m.

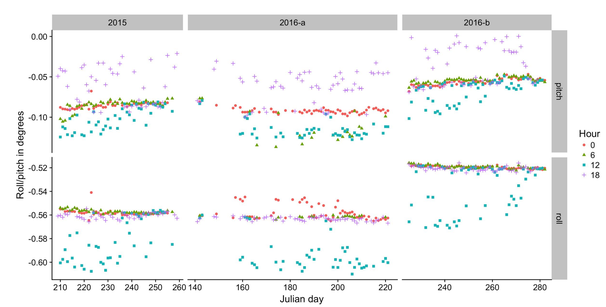


Figure 21: Mean inclinations, as reported by the scanner's internal inclination sensors, for each scan in 2015 and 2016, colored and shaped by nominal UTC hour of the scan. During the July 2017 site revisit, the ATLAS scanner hardware was changed, which caused a modification in the roll and pitch of the scanner. Pre-scanner-change data are presented as 2016-a, and post-scanner-change data are presented as 2016-b. The diurnal variation in the mean roll and pitch are clearly visible, likely caused by solar heating and expansion of the ATLAS guy wires.

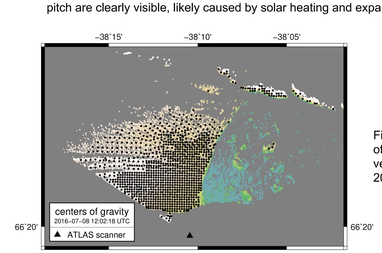


Figure 22 (left): The centers of gravity of the grid cells used to calculate velocities for the scan taken 2016-07-08 12:02 UTC.

Contact information

Inquiries, including requests for data, can be directed to the first author, Peter J Gadomski: peter.j.gadomski@erdc.dren.mil. The first author is available on Github at https://github.com/gadomski and on twitter at @petegadomski.

Selected software

With a few exceptions, this work was done with open-source software. Some key components were:

- PDAL: The Point Data Abstraction Library, https://www.pdal.io/.
- Two open-source implementations of Coherent Point Drift (CPD): https://github.com/gadomski/cpd and https://github.com/gadomski/cpd-rs/.

References

- Besl, P. J., & McKay, N. D. (1992). A Method for Registration of 3D-Shapes. IEEE Transactions on Pattern Analysis and Machine Intelligence, 14(2), 239–256. https://doi.org/10.1109/34.121791
- Finnegan, D. C., Hamilton, G. S., LeWinter, A., Gadomski, P. J., Stearns, L. A., & Kershner, C. M. (2016). High-Resolution Tidewater Glacier Monitoring Using Automated Multi-Temporal Terrestrial LiDAR; Year One Results, Helheim Glacier, Southeast Greenland. In AGU Fall Meeting Abstracts.
- Finnegan, D. C., LeWinter, A. L., Hamilton, G. S., Gadomski, P. J., & Stearns, L. A. (2015). Long-term Autonomous Tidewater Glacier Monitoring Using a Long-Range Terrestrial LiDAR Scanner; Helheim Glacier, Southeast Greenland. In AGU Fall Meeting Abstracts.
- Gadomski, P. J. (2016). Measuring Glacier Surface Velocities With LiDAR: A Comparison of Three-Dimensional Change Detection Methods. University of Houston.
- Howat, I. M., Joughin, I., & Scambos, T. A. (2007). Rapid changes in ice discharge from Greenland outlet glaciers. Science (New York, N.Y.), 315(5818), 1559–61. https://doi.org/10.1126/science.1138478
- Myronenko, A., & Song, X. (2010). Point set registration: coherent point drift. IEEE Transactions on Pattern Analysis and Machine Intelligence, 32(12), 2262–75.
- Nettles, M., Larsen, T. B., Elósegui, P., Hamilton, G. S., Stearns, L. A., Ahlstrøm, A. P., … Forsberg, R. (2008). Step-wise changes in glacier flow speed coincide with calving and glacial earthquakes at Helheim Glacier, Greenland. Geophysical Research Letters, 35.
- Zhang, X., Glennie, C. L., & Kusari, A. (2015). Change detection from differential airborne LiDAR using a weighted anisotropic iterative closest point algorithm. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 8(7), 3338–3346. https://doi.org/10.1109/JSTARS.2015.2398317

This work is dedicated to the memory of Gordon Hamilton.