Stereo2SWE:
Regional snow depth from high-res commercial satellite stereo imagery

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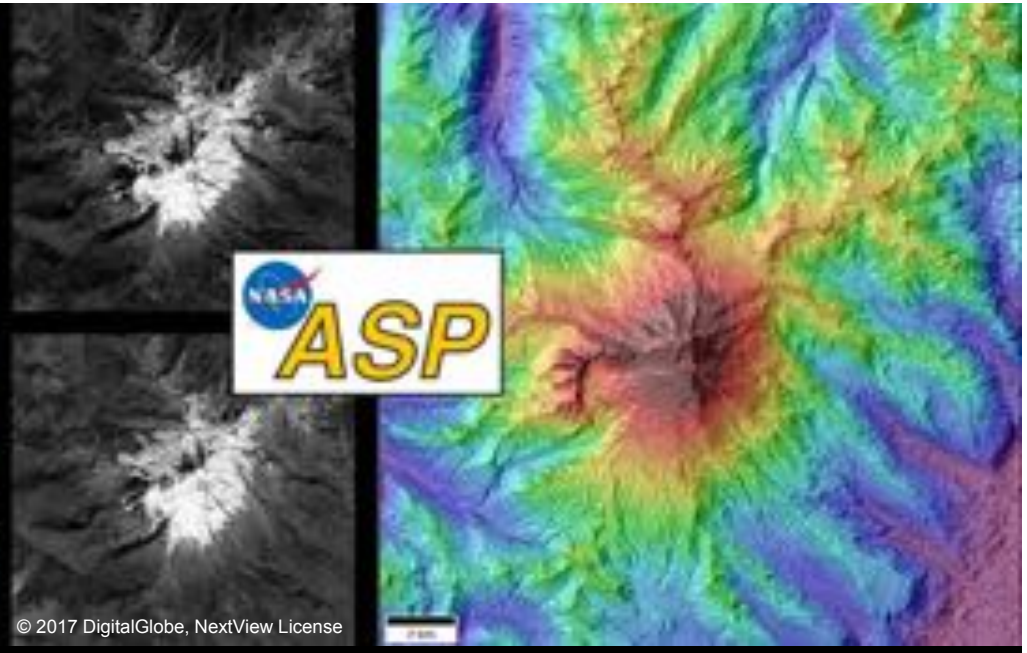
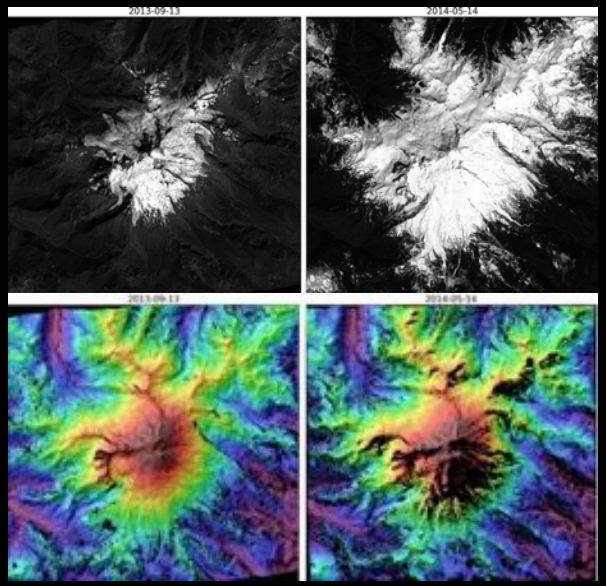
Along-track Stereo Collection

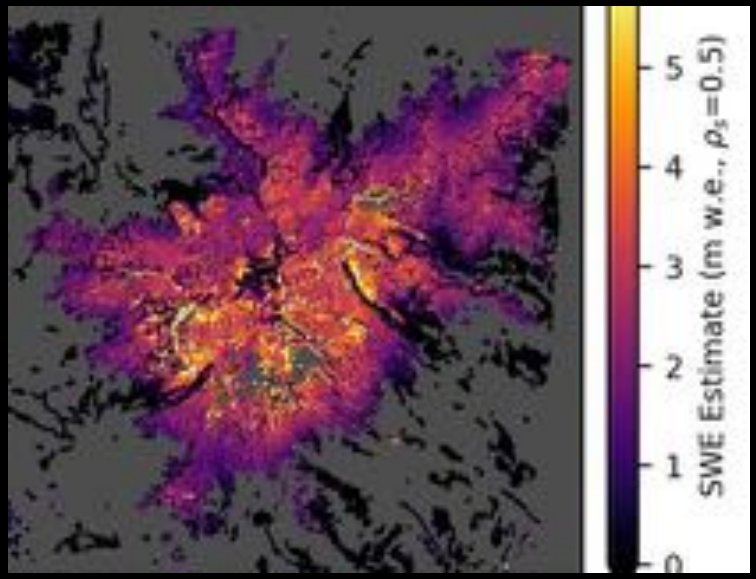


0.3-0.5 m images
13-17 km swath

2-m DEM



Snow-off Snow-on



Snow depth from ΔDEM, converted to SWE

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An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very-high-resolution commercial stereo satellite imagery

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ABSTRACT

We adapted the automated, open source NASA Ames Stereo Pipeline (ASP) to generate digital elevation models (DEMs) and orthoimages from very-high-resolution (VHR) commercial imagery of the Earth. These modifications include support for rigorous and rational polynomial coefficient (RPC) sensor models, sensor geometry correction, bundle adjustment, point cloud co-registration, and significant improvements to the ASP code base. We outline a processing workflow for ~0.5 m ground sample distance (GSD) DigitalGlobe WorldView-1 and WorldView-2 along-track stereo image data, with an overview of ASP capabilities, an evaluation of ASP correlator options, benchmark test results, and two case studies of DEM accuracy. Output DEM products are posted at ~2 m with direct geolocation accuracy of <5.0 m CE90/LE90. An automated iterative closest-point (ICP) co-registration tool reduces absolute vertical and horizontal error to <0.5 m where appropriate ground-control data are available, with observed standard deviation of ~0.1–0.5 m for overlapping, co-registered DEMs (n = 14,17). While ASP can be used to process individual stereo pairs on a local workstation, the methods presented here were developed for large-scale batch processing in a high-performance computing environment. We are leveraging these resources to produce dense time series and regional mosaics for the Earth's polar regions.
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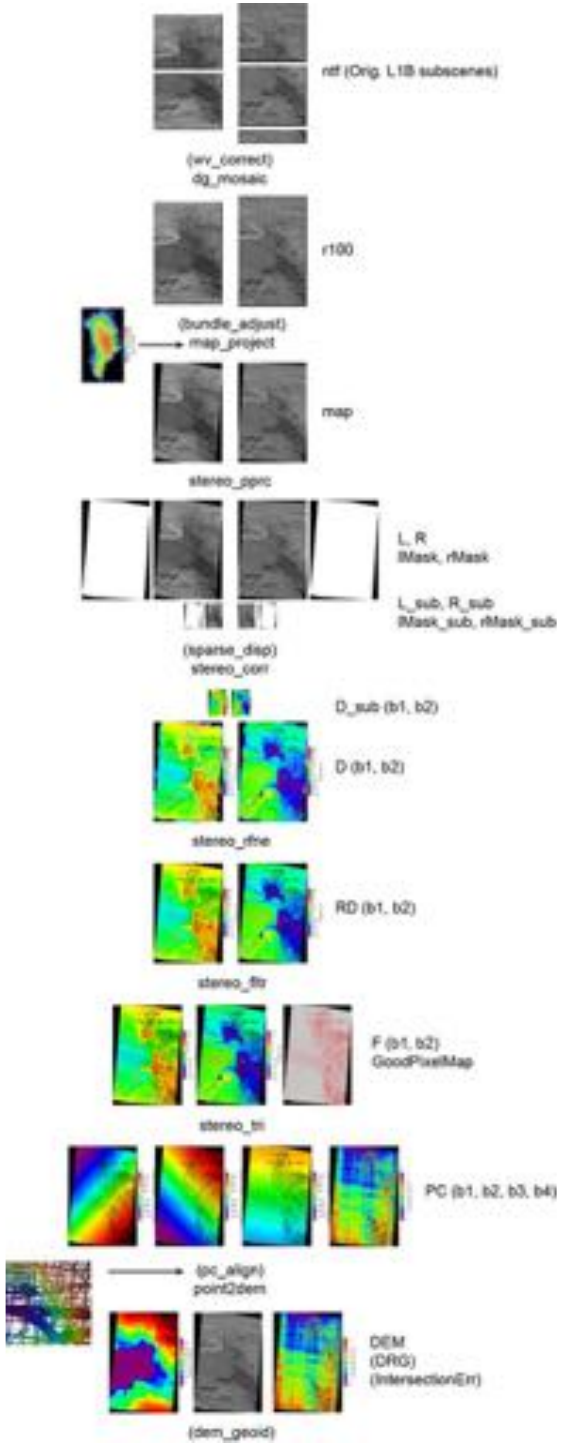
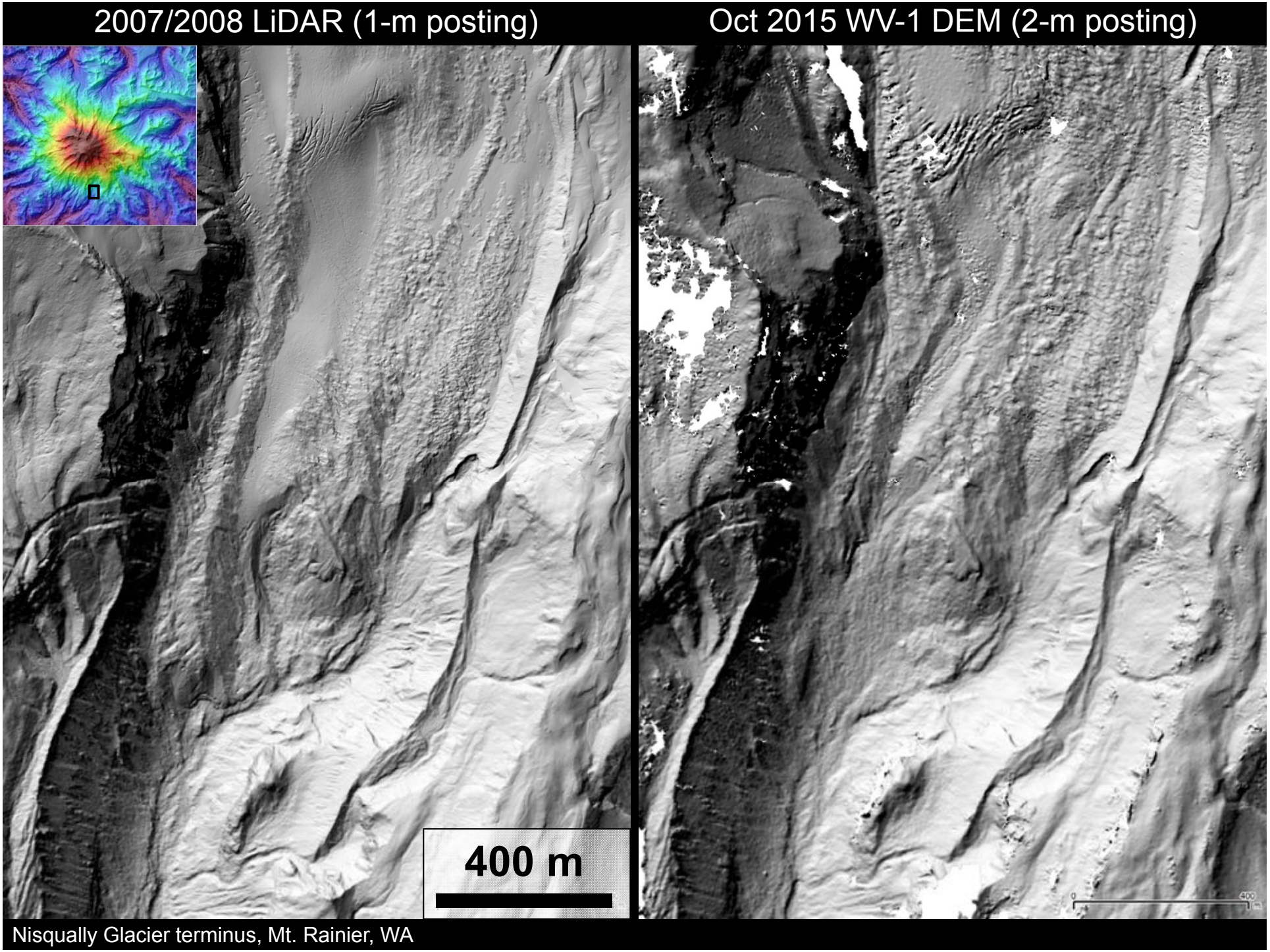
NASA Ames Stereo Pipeline

NASA Pleiades HPC
(Om nom nom nom…)

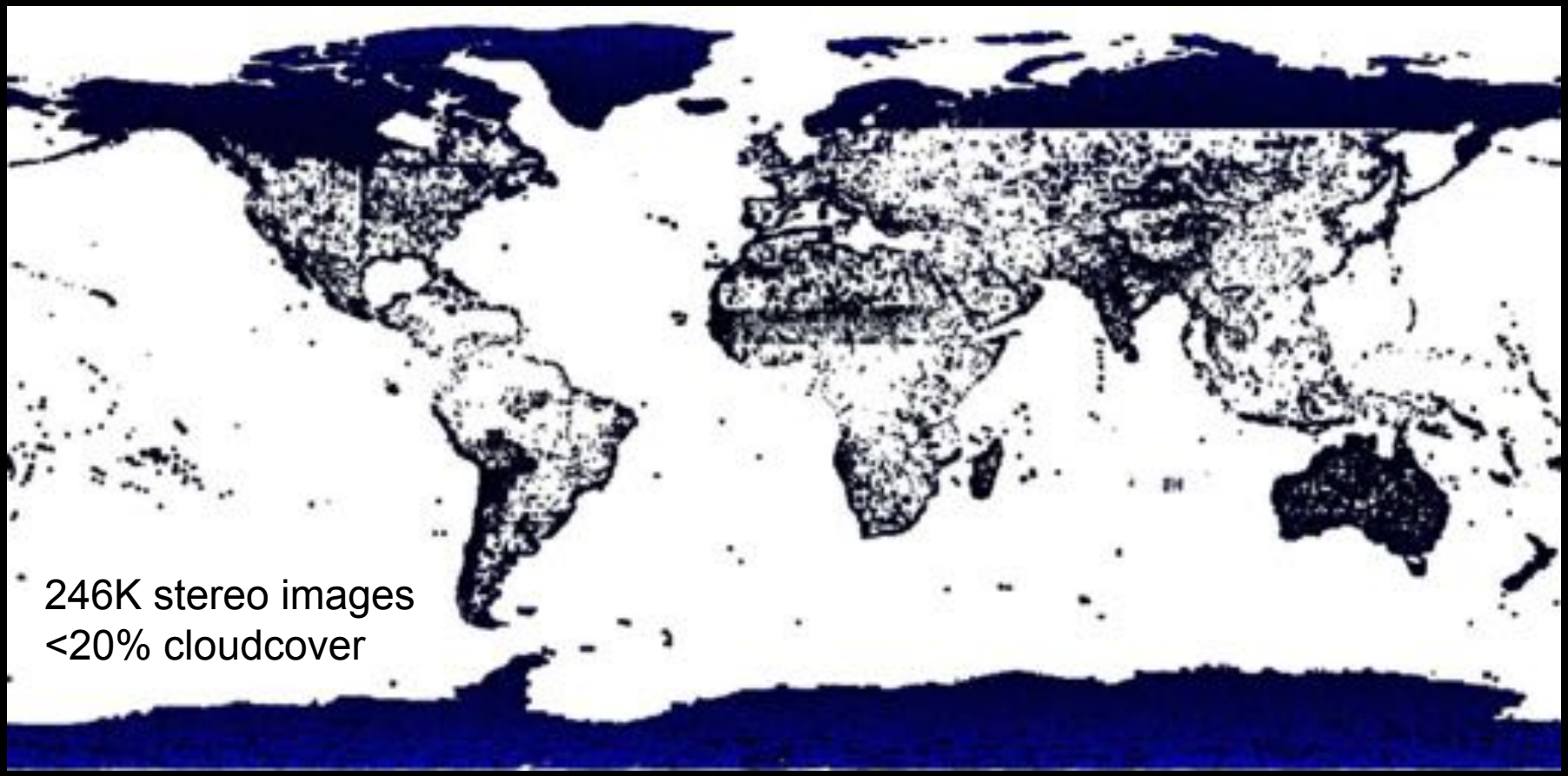


WV/ASP FAQ

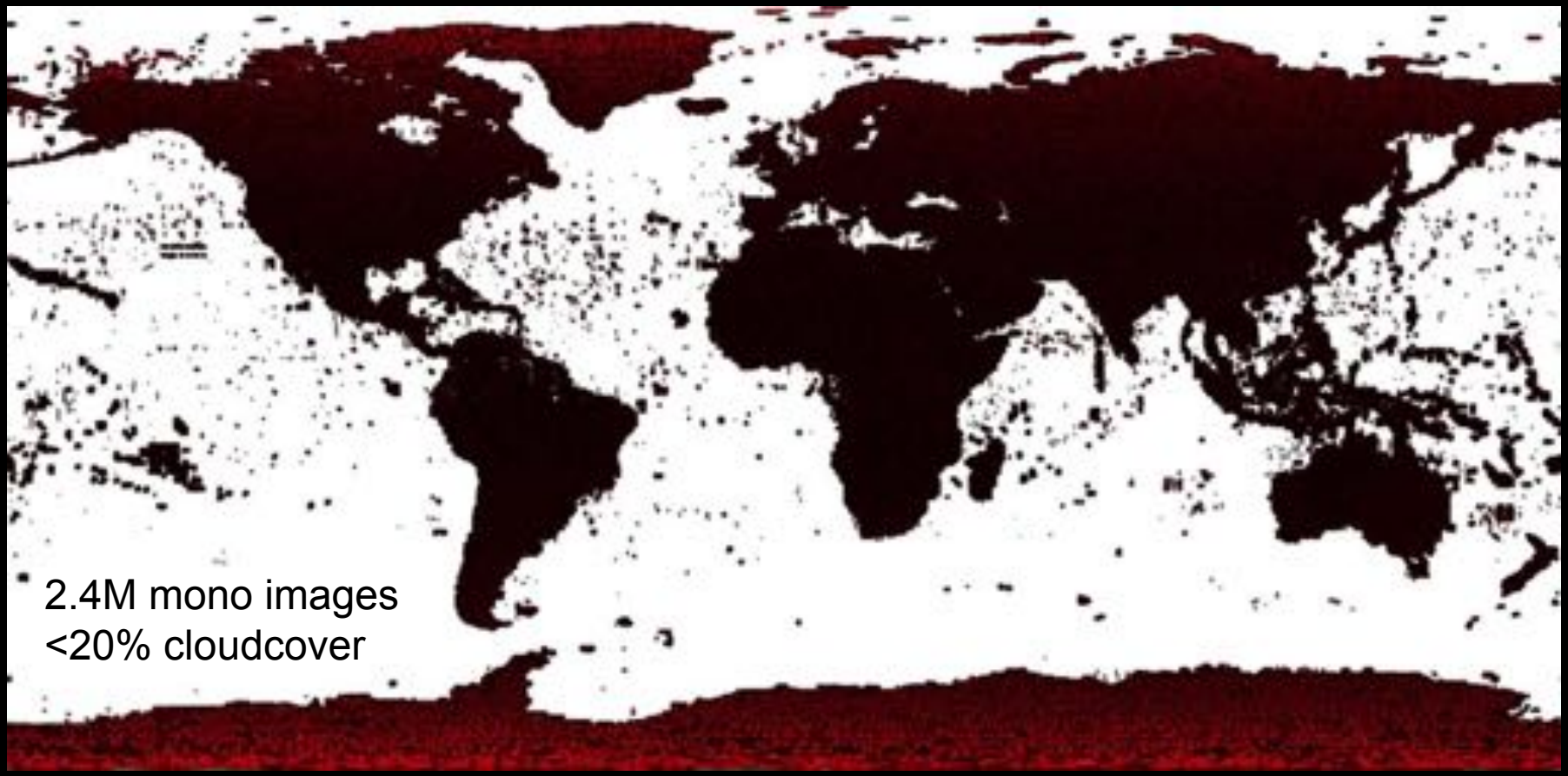
- Imagery: ~0.3-0.5 m, 10-11 AM local, <1-2 day repeat
  - 4-8 band MS imagery: ~1.2-1.9 m
  - ~200-7000 km^2 (~40K x 440K px)
- DEM posting: ~2 m, 8 m, 32 m
- “First-return” DSM (includes vegetation, buildings)
- DEM accuracy:
  - Uncorrected vert/horiz accuracy: <5 m CE90/LE90
  - Corrected/relative accuracy: <0.1-0.5 m
- Access/distribution:
  - Federally funded projects: imagery available at no cost through NGA NextView license
  - Derived products (i.e., DEMs) can be distributed freely


2007/2008 LiDAR (1-m posting)
Oct 2015 WV-1 DEM (2-m posting)
400 m
Nisqually Glacier terminus, Mt. Rainier, WA

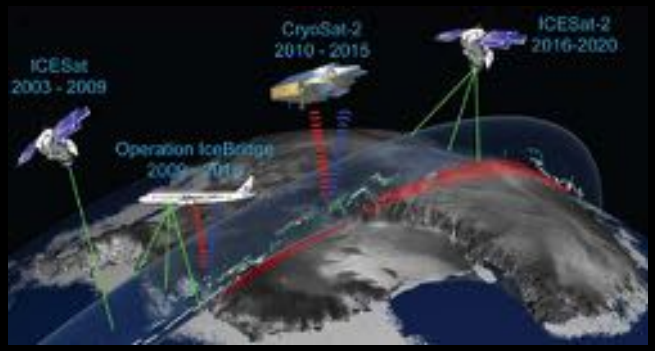
DigitalGlobe Stereo Archive (April 5, 2017)

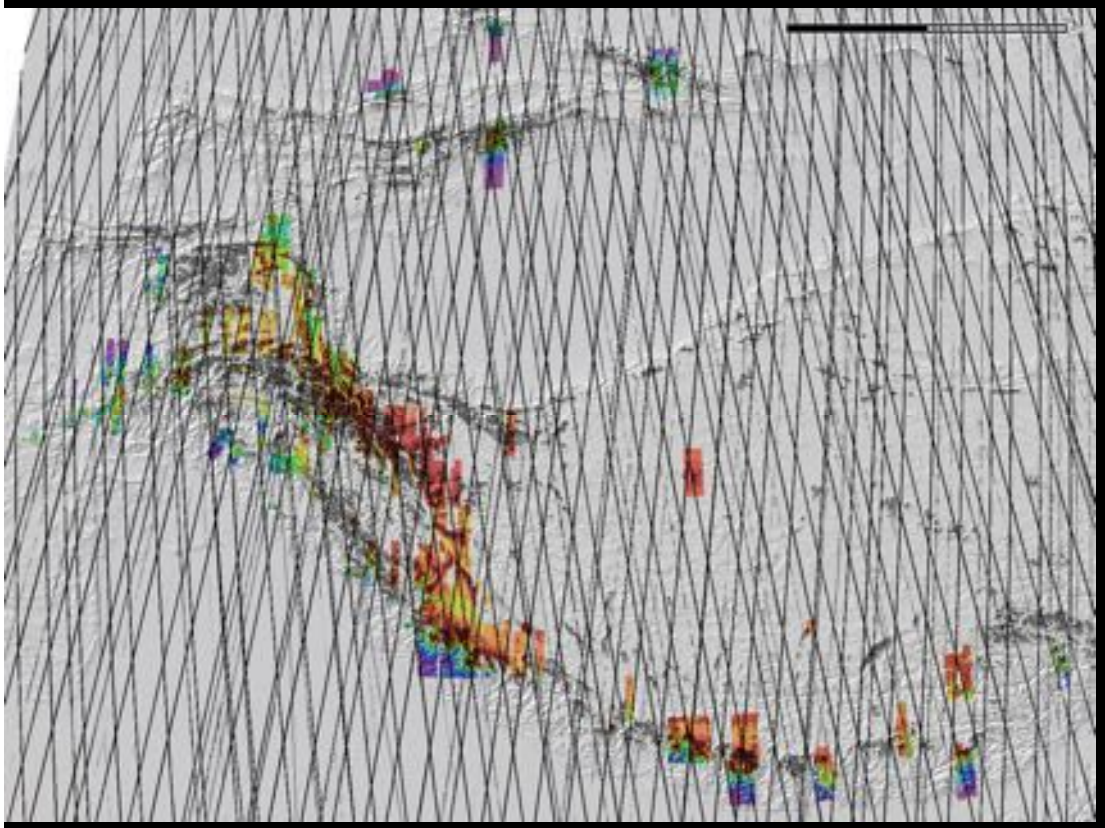


DigitalGlobe Mono Archive (April 5, 2017)

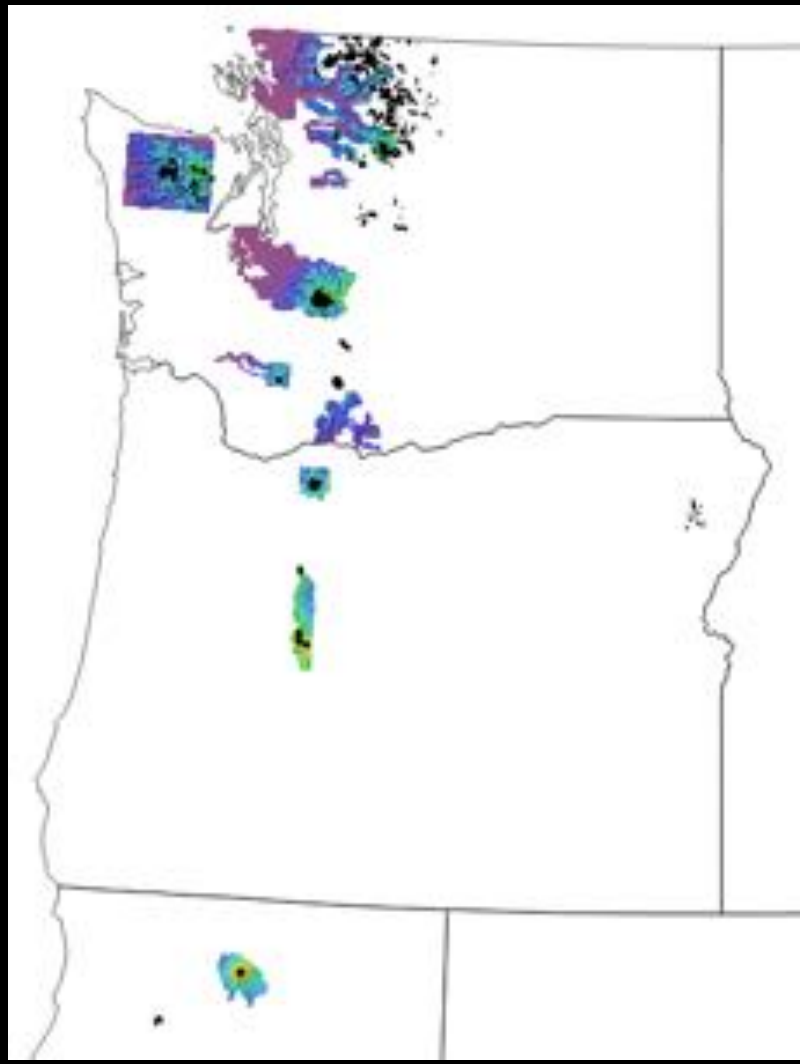


Control Data

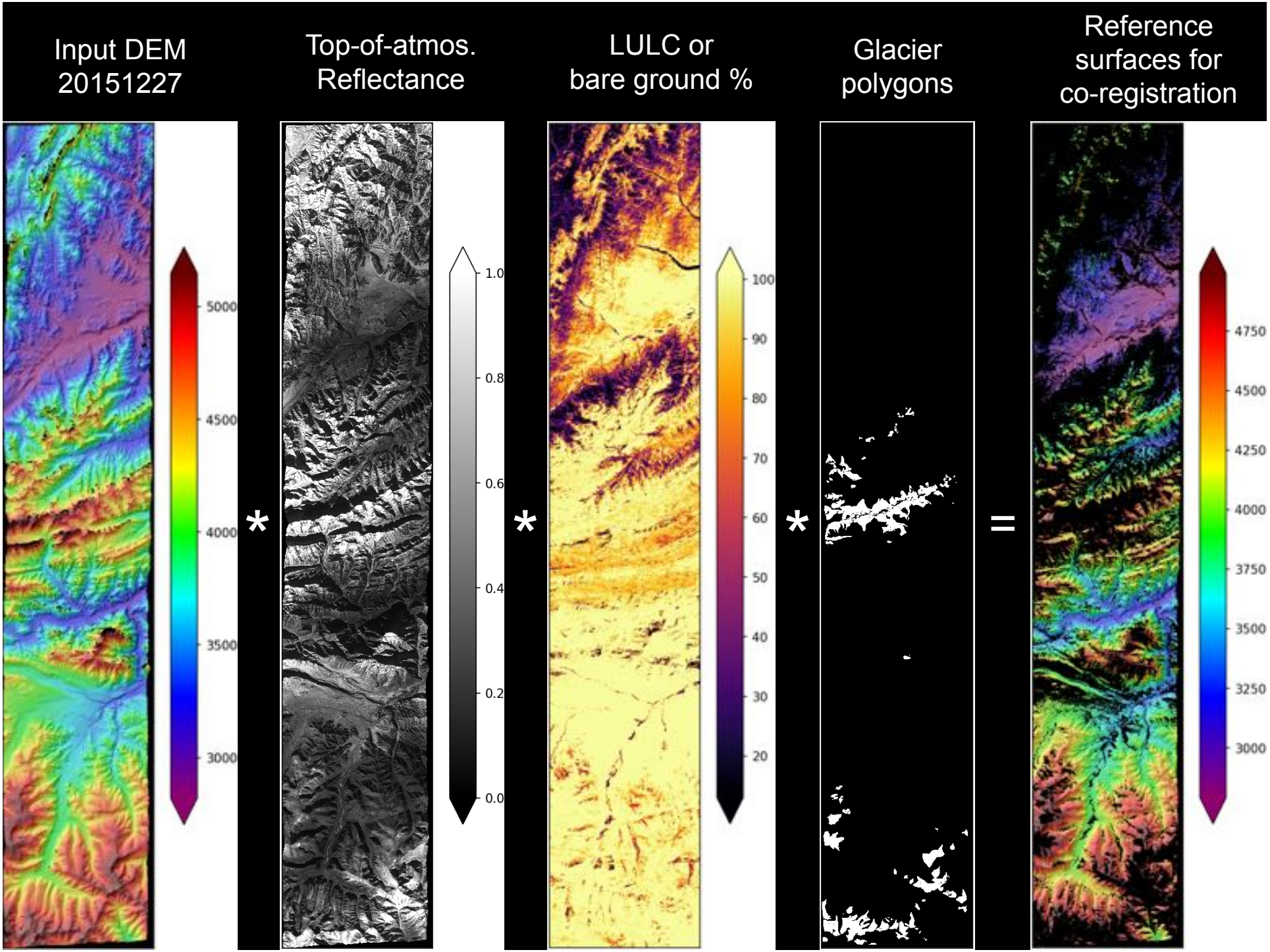


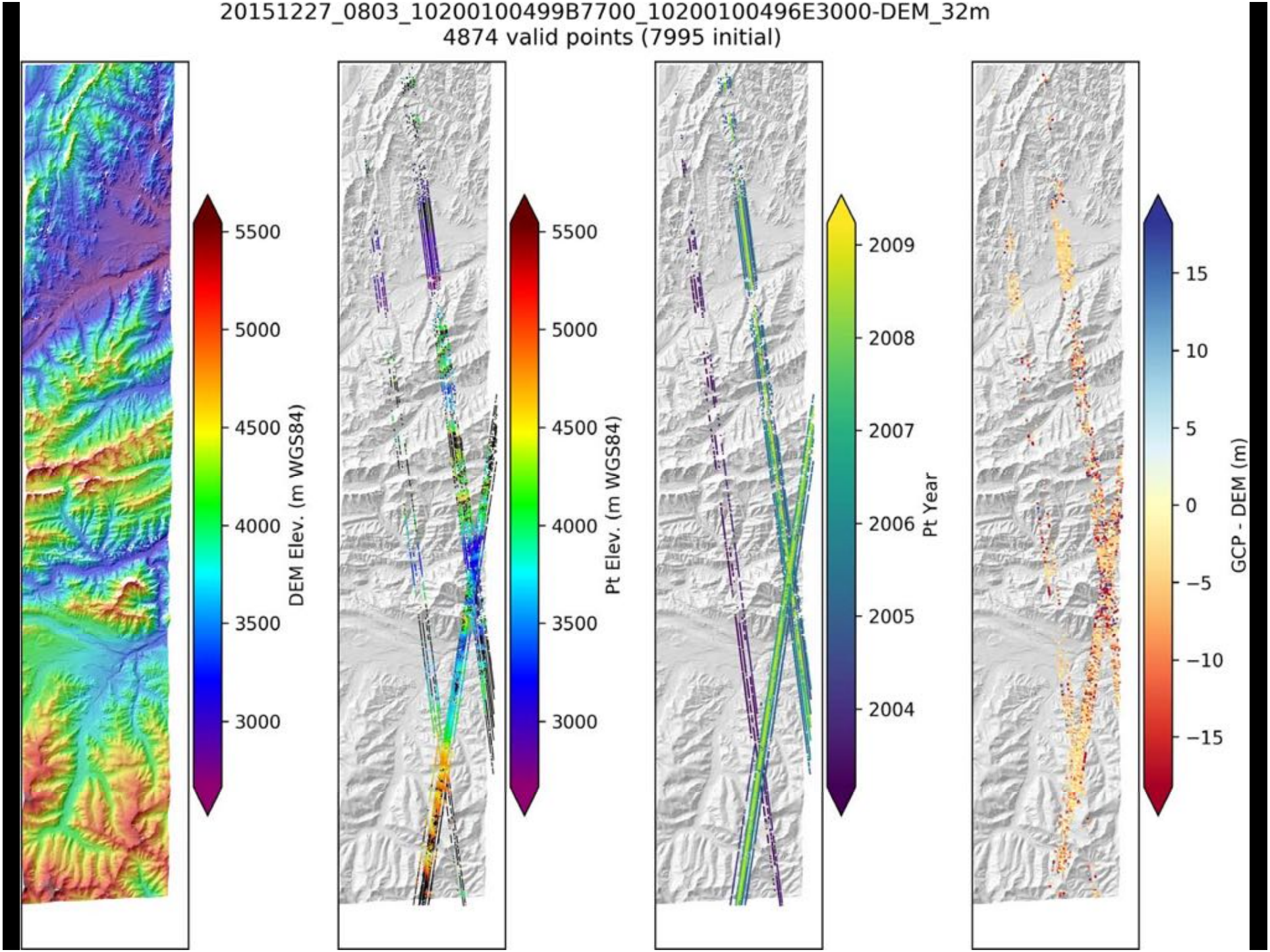


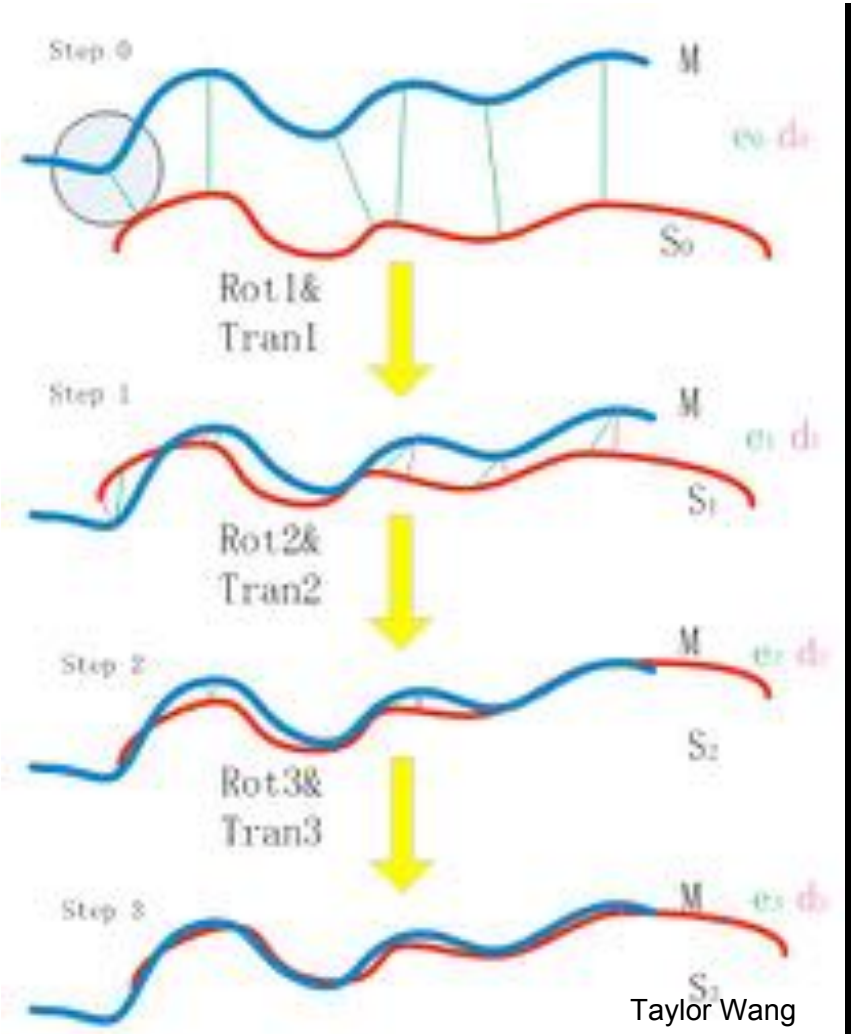
ICESat-1 satellite laser altimetry, High-mountain Asia



Airborne LiDAR near CONUS glaciers


Input DEM
20151227
5000
4500
4000
3500
3000
*
Top-of-atmos.
Reflectance
1.0
0.8
0.6
0.4
0.2
0.0
*
LULC or
bare ground %
100
90
80
70
60
50
40
30
20
*
Glacier
polygons
=
Reference
surfaces for
co-registration
4750
4500
4250
4000
3750
3500
3250
3000

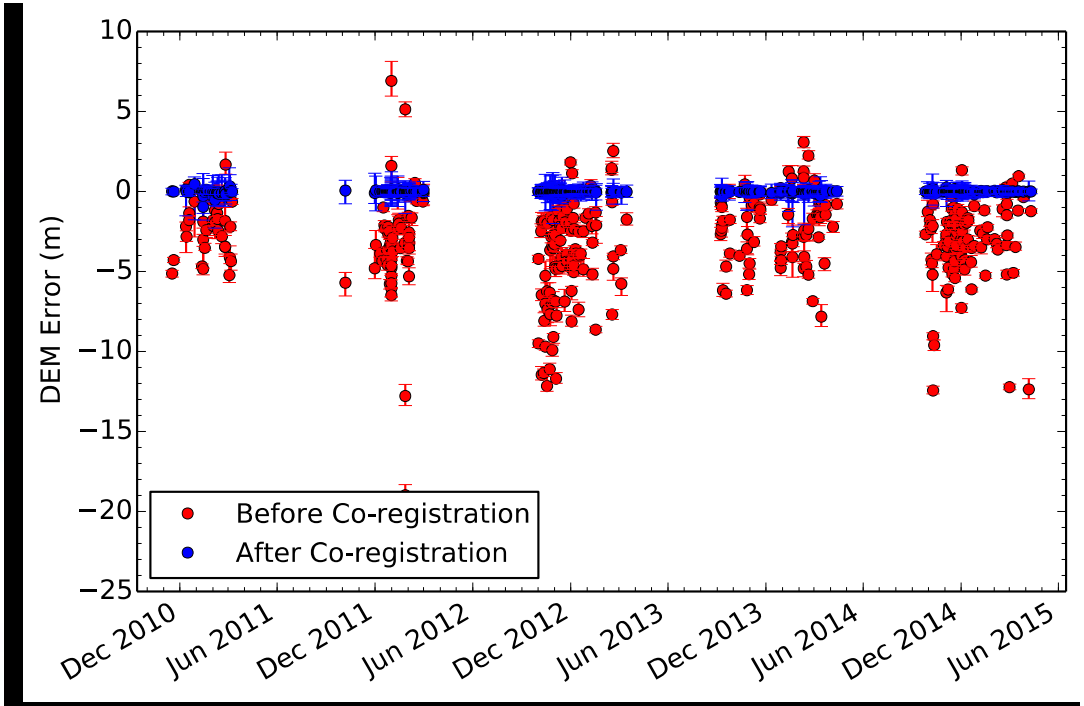

20151227_0803_10200100499B7700_10200100496E3000-DEM_32m
4874 valid points (7995 initial)
5500
5000
4500
4000
3500
3000
DEM Elev. (m WGS84)
5500
5000
4500
4000
3500
3000
Pt Elev. (m WGS84)
2009
2008
2007
2006
2005
2004
Pt Year
15
10
5
0
−5
−10
−15
GCP - DEM (m)



Taylor Wang

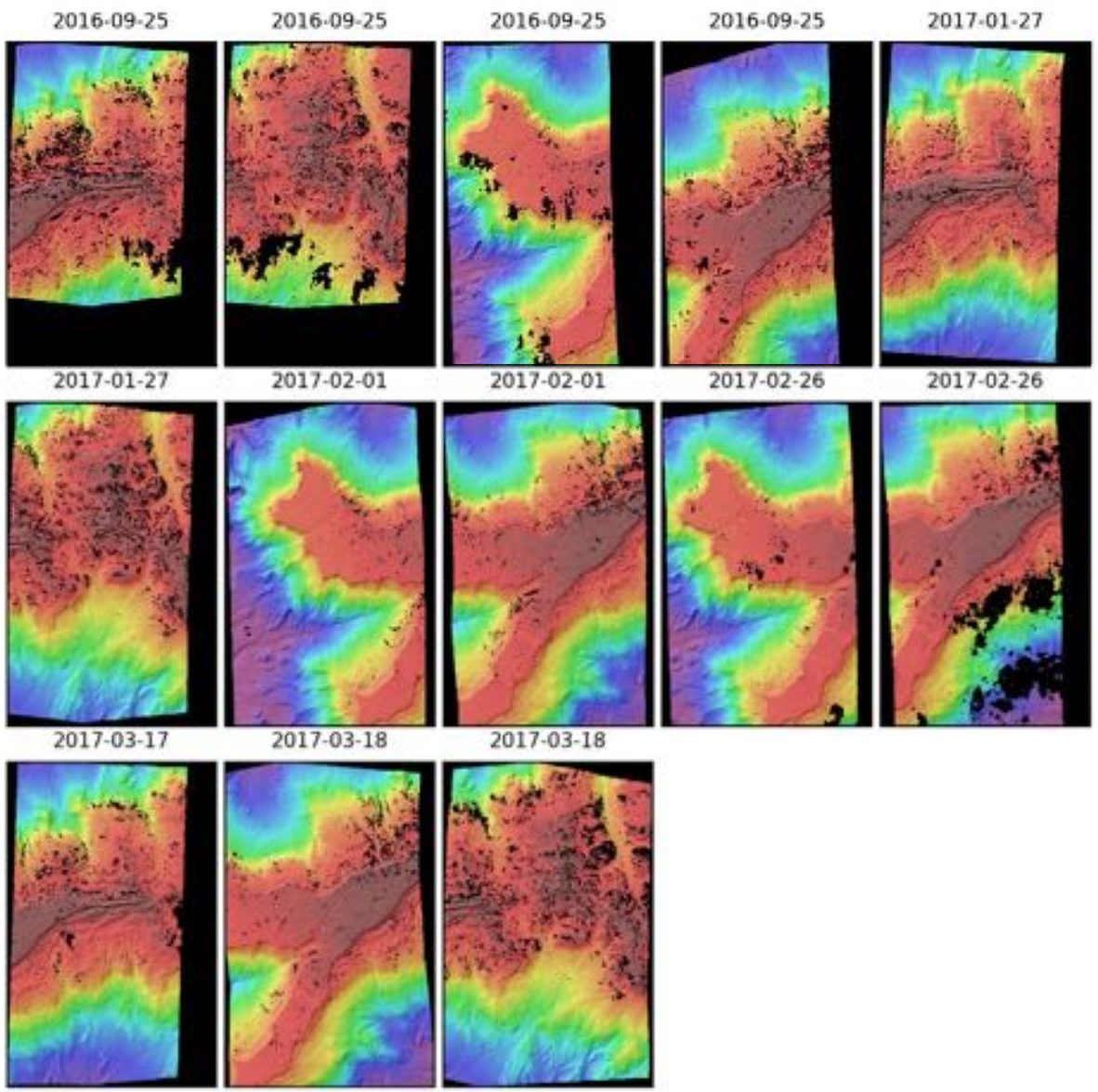
Iterative Closest Point (ICP) Co-registration

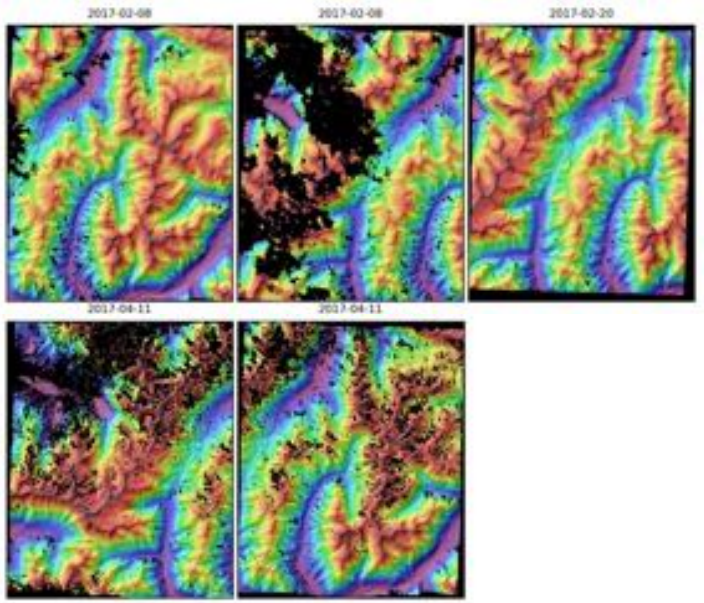
https://github.com/dshean/demcoreg



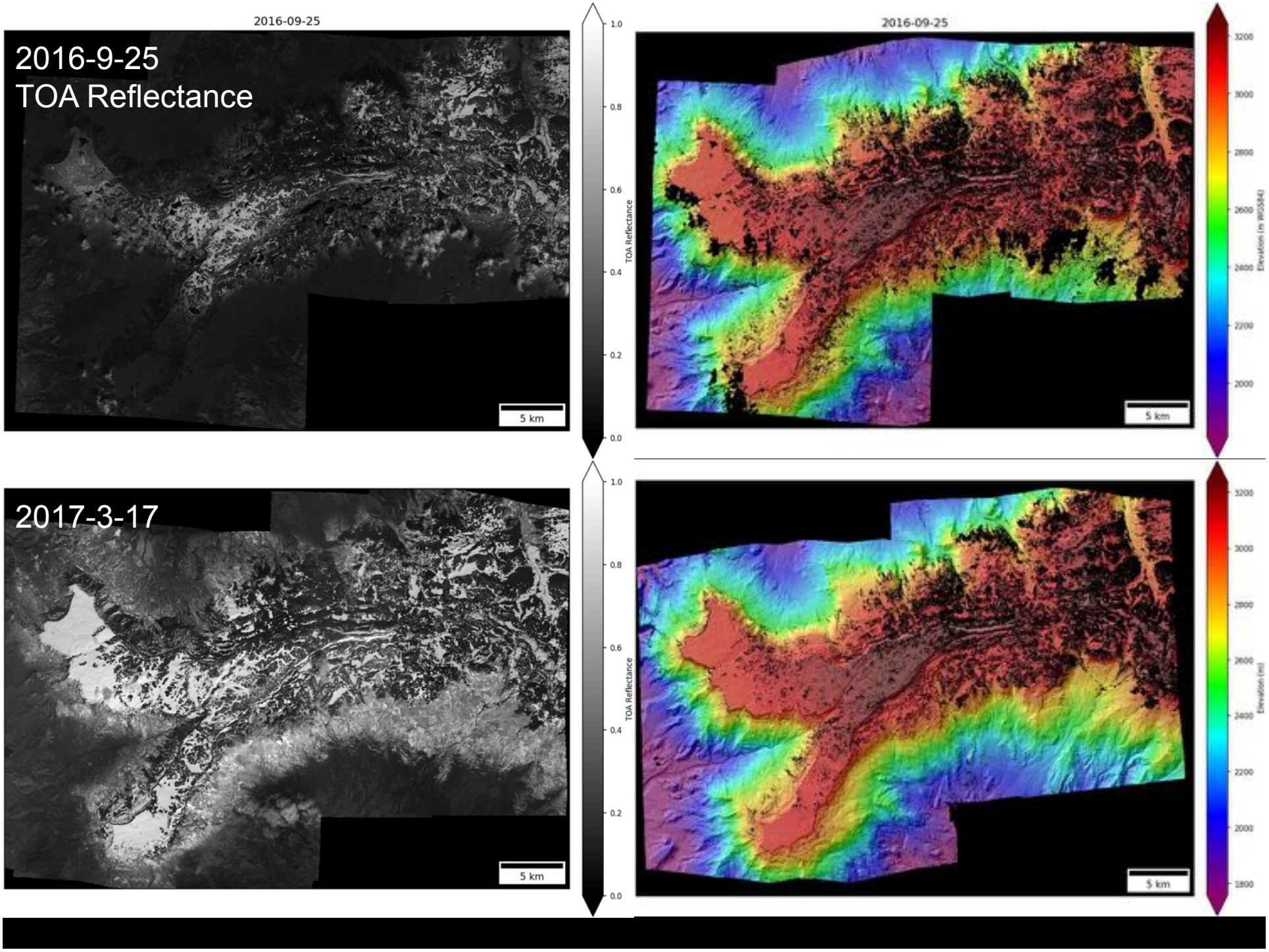
DEM errors before (red) and after (blue) ICP
One red/blue pair per DEM

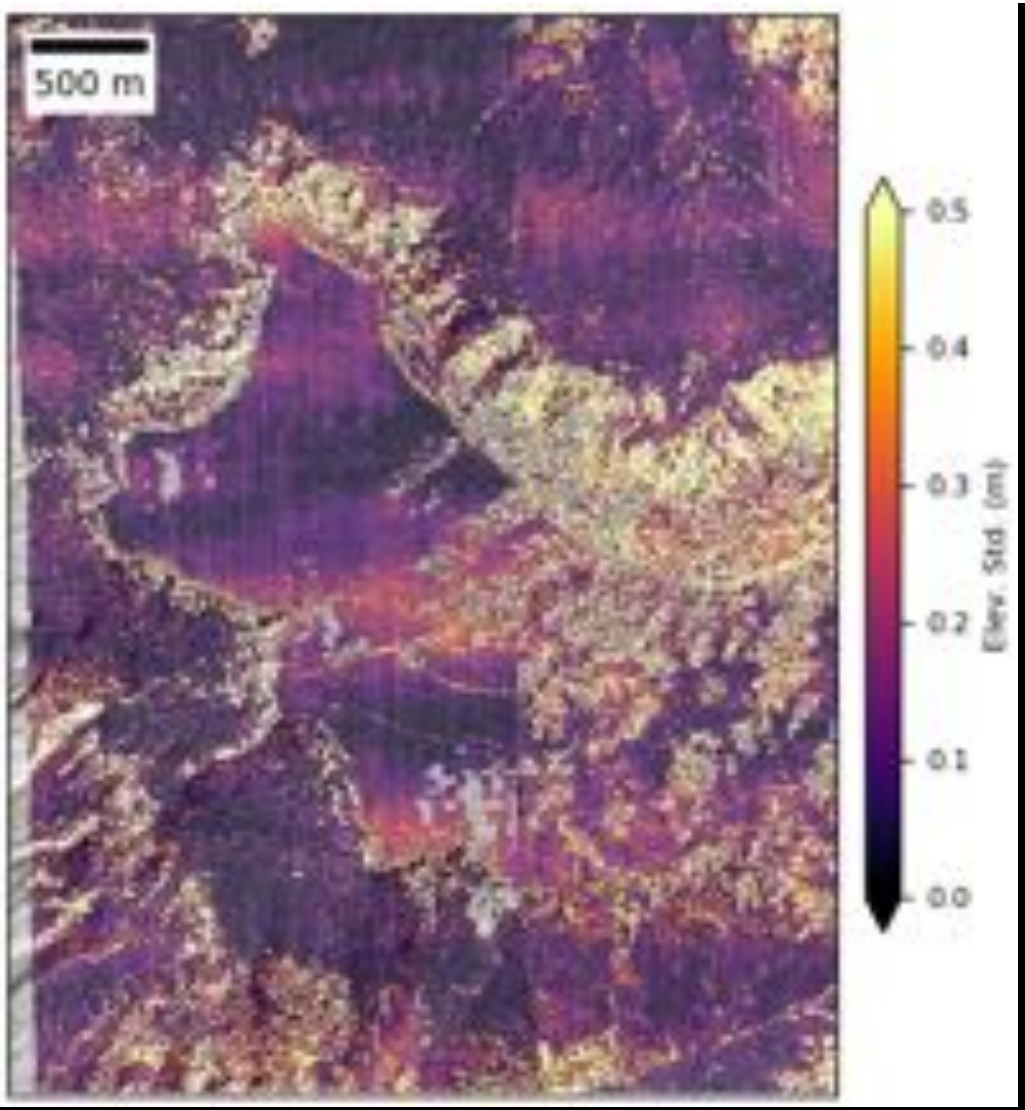
SnowEx'17 Preliminary DEMs





>34 obs in stereo archive

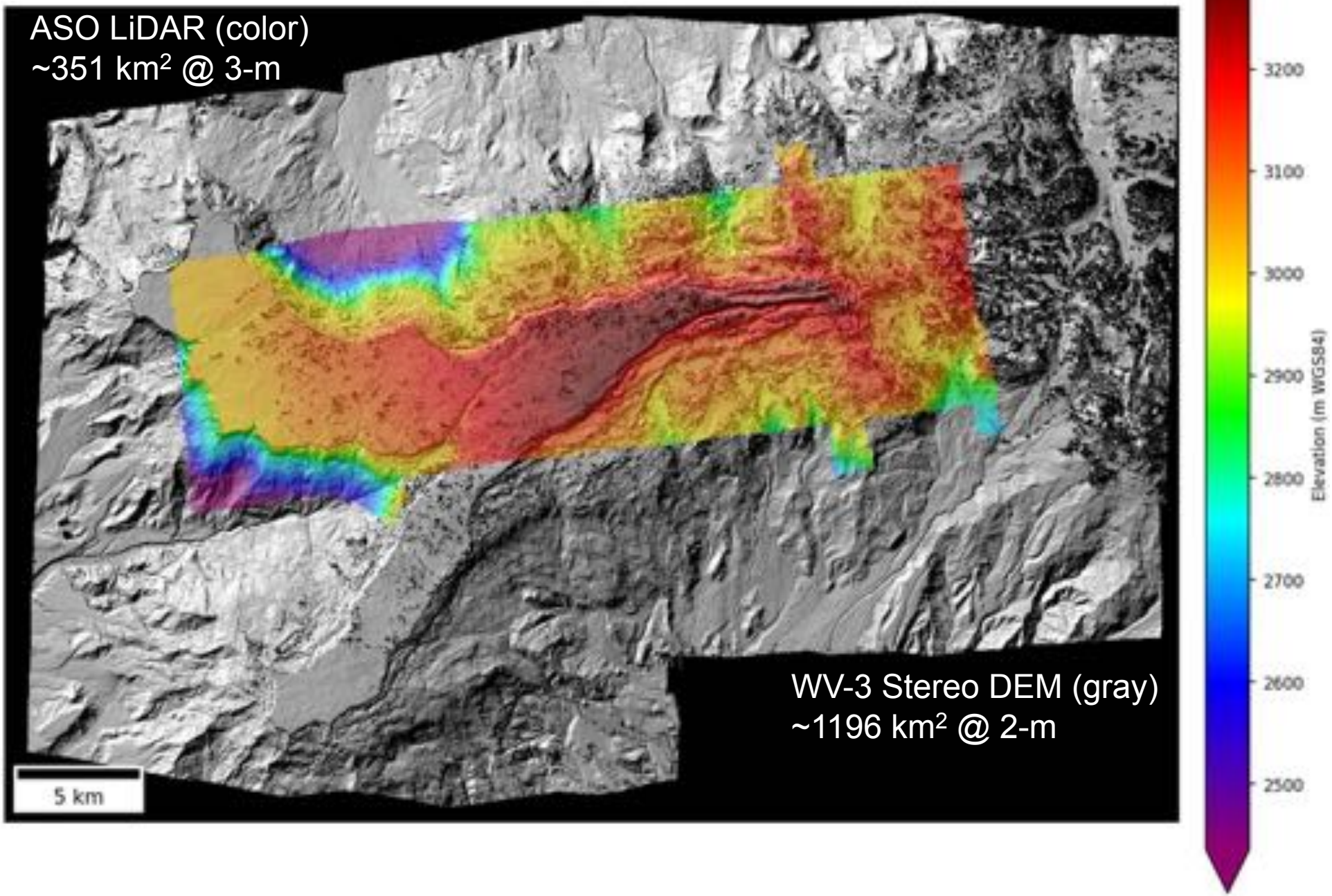

2016-09-25
2016-9-25
TOA Reflectance
5 km
TOA Reflectance
1.0
0.8
0.6
0.4
0.2
0.0
2016-09-25
5 km
3200
3000
2800
2600
2400
2200
2000
Elevation (m WGS84)
2017-3-17
5 km
TOA Reflectance
1.0
0.8
0.6
0.4
0.2
0.0
5 km
3200
3000
2800
2600
2400
2200
2000
1800
Elevation (m)



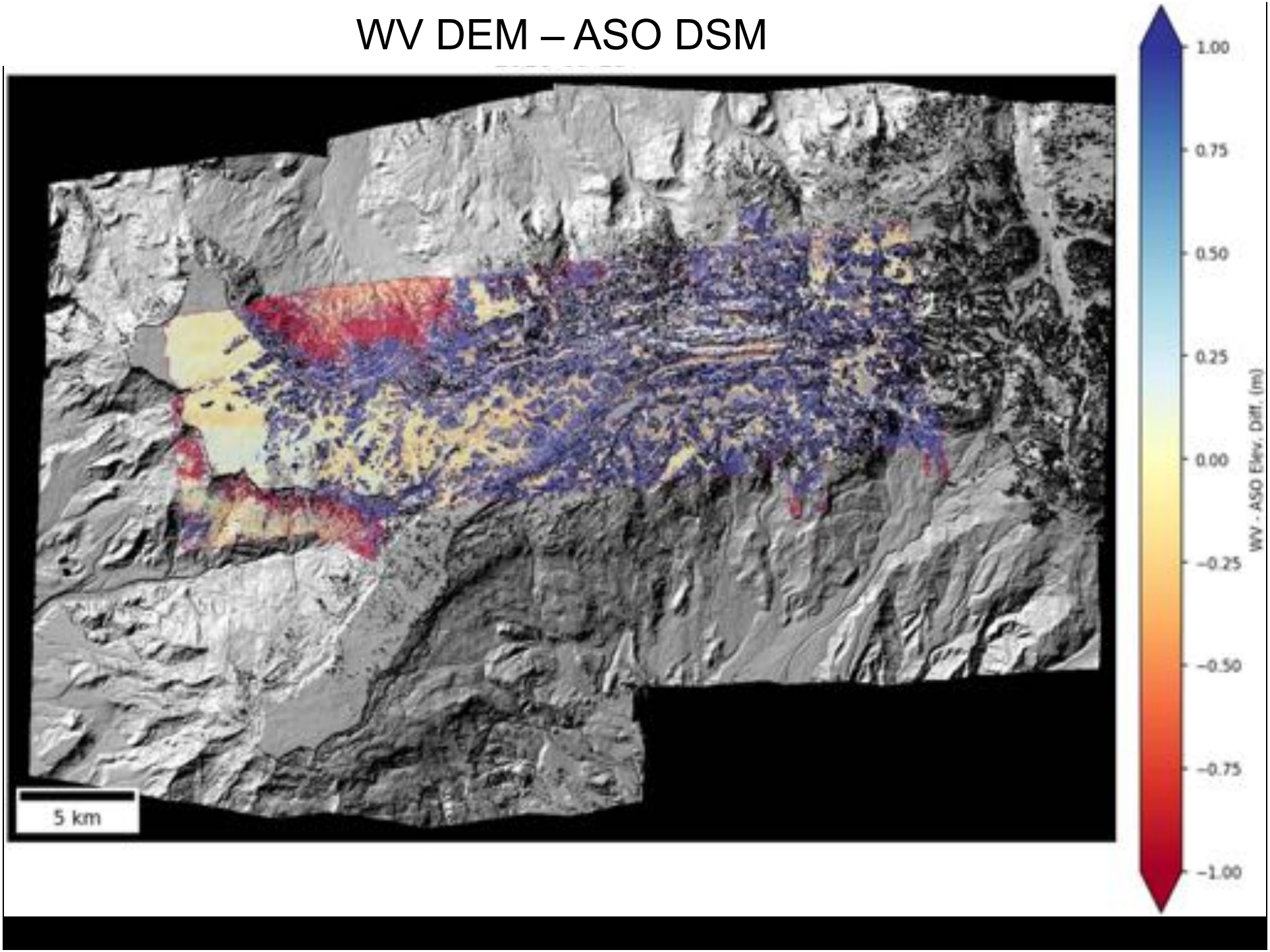
Elevation Standard Deviation

~0.1-0.3 m for unvegetated slopes

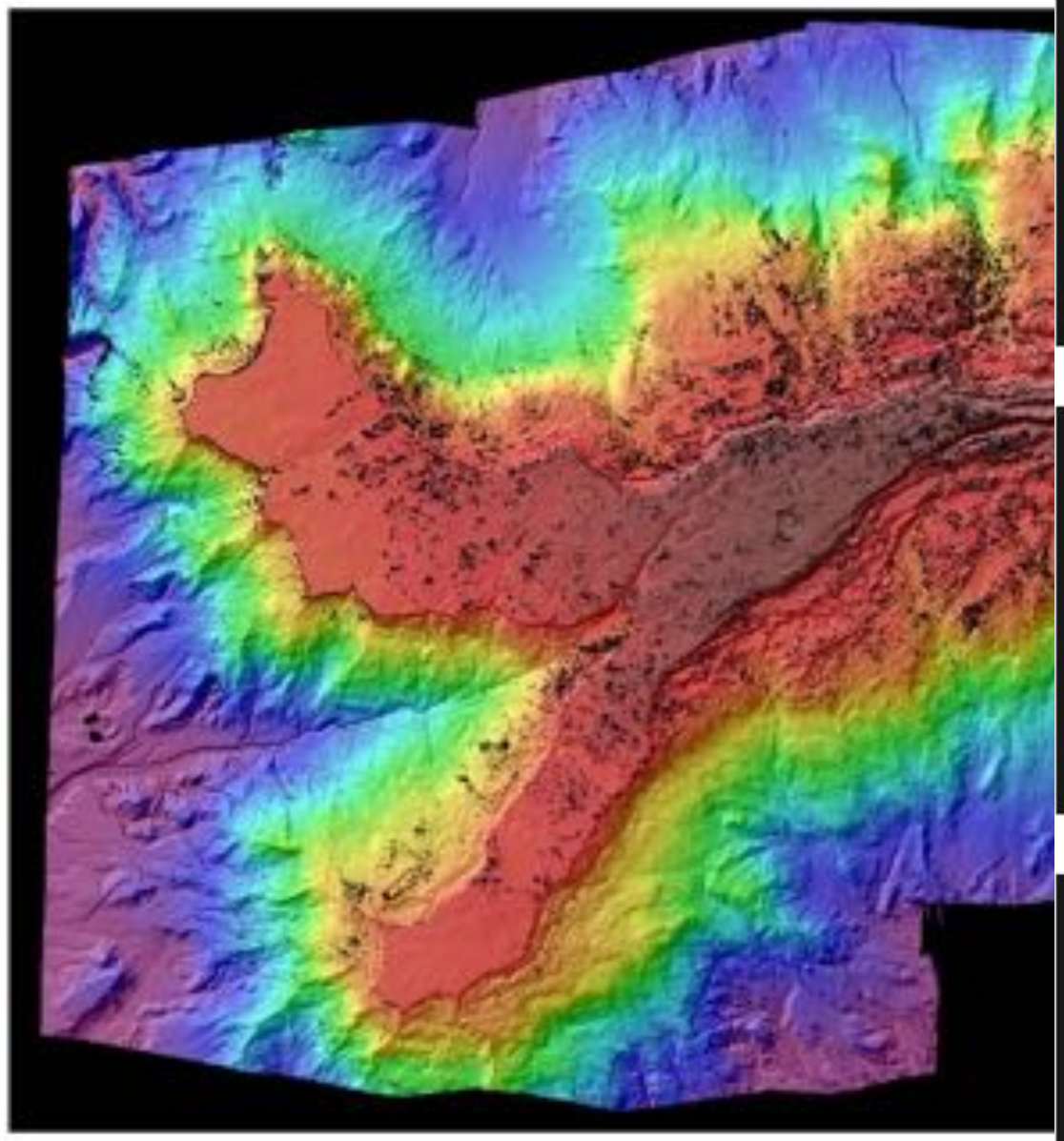
Sept. 25/26, 2016 (snow-off)



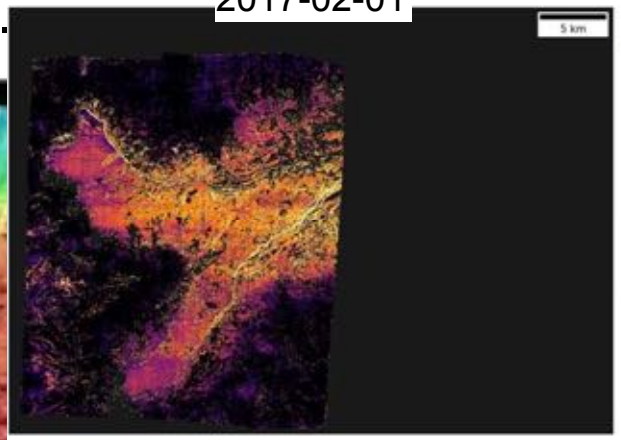
WV DEM – ASO DSM



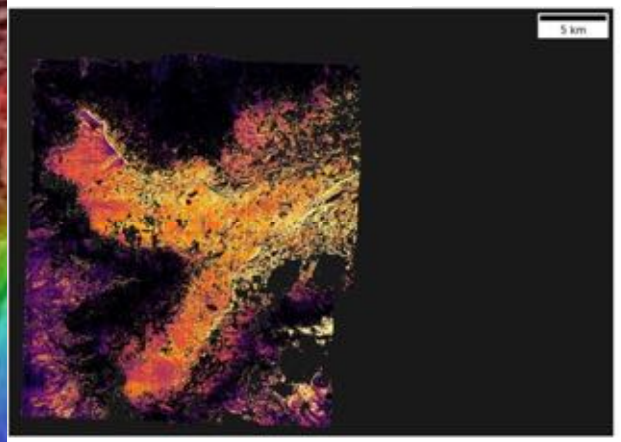
Sept. 25, 2016 (snow-



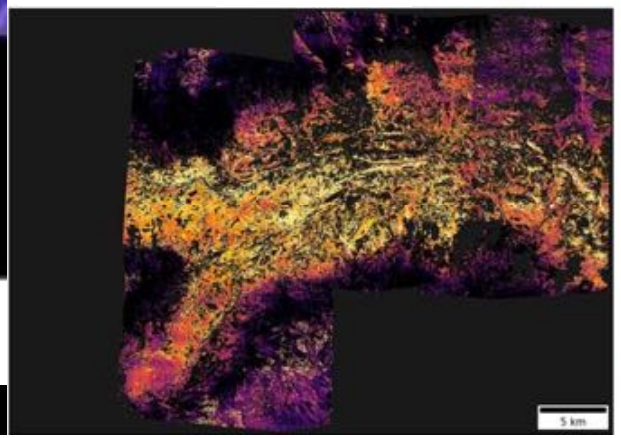
2017-02-01

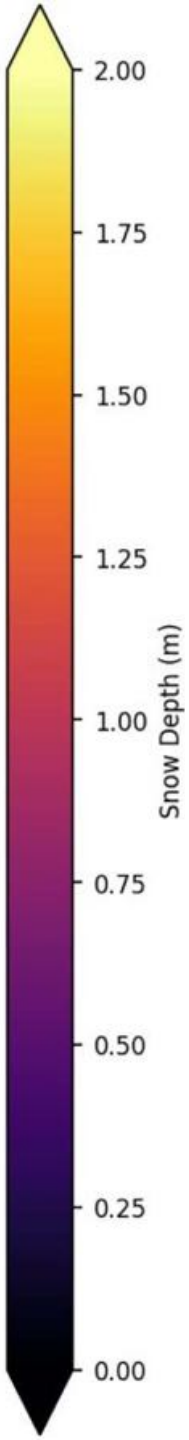


2017-02-26

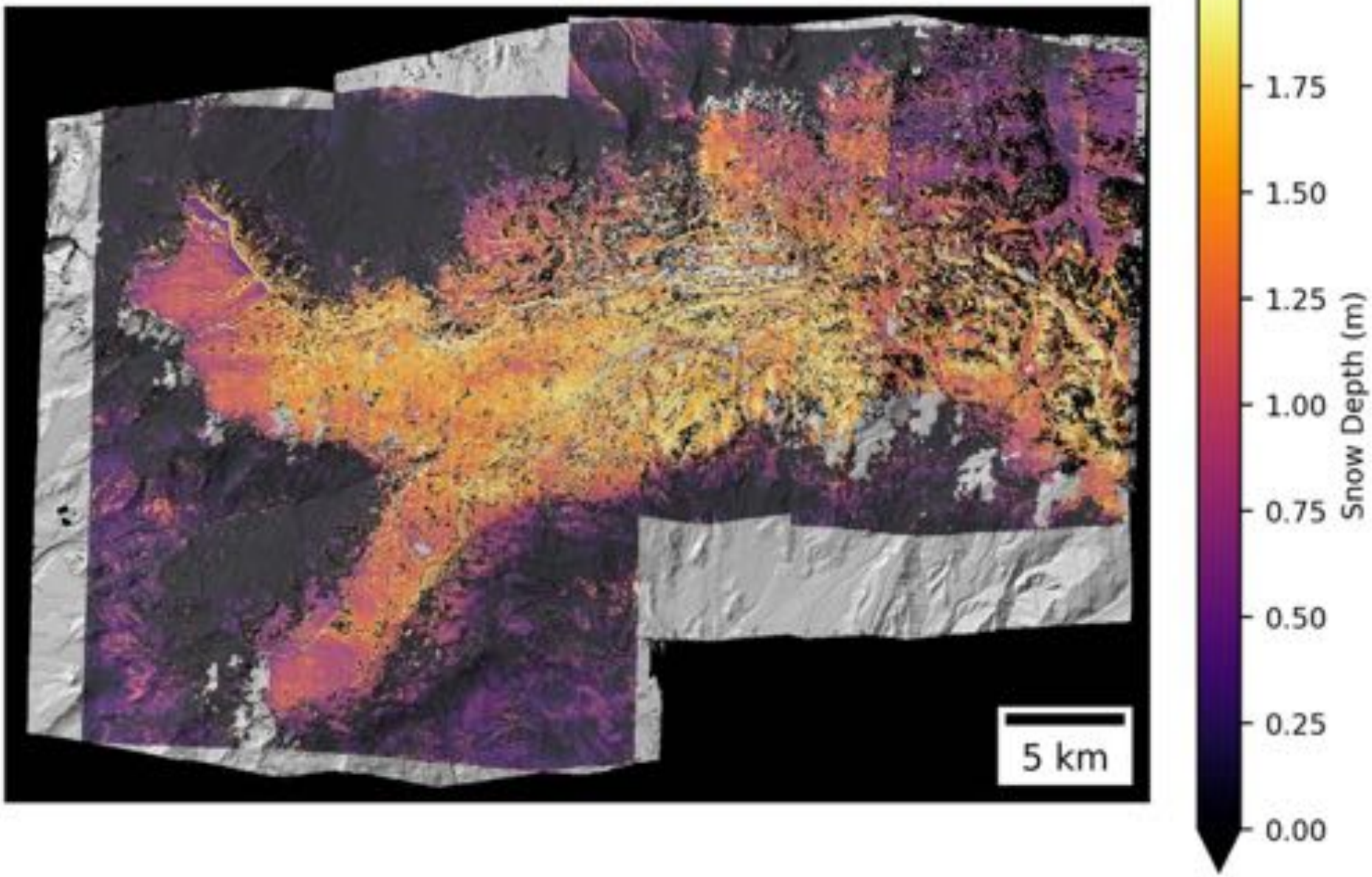


2017-03-17

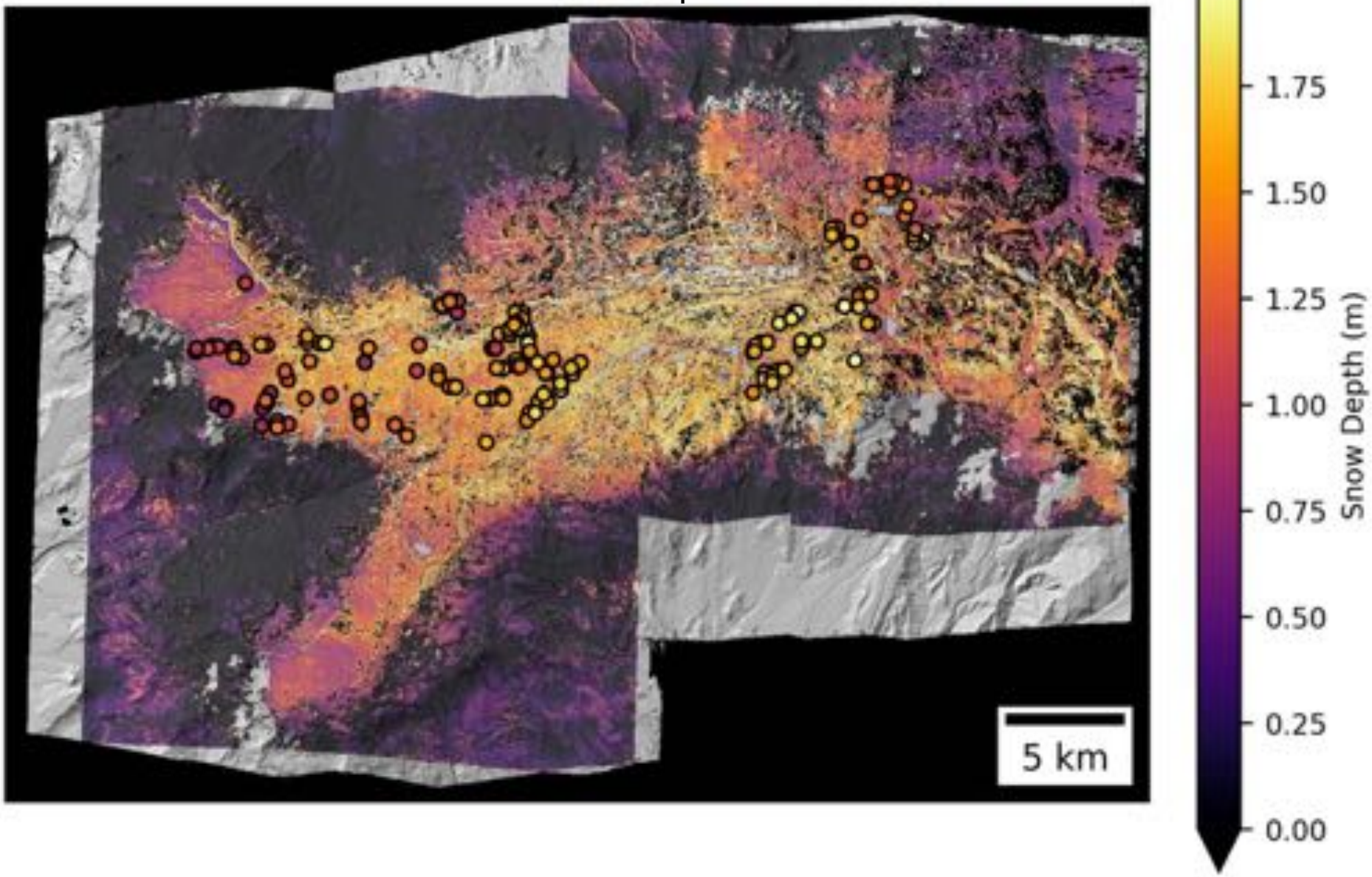




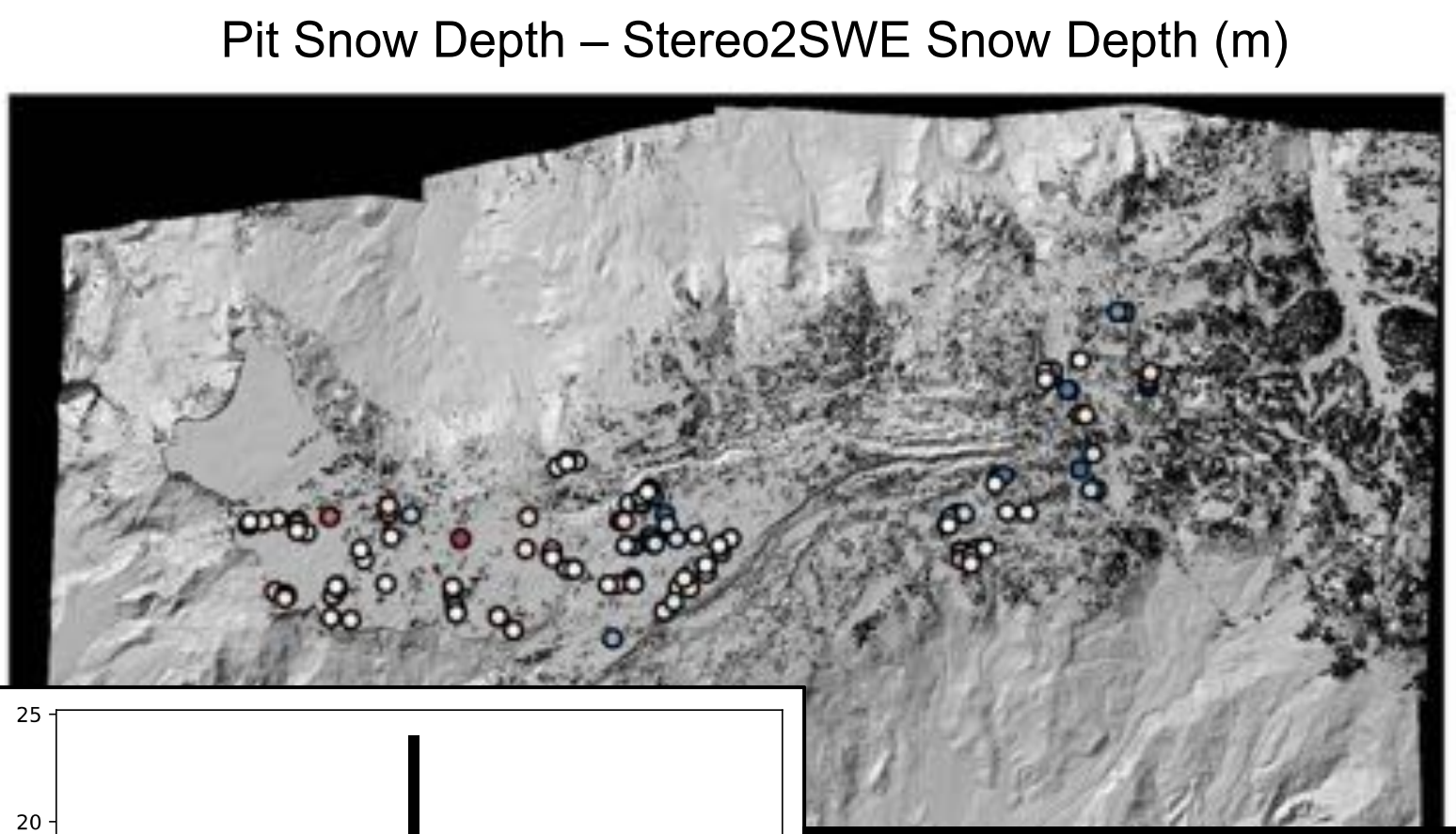
SnowEx'17 Snow Depth Composite (2/1/17, 2/26/17, 3/17/17)

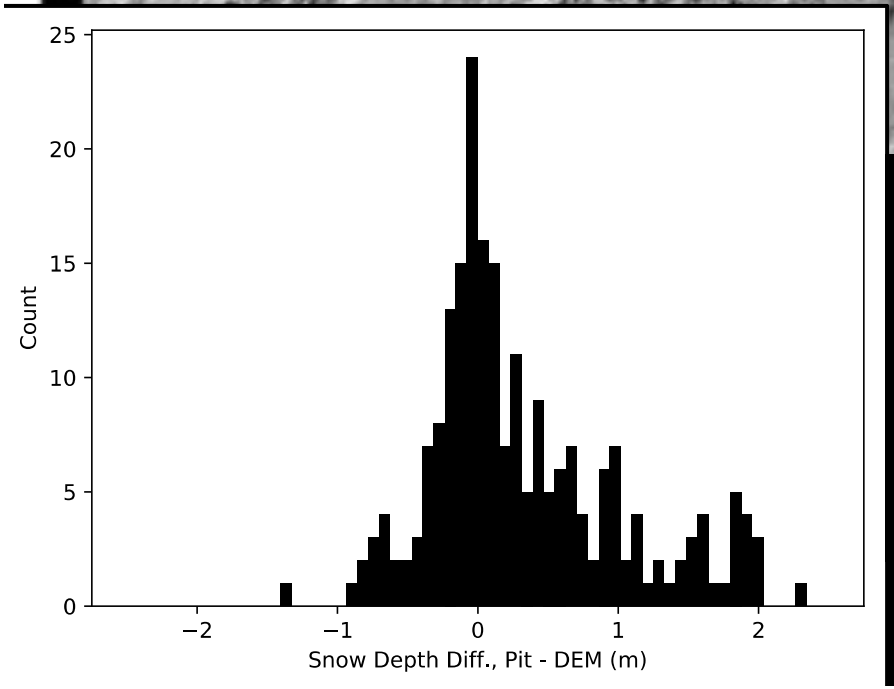


SnowEx'17 Snow Depth Composite (2/6/17, 2/26/17, 3/17/17)
~180 SnowEx'17 Pit Snow Depth Observations



Pit Snow Depth – Stereo2SWE Snow Depth (m)

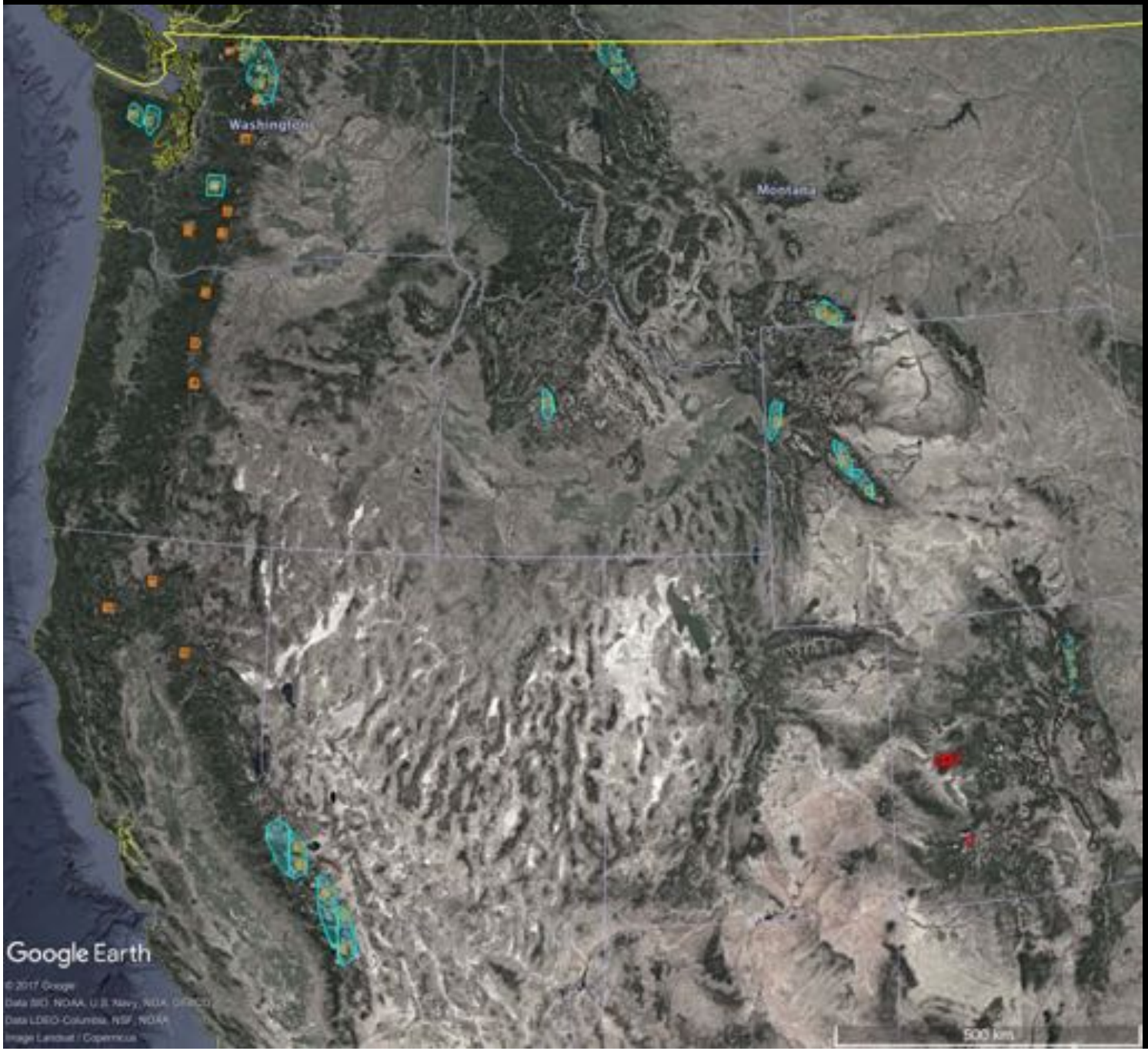




<u>Not really a fair comparison:</u>

- Variable DEM/pit timestamps
- Not accounting for vegetation
- Pit QC issues
- “Draft” DEMs/co-registration

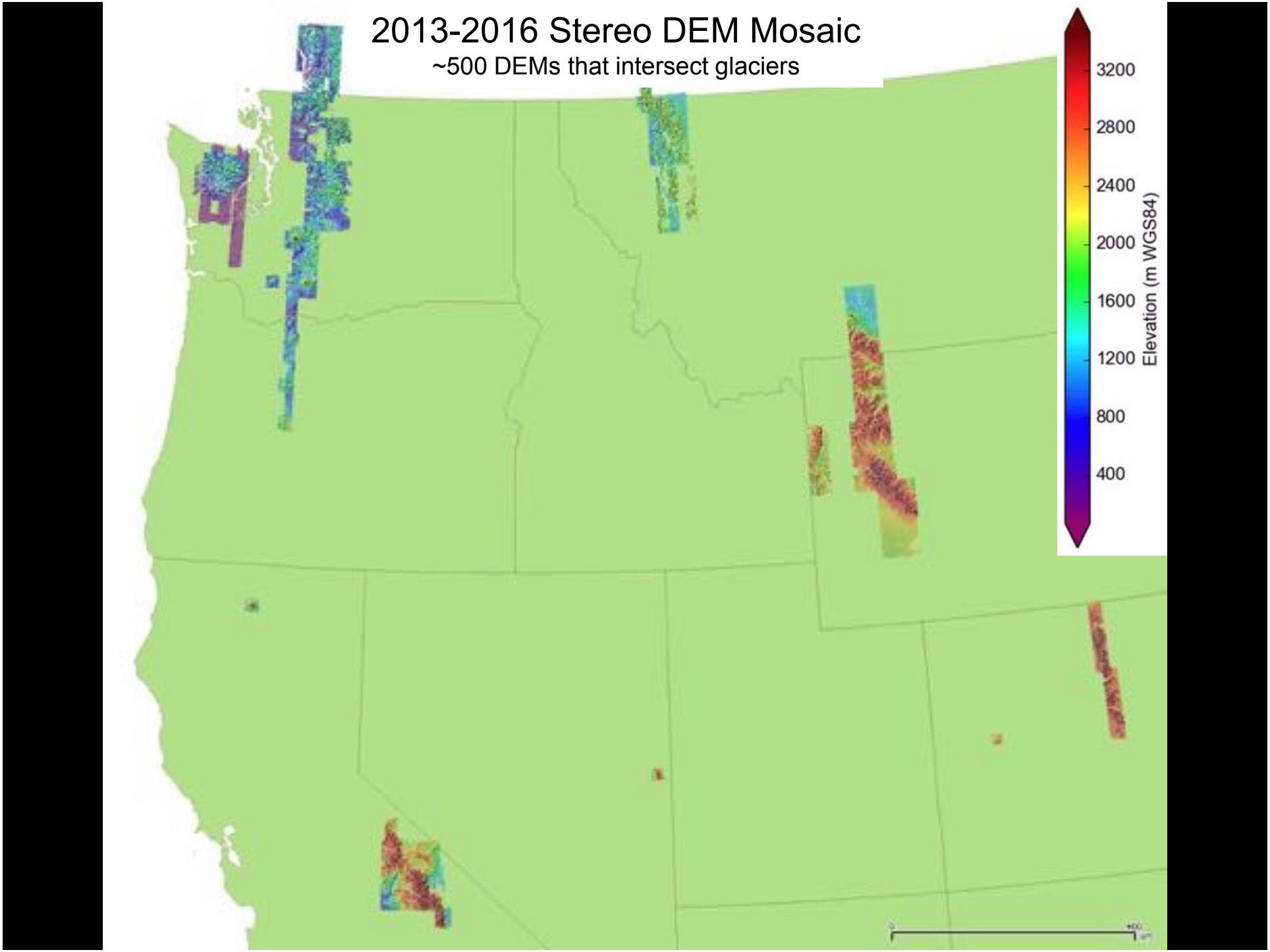
CONUS DG Stereo Interagency Tasking Plan (2017)

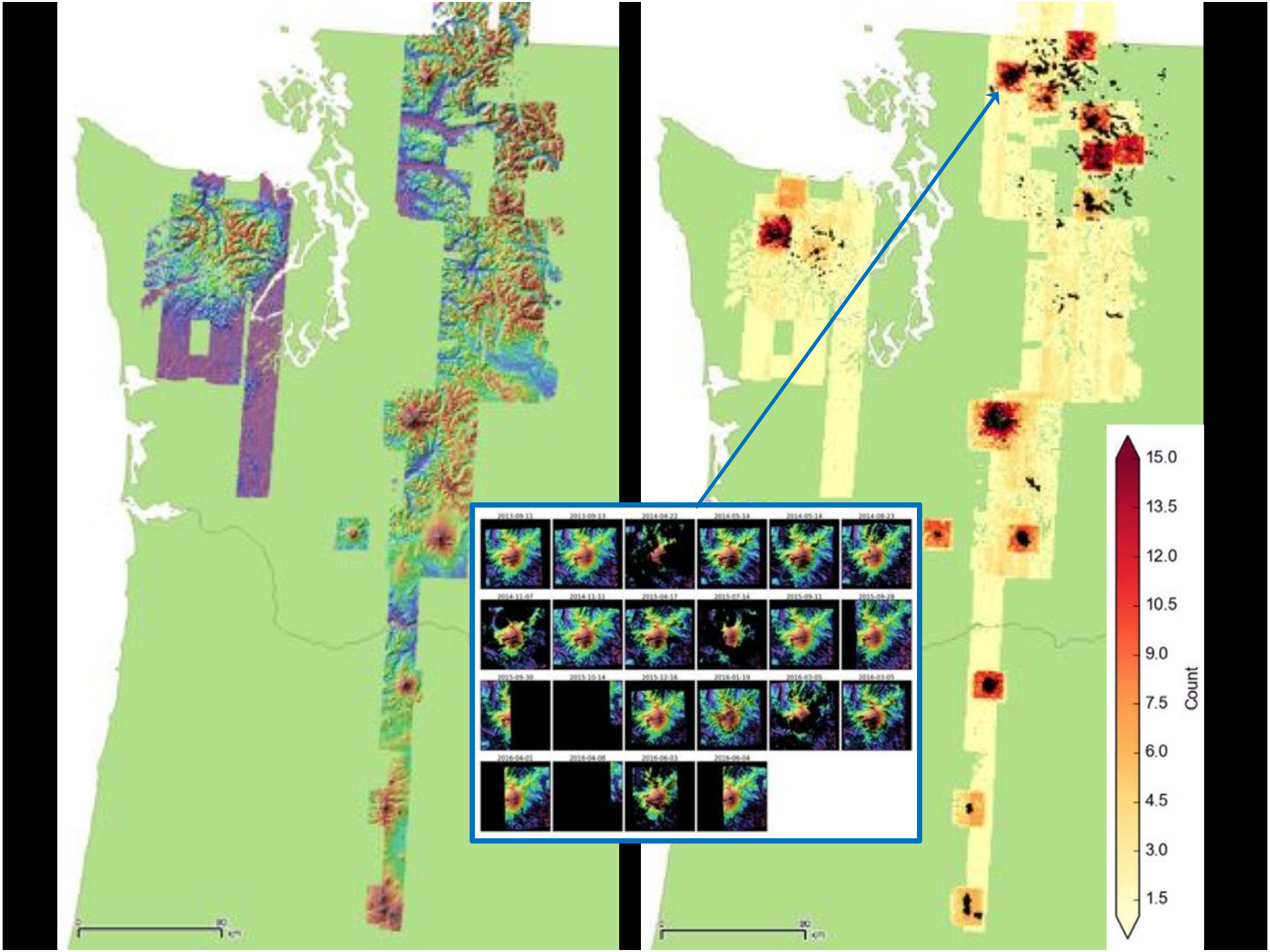


35 “point” collects:
- 2x summer
- 2x spring
- 4 sites monthly

14 area collects:
- 1x summer
- 1x spring

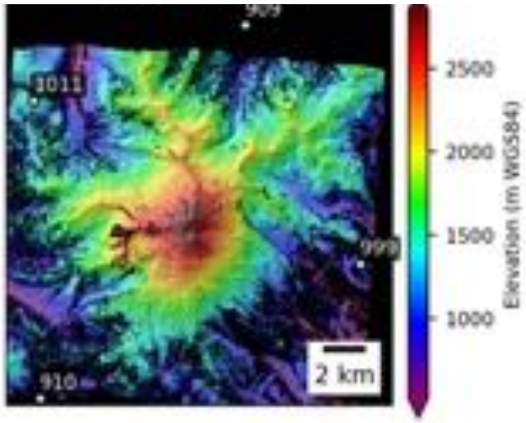
4 SnowEx’17 sites:
- Every ~2 weeks from Jan-May


2013-2016 Stereo DEM Mosaic
~500 DEMs that intersect glaciers
3200
2800
2400
2000
1600
1200
800
400
Elevation (m WGS84)

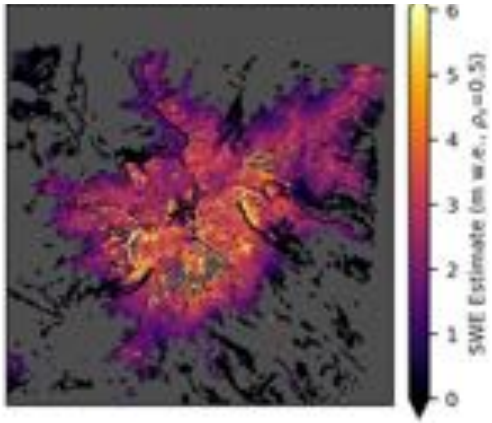

15.0
13.5
12.0
10.5
9.0
7.5
6.0
4.5
3.0
1.5
Count

WY2014

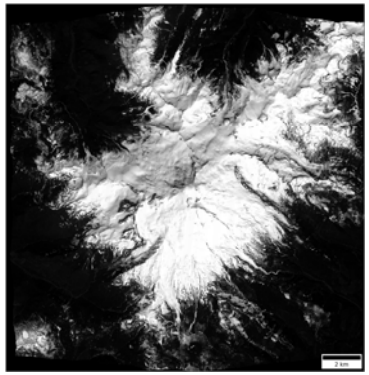
DEM



SWE



Reflectance



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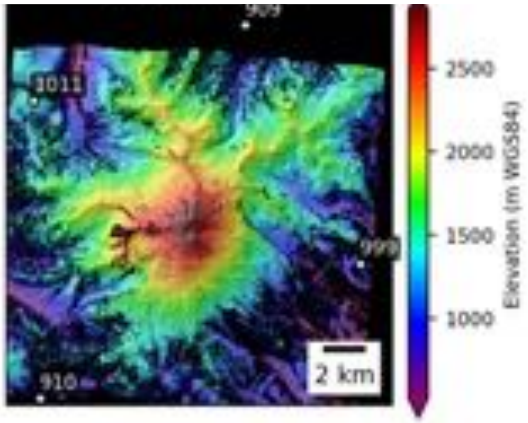
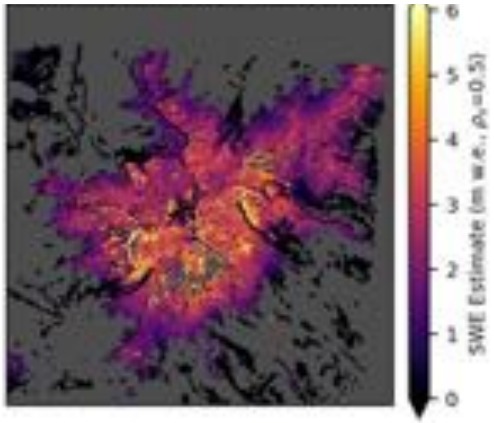
DEM

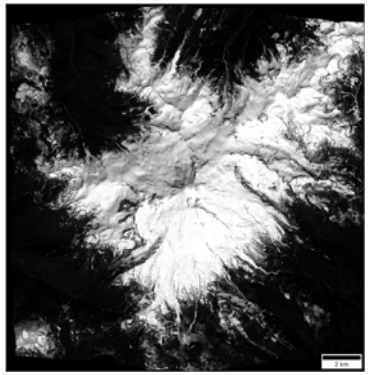
SWE

Reflectance

WY2014







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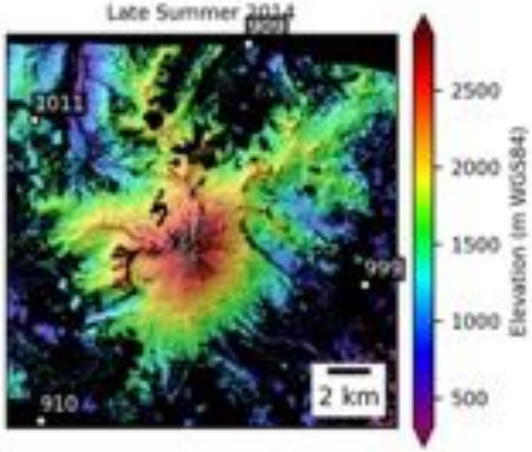
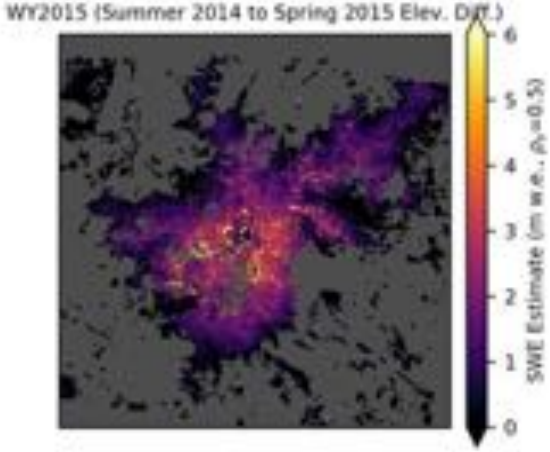
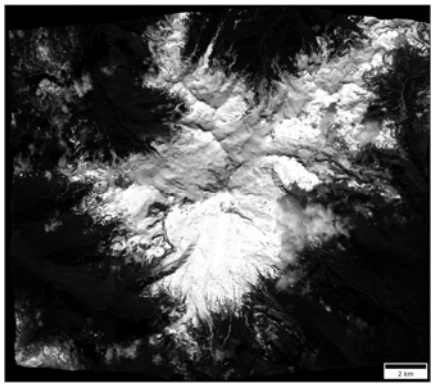
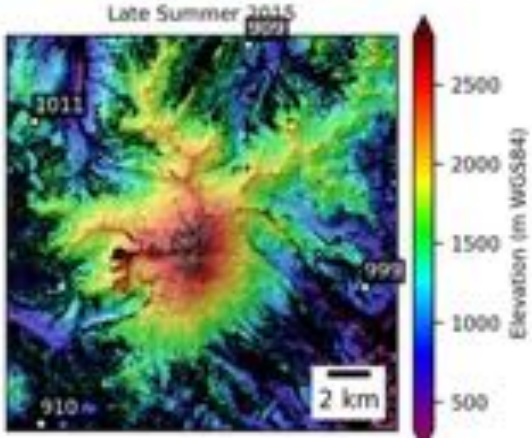
WY2015

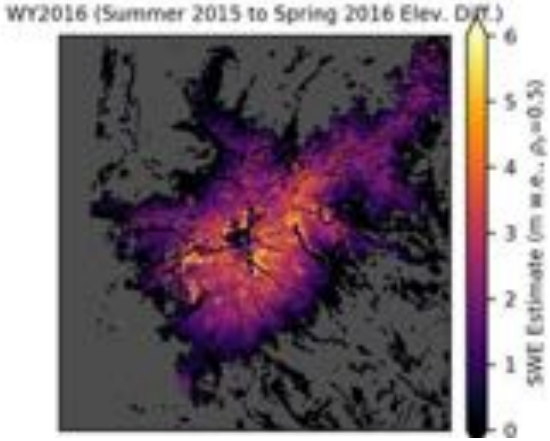


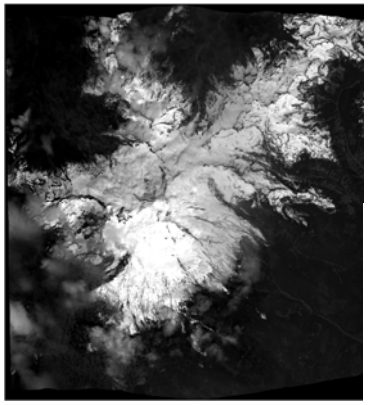


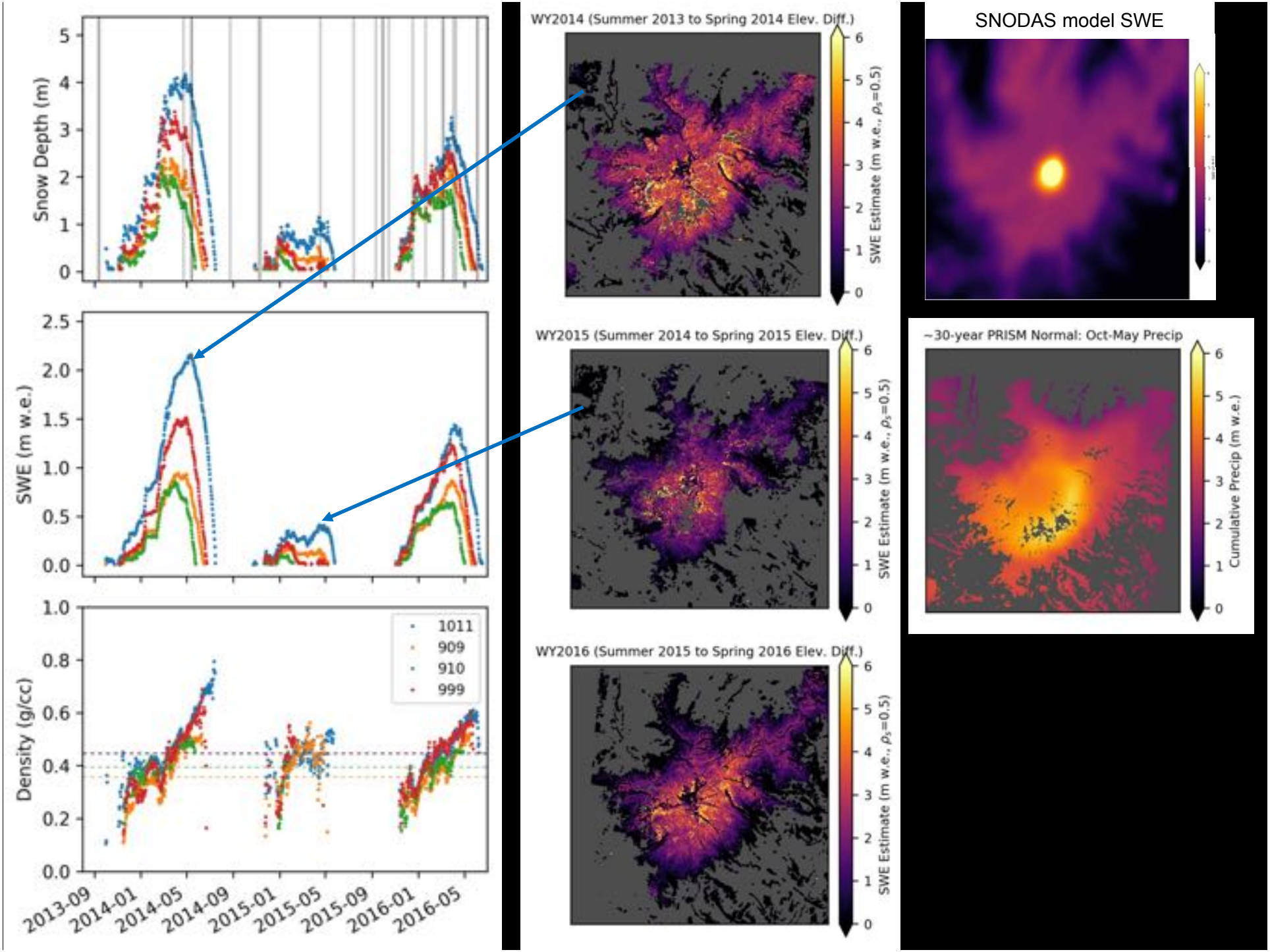


WY2016

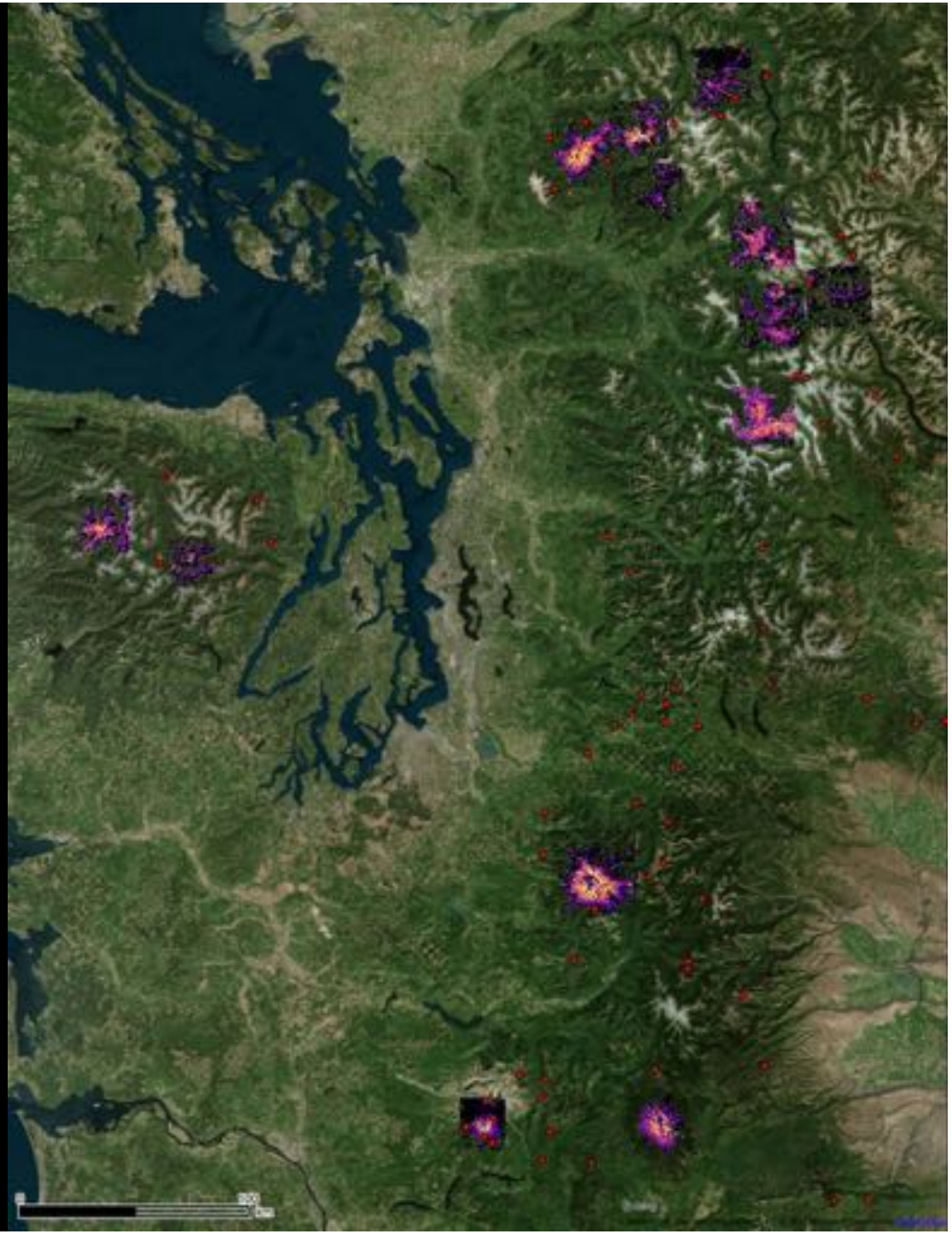


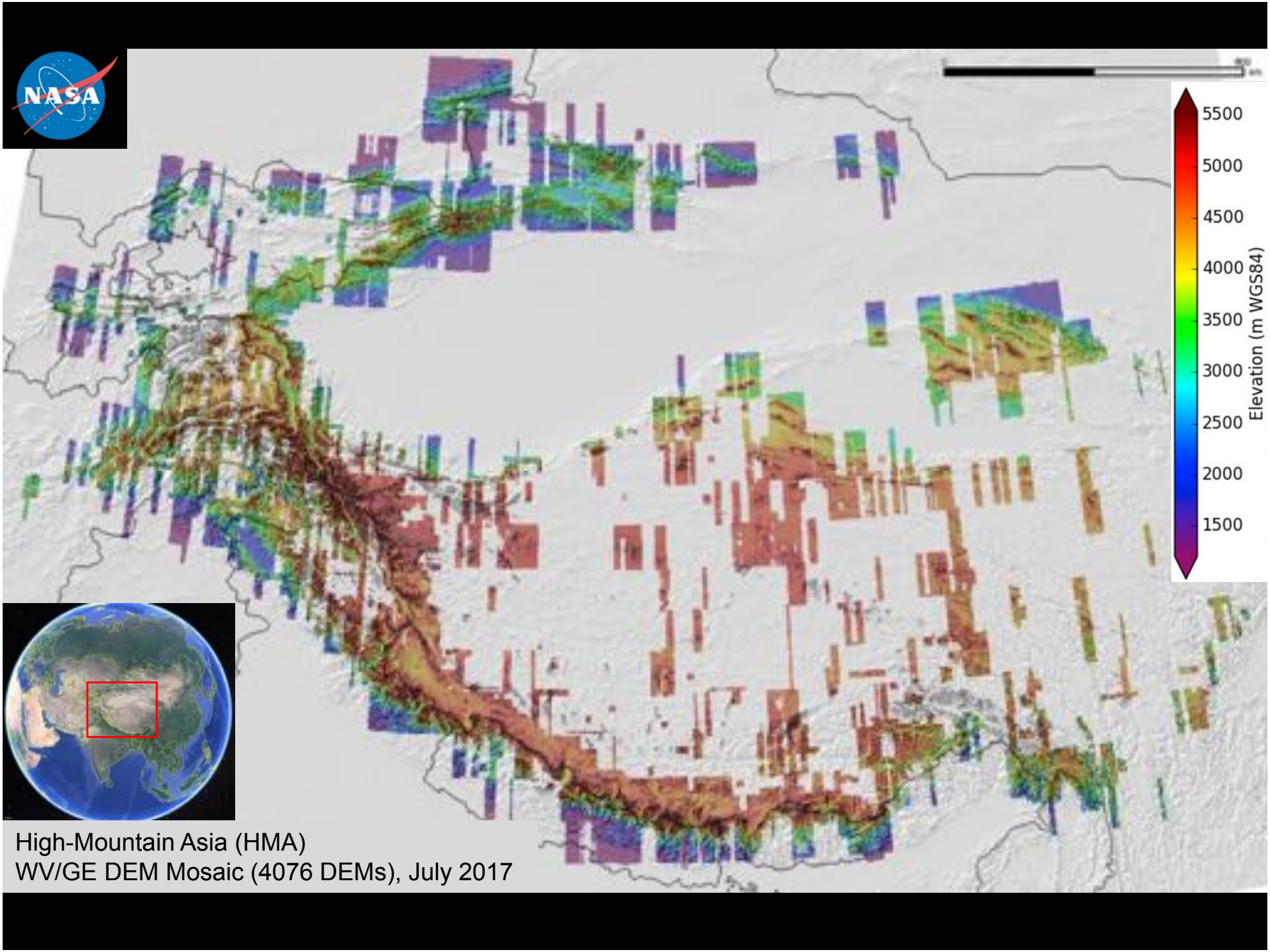




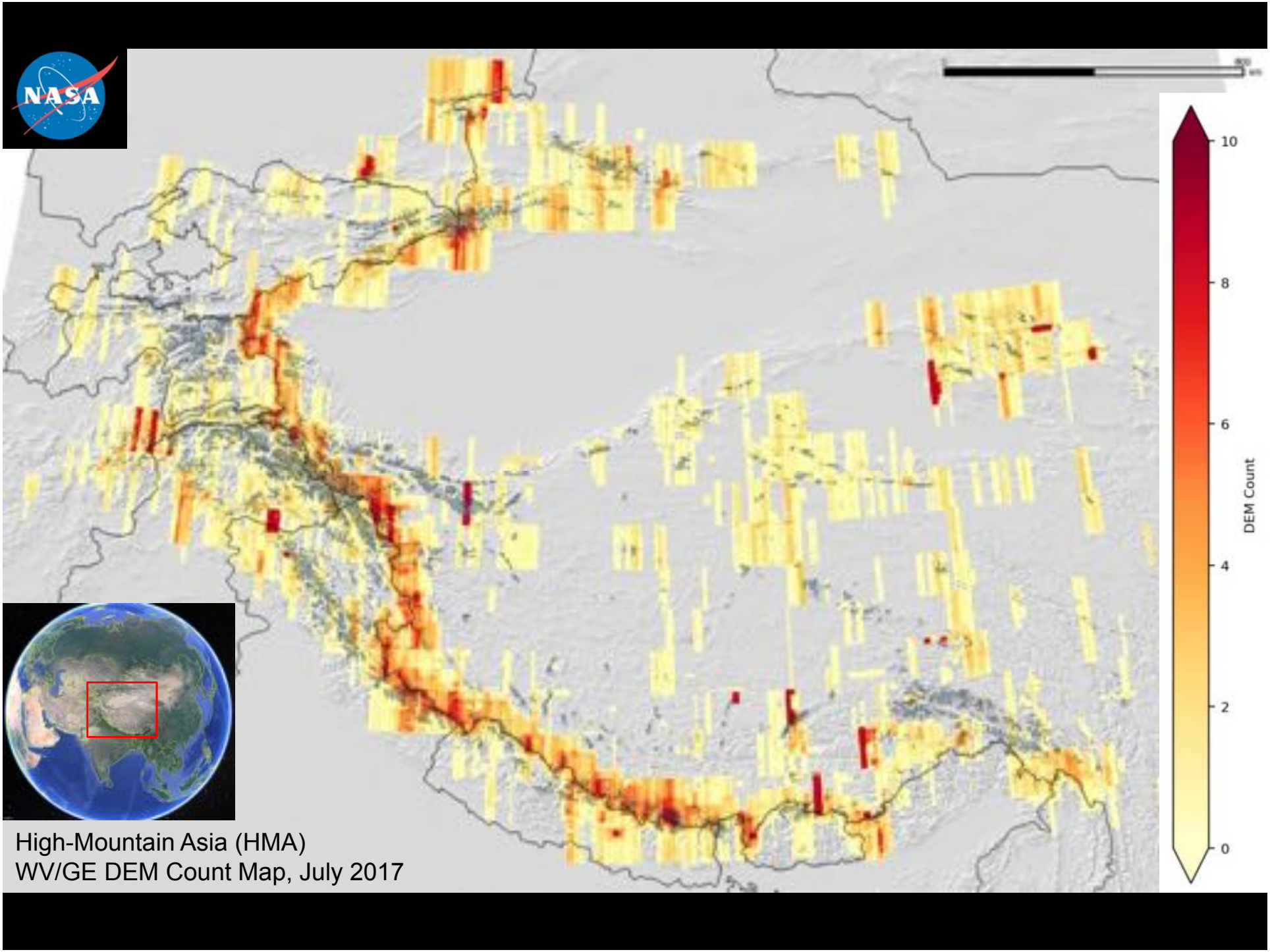

Snow Depth (m)
SWE (m w.e.)
Density (g/cc)
1011
909
910
999
2013-09
2014-01
2014-05
2014-09
2015-01
2015-05
2015-09
2016-01
2016-05
WY2014 (Summer 2013 to Spring 2014 Elev. Diff.)
WY2015 (Summer 2014 to Spring 2015 Elev. Diff.)
WY2016 (Summer 2015 to Spring 2016 Elev. Diff.)
SWE Estimate (m w.e., ρ_s=0.5)
SNODAS model SWE
~30-year PRISM Normal: Oct-May Precip
Cumulative Precip (m w.e.)

WY2016
Peak SWE estimate
m w.e.



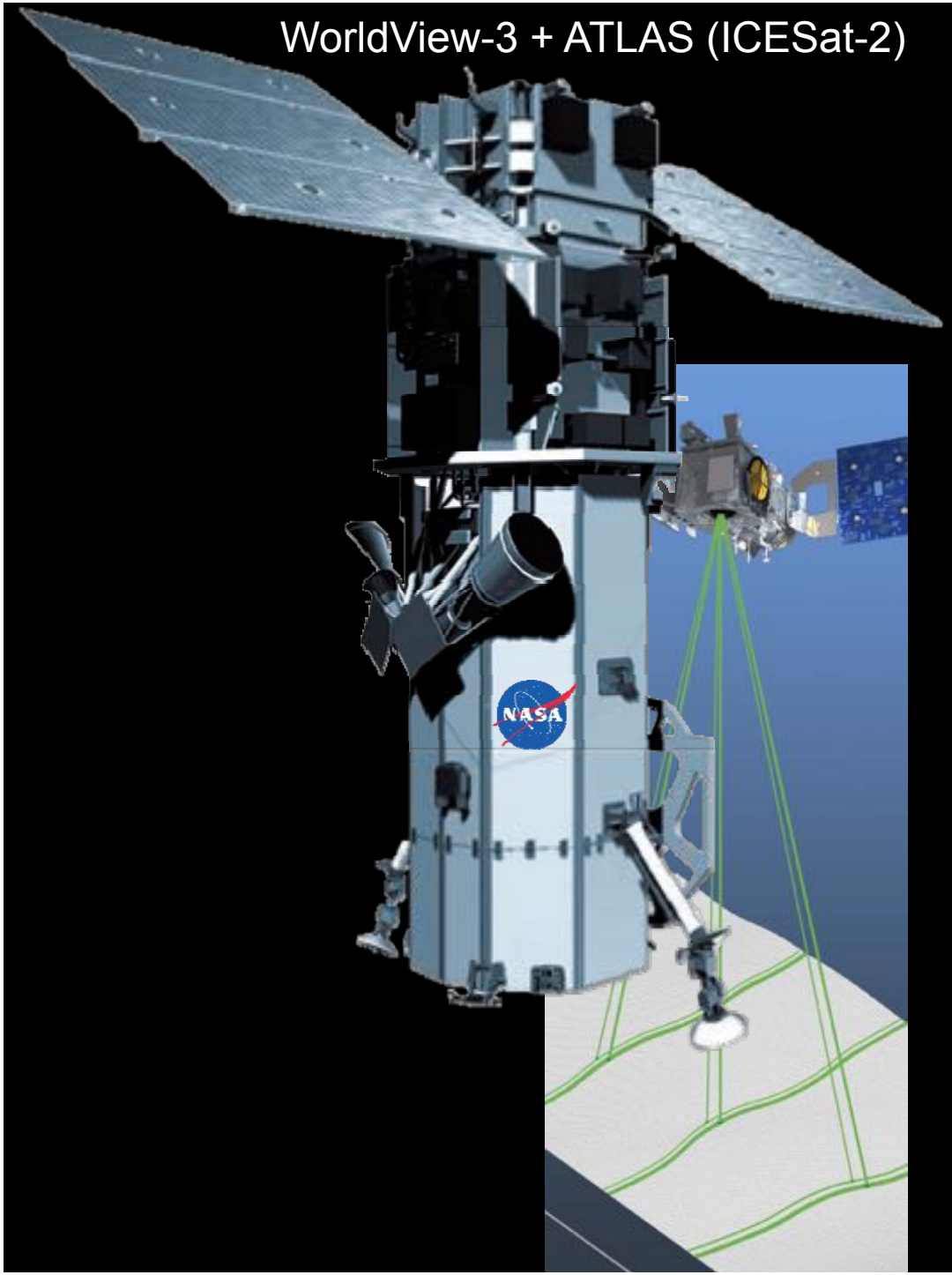


High-Mountain Asia (HMA)
WV/GE DEM Mosaic (4076 DEMs), July 2017

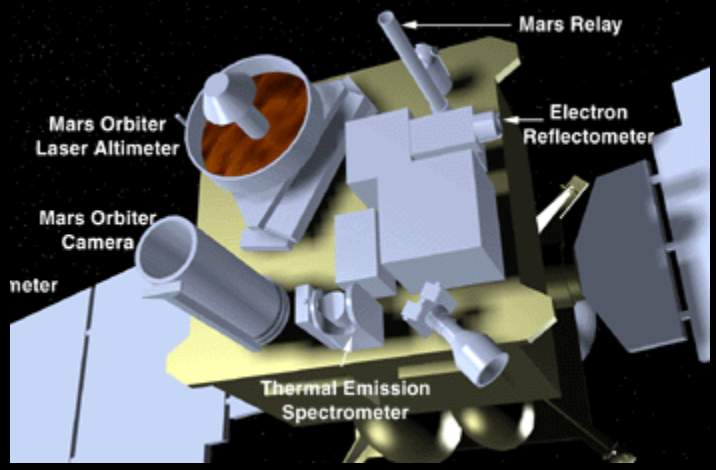


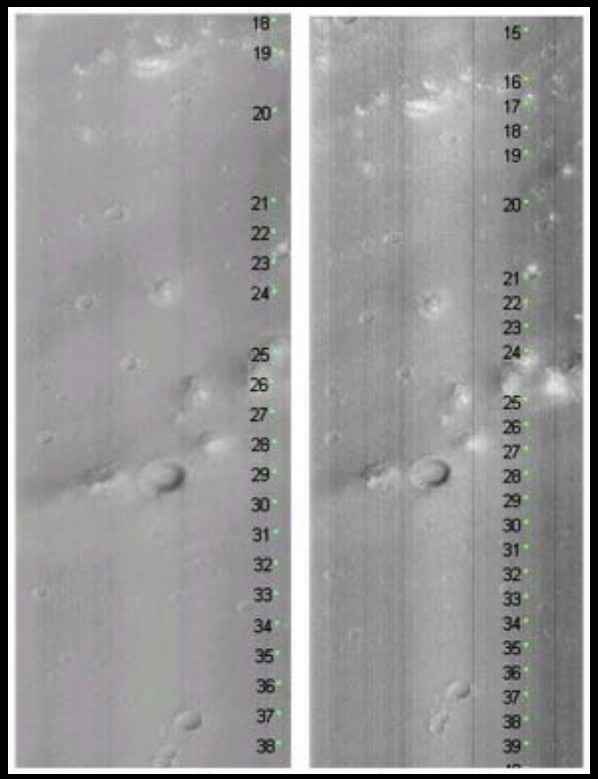
High-Mountain Asia (HMA)
WV/GE DEM Count Map, July 2017

WorldView-3 + ATLAS (ICESat-2)



NASA Mars Global Surveyor (1996-2006)





MOLA altimetry over MOC stereo images

Summary

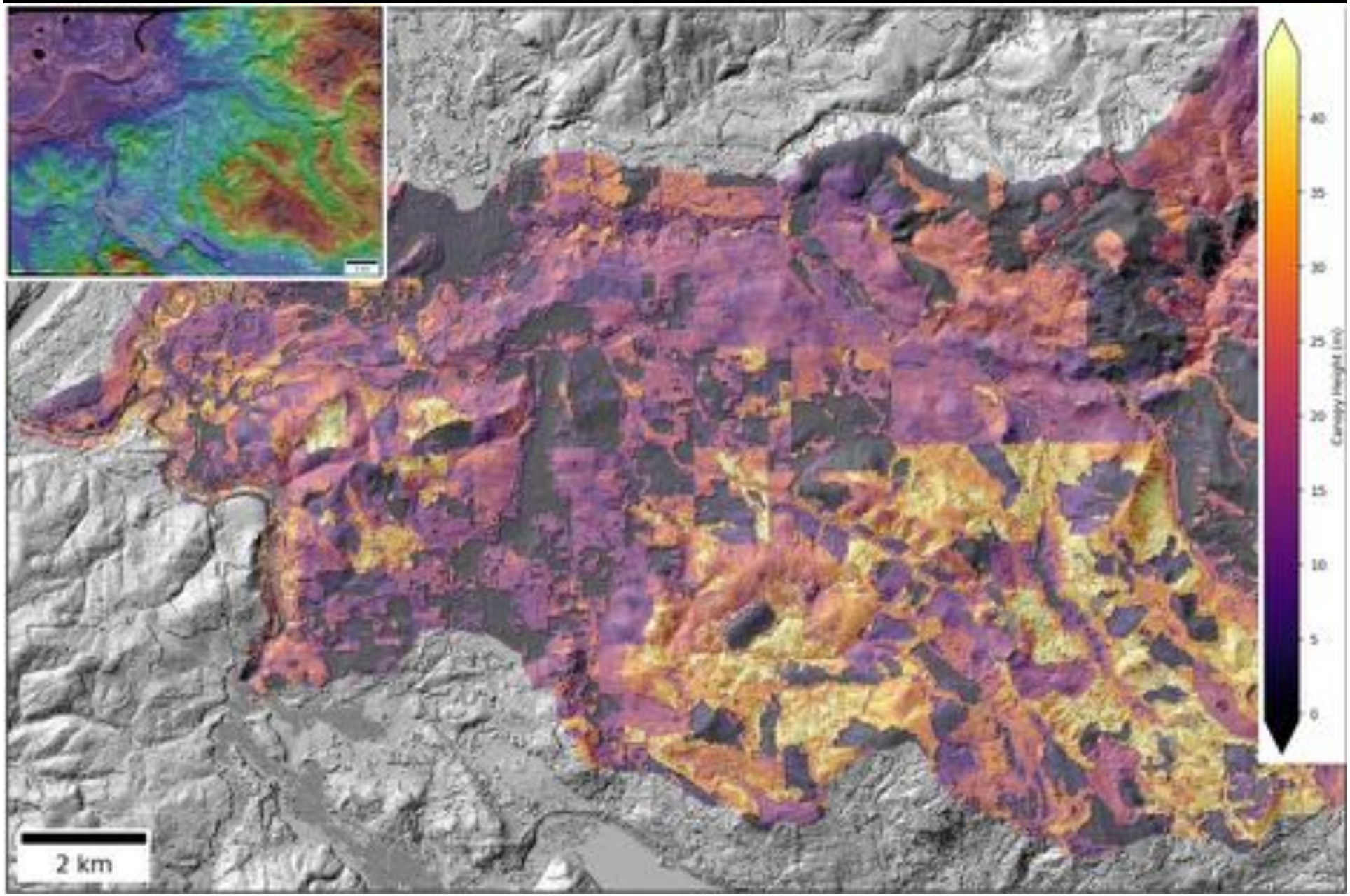
- 5 operational spacecraft offering sub-meter stereo imagery, no cost (seriously)
  - Tasking and archive access
- Scalable, automated, open-source workflow
  - 2-m DEM posting, <0.1-0.5 m accuracy
- Regional mosaics and dense time series
- Not LiDAR, but close
- Baselines are established:
  - Coverage, processing, product quality will only improve

Bonus

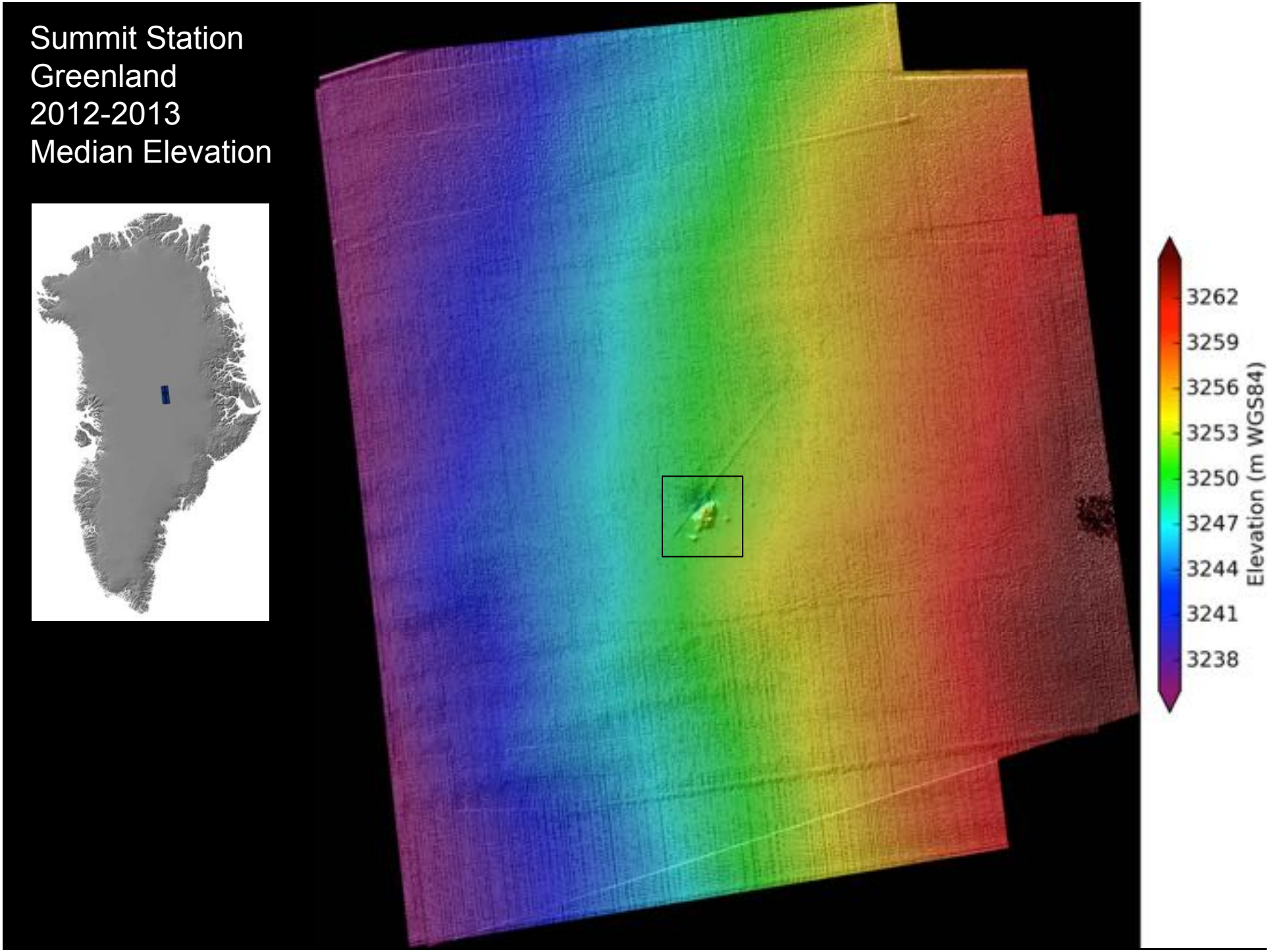
Commercial Stereo

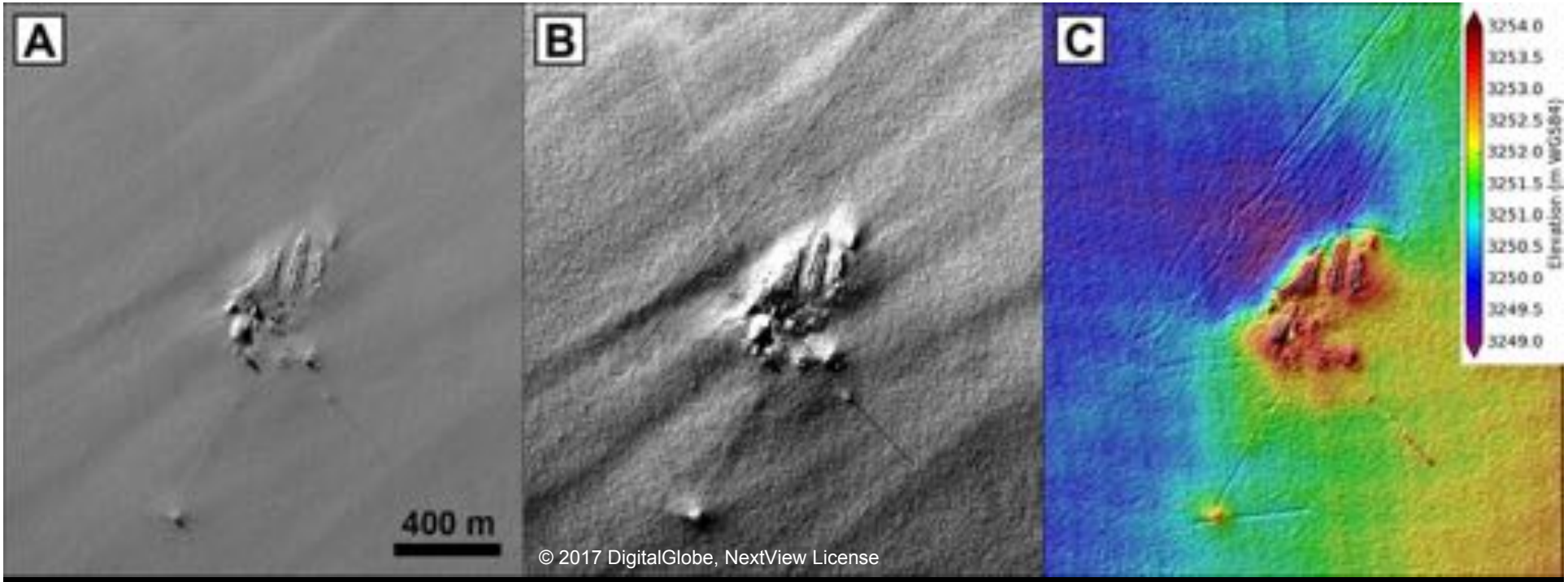
- Pros:
  - 2-m DEMs, 0.5 m orthoimages
  - Accuracy 5 m, <1 m relative/post-correction
  - ~17x17 point targets, ~110x110 km area collects
  - On-demand (<1-2 day repeat)
  - No direct cost (federal projects)
- Cons:
  - Competition
  - Clouds
  - DSM only (canopy height)
  - Occlusions over steep topography
  - Correlation artifacts and “blunders”

Canopy Height, Mashel Watershed, WA (



Summit Station
Greenland
2012-2013
Median Elevation



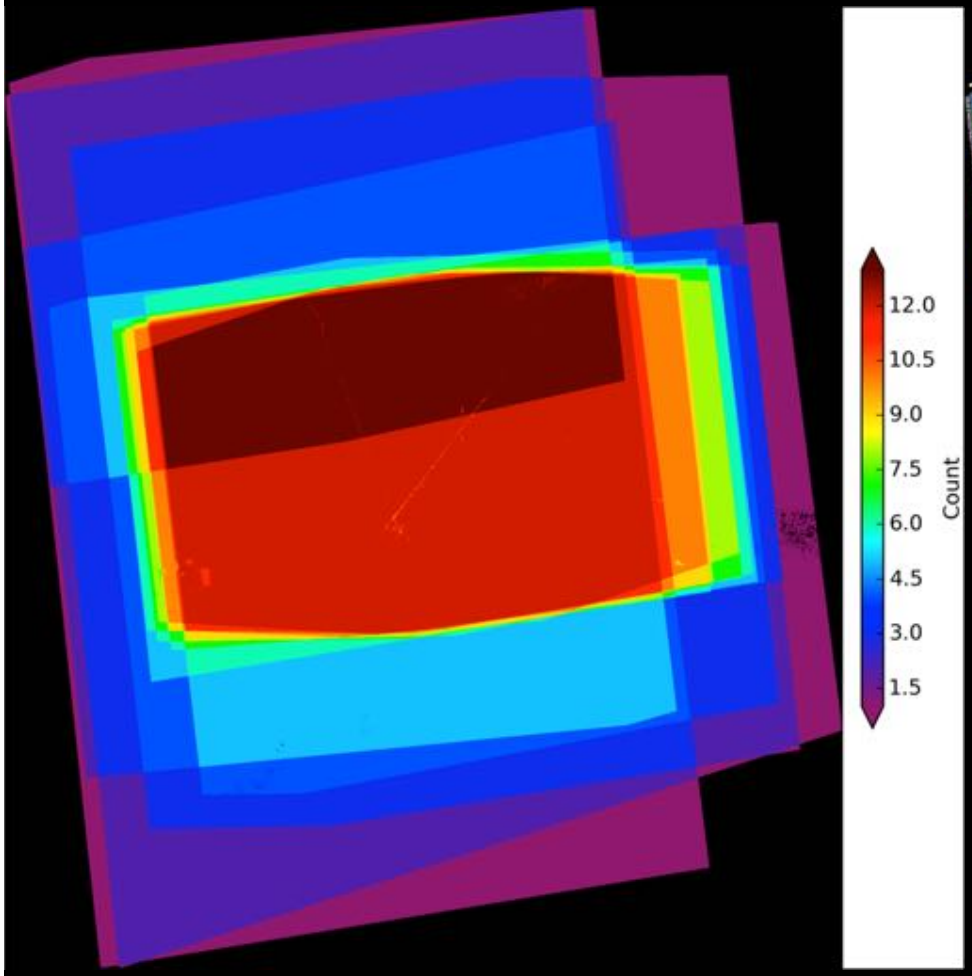


Summit Station
Greenland
July 14, 2013

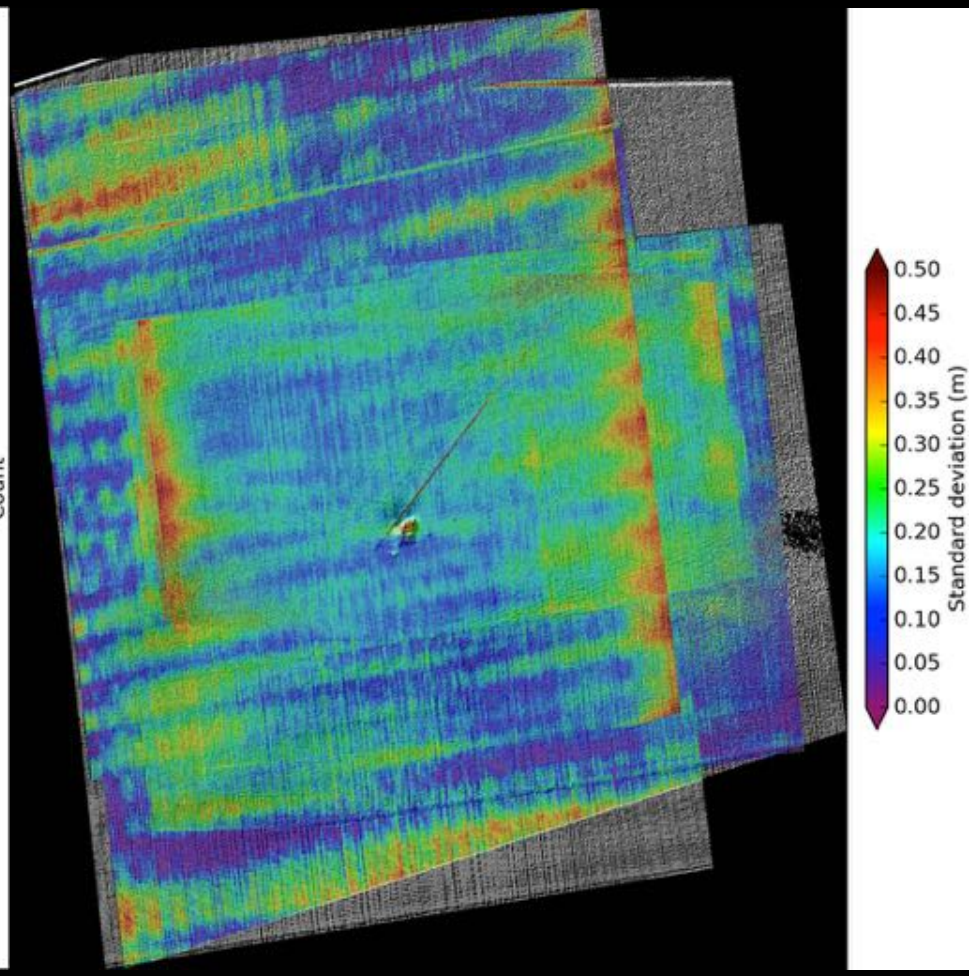
Ed Stockard (https://www.flickr.com/photos/coastaleddy/6961187802/)

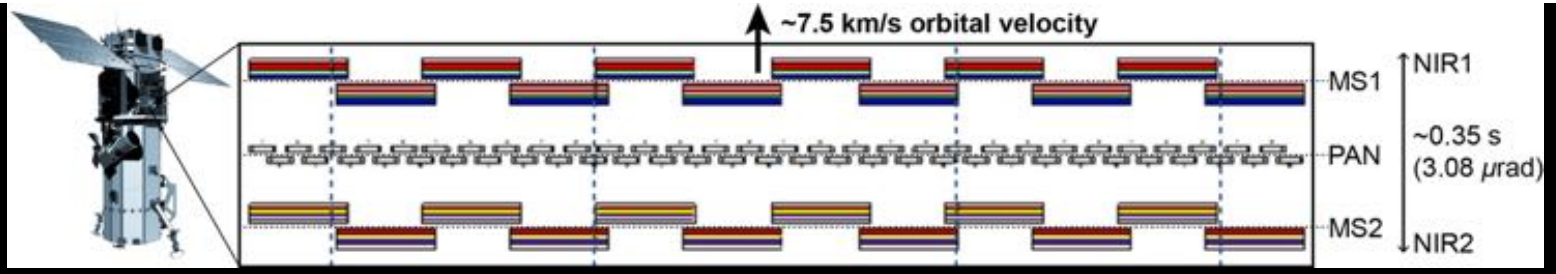
Summit Station, Greenland
Co-registered WV-1 and WV-2 DEMs
2012-2013

DEM Count



Elevation Standard Deviation
~10-30 cm



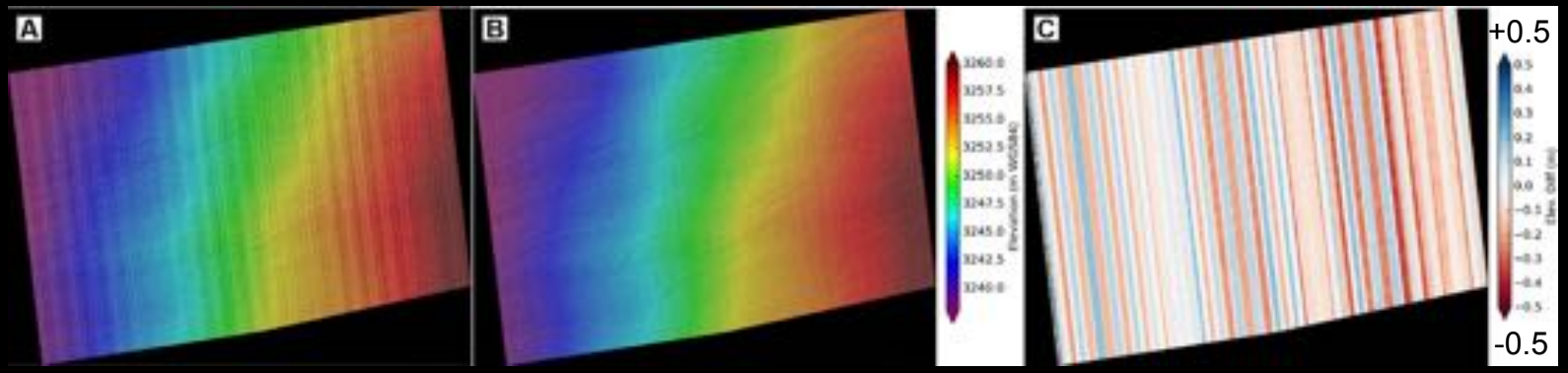


Before correction

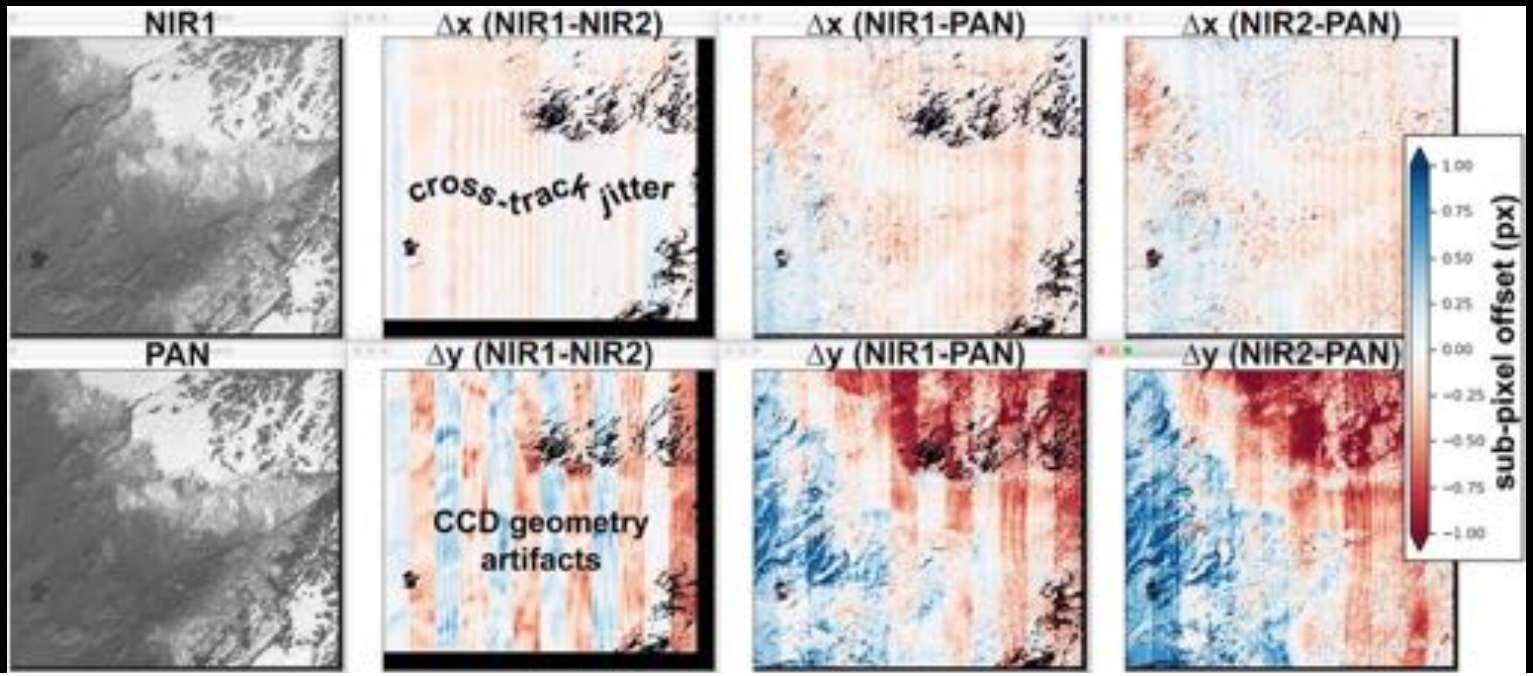
After correction

Difference (m)

WV-2



WV-3



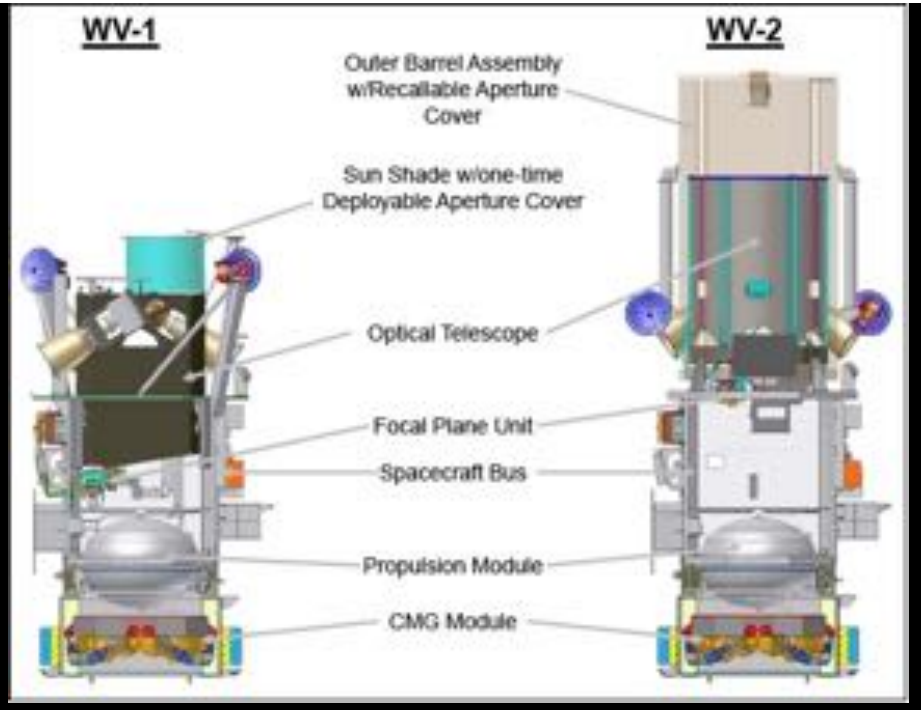
WorldView-2

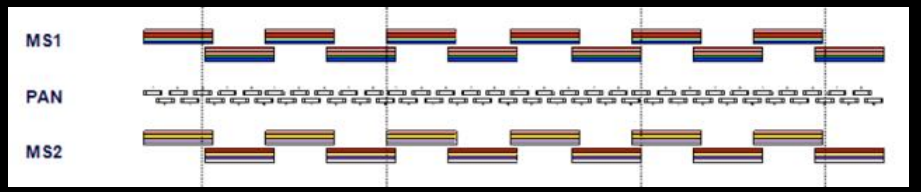
Spacecraft:

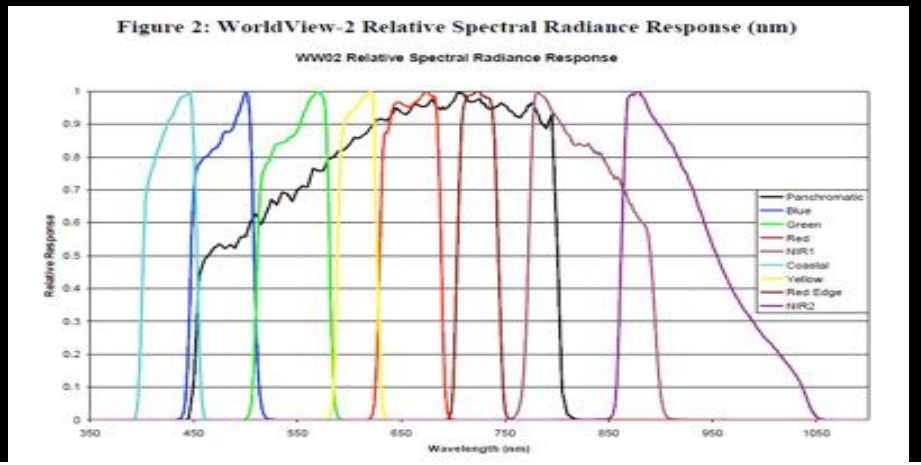
- 770 km altitude, 7.5 km/s velocity
- State of the art attitude control sys
- Off-nadir angles of >40°

Instrument:

- ~13.3 m focal length, ~1.1 m primary mirror, 1.28° FOV
- Panchromatic (0.46 m/px)
  - ~35420 samples (50 CCDs)
  - ~30K–462K lines
  - 16 Gigapixel camera (11 bit)
- 8-band multispectral (1.8 m/px)
  - 400-1040 nm







Summary

- WV-3 should provide <0.1-0.2 m accuracy
- High-elevation snow depth obs
- Building archive, corrections/processing will improve in future
- Automated, open-source tools are scalable

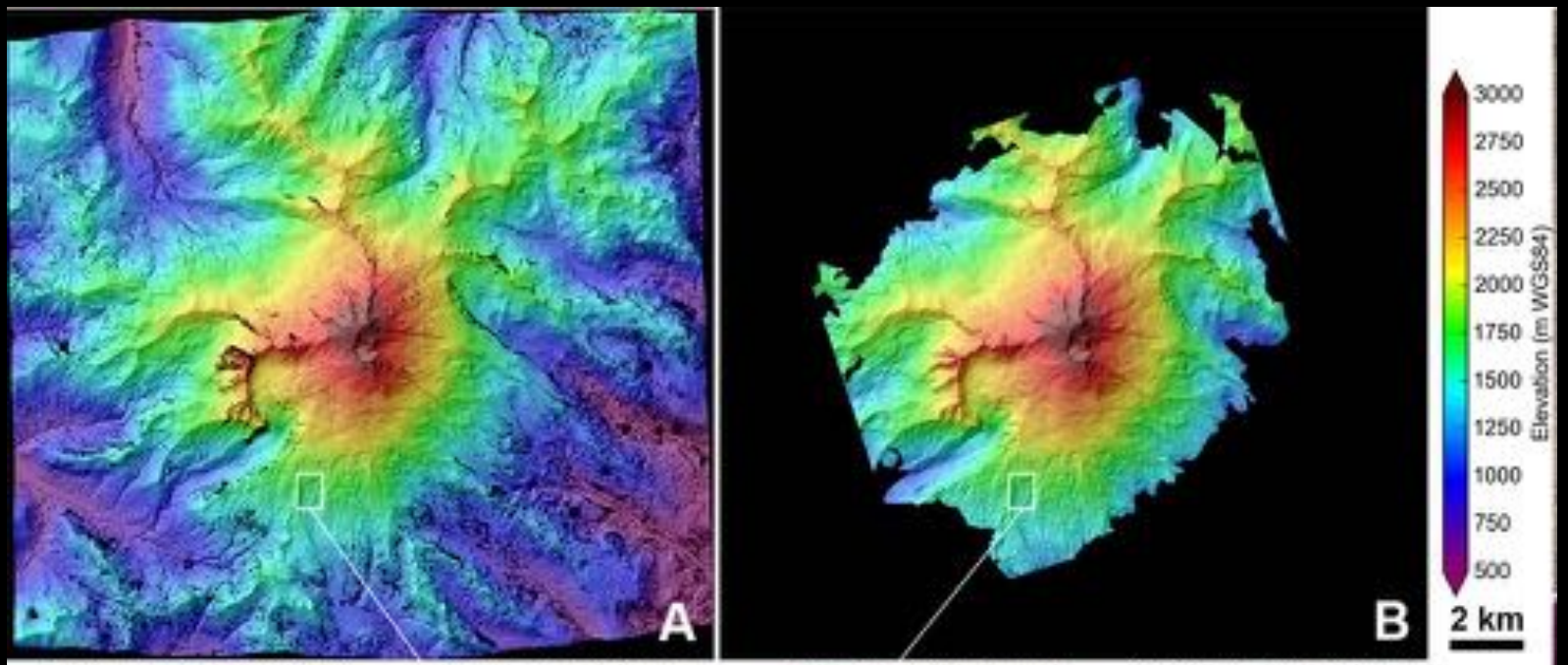
Future Work

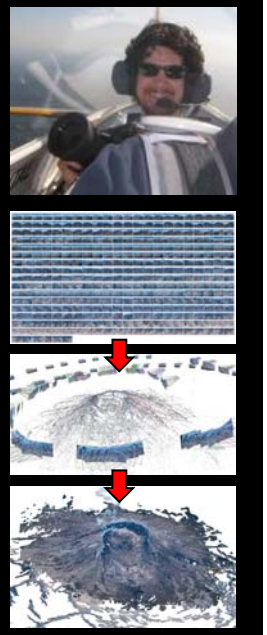
- WV-3 sensor corrections
- Re-run with “high-quality” DEM generation and co-registration, ~1-2 m DEM posting
- Comparisons with ASO, TLS, DGPS

DEM Sources

Satellite stereo DEM (9/13/13)

Oblique Aerial SfM (9/10/13)



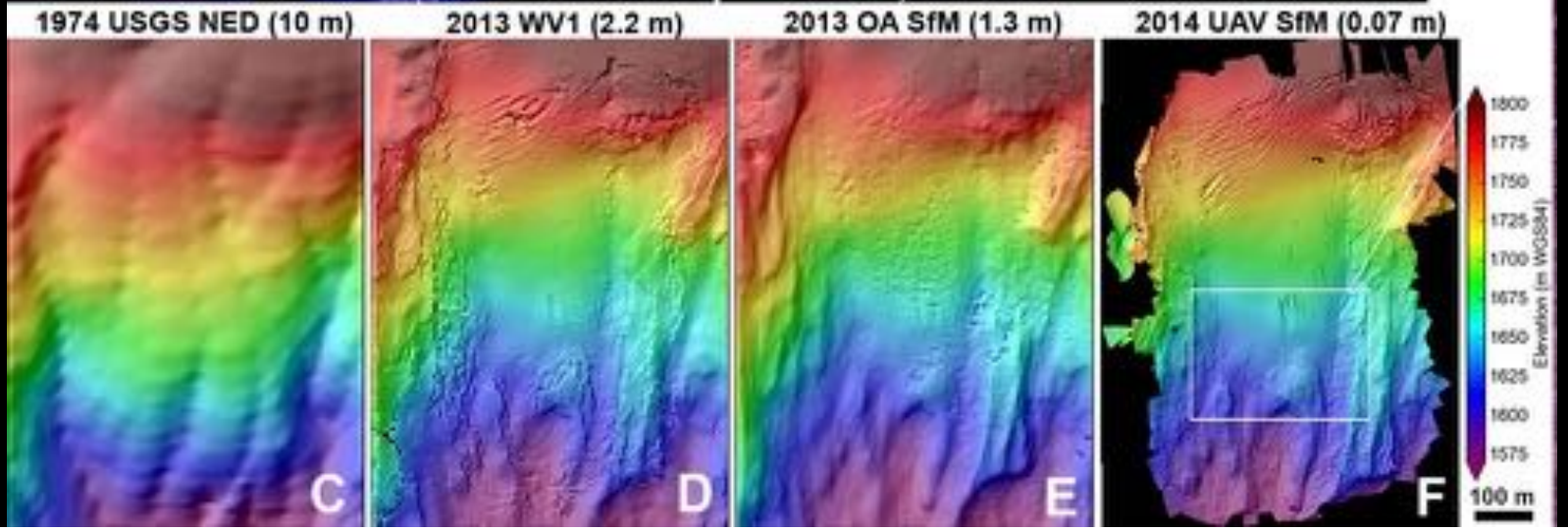


1974 USGS NED (10 m)

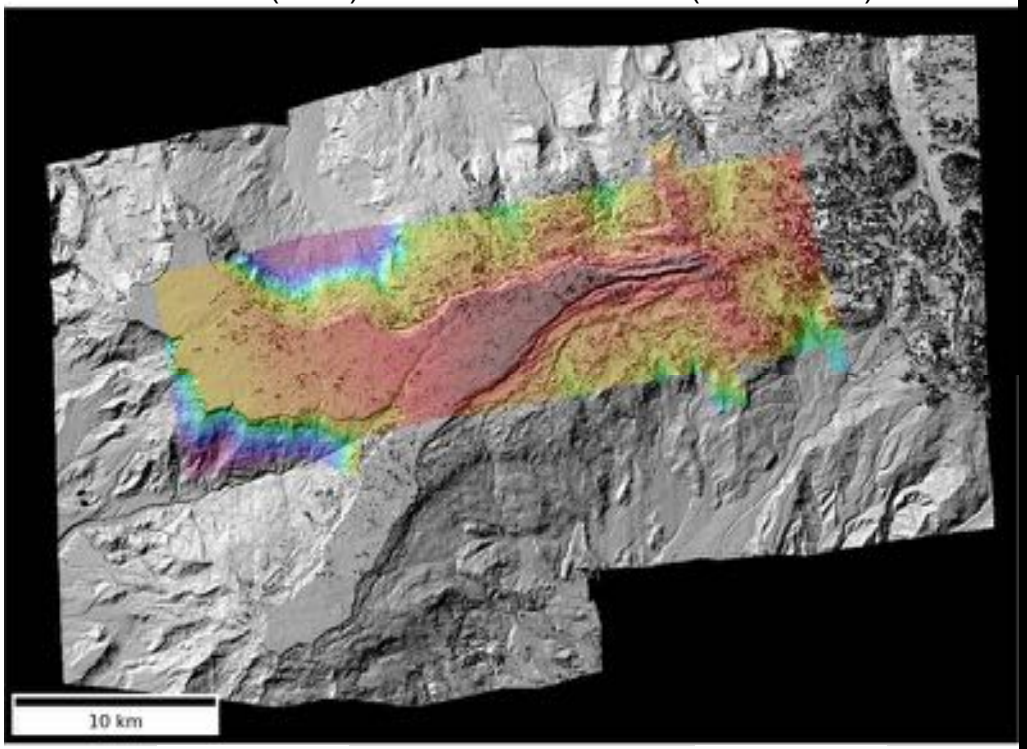
2013 WV1 (2.2 m)

2013 OA SfM (1.3 m)

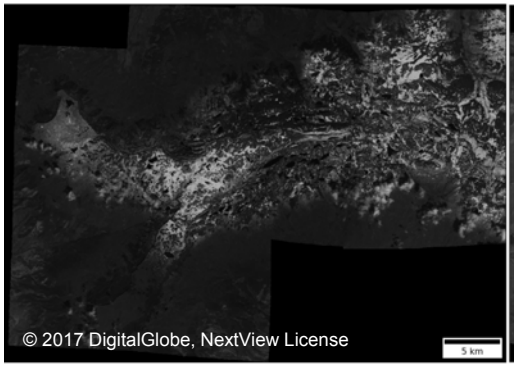
2014 UAV SfM (0.07 m)



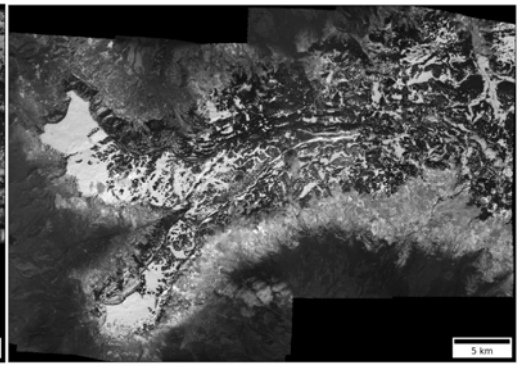
ASO LiDAR (color) over WV DEM mosaic (2016-09-25)



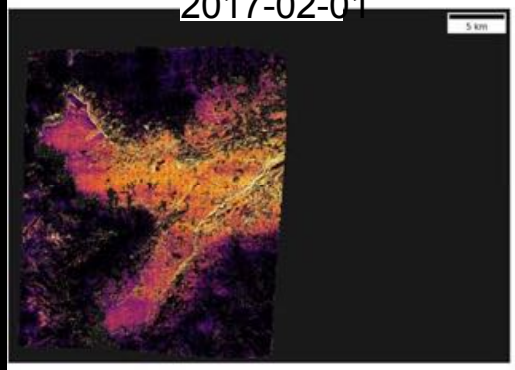
2016-09-25



2017-03-17



2017-02-01



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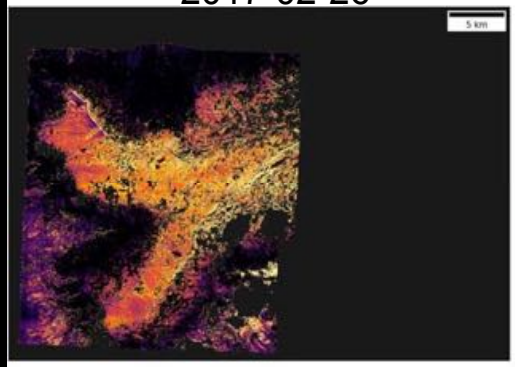

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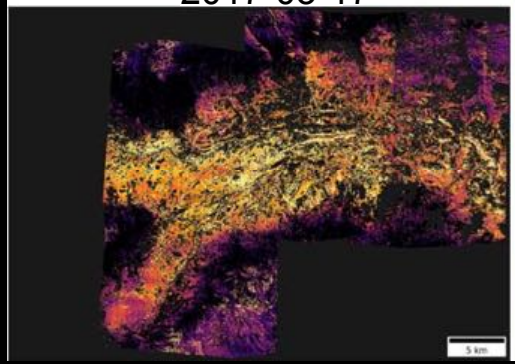
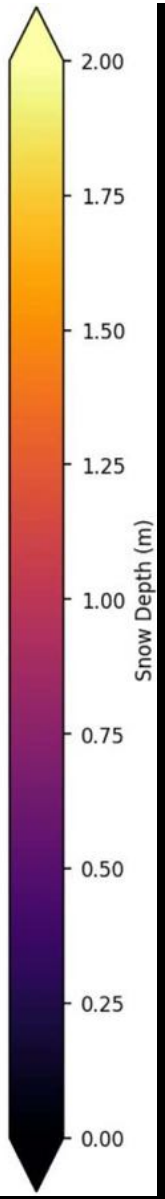
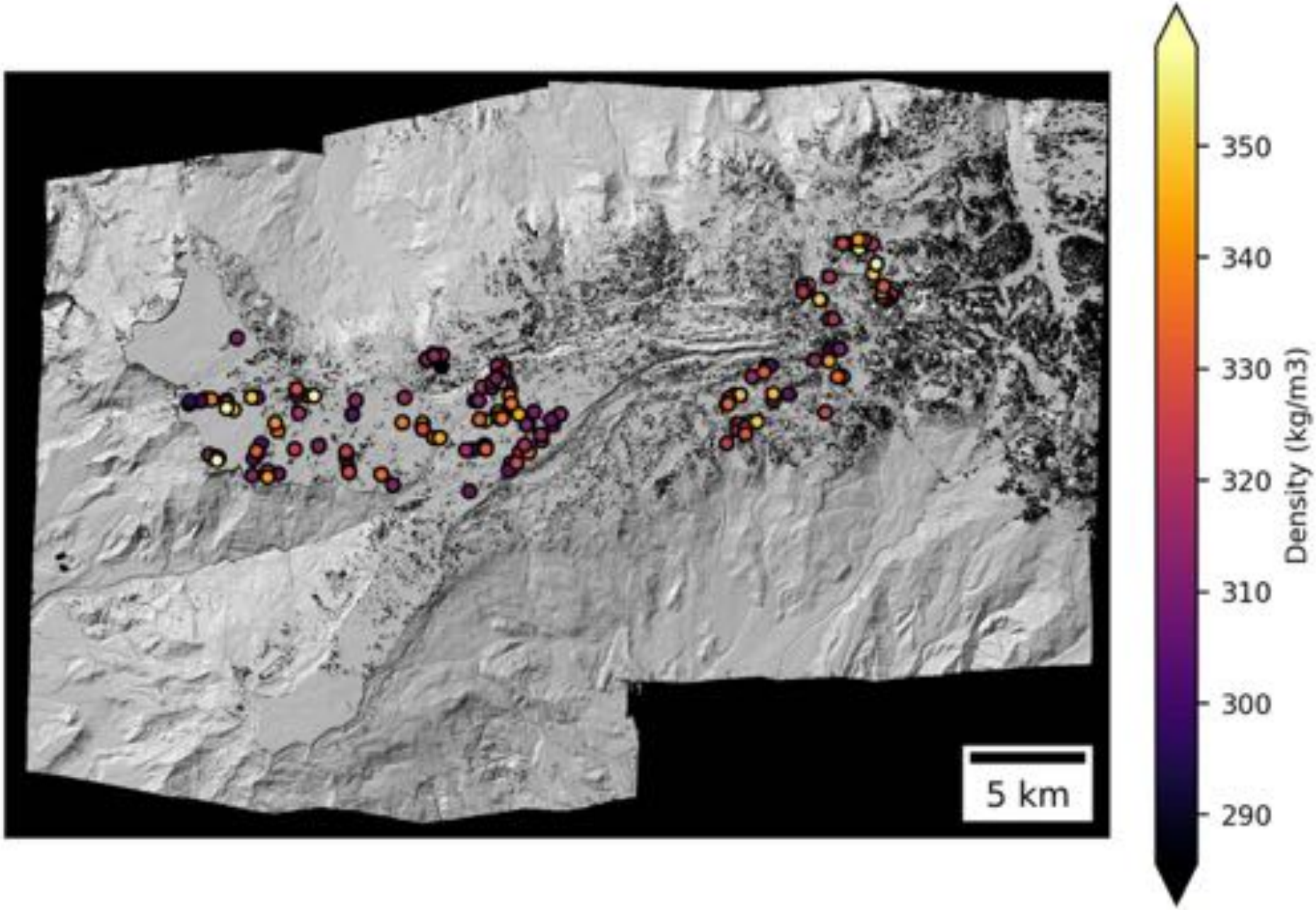
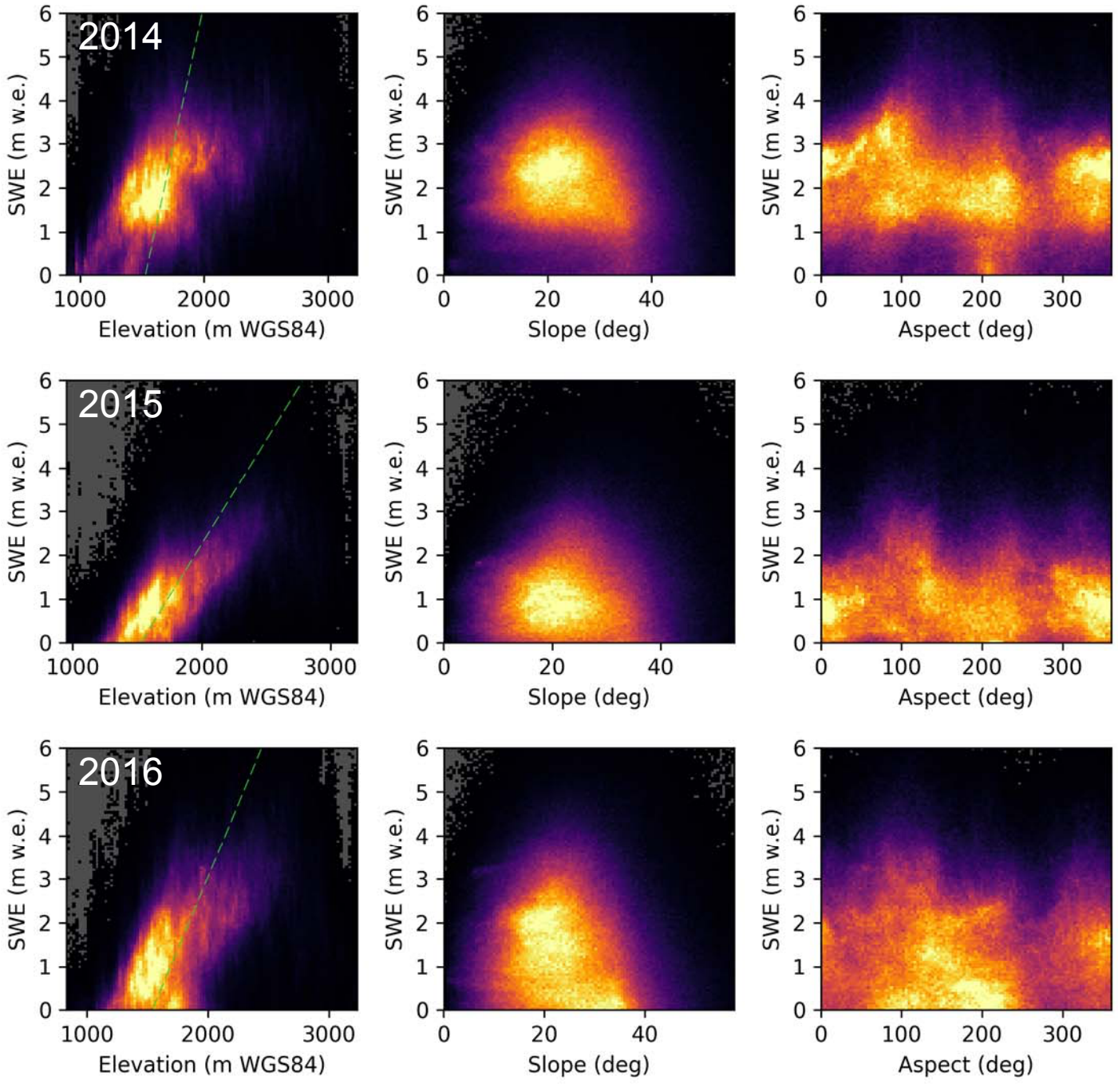


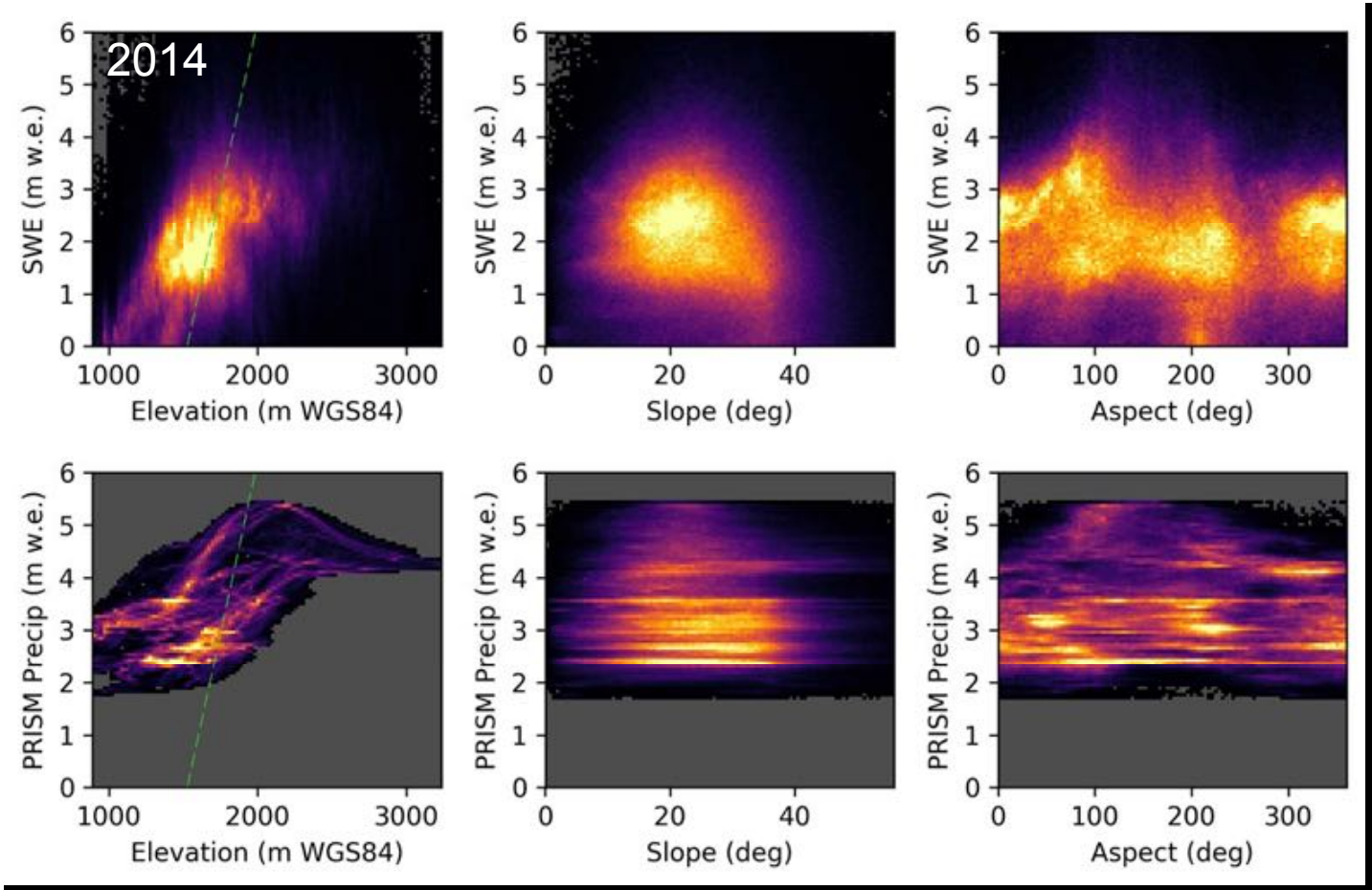




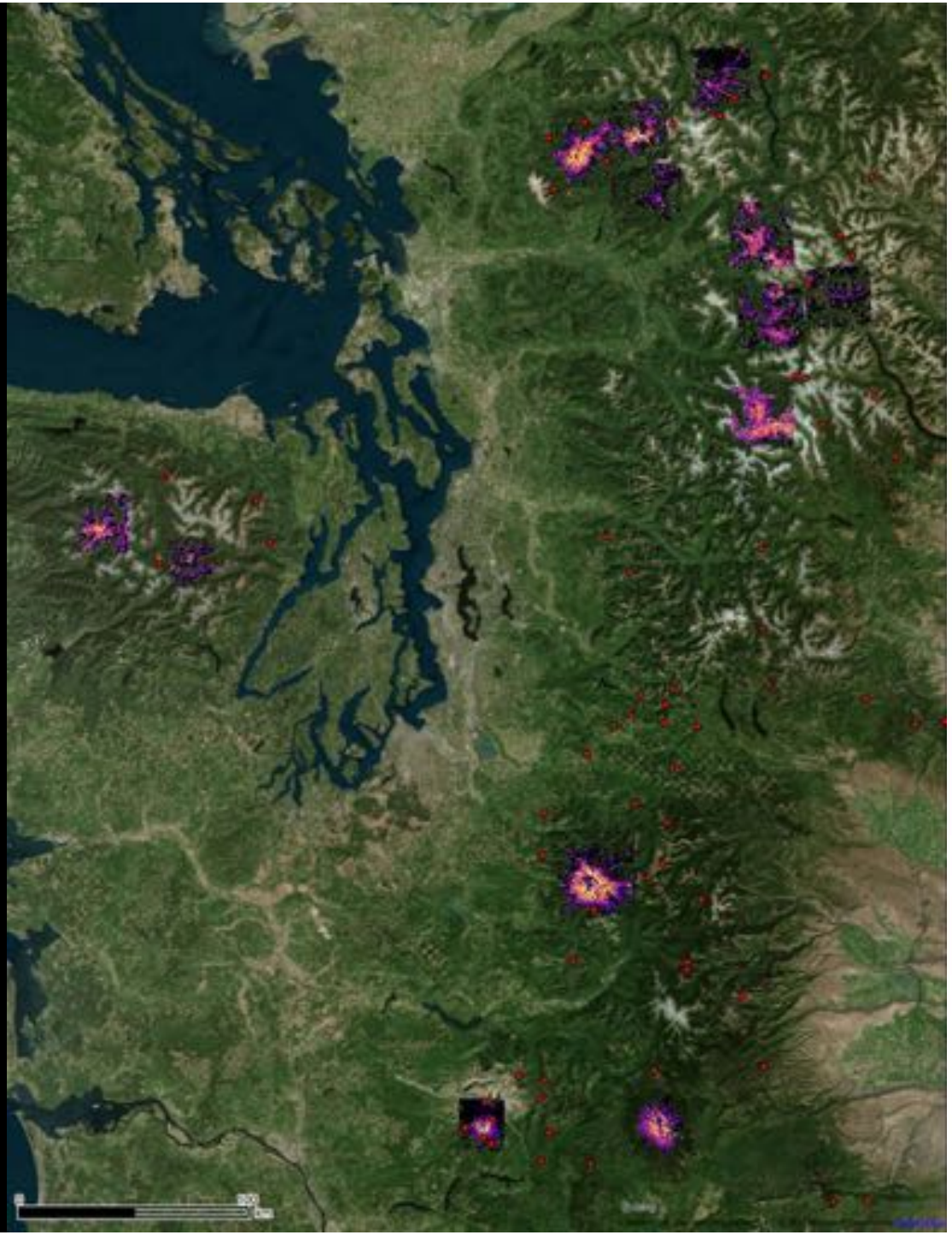
Mean Density: 322 kg/m3

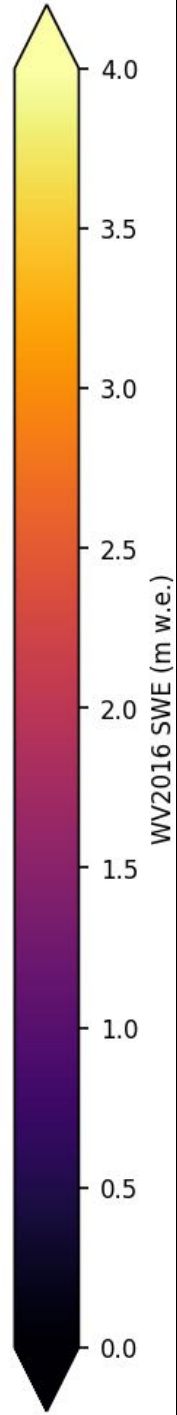
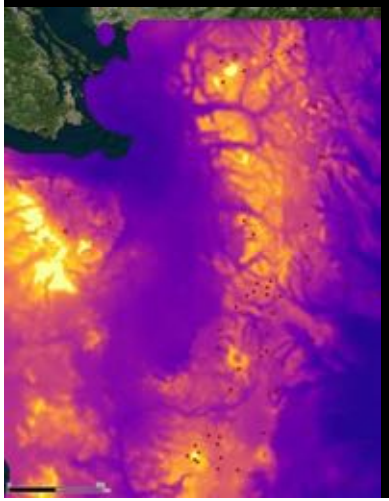


- Elevation
- Slope
- Aspect
- Coastal Proximity
- Trajectory
- Roughness


2014
SWE (m w.e.)
Elevation (m WGS84)
Slope (deg)
Aspect (deg)
PRISM Precip (m w.e.)
0
1
2
3
4
5
6
1000
2000
3000
0
20
40
100
200
300

WY2016
SWE estimate
m w.e.





PRISM precip
1980-2010, Oct-May