EO for measuring glacier topography and elevation changes

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generating dems from satellite data

typically, dems can be placed into two categories
  ▶ optical (e.g., aerial photos, ASTER, SPOT, Worldview, Planet)
  ▶ radar (e.g., SRTM, TanDEM-X, ERS-1/2)
each category has its own advantages/drawbacks
stereo photogrammetry
stereo photogrammetry

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optical sensors

- advantages:
  - (relatively) easy to understand
  - old images/data available (over 100 years in some places)
  - do-it-yourself (diy) dems
  - we know which surface we’re measuring

- disadvantages:
  - highly weather-dependent
  - snow is often featureless
  - shadows
radar interferometry

stay tuned after the coffee break!
radar sensors

▶ advantages:
  ▶ weather (and illumination) independent
  ▶ consistent illumination geometry

▶ disadvantages:
  ▶ what surface are we measuring?
  ▶ mountainous areas can be challenging
  ▶ often need more specialized equipment, software
generating/acquiring dems

- ASTER archive (global coverage, 2000-)
- ArcticDEM (thanks, Obama!)
- IPY/SPRIT DEMs (SPOT 5, 40 m resolution)
- SRTM (C-band, X-band)
- do-it-yourself with a camera
- regional-specific datasets (i.e., old maps)
errors/uncertainty

error/uncertainty sources include (but are not limited to):

- satellite/sensor motion (jitter)
- georeferencing errors
- radar penetration
- dems acquired at different times
- voids/nodata (due to poor contrast, clouds, etc.)
micmac aster (mmaster) test case

Girod et al., 2017
mmaster post-corrections

Girod et al., 2017
master post-corrections
mmaster dem differences

Girod et al., 2017
master dem differences
co-registration

errors/small shifts in georeferencing occur between different dems

- mis-alignment between two surface representations
- these errors become very obvious in difference image (resembles hillshade)
- can use offsets, slope, aspect to co-register
co-registration
co-registration

Nuth and Kääb, 2011
co-registration

Paul et al., 2015
co-registration and volume changes

\[ \Delta V: -0.68 \text{ km}^3 \]
\[ \Delta V: -1.99 \text{ km}^3 \]
\[ \Delta V: -2.17 \text{ km}^3 \]

\[ \Delta x: -32.6 \text{ m} \]
\[ \Delta y: 17 \text{ m} \]
\[ \Delta z: 4.9 \text{ m} \]
radar penetration

- radar signals penetrate snow, ice to (generally) unknown degree
- depth of penetration depends on properties of snow, ice, as well as signal (i.e., wavelength)
- in other words, spatially and temporally varying
- impact/importance of penetration depends on application
srtm c- and x-band comparison

Gardelle et al., 2012
srtm c- and x-band comparison
Figure 2: Rates of elevation change vs. elevation for the JIF from 2000 to 2013 (a) and for the SIF from 2000 to 2014 (b). Results from this study are compared to the $dh/dt$ values obtained in two earlier studies using a similar method (Melkonian et al., 2014, 2016). The grey histograms show the area-altitude distribution.

Berthier et al., 2018
tandem-x vs pléiades

Fig. 5. Elevation difference between (a) TDX 2013/10/21 and Pléiades 2013/09/20 DEMs, (b) TDX 2013/02/01 and Pléiades 2012/08/19 DEMs. Positive values indicate that TDX is above Pléiades. The Mont-Blanc summit (4810 m) is marked with a yellow triangle. The background is a shaded relief of the Pléiades 2012 DEM.

Dehecq et al., 2016
tandem-x vs pléiades
tandem-x vs in-situ snow
temporally inconsistent dems

many older dems are made from data acquired over many years from different sources

▶ sometimes dates are incorrectly recorded
▶ surveys may end one year, continue 1-2 years later
▶ borders, other boundaries may have inconsistent data
spot the international border!
acquisition dates

Larsen et al., 2007
spot the survey boundary!
dem differencing and geodetic mass balance

- elevation change can be used to estimate glacier volume (and mass) changes
- basic principle is continuity:

\[ \frac{\partial h}{\partial t} = \dot{b} + \nabla q \]

- integrated over glacier surface*, \( \nabla q = 0 \)
- otherwise, have to partition dynamic, climatic changes
spatially incomplete data
creating artificial voids
method comparison
method comparison

![Box plots showing method comparison](image)

- poly hyp
- mean hyp
- median hyp
- median dh
- mean dh
- ind. polyfit el.
- ind. median el.
- ind. mean el.
- 1km neighborhood
- glob. polyfit el.
- glob. median el.
- glob. mean el.
- z interp.
- dh interp.

The x-axis represents the difference to truth (km³) ranging from -1.00 to 1.00.
estimating uncertainties in dem differences

- stable ground differences to a higher-resolution/higher-quality dem (if available)
- stable ground differences to ICESat elevations (also if available)
- with a third product, can also use residuals of co-registration vectors
- if no external data available, estimate RMSE in off-glacier areas from difference map
estimating uncertainty

Paul et al., 2017
glacier elevation changes: alaska

Berthier et al., 2010
glacier elevation changes: patagonia


Willis et al., 2012, *GRL*
permafrost/rock glacier elevation change: switzerland

Kääb and Vollmer, 2000
snow depths: alaska

Nolan et al., 2015
summary

- lots of dems available from lots of different sources
- important to consider source, limitations (depends on study goal)
- co-register your dems in x, y, and z
- metadata is important!