The potential of Sentinel-2 for investigating glaciers and glacier lakes

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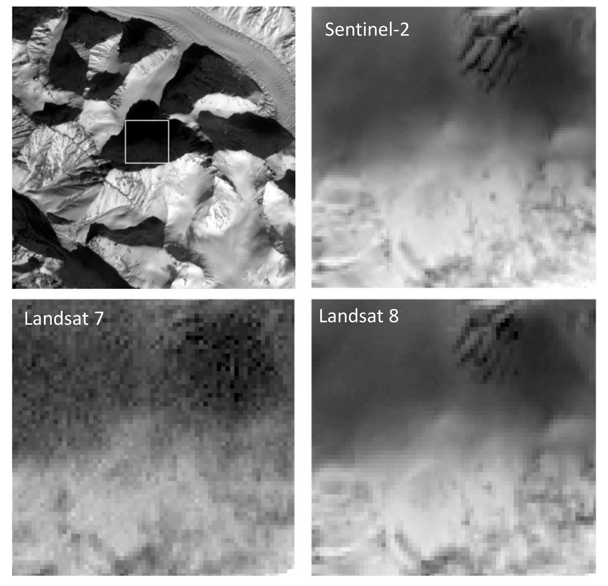
Introduction and background

Sentinel-2 (S2) features a number of characteristics that will improve mapping and monitoring of glaciers and related hazards from space:

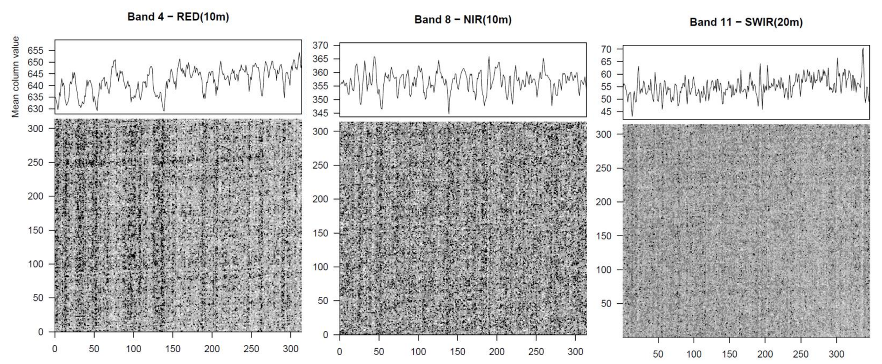
- **Spatial resolution of 10-20m**
- **12-bit radiometric resolution**
- **Repeat cycle of at least 10 days, eventually becoming 5 days (even higher towards the poles)**

In this study we show a selection of tests on the radiometric and geometric performance relevant to glaciological image analysis. We present three glaciological use cases related to these findings.

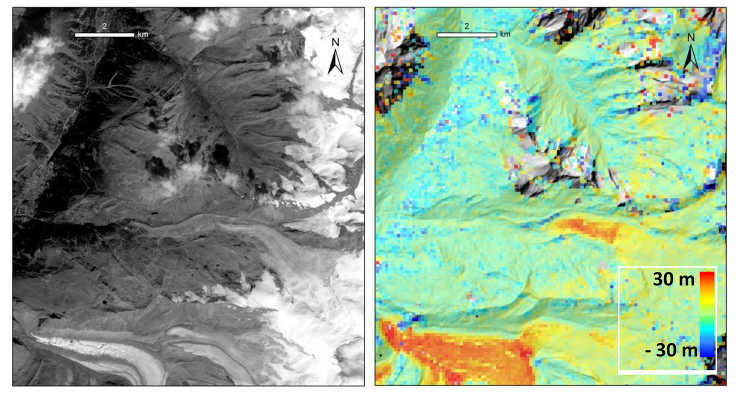


Above: Glacier with crevasses in shadow (from Karakoram). All examples using band 8 of the respective sensors with enhanced histograms. No particular stripes was found in shadowed areas for the visible and near-IR bands as presented in the figures to the left.

Radiometric noise



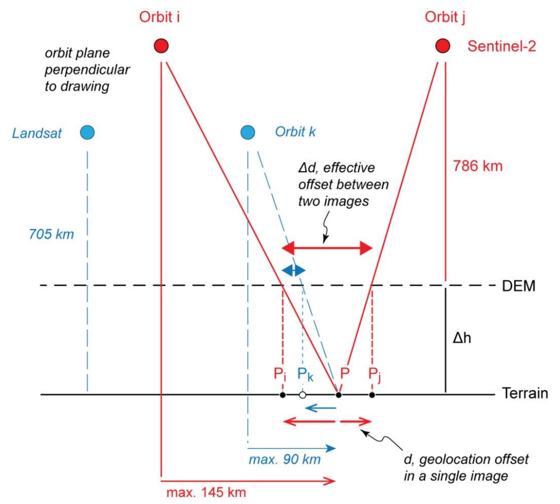
Above: Both along-track (vertical) and cross-track (horizontal) stripes become visible over dark surfaces (water). The graphs show mean values for each pixel column.



Above: Cross-track offsets between S2 and Landsat-8 from the SAME DAY (Zermatt, Switzerland, Gorner and Findelen Glacier). Geolocation biases would affect e.g mapping of glacier outlines, because of different orbit settings and use of other DEMs in the orthorectification process.

Vertical errors in DEM

Cross-track offsets in orthoprojected Sentinel-2 L1C data due to vertical errors in the used DEM have to be considered (see figures). In particular at glacier tongues, DEMs will typically be outdated due to glacier shrinkage. For latitudes larger than 60 degree North (i.e. north of the SRTM coverage) we found geolocation bias patterns of the same order of magnitude in several locations in the scenes, not only over glaciers.



Above: Max. S2 Off-nadir distance = 145 km (P and P_i):

$$d_{max(S2)} \approx \Delta h/5.5$$

Different orbits adds up. Twice as much shift (P_i and P_j):

$$\Delta d_{max(S2)} \approx \Delta h/2.7$$

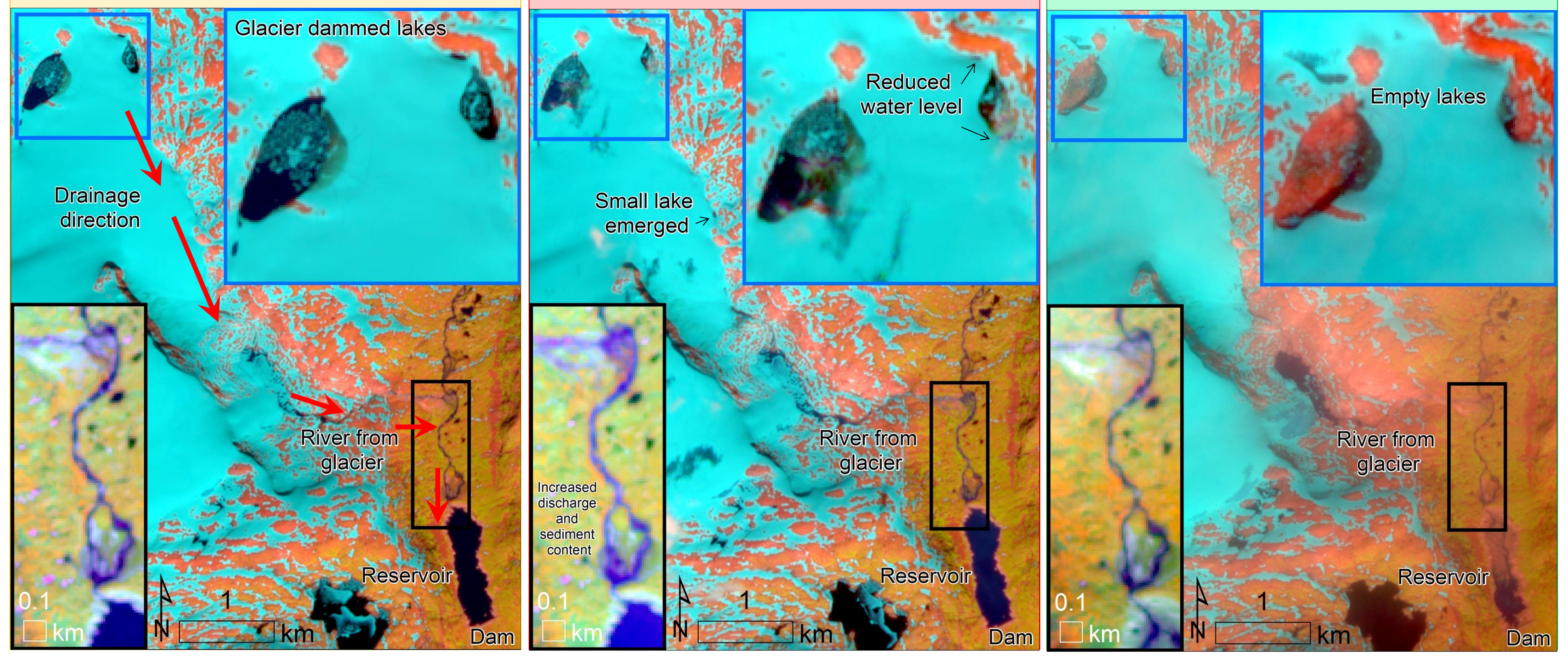
Based on S2 commissioning and ramp-up phase data, we find co-registration accuracy between repeat scenes of around 1/10 pixel, and a geo-location accuracy of one-two pixels. Both error magnitudes are well acceptable for most glaciological applications. Vertical errors in DEMs strongly affect the quality of the orthorectified satellite image.

2) Surveillance of glacier lakes outburst floods (GLOF)

3 days before GLOF
18.Aug.2015
Red arrows indicate drainage direction of water (False color composite: S2 bands 11,8,4, River inset S2-bands 8,11,4)

Ongoing GLOF
21.Aug.2015
Notice the increased river discharge and sediment content in the river and reservoir (stronger blue color). A small lake has emerged and another disappeared.

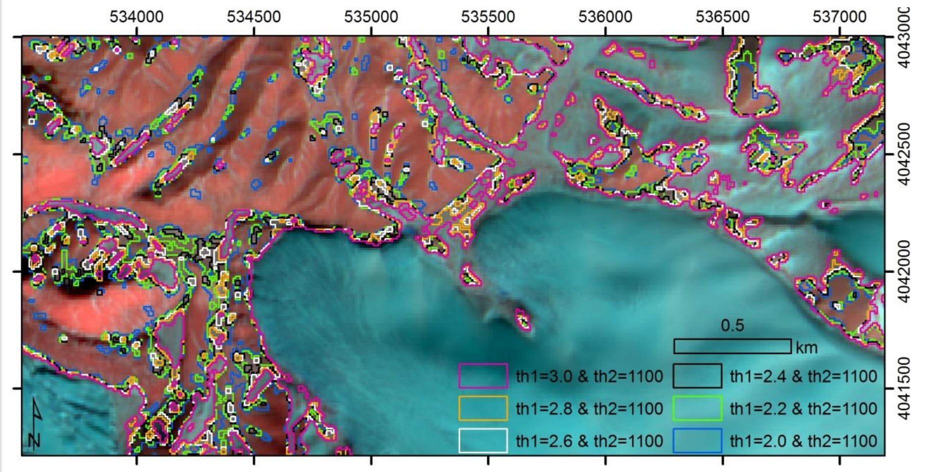
After GLOF
10.Sept.2015
3 weeks after the GLOF. Notice that both lakes have been drained and it is an indication that they have a connected subglacial channel system.



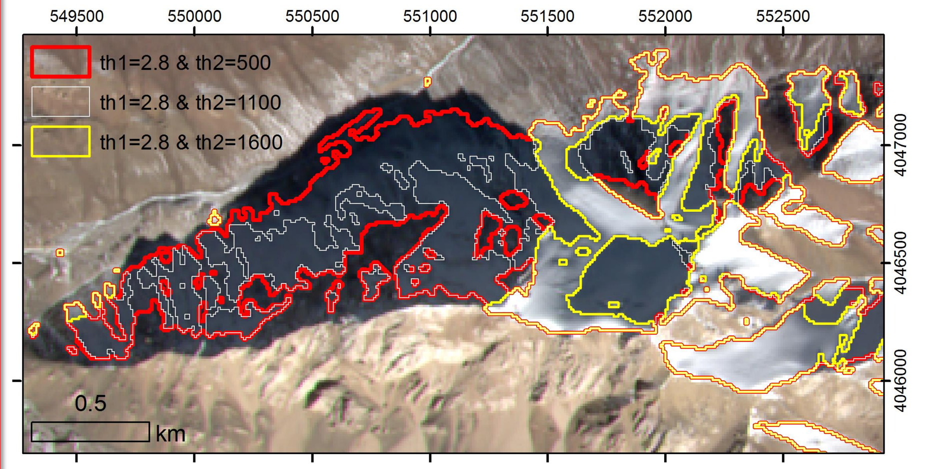
The glacier Harbardsbreen in Norway has had frequent glacier lake outburst floods (GLOFs, also called Jøkulhlaups. See red dot on Norwegian map for location). Seven previous GLOFs have been registered and the most recent GLOF was 20-24 August 2015. Ca. 6 millions m^3 of water accumulated in the reservoir and 20 houses were in danger down valley. Due to the advantage of higher temporal, spatial and radiometric resolution compared to many previous optical satellites, it is possible to use Sentinel-2 as an additional information source for surveillance of GLOFs throughout the year.

Above: Photo from 18.Aug.2015 of the largest glacier dammed lake (Photo taken in south-west direction). On the Sentinel-2 images it is possible to observe the uplift of the glacier ice around the lake perimeter due to the pressure of the water (Figures to the right).

1) Multispectral glacier mapping



Top : A thin snow layer is present around the glacier perimeter and the variation in area differs between various *th1*. Many mixed pixels of snow and bare ground.

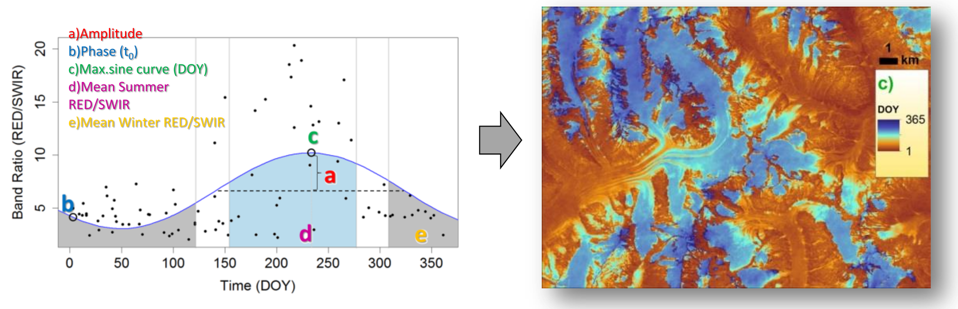


Bottom: The 12-bit radiometric resolution makes glacier mapping in shadowed areas feasible. *th2* is included to better map glaciers in shadow and the figure illustrate the threshold sensitivity between three *th2* (The best performance here is with *th1*= 2.8 and *th2*=1100). Both figures are from glacier areas in northern Tibet.

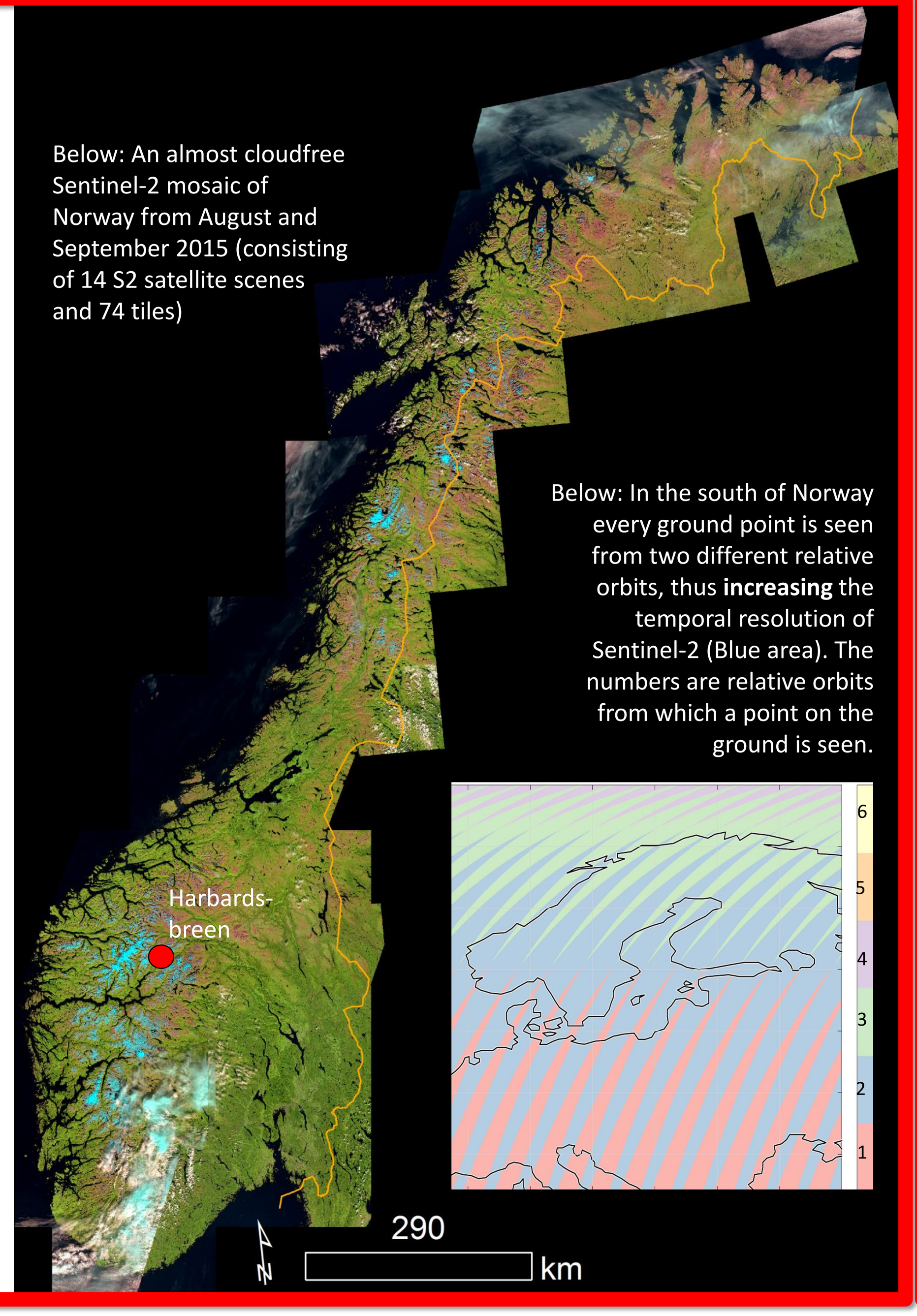
The multispectral band ratio for glacier mapping performs well with Sentinel-2 images.

$$R_{red/SWIR} = \underbrace{\frac{DN_{red4\ (665-695nm)}}{DN_{SWIR11\ (1610-1700nm)}}}_{\text{Threshold 1 (th1)}} + \underbrace{DN_{Blue2}}_{\text{Threshold 2 (th2)}}$$

Left figures present some glacier mapping challenges. With higher spatial and radiometric resolution the measurement accuracy will improve, but it also makes it a more difficult task to manually choose the threshold values, and to choose a single satellite scenes for mapping. With increased temporal resolution of Sentinel-2 images (Right figures) it is possible to exploit the seasonality of snow and ice and use curve fitting to map glaciers (Figures below).



Above: We can utilize the higher temporal resolution with Sentinel-2 when mapping glaciers, especially in higher latitude regions. Image stack of Landsat 5TM and 7ETM+ show seasonality in glacier pixels with a dissimilar seasonal signal on- and off-glacier (here 4 years of satellite images are simulating 1 year)

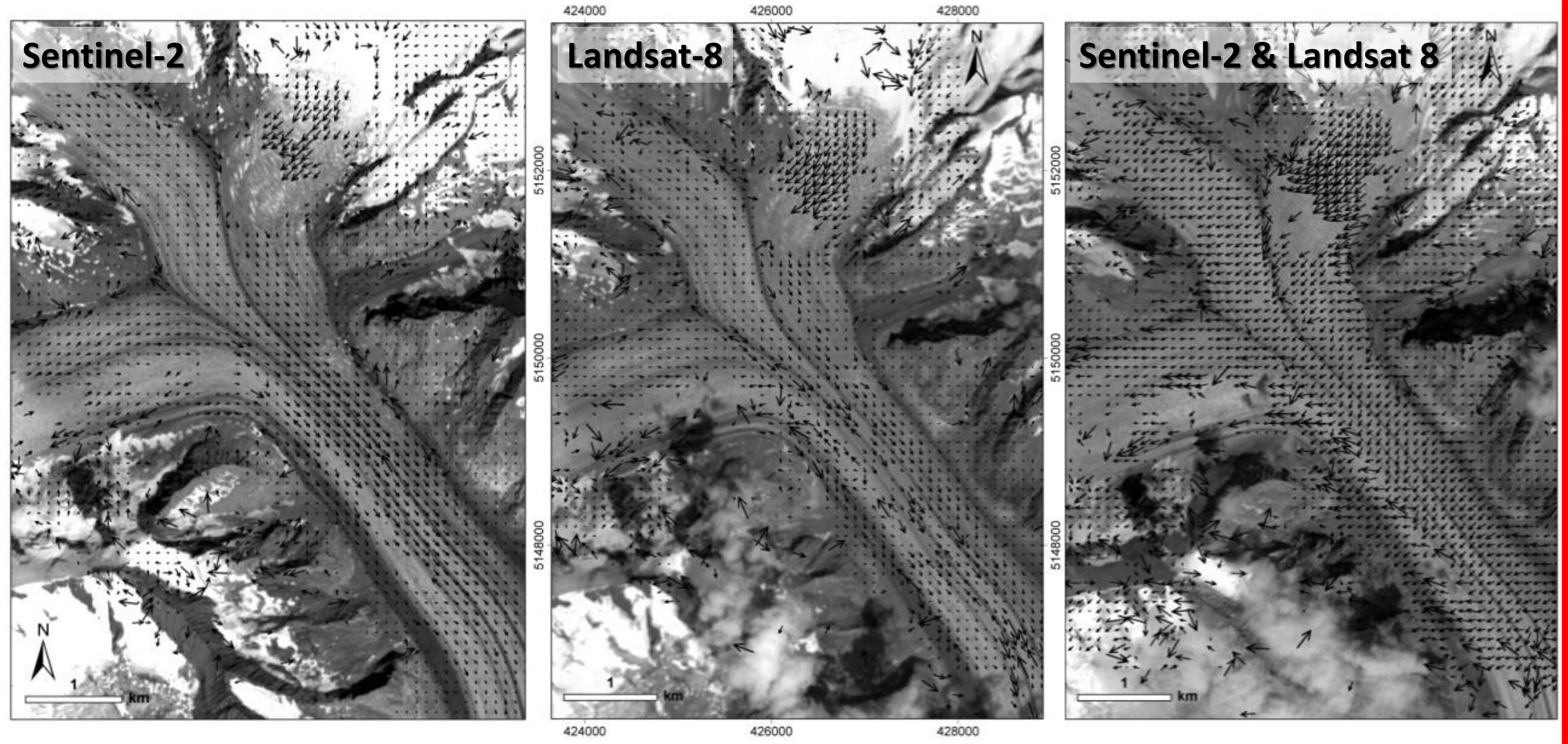


Below: An almost cloudfree Sentinel-2 mosaic of Norway from August and September 2015 (consisting of 14 S2 satellite scenes and 74 tiles)

Below: In the south of Norway every ground point is seen from two different relative orbits, thus **increasing** the temporal resolution of Sentinel-2 (Blue area). The numbers are relative orbits from which a point on the ground is seen.

3) Glacier velocities

From Sentinel-2 data it becomes possible to track velocities of smaller glaciers and even over seasonal scales, as we demonstrate for the European Alps. This opens up the possibility for obtaining both summer and annual velocities from the same sensor. Sentinel-2 geolocation biases as presented above can be avoided to a large extent for glacier velocity measurements by relying on repeat data from the same relative orbit.



Above: Ice velocities derived from S2 and Landsat 8 satellite images from Aletschgletscher, Switzerland. (a) Sentinel-2 from 30 July and 8 Sept. 2015 (b) Landsat-8 7 Aug. and 9 Sept. 2015 (c) Landsat-8 from 7 Aug. and Sentinel-2 from 8 Sept.2015. Note that ice velocity cannot be retrieved when combining Landsat 8 and Sentinel-2.

Outlook

Sentinel-2 is an ideal backbone for operational services for environmental assessments. Relying on future algorithms there is a potential for automatic products of all three use cases presented here. For example once an algorithm for automatic snow/ice mapping based on time series becomes better established, a corresponding annual product might be computed on the satellite data server side as a high-level product.

References:

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