Evaluation of Sentinel-2: Case Study of Land Cover Classification and Ice Velocity

Torgeir Ferdinand Klingenberg

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Department of Geoscience
Faculty of Mathematics and Natural Sciences

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Evaluation of Sentinel-2: Case Study of Land Cover Classification and Ice Velocity

Torgeir Ferdinand Klingenberg
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Abstract

A new era of open-access satellite data is upon us and satellite sensors as the Sentinel-2A and its twin satellite Sentinel-2B, will together provide imagery with relative high temporal resolution, and improve state of art environmental monitoring and science studies, as on e.g., land cover, cryosphere and ocean. The team behind Sentinel-2 is reporting a high measured co-registration accuracy between repeat orbit, as this is crucial for users by the Sentinel-2. However, registered co-registration displacement between two different relative orbits is reported to be high, and limits the full potential of Sentinel-2 data. Firstly in this thesis, a study of the geometric performance was carried out, testing both repeat and different relative orbits for the Sentinel-2A sensor. The study was carried out on different topography in order to determine errors related to the digital surface model used in the ortho-rectification of Sentinel-2A scenes. The main result was, because of a poor representation of the true surface of the digital surface model used in the ortho-rectification process, that horizontal displacement between two correlated images from different relative orbits is larger in high elevated topography where the surface model does not cope the steep increase in mountainous topography. Secondly this thesis has measured the ice velocity of three glaciers in Norway and four calving glaciers at the Greenland Ice Sheet using the Sentinel-2A satellite, as it is vital to know ice velocity dynamics as a response to climate change. The measured ice velocity was found to have high accuracy, and possible synergy with other Sentinel satellites, as e.g., Sentinel-1 is proposed. Thirdly, a land cover classification was assessed in a typical agricultural landscape in southeast Norway and western Sweden, by using both Landsat-8, and Sentinel-2A satellites for comparison of spectral differences, processing levels and seasonal changes. Overall good agreement was found on all sensors and processing levels, but classes which shares similar spectral response were poorly mapped by all classifications parameters.
Acknowledgements

First of all I would like to thank my supervisors professor Andreas Kääb and PhD candidate Solveig H. Winsvold for all help with my thesis. Thank you Andreas Kääb, for introducing me to the remote sensing and let me be a group teacher in your courses, I really enjoyed it and I learned so much! You were always there to answer questions and explain stuff when I show up at your office. Solveig H. Winsvold, your expertise, friendliness and our constructive discussions have been greatly appreciated, a big good luck with your new job at NVE, I guess we meet again somehow.

Thanks to Liss M. Andreassen (NVE), for allow me to work with Sentinel-2 at NVE, I guess we both learned something in this process. Also thanks to the project Copernicus bretjeneste for founding my work at NVE. Furthermore, I am grateful for Norsk Romsenter for being a co-founder of the Copernicus bretjeneste, but also for founding my trip to the Alpbach Summer School 2016. To meet the people behind Sentinel and ESA was really valuable and fun. A big thanks for the green team at Alpbach Summer School, proposing the WAVE-E satellite was really fun, and it is nice to see the continuous work on the satellite, go WAVE-E!

I am grateful to all my fellow students, who have challenged me, and influenced my thinking and reasoning abilities through my years of study and writing this thesis. Special gratitude are given to my fellow geomatic student Vetle Odin Jonassen, because of his close companionship and his constructive and insightful help through the study.

Finally, a special thanks goes to my parents and my brother for supporting me and being patient through this time.

Torgeir Ferdinand Klingenberg
Oslo, Norway. June 1, 2017
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<th>Description</th>
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<tbody>
<tr>
<td>AOI</td>
<td>Area-Of-Interest</td>
</tr>
<tr>
<td>ASTER</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer</td>
</tr>
<tr>
<td>BOA</td>
<td>Bottom-of-Atmosphere</td>
</tr>
<tr>
<td>CCI</td>
<td>Climate Change Initiative</td>
</tr>
<tr>
<td>CIAS</td>
<td>Correlation Image Analysis Software</td>
</tr>
<tr>
<td>D-InSAR</td>
<td>Differential-Satellite Radar Interferometry</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>DN</td>
<td>Digital Number</td>
</tr>
<tr>
<td>DSM</td>
<td>Digital Surface Model</td>
</tr>
<tr>
<td>DTM</td>
<td>Digital Terrain Model</td>
</tr>
<tr>
<td>EO</td>
<td>Earth Observation</td>
</tr>
<tr>
<td>EOS</td>
<td>Earth Observation Satellite</td>
</tr>
<tr>
<td>EROS</td>
<td>Earth Resource Observation and Science</td>
</tr>
<tr>
<td>ESA</td>
<td>Earth Space Agencys’s</td>
</tr>
<tr>
<td>ETM+</td>
<td>Enhanced Thematic Mapper Plus</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>FPN</td>
<td>Fixed Pattern Noise</td>
</tr>
<tr>
<td>GCP</td>
<td>Ground Control Point</td>
</tr>
<tr>
<td>GMES</td>
<td>Global Monitoring for Environment and Security</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GRI</td>
<td>Global Reference Images</td>
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<tr>
<td>IDL</td>
<td>Interactive Data Language</td>
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<tr>
<td>IMBIE</td>
<td>Ice Sheet Mass Balance Inter-Comparison Exercise</td>
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<tr>
<td>InSAR</td>
<td>Satellite Radar Interferometry</td>
</tr>
<tr>
<td>ISODATA</td>
<td>Iterative Self-Organizing Data Analyst Technique</td>
</tr>
<tr>
<td>L0</td>
<td>Level-0</td>
</tr>
<tr>
<td>L1T</td>
<td>Level-1 Terrain</td>
</tr>
<tr>
<td>LAI</td>
<td>Leaf-Area-Index</td>
</tr>
<tr>
<td>MD</td>
<td>Minimum-Distance</td>
</tr>
<tr>
<td>MLC</td>
<td>Maximum Likelihood Classifier</td>
</tr>
<tr>
<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer</td>
</tr>
<tr>
<td>MPC</td>
<td>Mission Performance Centre</td>
</tr>
<tr>
<td>MSI</td>
<td>Multi-Spectral imaging Instrument</td>
</tr>
<tr>
<td>NAO</td>
<td>North Atlantic Oscillation</td>
</tr>
<tr>
<td>NCC</td>
<td>Normalized Cross-Correlation</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalised Difference Vegetation Index</td>
</tr>
<tr>
<td>NIBIO</td>
<td>Norwegian Institute of Bioeconomy Research</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>---------</td>
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</tr>
<tr>
<td>NIR</td>
<td>Near Infrared</td>
</tr>
<tr>
<td>NMAD</td>
<td>Normalized Median Absolute Deviation</td>
</tr>
<tr>
<td>NVE</td>
<td>Norwegian Water Resources and Energy Directorate</td>
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<tr>
<td>OLI</td>
<td>Operational Land Imager</td>
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<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SPOT</td>
<td>Satellite Pour l’Observation de la Terre</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topography Mission</td>
</tr>
<tr>
<td>SWIR</td>
<td>Short Wave Infrared</td>
</tr>
<tr>
<td>TIRS</td>
<td>Thermal Infrared Sensor</td>
</tr>
<tr>
<td>TOA</td>
<td>Top-of-Atmosphere</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicles</td>
</tr>
<tr>
<td>USGS</td>
<td>U.S. Geological Survey</td>
</tr>
<tr>
<td>VNIR</td>
<td>Visible and Near-Infrared</td>
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Chapter 1

Introduction

A new era of open-access satellite data is upon us (Wulder & Coops, 2014), and with new satellite sensors with medium to relative high temporal resolution as e.g., Landsat-8 and Sentinel-2, enormous amount of images are available for Earth observation (EO) users. With satellites as Landsat-8 and Sentinel-2 both with medium to high spatial resolution, their imagery will improve state of art environmental monitoring and science studies (Wulder & Coops, 2014).

The optical satellite Landsat-8 carrying the instrument Operational Land Imager recently got company by the European Space Agency’s (ESA) Sentinel-2A and Sentinel-2B, which are carrying a similar sensor called Multi-Spectral imaging Instrument. Both of the instruments are using pushbroom sensors, rather than whiskbroom sensors, which were used by the earlier Landsat satellites. The Sentinel-2 and Landsat-8 satellites will both be important for land surveying and monitoring trends that possibly relates to climate change (Vaughan et al., 2013). Both are planned to be operational for a long time, as future missions on new satellite sensors are already planned (Mas et al., 2016), which will be good for monitoring change detection (Wulder & Coops, 2014).

Earth observation satellites (EOS) provide important data to monitor changes on the Earth’s surface. EOS with medium to high spatial resolution as the Sentinel-2 and Landsat-8 are capable to monitor changes of terrestrial domains e.g., land cover, glaciers and lakes (Malenovský et al., 2012; Stocker et al., 2013) variables which are classified as essential climate variables, and a long term continuity of this observation are vital (GCOS, 2016). These EOSs are capable to cover the most remote places on Earth as e.g., Antarctica, Greenland or sea-ice both time and cost-effective.

The Sentinel-2 satellite is part of a satellite constellation of six Sentinel satellites, all a part of the Copernicus program, earlier known as the Global Monitoring for Environment and Security (GMES) program, a collaboration project headed by the European Commission and ESA. The Copernicus aims to use satellites and in situ observations to retrieve information for environment and security usages, and are thereby not only meant for research (Booz & Company, 2011).
CHAPTER 1. INTRODUCTION

1.1 Motivation

In order to use data from the optical satellites like Sentinel-2, we need to know that we can trust the data acquired by the sensors and that the data is consistent through time. With new sensors, new challenges arrives, and therefore the sensors need to be calibrated and validated to overcome the satellite mission requirements (Drusch et al., 2010). Currently the Sentinel-2A has been in space for approximately two years, and has been fully operative since October 2015, while the twin satellite Sentinel-2B has only been in space for 3 months, and is planned to be fully operational in summer 2017. As these satellite sensors are new, the main motivation in this master thesis is to test how accurate the Sentinel-2A satellite is, especially how accurate the geometric performance is, as this is a key issue for the data quality.

Normally the radiometric performance is often tested along the geometric performance, but because the radiometric performance has proven to be significant for land cover classification and ice velocity purposes (Kääb et al., 2016; Paul et al., 2016), and the geometric performance has a greater impact for a normal user of Sentinel-2 (Kääb et al., 2016), it was decided to not focus on testing the radiometric performance.

1.2 Objectives

The main objective of this study is to test the geometric performance of the Sentinel-2A satellite imagery, and how this affect the geolocation for repeating orbits. Further, the satellite sensor is tested in two typically geoscientific applications:

- **Ice velocity:** Glacier velocity is derived from Sentinel-2A imagery at three smaller glacier in Norway and on four outlet glacier of the Greenland Ice Sheet. The result would be compared to previous velocity measurements, using similar or other techniques.

- **Land cover classification:** A case study of land cover classification in southeast Norway. To assess the quality of the Sentinel-2 imagery, it is compared to the Landsat-8 satellite, and a classification done by the Norwegian Institute of Bioeconomy Research (NIBIO) in an agricultural region.

Both case studies are affected by some challenges with the geolocation accuracy of the satellite images and may therefore cause errors in the processed end results.

1.3 Outline

The thesis is structured into eight chapters. Chapter 1 starts with the introduction of the thesis. Chapter 2 introduce the Landsat-8 and Sentinel-2 satellite sensors because at a later stage they will be compared against each other. Chapter 3 goes through the study areas and data for the geometric performance test and the two case studies. Chapter 4 describes the theoretical background needed for this study, starting with geometric performance and radiometric performance.
Further, the background information of the two case studies are described. In Chapter 5 the methods used for measuring the geometric performance are presented. The case study of measuring ice velocity at different glaciers, is basically equal to the method for geometric performance test, but differ in the post-processing. The last part of the methods describes the land cover classification. The results are presented in Chapter 6, and Chapter 7 discusses and compares these results to other literature and measurements. Chapter 8 concludes the work of this thesis and the Appendix A follows after the Bibliography containing optional results and appendage.
Chapter 2

Satellite Sensor Overview

To be able to assess the classification quality of Sentinel-2, it is compared to the Landsat-8 satellite, which has similar sensor bands and both are therefore included in the satellite sensor overview.

2.1 Landsat-8 OLI

2.1.1 Mission Overview

Landsat-8 was launched in February 2013, and joins the same orbit as Landsat-7, increasing the repeat time of the active Landsat satellites (Pour & Hashim, 2015). In the process of launching Landsat-8, the new Landsat observatory was developed through an interagency partnership between NASA (National Aeronautics and Space Administration) and the Department of the Interior U.S. Geological Survey (USGS) (Irons & Loveland, 2013; Roy et al., 2014), the cooperation had characterization and calibration of the instruments and collection of data as their key aspect (Markham et al., 2015). Today it is USGS who archives all the 700 free and open scenes over the Earth per day into the USGS Earth Resource Observation and Science (EROS) Center, South Dakota (Roy et al., 2014; Wulder & Coops, 2014). Landsat-8 has a 16 day repeat cycle, meaning each site would be overpassed 22-23 times per year (Roy et al., 2014). Key mission objectives for the Landsat-8 are:

- Provide data continuity with Landsat 4, 5 and 7 (Zanter, 2016).
- Provide a 16 repeat day coverage, and with Landsat-7 it will provide a 8 day repeat coverage (Zanter, 2016).
- Provide a global archive of sun-lit, substantially cloud-free, land images, which are periodically refreshed (Zanter, 2016).
2.1.2 Sensor Overview

Landsat-8 carries two sensors: Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). However, this thesis will put more interest of the OLI sensor, since it has similar resolutions as the Sentinel-2 Multi-Spectral imaging Instrument (MSI). In Table 2.1 the spectral bandwidths are summarized for Landsat-8 and Sentinel-2. The OLI is comparable similar to the older Landsat 7 Enhanced Thematic Mapper plus (ETM+). The largest difference from ETM+ are two bands: The new band 1 ($\lambda = 443$ nm), where the change is to improve sensitivity to chlorophyll e.g., materials in coastal waters and for retrieving atmospheric aerosol properties and the new band 9 ($\lambda = 1360$ nm), to improve cirrus cloud detection (Roy et al., 2014).

The OLI is a pushbroom sensor with 14 individual overlapping focal planes aligning long arrays of detectors across-track (Roy et al., 2014; Knight & Kvaran, 2014). Compared to the previous Landsat instruments, which used the whiskbroom sensor, the OLI pushbroom sensor provides improved signal-to-noise ratio (SNR) performance (Irons et al., 2012). A challenge of using the pushbroom sensor is achieving spectral and radiometric response consistently across the focal plane with the consequent need to cross-calibrate thousands of detectors per spectral band (Irons et al., 2012). The SNR improvement for OLI compared by Landsat ETM+ is exceeded by a factor of at least eight (Irons et al., 2012; Roy et al., 2014), and because of the improvement it is now possible to create 12-bit scenes, compared to the ETM+ 8-bit, meaning $2^{12} = 4096$ grey levels instead of $2^8 = 256$ grey levels (Roy et al., 2014). For delivery, the final product is scaled to 16-bit (Roy et al., 2016).

Table 2.1: Spectral position ($\lambda$), spectral bandwidth ($\Delta \lambda$) and spatial resolution of the Sentinel-2 bands and the Landsat-8 bands. Table modified from van der Meer et al. (2014), Knight & Kvaran (2014) and Pour & Hashim (2015).

<table>
<thead>
<tr>
<th>Band#</th>
<th>$\lambda$ (nm)</th>
<th>$\Delta \lambda$ (nm)</th>
<th>Res (m)</th>
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<td>11</td>
<td>1610</td>
<td>90</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2190</td>
<td>180</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.1.3 L1T Data Product

Scenes of interest can freely be downloaded from USGS, and contain a radiometrically and geometrically Level 1 Terrain corrected product (L1T) (Loveland & Dwyer, 2012), see Table 2.2. To generate this product, inputs from both OLI and TIR sensors are used in addition to the input from the spacecraft, ground control points (GCPs) and digital elevation models (DEMs) (Zanter,
Table 2.2: Description of the standard L1T Landsat product. Table modified from Loveland & Dwyer (2012).

<table>
<thead>
<tr>
<th>Product type</th>
<th>Systematic or precision terrain correction pending availability of ground control points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel size</td>
<td>15-30 m (OLI) 100 m (TIRS)</td>
</tr>
<tr>
<td>Map projection</td>
<td>Universal transverse Mercator</td>
</tr>
<tr>
<td>Datum</td>
<td>WGS84</td>
</tr>
<tr>
<td>Orientation</td>
<td>North-up</td>
</tr>
<tr>
<td>Resampling method</td>
<td>Cubic convolution</td>
</tr>
<tr>
<td>Output format</td>
<td>GeoTIFF</td>
</tr>
<tr>
<td>Geometric accuracy</td>
<td>~30 m root mean squared error (RMSE) (U.S.), ~50 m RMSE (global)</td>
</tr>
</tbody>
</table>

2016). Additionally to be geometrically rectified, the image is also radiometrically corrected. This will remove relative detector differences and differ artefacts (Zanter, 2016).

2.2 Sentinel-2

2.2.1 Mission Overview

The Sentinel-2A was launched in June 2015 and is the first of two satellites flying in the same orbit, carrying the MSI with 13 spectral bands for the Copernicus programme. The Copernicus programme is a collaboration project with the European Commission and ESA to establish a European ability for the delivery and use of monitoring information for environmental and security applications (ESA, 2012). Key mission objectives for the Sentinel-2 are:

- Provide systematic global asset of high-resolution multi-spectral imagery with its temporal resolution of five days (Drusch et al., 2012).
- Provide improved continuance of the SPOT (Satellite Pour l’Observation de la Terre) satellite programme (ESA, 2012).
- Provide images for the most modern operational product, for instance land-cover maps, change detection maps, and geophysical variables (Drusch et al., 2012).
- Provide «land monitoring, emergency response and security services» (ESA, 2012, p. 3).

The Sentinel-2 satellite will cover land and coastal areas, has a high revisit of five days under the same viewing conditions, offer high spatial resolution, with a wide field of view, using the MSI to cover the visible, near-infrared and short-infrared electromagnetic spectrum range (Gascon et al., 2016).

In order to deliver products with a five day revisit, two identical Sentinel-2 satellites (known as Sentinel-2A and 180° apart Sentinel-2B) are launched both with the same MSI. Each satellite is working on the opposite side of the other satellite in a sun-synchronous orbit at 786 km altitude (Drusch et al., 2012). To keep the five-day revisit time continue when a satellite reaches its end of life, future constellations are planned as the Sentinel-2C and Sentinel-2D (Mas et al., 2016).
Each constellation has 14+3/10 revolutions per day, and passes equator at 10:30 a.m. local time. The time were chosen as a compromise between minimizing cloud cover and ensuring suitable sun illumination, but also have a close overpass time to the other EOS as Landsat and SPOT, making directly comparison for long time series possible (Drusch et al., 2012). Because of the wide swath of 290 km, the satellite has the potential to have a shorter revisit time in the higher latitude where neighbouring orbits overlap each other, as displayed in Figure 2.1.

Figure 2.1: Because of the large swath of 290 km for Sentinel-2A, the temporal resolution increases towards the poles, as illustrated: Upper panel: global pattern. Lower panel: The effectiveness of increasing temporal resolution is highly visible in the increasing latitude. This will be doubled when Sentinel-2B is operational. Figure from Kääb et al. (2016).

2.2.2 Sensor Overview

Sentinel-2 are carrying an optical instrument payload that will sample 13 spectral bands (ESA, 2015). In Table 2.1 the spectral bandwidth signatures are summarized for Landsat-8 and Sentinel-2.

The bands spread over the VNIR (visible and near-infrared) and SWIR (short wave infrared) domains. The channels are as follow:

- 4 bands at 10 m resolution: blue (490 nm), green (560 nm), red (665 nm) and NIR (near-infrared) (842 nm).
- 6 bands at 20 m resolution: four bands for vegetation applications (705 nm, 740 nm, 783 nm and 865 nm) and two larger SWIR bands for snow, ice and cloud detection or vegetation stress
assessment (1610 nm and 2190 nm) (Gascon et al., 2016).

- 3 bands at 60 m resolution: designed for atmospheric corrections and cloud detection. Where the potential for 443 nm is aerosols, 940 nm is water vapour and 1375 nm is cirrus detection (Gascon et al., 2016).

Figure 2.2: Comparison of band wavelength (nm) and spatial resolution (m) of Sentinel-2 MSI, Landsat-8 OLI and SPOT6/7 satellite. Figure from Drusch et al. (2012).

The spectral band selections of Sentinel-2 are similar to the Landsat and SPOT wavelengths, but the Sentinel-2 bands are narrower compared to the Landsat-8 (ESA, 2015) as seen in Table 2.1 and in Figure 2.2. The NIR band 8A of Sentinel-2 is for instance narrower than the Landsat-8, this is because the Landsat NIR band was found to be very much contaminated by water vapour, which will lead to less sensitivity to e.g., soil iron oxide content (ESA, 2015). Because of the narrowness of the 8A band, it will avoid contamination from water vapour, but it is still able to represent the vegetation and iron oxide content for soil in the NIR plateau (ESA, 2015). As for monitoring vegetation, forestry and agriculture the vegetation/red-edge bands 5 to 8A have proven to be useful e.g., to determine chlorophyll content, leaf-area-index (LAI) and leaf chlorophyll concentration (Frampton et al., 2013).
2.2.3 L1C Data Product

Processing steps of Sentinel-2 raw data Level-0 (L0) to the public product Level-1C (L1C), includes radiometrical and geometrical calibration, and is summarized in Figure 2.3 and further described below:

- **Level-1A**: In order to generate the level-1A (L1A) products, the raw data L0 is gone through a process which is split into two parts: the first step is to gather the telemetry data of the image and create a preliminary quick-look and a cloud generation of the quick-look. The second step is delayed until the ancillary data arrives after the satellite passes, and the data is being decompressed, formatted and a coarse co-registration is applied.

- **Level-1B**: Products of L1A are being radiometric processed, converting the instruments counts into physical units (radiance). With the image being radiometric corrected, the geometric viewing model is refined, using GCPs. (In the future corrected using a set of Global Reference Images (GRI), see Section 4.1.2 for more about the planned reference images). The Top-of-Atmosphere (TOA) radiance is in sensor geometry, same as L1A products.

- **Level-1C**: The final product to the end user, is generated from the L1B where the resampling function is applying a geometric transformation (generation of orthophoto) and a radiometric interpolation (radiance values is resampled using a B-spline function). The conversion from radiances to reflectance (in TOA) values is applied. The last step before the L1C is given to the public, are the computation of the cloud mask. Table 2.3 summarizes key information about the final product public distributed by ESA.

![Figure 2.3: Processing steps for generate the user product Level-1C for Sentinel-2, all steps is completely handled by the ground segment. Figure from Gascon et al. (2016).](image-url)
Table 2.3: Description of the standard Level-1C Sentinel-2 product. Parameters from ESA (2015).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product type</td>
<td>Pre-defined grid of $100 \times 100$ km$^2$, based on UTM/WGS84</td>
</tr>
<tr>
<td>Pixel size</td>
<td>10 m, 20 m and 60 m</td>
</tr>
<tr>
<td>Map projection</td>
<td>Universal transverse Mercator</td>
</tr>
<tr>
<td>Datum</td>
<td>WGS84</td>
</tr>
<tr>
<td>Orientation</td>
<td>North-up</td>
</tr>
<tr>
<td>Resampling method</td>
<td>B-splines</td>
</tr>
<tr>
<td>Output format</td>
<td>JPEG2000</td>
</tr>
</tbody>
</table>

2.2.4 Higher Order Products

Given the public L1C product from the ground segment the user has the opportunity to further process the product, as listed below, a set of up to date products has been developed and new products are being developed (Drusch et al., 2012):

- Level-2A: Level-2A (L2A) is the Bottom-of-Atmosphere (BOA) reflectance product generated using a scene classification and apply atmospheric corrections to the L1C, an example is given in Figure 2.4, notice the cirrus correction.

- Level-2B: With the biophysical processor Level-2B (L2B), with the use of a L2A BOA product it is possible to generate single products of e.g., LAI, canopy chlorophyll content and canopy water content.

- Level-3: Level-3 (L3) is Spatio-Temporal Synthesis product generated from multiple L2A BOA image over same scene. Given multiple scenes with different cloud cover, a final image with least cloud cover is generated.
Figure 2.4: A simulated Level-1C TOA image (left) and user generated Level-2A BOA image (right), and shows the difference by applying atmospheric correction to a L1C product. Figure from ESA (2015).
Chapter 3

Study areas and data

The study consists of three different sets of locations and data. One was meant to test the geometric performance in different locations with different topography. The second was carried out for land cover classification, in a typically agricultural landscape. The last one was to measure the ice velocity at glaciers in Norway and the Greenland Ice Sheet.

3.1 Geometric Performance

3.1.1 Russian Siberia and Norway

To fully test the geometric performance of Sentinel-2A, displacement measurements at different locations with varying topography are important. In this thesis, three landscapes are used:

(i) Flat tundra landscape, close to the Lena River, Russia, further refereed to flat tundra in this thesis.

(ii) Mountain landscape of southwestern Norway, further refereed to hilly and mountainous in this thesis.

(iii) Combination between the flat and mountainous landscape between the Lena River and the Verkhoyansk Range, Russia, further refereed to flat and hilly in this thesis.

See Figure 3.1 for the locations of the different study areas.

The satellite images available for testing the geometric performance were varying. Different appearance of cloud cover, snow cover and different illumination, affected the potential selection of scenes to perform image matching with, in order to have enough stable points to get a significant result. Table 3.1 lists all scenes used for the geometric performance test over Norway and the Russian Siberia. To verify the horizontal displacement between different relative orbits, the Sentinel-2 DEM which are used for ortho generation by the ground segment is compared by the best national DEM covering the mountain and hilly topography in Norway. The DEM used
Figure 3.1: Study sites for the geometric performance test. a) to c) displays a RGB image of the Sentinel-2 working tile for each site (100 x 100 km), whereas d) displays the layer extent of each location of a-c on a world map: a) Tile 51WWR: Flat landscape located east to the Lena River in the Russia Siberia. Date of image: 21.06.2016. b) Tile 51WXS: Flat and mountain terrain in the foot of the Verkhoyansk Range. Date of image: 16.09.2016. c) Tile 32VMQ: Mountain terrain of the western Norway. Date of image: 11.10.2016. d) World map with layer extent of a-c. (i) Denotes the location of land cover classification, located between eastern Norway and western Sweden as displayed in Figure 3.3. Background map: ESRI.
by Sentinel-2 is the PlanetDEM90 (Kääb et al., 2016; Gascon et al., 2016), which is owned by PlanetObserver, and is an improved version of the Shuttle Radar Topography Mission (SRTM) and uses other multisource data outside the SRTM coverage to give a complete DEM of the entire world (PlanetObserver, 2014). Multisource data used outside the SRTM coverage (60° north) are for this thesis Russian maps with scale of 1:100,000 and 1:200,000 (PlanetObserver, 2014; Kääb et al., 2016).

The data is not given public, but a few free test samples were earlier provided by the CloudEO AG (data downloaded from: http://store.cloudeo-ag.com/planetdem-90, at 05.01.2017, but is now re-linked to the CloudEOs store). Of one of the free test samples earlier available, one covers western Norway and it covers about 80% of tile 32VMQ.

To compare the quality of the PlanetDEM90, the best national DEM provided by the Norwegian Mapping Authority Kartverket is used as «reference». The two DEMs are displayed in Figure 3.2. Notice the PlanetDEM90 is a surface model (DSM) which represents the terrain surface, it simply means that the elevation lays on top of buildings and vegetation canopy, while the DEM from Kartverket represents a terrain model (DTM), representing the ground surface (Gjertsen et al., 2014). The difference models should be taken into consideration.

Figure 3.2: Top: DEM covering the 32VMQ tile, see b) in Figure 3.1 for image. DEM to the left is provided by Kartverket, and DEM to right is a test sample of PlanetDEM90, provided by CloudEO AG. Bottom: Zoomed in at a high mountain relief at Hauduken in the Møre and Romsdal county, as indicated in the red extent in the images above. Coordinate grid: WGS 1984 - UTM zone 32N.
Table 3.1: List of all Sentinel-2 images used for the geometric performance test. Choice of reference images is symbolized as * and the baseline denotes the time (days) from reference image for each test site.

<table>
<thead>
<tr>
<th>Tile</th>
<th>Date</th>
<th>Relative orbit</th>
<th>Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat tundra</td>
<td>08.06.2016</td>
<td>R018</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>14.06.2016</td>
<td>R104</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>21.06.2016</td>
<td>R061</td>
<td>7</td>
</tr>
<tr>
<td>Tile 51WWR</td>
<td>28.06.2016</td>
<td>R018</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>02.09.2016</td>
<td>R104</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>16.09.2016</td>
<td>R018</td>
<td>80</td>
</tr>
<tr>
<td>Flat and hilly</td>
<td>18.07.2016</td>
<td>R018</td>
<td>60</td>
</tr>
<tr>
<td>Tile 51WXS</td>
<td>20.08.2016</td>
<td>R061</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>02.09.2016</td>
<td>R104</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>03.09.2016</td>
<td>R118</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>16.09.2016</td>
<td>R018</td>
<td>*</td>
</tr>
<tr>
<td>Mountainous</td>
<td>04.10.2016</td>
<td>R137</td>
<td>*</td>
</tr>
<tr>
<td>Tile 32VMQ</td>
<td>08.10.2016</td>
<td>R051</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>11.10.2016</td>
<td>R094</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>14.10.2016</td>
<td>R137</td>
<td>10</td>
</tr>
</tbody>
</table>

3.2 Land Cover Classification

3.2.1 Southeastern Norway and western Sweden

The study area is located in the southeastern part of Norway and western part of Sweden as shown in Figure 3.3. The area covers a Sentinel-2 tile size (100 × 100 km) and the region covers several land cover classes, with evergreen forest, open field, mire, water and agriculture as the dominant classes.

3.2.2 Data

Both Landsat-8 and Sentinel-2 satellite images were used in the study, and data used are listed in Table 3.2. In order to do a classification, similar spatial resolution is necessary on all bands for each scene. For all bands on Landsat-8 not similar 30 m resolution were resampled to 30 m, for Sentinel-2 all bands not similar 10 m were resampled to 10 m. For a most fair comparison between the two sensors, in addition to use all bands on Sentinel-2, using bands «similar» to Landsat-8 was also classified, meaning removing band 5, 6, 7, 8 and 9 for the Sentinel-2 satellite.

As users of Sentinel-2 have the opportunity to produce the BOA as the L2A product from a L1C (TOA), this was also processed. Bands 1, 9 and 10 are not included in the L2A product and therefore not used in the classification, and as the other Sentinel-2 product, all bands not similar to 10 m were resampled to a 10 m resolution.

For comparison of the classification results, a land cover classification by NIBIO is used, known as AR5, which represent different classified land resources (Ahlstrom et al., 2014).
Figure 3.3: Study area for the land cover classification, displaying RGB composite of a Sentinel-2 tile size scene (100 × 100 km) acquired on 05.10.2016. Location of area are displayed as (i) in Figure 3.1. Red extent represent the area of interest (AOI), and letters represents landmarks of: Gardermoen Oslo airport, Lillestrøm and Kongsvinger. Coordinate grid: WGS 1984 - UTM zone 32N, with north up.

Table 3.2: Solar elevation and Azimuth in degrees [deg], acquisition scene centre time and cloud cover percent for each scene used for the land cover classification. Angles, time and cloud cover from their respective meta-data files. * Cloud percentage for Landsat-8 is for the entire scene and not for the study area (which is a Sentinel-2 tile), for Sentinel-2, the cloud percentage seems rather underestimated.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Sentinel-2</th>
<th>Landsat-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tile/Path/Row</td>
<td>32VMP</td>
<td>197/18</td>
</tr>
<tr>
<td>Date</td>
<td>16.08.2016</td>
<td>05.10.2016</td>
</tr>
<tr>
<td>Solar elevation</td>
<td>43.2</td>
<td>25.0</td>
</tr>
<tr>
<td>Sun Azimuth</td>
<td>169.0</td>
<td>175.3</td>
</tr>
<tr>
<td>Cloud cover*</td>
<td>0.14%</td>
<td>0.41%</td>
</tr>
</tbody>
</table>
CHAPTER 3. STUDY AREAS AND DATA

3.3 Glacier Velocity

The glacier velocity mapping using the Sentinel-2A satellite was done at three glaciers in Norway: Engabreen, Nigardsbreen and Rembesdalskåka (Figure 3.4) and on four outlet glaciers located on the western coast of the Greenland Ice Sheet: Sermeq Avannarleq, Sermeq Kujalleq, Kangilernata Sermia and Eqip Sermia, all north of Jacobshavn Glacier (Figure 3.5).

3.3.1 Norway

The Norwegian glaciers are situated on the mountains of the Caledonian orogeny, which extends from the northern parts of Britain through Scandinavia (Rangwala et al., 2015). The western maritime glacier is highly controlled by the North Atlantic Oscillation (NAO) index, which is based on the normalised pressure difference between Iceland and the Azores (Nesje et al., 2000; Rangwala et al., 2015). When the pressure is high near the Azores, and low close to Iceland, westerly warms winds flows over Norwegian mountains, the index is then positive, while the pressure difference between the Azores and Iceland is lower, the index is negative and westerly warms winds are then situated over south-Europe (Nesje et al., 2000; Rangwala et al., 2015). While the different indexes influence the entire Norway, because of different elevations the glaciers are located at, the NAO index influence differs. Positive NAO will indicate for the Norwegian glaciers located at the coast (maritime) warm and wet winters, which often results in high winter precipitations at glaciers that are above a critical elevation, but increase in wet precipitations if below the critical elevation line (Nesje et al., 2000; Andreassen et al., 2012; Rangwala et al., 2015). The negative index will in turn represent less precipitation, as the winters is colder and drier (Andreassen et al., 2012).

Norway is covered by over 3143 glacier units (Andreassen et al., 2012), and in this study the three glacier units are mainly chosen because they have reasonably high movement, and they have recently been measured by different correlation tools and by GNSS (Global Navigation Satellite System) stake measurements. These glaciers are also chosen because they are of special interest for the Copernicus Glacier Service, because they wanted to know how well ice velocity measurements is working with the use of Sentinel-2. In Figure 3.4 the three glacier units: Engabreen, Nigardsbreen and Rembesdalskåka is displayed with their drainage basin and their location in Norway.

The three glaciers are a part of a yearly glacial investigation program of total 13 glaciers and one icepatch by the Norwegian Water Resources and Energy Directorate (NVE). NVE yearly investigates the mass balance of the reference glaciers, and other glaciology parameters as glacier length, velocity, jøkulhaup and a subglacial laboratory could be monitored at different glaciers (Kjøllmoen et al., 2016).

3.3.1.1 Engabreen

Engabreen (66°40'N, 13°45'E) is an outlet glacier of Vestre Svartisen inventory, situated in northern Norway (Figure 3.4). Engabreen covers an area of approximately 37 km² and ranges from 89 to 1575 m a.s.l. (2008) (Kjøllmoen et al., 2016) with a mean slope of 7° (Andreassen et al.,
Figure 3.4: Study sites for glacier velocity measurements in Norway. Red extent is the glacier basin of: Engabreen, Nigardsbreen and Rembesdalskåka, as mapped in 2008, 2013 and 2010 respectively.

The glacier is unique with its Subglacial Laboratory facility, accessible via a tunnel 550 m a.s.l. under Engabreen where pressure sensor records have been monitoring subglacial parameters since 1992 (Jackson, 2000; Kjøllmoen et al., 2016). The laboratory takes advantage of the subglacial intakes beneath the glacier as a part of a large hydropower development (Kjøllmoen et al., 2016), as it gives direct access to the bed of the glacier. In the laboratory, scientists are capable to measure subglacial parameters and perform other experiments (e.g., Jackson (2000); Lappegard & Kohler (2005); Telling et al. (2015)).

3.3.1.2 Nigardsbreen

Nigardsbreen (61°42’N, 7°08’E) is an outlet glacier of Jostedalsbreen, the largest ice cap in Norway, situated in the western part of southern Norway (Figure 3.4). Nigardsbreen covers
CHAPTER 3. STUDY AREAS AND DATA

an area of approximately 46.6 km$^2$ (2013) (Kjøllmoen et al., 2016) which is almost 10% of the total size of Jostedalsbreen (474 km$^2$, 2012) (Andreassen et al., 2012; Kjøllmoen et al., 2016) and ranges from 330 to 1952 m a.s.l. (2013) (Kjøllmoen et al., 2016) with a mean slope of $8^\circ$ (Andreassen et al., 2016).

The glacier holds long records of investigation, as the first year of mass balance investigations was in 1962. The first frontal length was measured as early as 1899 (Andreassen et al., 2012) but also historical data dating back to 1748 (Østrem et al., 1976), and reports of advance that destroyed farm buildings in the 1743 are found (Eide, 1955).

In addition to long records of mass balance and glacier length measurements (Nussbaumer et al., 2011), glacier velocity records were earlier investigated as early as 1937 and 1938 by a German expedition (Pillewizer, 1950), using terrestrial photogrammetric methods (Wangensteen et al., 2006).

3.3.1.3 Rembesdalskåka

Rembesdalskåka (60°32'N, 7°22'E) is an outlet glacier of Hardangerjøkulen ice cap, situated at the northwestern border of the Hardangervidda plateau (Figure 3.4). Rembesdalskåka covers an area of approximately 17 km$^2$ and ranges from 1066 to 1854 m a.s.l. (2010) with a mean slope of $7^\circ$ (Andreassen et al., 2016).

Rembesdalskåka drains towards the populated valley Simadalen and Hardangerfjorden, and has been flooded by jøkulhaups from the glacier-dammed lake Demmevatnet several times (Kjøllmoen et al., 2016). The most recent event was in 25. August 2014, 76 years after the previous event (Kjøllmoen et al., 2016). Calculations by the hydropower company Statkraft estimated the lowering of Demmevatn to be about 2 million m$^3$ in only three hours (Jackson & Ragulina, 2014).

3.3.2 Greenland

The Greenland Ice Sheet is the largest mass of glacier ice in the northern hemisphere, which stretches out 2500 km from north to south, and up to 1000 km from east to west (Figure 3.5) (Benn & Evans, 2010). The ice sheet covers an area of 1,736,000 km$^2$ (Benn & Evans, 2010) and a volume of 2,960,000 km$^3$ (Bamber et al., 2013), containing about ten per cent of Earth’s total fresh water (Benn & Evans, 2010), and has the potential of raising the mean sea level by 7.36 m (Bamber et al., 2013).

The outlet glaciers of Greenland terminate either on land or in lakes, but also in tidewater, which often link to the largest and fastest flowing glaciers (Benn & Evans, 2010). In contrast to the glaciers in the mainland of Norway, outlet glaciers at Greenland have the potential to calving at the termini of tidewater, and the calving stands for over half of the total losses of ice from the ice sheet (Rignot & Kanagaratnam, 2006; Joughin et al., 2008; Benn & Evans, 2010). For a long time it was thought that the time scale for ice sheet dynamic response to climate are typically considered to be hundreds to thousands of years given the thick cold ice was impenetrable barrier to surface-to-bed drainage (Alley & Whillans, 1984; Zwally et al., 2002;
Benn & Evans, 2010), until a paper by Zwally et al. (2002) presented results of ice flowing seasonally. The ice acceleration during the surface melting, followed by deceleration after the melting ceases, indicate that glacial sliding was enhanced by rapid migration of surface meltwater to the ice-bedrock interface (Zwally et al., 2002). The surface melt water flows into moulins and crevasses and quickly flows to the bottom and drains subglacially (Zwally et al., 2002). Instead of the slow and persistent moving ice, rapid, large-scale, dynamic response of ice sheets could be coupled to surface melting and ice-sheet flow as a response of climate warming (Zwally et al., 2002).

The study of ice velocity on the Greenland Ice Sheet is of maritime terminating outlet glaciers in the west coast. Recent studies suggest that the area change of glaciers in the south west and central western part (Figure 3.5) of the ice sheet is correlated with the local sea surface temperature and the NAO index, based on measurements from 1999-2013 by T. S. Jensen et al. (2016). The four outlet glaciers terminate in the sea, in Figure 3.5 from top: Sermeq Avannarleq, Sermeq Kujalleq, Kangilernata Sermia and Eqip Sermia. The Sermeq Avannarleq glacier net area change was for the period 1999-2013 measured to be -8.8 km$^2$ by T. S. Jensen et al. (2016).

Figure 3.5: Study sites of glacier velocity in Greenland. Red square extent is the glacier complex north of the Jakobshavns glacier. Numbers indicate the different calving glaciers: (1) Sermeq Avannarleq, (2) Sermeq Kujalleq, (3) Kangilernata Sermia and (4) Eqip Sermia. Background polygon of Greenland is produced by E. Rignot and J. Mouginot and used by IMBIE 2016.
3.3.3 Data

The study data is displayed in Table 3.3 for all of the ice velocity measurements. For each site the same relative orbit is used between the first and second image, this is because ortho-rectification errors due to DEM errors are too large in regions with much topography and much elevation change between the acquisition and the PlanetDEM90 source date (Kääb et al., 2016) (see Section 4.1.1). As the same relative orbit must be used, the amount of good scenes drops dramatically. The study sites might have different surface conditions on each acquisition due to cloud cover, snowfall or shadowing of high mountains due to change in the solar angle.

Table 3.3: Sentinel-2A satellite images used for each ice velocity test. The same relative orbit is used for each location. Each scene are more or less cloudless for each glacier complex.

<table>
<thead>
<tr>
<th>Location</th>
<th>Tile</th>
<th>Date time 1</th>
<th>Date time 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engabreen</td>
<td>33WVQ</td>
<td>23.07.2016</td>
<td>22.08.2016</td>
</tr>
<tr>
<td>Rembesdalskåka</td>
<td>32VMN</td>
<td>18.09.2016</td>
<td>08.10.2016</td>
</tr>
<tr>
<td>West coast of Greenland</td>
<td>22WEC</td>
<td>14.07.2016</td>
<td>03.08.2016</td>
</tr>
</tbody>
</table>

3.3.4 Reference Data

From the Norwegian glaciers used for glacier velocity, different reference data and methods were used to validate the ice velocity measurements at each test location, as listed in Table 3.4.

Table 3.4: Earlier studies performed at glaciers which is used to validate measured velocity using Sentinel-2A satellite. Table abbreviations: NCC = normalized cross-correlation and SAR = synthetic aperture radar.

<table>
<thead>
<tr>
<th>Glacier</th>
<th>Study</th>
<th>Dataset</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engabreen</td>
<td>Jackson et al. (2005)</td>
<td>Aerial photographs</td>
<td>NCC</td>
</tr>
<tr>
<td></td>
<td>Messerli &amp; Grinsted (2015)</td>
<td>Time lapse camera</td>
<td>NCC</td>
</tr>
<tr>
<td></td>
<td>Messerli (2015)</td>
<td>Landsat-8</td>
<td>NCC</td>
</tr>
<tr>
<td></td>
<td>Kjøllmoen et al. (2016)</td>
<td>GPS</td>
<td>Repeated surveys</td>
</tr>
<tr>
<td>Nigardsbreen</td>
<td>Wangensteen et al. (2006)</td>
<td>Aerial photographs</td>
<td>NCC</td>
</tr>
<tr>
<td>Rembesdalskåka</td>
<td>Kjøllmoen et al. (2016)</td>
<td>GPS</td>
<td>Repeated surveys</td>
</tr>
<tr>
<td>Greenland</td>
<td>Nagler et al. (2015)</td>
<td>Sentinel-1 (SAR)</td>
<td>Feature tracking</td>
</tr>
</tbody>
</table>

Since 2015, annual measurements of ice velocity have been measured by the Greenland Ice Sheet CCI (Climate Change Initiative) Project (Nagler et al., 2015), and are used as reference of the velocity study of the Greenland Ice Sheet. The Greenland ice velocity map 2016/2017 from Sentinel-1 [version 1.0] is delivered in the NetCDF file format and the horizontal velocity is calculated (see section 5.2.2) by using the easting (vx) and northing (vy) velocity in true meters per day, provided at 500 m grid.
Chapter 4

Theoretical Background

This theory chapter consists of the overview needed for the methodology and further in this thesis.

4.1 Geometric Performance

By the Sentinel-2 mission team, different mission requirements are set in order to provide the Copernicus mission objectives. One key issue is the Geo-location Requirement (Drusch et al., 2010). A geo-location error is a mislocation of the observed data samples geographic location relative to where it correctly should be located (Purdy et al., 2006). In addition, images acquired at different time, but covering same location, shall also have a precise geo-location, relative to each other, known as temporal co-registration. In order to reduce or avoid human intervention in the geo-location process, the Copernicus team stress the issue of having an accurate automatic geo-location (Drusch et al., 2010). Sentinel-2 geo-location requirements are listed in Table 4.1, and Sentinel-2’s team for calibration and validation states the geometric accuracy is far above of what is required for the satellite in order to the mission requirements being met (Gascon et al., 2016). However, there are some challenges of the geometric performance (Kääb et al., 2016).

Table 4.1: Geo-location error requirements for Sentinel-2 (Drusch et al., 2010) and achieved results by the calibration and validation team (Clerc & MPC-Team, 2017; Gascon et al., 2016).

<table>
<thead>
<tr>
<th>Requirement class</th>
<th>Required</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geo-location accuracy</td>
<td>The geo-location accuracy of Level 1C data (i.e. the ortho-rectified image) shall be better than or equal than $\pm 1$ pixel RMS of the sensor spatial resolution without using GCPs.</td>
<td>0.5 pixel</td>
</tr>
<tr>
<td>Multi-temporal co-registration</td>
<td>The co-registration between two images acquired at different times shall be accurate to $\pm 2$ pixels, with repeat orbit.</td>
<td>1.12 pixel</td>
</tr>
</tbody>
</table>

The performance of the satellite could be separated into three error budget terms as listed by
Kääb et al. (2016, p. 6): (i) overall scene offsets, (ii) higher-order offsets pattern and (iii) ortho-rectification offsets due to DEM errors:

(i) Multi-temporal co-registration accuracy, due to errors based on random noise, but also systematic patterns such as attitude jitter and calibration errors (Kääb et al., 2016).

(ii) Shifts and rotation/deformation applied to the entire scene and are system-specific geolocation biases in the image data with respect to the true ground location of the measurements. The biases arise from errors or inaccuracies in spacecraft attitude (e.g., on-board star tracker) or position measurements (e.g., on-board GPS receiver) or in the subsequent solution of the image orientation parameters (Kääb et al., 2016).

(iii) Vertical errors in a DEM elevation used for ortho-rectification or terrain correction of the raw data propagate into a pattern of local horizontal off-nadir offsets in the ortho-rectified products. Depending on the off-nadir view angle, in particular in cross-track direction, and the magnitude of the elevation error the effect of vertical elevation errors varies (Kääb et al., 2016). Summarized in Figure 4.1.

Sentinel-2 or Landsat imagery are affected by all above error budget terms, and users have little possibility to improve or remove these errors. This is due to all of their products before L1C (Sentinel-2) or L1T (Landsat-8) is not given to the public. If given to public, the users could e.g., use an improved DEM for ortho-rectification and improve vertical errors (iii) from the original product. The land segment of the Sentinel-2 and Landsat-8 is today responsible to delivering users the best product, and is capable to report errors as for instance on the board star tracker or the on-board GPS receiver and improve this. Errors due to overall scene offsets (i) and higher-order offsets pattern (ii) could be improved by improving reference scenes for co-registration (see Section 4.1.2).

4.1.1 Ortho-rectification Errors Due to DEM Errors

Illustrated in Figure 4.1 vertical errors in a DEM would translate into horizontal errors in the orthorectified satellite scene. The significance of the error depends on (i) off-nadir view angle, in particular in cross-track direction, and (ii) DEM elevation errors, to the true terrain. Using the flight height and the swath width from the two satellites Sentinel-2 and Landsat-8, the maximum ortho-rectification offset distance \( d_{max} \) could be calculated for the DEM error \( \Delta h \) and the flight height divided by the maximum off-nadir distance (which is the half of the swath width) (Kääb et al., 2016). The maximum off-nadir offset for Sentinel-2 which has a flight height of 786 km and a swath width off 290 km would then translate into Formula 4.1

\[
 d_{max(S2)} \approx \Delta h / 5.4
\]

(4.1)

For Landsat-8 with flight height of 705 km and a swath width off 185 km it would translate into Formula 4.2

\[
 d_{max(L8)} \approx \Delta h / 7.6
\]

(4.2)

The ortho-rectification errors would double if the target in scene are seen from different sides of relative orbits, as illustrated in Figure 4.1. As illustrated in Figure 4.1 when we compare
Figure 4.1: The figure shows how effective vertical errors $\Delta h$ in a DEM used in the ortho-rectification of the satellite scene translate into horizontal offsets from the true point $P$. The geolocation offsets $d$ are present in a scene, due to vertical DEM errors, and depending on the magnitude of the DEM error and distance from nadir, viewing from orbit $i$, $j$ or $k$, to the point $P$, the horizontal displacements $P_i-P$, $P_j-P$, or $P_k-P$, become present. The displacement doubles when comparing orthoimages from two different orbits, as either from same satellite altitude $P_i-P_j$ or two different $P_i-P_k$, as symbolised as Sentinel-2 and Landsat-8. Figure from Kääb et al. (2016).

Two orthoimages, the two orbits $i$ and $j$, would translate into the projection offset of $P_i$ and $P_j$ of target point $P$, and the intersection of the two neighbour swaths is the point of the relative maximum offset $\Delta d$ of two satellite scenes (Kääb et al., 2016). Using scenes for two relative different orbits would for Sentinel-2 give us:

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

(4.3)

and for Landsat-8:

$$d_{\text{max}(L8)} \approx \Delta h/3.8$$

(4.4)

Formula 4.1-4.4, simply shows how the ortho-rectification errors increase using different relative orbits. The need for using two different orbits is relevant when the follow-up scene is under cloud cover, or the ground change too much during one orbit revolution.

The DEM error $\Delta h$ are typically controlled by two types of errors: (i) production and measurements errors between the true terrain elevation and used DEM, this refers also to low resolution of the DEM used, or (ii) changes in the terrain itself, between the acquisition of making the DEM and the satellite scene acquisition (Kääb et al., 2016). Examples of (ii) could be for instance changes in glacier height, or landslide. (i) and (ii) may be in the same order.
4.1.2 Co-registration Errors Due to Calibration Errors

In the chain of processing the final product of a satellite product, the geometric refining is coming after the radiometric correction. The algorithm aims at improving the multi-temporal co-registration, but also the geo-location accuracy as in, overall scene offsets (i) and higher-order offsets pattern (ii) (Gascon et al., 2016). Currently, the Mission Performance Centre (MPC) which aims to update and validate on-board and on-ground configuration parameters, is working on Global Reference Images (GRI), which should be assessed for improving the geometric refining on the production of L1B and L1C products for the Sentinel-2 (Gascon et al., 2016). The under development GRI is a set of cloud-free images over a given area for each relative orbit, and based on tie-points and GCPs between the reference and the working scene a bundle block adjustment is used between the two scenes (Baillarin et al., 2012; Gascon et al., 2016). As a second stage of developing/improving the GRI database, simply adding new images of cloud free images, of areas which were cloudy before would improve the database. The GRI is scheduled for completion by the last quarter of 2017, and in 2018 Landsat-8 is planned to be realigned for consistency with the Sentinel-2 GRI, which will improve misalignments between the two satellites products (Storey et al., 2016).

4.2 Radiometric Performance

Satellite systems like the Sentinel-2 and Landsat-8 are required to have strict radiometric performance in order to delivery of the best possible product. The Sentinel-2 images will obtain a physical value (radiance or reflectance) from the numerical output provided by the sensor instrument, and therefore good knowledge of the instrument sensitivity is required (Drusch et al., 2012).

The stringent requirements which are set for the radiometry, require good calibration knowledge and therefore this radiometric requirement is set, as Drusch et al. (2012, p. 31) writes:

«Any error on the absolute calibration measurement directly affects the accuracy of this physical value. For the absolute calibration knowledge uncertainty a threshold value of 5% is required with a goal of 3%. In the same way, the cross-band and multi-temporal calibration knowledge accuracies were set to 3% and 1%, respectively.»

The requirements for signal-to-noise ratio and measured radiance levels for each spectral band are presented in Table 4.2 and Table 4.3 sum up the radiometric requirements for Sentinel-2.

The radiometric requirements were tested by the calibration and validation team: Clerc & MPC-Team (2017); Gascon et al. (2016) and all radiometric requirements set for the Sentinel-2 satellite (Table 4.3) was passed, see Table 4.2 for measured Lref. However, Gascon et al. (2016) reports improved work on pixel response stability (i.e. fixed-pattern noise (FPN)) should be scheduled in near future. Pixel response stability affect the pixel reflectance over homogeneous surfaces for a band and may degrade the accuracy of classification results and offset tracking (Kääb et al., 2016). In case of a degraded performance is observed a dedicated calibration activity and possible investigations can be triggered, this could be processes such as changing the linearity model, changes in the dark signal calibration and relative gains calibration (Gascon et al., 2016).
Table 4.2: Reference radiance \([\text{W/m}^2/\text{sr/}\mu\text{m}]\) (\(L_{\text{ref}}\)), SNR at required \(L_{\text{ref}}\) and SNR at measured \(L_{\text{ref}}\). Values from Clerc & MPC-Team (2017).

<table>
<thead>
<tr>
<th>Band #</th>
<th>(L_{\text{ref}})</th>
<th>SNR at required (L_{\text{ref}})</th>
<th>SNR at measured (L_{\text{ref}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>129</td>
<td>129</td>
<td>1372</td>
</tr>
<tr>
<td>B2</td>
<td>128</td>
<td>154</td>
<td>214</td>
</tr>
<tr>
<td>B3</td>
<td>128</td>
<td>168</td>
<td>249</td>
</tr>
<tr>
<td>B4</td>
<td>108</td>
<td>142</td>
<td>230</td>
</tr>
<tr>
<td>B5</td>
<td>74.5</td>
<td>117</td>
<td>253</td>
</tr>
<tr>
<td>B6</td>
<td>68</td>
<td>89</td>
<td>220</td>
</tr>
<tr>
<td>B7</td>
<td>67</td>
<td>105</td>
<td>227</td>
</tr>
<tr>
<td>B8</td>
<td>103</td>
<td>174</td>
<td>221</td>
</tr>
<tr>
<td>B8A</td>
<td>52.5</td>
<td>72</td>
<td>161</td>
</tr>
<tr>
<td>B9</td>
<td>9</td>
<td>114</td>
<td>222</td>
</tr>
<tr>
<td>B10</td>
<td>6</td>
<td>50</td>
<td>390</td>
</tr>
<tr>
<td>B11</td>
<td>4</td>
<td>100</td>
<td>159</td>
</tr>
<tr>
<td>B12</td>
<td>1.5</td>
<td>100</td>
<td>217</td>
</tr>
</tbody>
</table>

Table 4.3: Radiometric requirements for Sentinel-2 (Drusch et al., 2010) and achieved results by the calibration and validation team (Clerc & MPC-Team, 2017; Gascon et al., 2016).

<table>
<thead>
<tr>
<th>Requirement class</th>
<th>Required</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute radiometric accuracy</td>
<td>The absolute radiometric accuracy shall be 3% (goal) / 5% (threshold).</td>
<td>5% threshold confirmed</td>
</tr>
<tr>
<td>Inter-band calibration</td>
<td>The inter-band calibration accuracy shall be 3%.</td>
<td>Confirmed</td>
</tr>
<tr>
<td>SNR and radiance levels</td>
<td>Signal-to-noise ratio radiance reference, required radiance and measured radiance for each spectral band are presented in Table 4.2</td>
<td>Confirmed</td>
</tr>
</tbody>
</table>
Example of radiometric noise test over a homogeneous surface was conducted by Kääb et al. (2016) and along-stripes of one pixel in width were found (Figure 4.2). However, the results by Kääb et al. (2016) were tested on the first Sentinel-2A images available from the commissioning phase of the satellite, and new calibration algorithms might have further improved the radiometric performance.

Figure 4.2: For band 4, 8 and 11, sections of about 300 × 300 pixels over homogeneous pattern of dark water with enhanced histograms. The upper curve indicate the along-track column means in digital number. Stripes, both along-track (vertical) and cross-track (horizontal) become visible. Figure from Kääb et al. (2016).

4.3 Mapping Surface Displacement

4.3.1 Background

Surface displacement includes processes of material such as rock, sediments, snow and ice that move under the influence of gravity or freezing and thawing processes (i.e. periglacial slope processes) (Press, 2003; Haeberli et al., 2006). The material could move by difference land-processes, as the material can e.g., fall, topple, slide, spread, flow or creep (Varnes, 1978; Haeberli et al., 2006; Hungr et al., 2013). In order to measure the displacement using remote sensing tools, the flow and creep processes, are the most suitable to measure as they occur over a period of time, and not as a sudden event (Karstensen, 2009) or changing the terrain entirely.

Using remote sensing to measure surface displacement is perhaps the best tool to use, as no physical contact is needed (in contrast to usage of e.g., GPS). A huge amount of open access satellite data exist (e.g., satellite archives of Landsat, MODIS, ASTER and Sentinel-1/2/3), making surface displacement comparable in time and possible to measure slow movements as e.g., rock glaciers over long time. Choosing optical remote sensing, the user has various types of instruments to choose from, ranging from small time laps cameras (e.g., Messerli & Grinsted (2015)) to sensors with large swath dimensions as the MODIS or Sentinel-3 (e.g., Haug et al. (2010)) which is capable to cover large areas in one overpass, making surface displacement measurements on large areas as ice sheets feasible. Of methods to use for measuring surface displacement, several exist, as listed by Kääb (2005, p. 63):

(i) Qualitative analysis of movements
(ii) Digital image matching of repeat optical data  
(iii) Digital image matching of repeat SAR data  
(iv) Differential SAR interferometry (DInSAR)  
(v) Repeat terrestrial and satellite geodesy  
(vi) Analogue and analytical photogrammetric methods  
(vii) DTM matching  
(viii) Terrestrial SAR  
(ix) Mechanical methods

The main technique used to measure the co-registration error and ice velocity in this thesis are the image matching technique of optical data (ii), but because displacement measuring methods (iii), (iv) and (v) is used in the validation of the ice velocity measurements, they are shortly described in Section 4.3.6, after the image matching technique, described below.

4.3.2 Image Matching

Both of the geometric performance test and the glacier velocity tests, included in this thesis, are based on an image matching technique of finding corresponding features between two images at two different times to give the corresponding displacement of features between the two images. The image matching technique is used for several different applications, Debella-Gilo & Kääb (2011, p. 130) lists some of them: automatic image (co-)registration between two images (Zitová & Flusser, 2003), stereo parallax matching in order to generate DEM (Toutin, 2001) and displacement measurements e.g., topics in geoscience applications: glacier and rockglacier velocity (Kääb & Vollmer, 2000; Kääb, 2002; Debella-Gilo & Kääb, 2011; Altena & Kääb, 2017), landslides (Kääb, 2002), ice velocity on ice sheets (Haug et al., 2010), river flow (Kääb & Prowse, 2011) and surface kinematic of periglacial sorted circles (Kääb et al., 2014). As several image matching techniques exist, to classify them differently, the technique could be divided into the difference algorithm domain or search strategy.

4.3.2.1 Algorithm Domain

There are large variety of existing image matching algorithms that could be divided into the two image operating domains, the spatial or frequency domain. The spatial domain, is linked to use the (x,y) coordinate space of images (Lillesand et al., 2007), while the frequency domain is using an alternative coordinate space, where the images are «separated into its various spatial frequency components through application of a mathematical operation known as the Fourier transform» (Lillesand et al., 2007, p. 516-517). Example of algorithm used for image matching of the two domains as listed by Heid & Kääb (2012, p. 340) follows:

- Spatial domain: Normalized cross-correlation (Kääb & Vollmer, 2000) and least square matching (Toutin, 2001).
• Frequency domain: Cross-correlation using Fast Fourier transform (FFT) (Haug et al., 2010) and phase correlation using FFT (Leprince et al., 2007).

In this thesis the focus has been on the normalized cross-correlation which is further described in Section 4.3.3.

4.3.2.2 Search Strategy

From the large variety of algorithm of image matching, the search strategy could differ. The automation of the feature registration step can mainly be classified as: area based or feature based (Zitová & Flusser, 2003).

• The area based search strategy uses (often) rectangular search windows with predefined size for the correspondence estimation (Zitová & Flusser, 2003). All mentioned algorithm in section 4.3.2.1 are using this searching strategy.

• The feature based search strategy is to find corresponding features as point, lines or regions between the two images. The strategy depends less on accurate co-registration and handles complex image distortions better (Zitová & Flusser, 2003).

4.3.3 Normalized Cross-correlation

To measure the displacement between two images, the normalized cross-correlation (NCC) is an algorithm which has proven to be robust, and used in several studies of surface displacement (Heid & Kääb, 2012). The NCC matching method is categorized to be simple to use and reliable, and is often used in velocity measurements of glaciers (Lewis, 1995; Heid & Kääb, 2012). Figure 4.3 shows how the NCC function is working in principal with two orthoimages captured at two different times, and expressed by Equation 4.5.

\[
\Phi(i, k) = \frac{\sum_j \sum_l s(i + j, k + l) - \frac{\sum_j \sum_l T_{test}}{N_{test}} \times m(j, l) - \frac{\sum_j \sum_l T_{ref}}{N_{ref}}}{\sqrt{\sum_j \sum_l s^2(i + j, k + l) - \frac{\sum_j \sum_l T_{test}}{N_{test}}} \times \sum_j \sum_l m^2(j, l) - \frac{\sum_j \sum_l T_{ref}}{N_{ref}}}
\]
Where:

- \( \Phi \) = the cross-correlation function
- \((i, k)\) = coordinates inside the test block
- \((j, l)\) = coordinates inside the reference block
- \( s \) = is the spatial grey-value function of the test block
- \( s(i, k) \) = is the corresponding grey value at location \((i, k)\)
- \( m \) = is the spatial grey-value function of the reference block
- \( m(j, l) \) = is the corresponding grey value at location \((j, l)\)
- \( T \) = is the sum of grey values of the test or reference block
- \( N \) = is the number of pixels of the test or reference block \((N_{ref} = N_{test})\)

The NCC function uses an area based search strategy in the spatial domain, of which:

1. Assuming an image over an area of time 1 and another image over the same area of time 2.
2. The first image is taken as the reference image, and a «reference block» is searched for features (equal contrast) within the second image using a «test block».
3. The \( T \) normalized is calculated of the reference block and compared to every normalized \( T \) test block.
4. If the corresponding feature is successfully found (i.e. the highest correlation of all test blocks within one reference block), the difference in the feature central pixel coordinate of the reference block and test block is equal the horizontal displacement (Kääb & Vollmer, 2000).

In Equation 4.5 the \( T \) term normalizes the grey values of the reference and test block, ensuring that the difference in overall grey value does not affect the correlation result as different illumination conditions between the two acquisitions often occur (e.g., shadow of mountains) (Kääb & Vollmer, 2000; Heid & Kääb, 2012). The surface displacement is measured using CIAS (Correlation Image Analysis Software) (Kääb & Vollmer, 2000; Heid & Kääb, 2012; Kääb, 2015) which is a free software for matching offsets between two greyscale images (i.e. single band), written in IDL (Interactive Data Language) program language. Using CIAS and others NCC applications for surface displacement measurements, two conditions must be given: The reference and search block window size, which incorrectly chosen could give none or false result and very long computation time. While choosing the test block size it is important that the size of the block could cover the maximum displacement, so that the test block relative with the reference block can be found in the test block (Kääb & Vollmer, 2000). While choosing a large test block in order to cover the largest displacement, if chosen too large, the computation time is in risk of being very long (Heid & Kääb, 2012).

While the NCC algorithm is popular for surface displacement, several drawbacks are reported, as mentioned in the study of Debella-Gilo & Kääb (2011), e.g.:

- Sensitivity to noise in the image e.g., snow, shadow, clouds.
• Sensitivity to large change in scale, rotation or shearing between the two images being measured.
• The displacement is in principal limited to the minimum of the pixel size, but studies as Debella-Gilo & Kääb (2011) have shown sub-pixel precision using NCC when measuring displacement.
• In order to get meaningful measurements the displacement has to be greater than the co-registration error.

The last point shows the potential to measure how accurate the co-registration is, when measured on ground stable areas.

4.3.4 Displacement of Co-registration

Using image matching applications like CIAS, the co-registration accuracy between the two orthoimages which are being matched needs to be equal or higher than the matching algorithm, in order to trust the displacement result. The co-registration error of orthoimages with DEM effects, as mentioned in Section 4.1.1 is eliminated when matching images with equal relative orbit because the DEM effects is in theory equal in both images of which are being matched (Kääb et al., 2016). The remaining errors are due to higher-order offset patterns and overall scene offset such as jitter, shift, or inaccuracies in the spacecraft attitude (e.g., on-board star tracker) and GPS measurements. When using image matching of two ortoimages of different
relative orbits, the vector sum of two horizontal projections of vertical DEM errors becomes visible as the displacement between orthoimages when matching images with stable ground, in addition to the errors when matching equal repeat orbit orthoimages (Kääb et al., 2016).

The error is expected to be larger over places as mountain areas with steep slopes, or where the terrain has changed, typically places where landslides have occurred or at glacier tongues where the glacier has retreated after the acquisition of the DEM (Kääb et al., 2016). To avoid image matching of orthoimages with DEM effects, images which is ortho-rectified using simultaneous stereo data (e.g., ASTER or SPOT5) for stereo parallax matching for DEM generation could be used (Toutin, 2001; Nuth & Kääb, 2011).

4.3.5 Ice Velocity

The large variety of sensors and data archives of different satellite missions make it possible to map and monitor glacier ice velocity, and ice sheet flow on a global scale (Heid & Kääb, 2012; Paul et al., 2015). Each ice movement measurements provides unique glaciological information, such as «mass flux, flow modes and flow instabilities (e.g., surges), subglacial processes (e.g., erosion), supra- and intra-glacial mass transport, and the development of glacier lakes and associated hazards (Kääb et al., 2005)» (Paul et al., 2015, p.417). Knowledge of ice flow at different places and at different times (spatio-temporal variations) has the potential to improve our knowledge of climate change, either within or between regions (Scherler et al., 2011; Paul et al., 2015). Glaciers and ice sheets are at present shrinking (Vaughan et al., 2013), and in response of this, surface velocity is currently slowing down in many mountain regions (Paul et al., 2015), «a dynamic behaviour that in turn will also influence their response to future climate change» (Paul et al., 2015, p.417).

Calculating ice velocity using image matching follows the same principal as for displacement measurements of co-registration. The temporal baselines of the repeat acquisitions are subjected to two essential constraints: (i) the displacement of the glacier is significance larger than the accuracy of the matching algorithm, and (ii) minimum surface change due to snow fall, deformation and melting between the repeat acquisitions, so that the corresponding intensity or phase period has a higher probability to be correctly found (Paul et al., 2015).

4.3.6 Other Methods to Derive Surface Displacement

Instead of using the image matching technique to derive the ice velocity or ground displacement from optical satellites, radar satellites could be used, by using either satellite radar interferometry (InSAR) or differential InSAR (D-InSAR). This thesis does not use synthetic aperture radar (SAR), and the technique to measure the displacement between repeat radar satellites. However, key points for ice velocity and ground displacement using SAR are as follows:

- Using InSAR technique, ground or glacier surface displacement, can be measured at centi- to millimetres displacement (Raup et al., 2015).
- The topographic effect has to be removed, either from an existing DEM which has the potential of deriving the displacement with two radar overflights, or to create a DEM
from three overflights (combining two interferograms) known as differential InSAR (D-InSAR) (Raup et al., 2015).

- InSAR or D-InSAR requires short baseline in order to achieve high enough phase coherence (Paul et al., 2015).
- Other problems with this technique are related to data availability and layover in regions of high relief (Raup et al., 2015).

Of other methods to mention is simple usage of modern GNSS tools as real time kinematic surveys, trigonometrically surveys of stakes drilled into the ice (Østrem et al., 1976) or older techniques of photogrammetric methods as introduced by Finsterwalder (1931). As early as 1893 Rekstad invented a special method to derive glacier velocity, by combining usage of a fixed staff for levelling and a theodolite, reading ice velocity at 30 minutes possible (Rekstad, 1893; Østrem et al., 1976).

### 4.4 Image Classification

#### 4.4.1 Land Cover Classification

Land cover classification relates to biophysical cover of the Earth’s terrestrial surface, identifying classes as vegetation, water, bare soil, agriculture cover or human infrastructure (Gómez et al., 2016). Earth’s physical and biophysical changes through time are important to monitor for many different reasons e.g., for policymakers, researchers, non-governmental organizations or farmers (Wulder & Coops, 2014). As monitoring change of land cover in small regions is important for a farmer, classifying the land cover on the complete Earth is important to scientist as land cover is recognized as an essential climate variable for climate modelling (Flato et al., 2013) and is an important input to models of ecosystems services (Andrew et al., 2014; Gómez et al., 2016).

Another research area where land cover classification by satellites proves to be a valuable tool, is analysis of phenology in both regional (e.g., MODIS and Sentinel-3 (Karlsen et al., 2014)) and local (e.g., SPOT, Landsat-8 and Sentinel-2) scales, as EOSs in northern Arctic has proven to support field phenological observations, as this is both time-consuming and expensive for this region (Myneni et al., 1997; Xu et al., 2013; Karlsen et al., 2014).

When studying time series of land cover, changes in land cover become visible, and it is possible to understand and monitor land cover trends, e.g., vegetation phenology (Karlsen et al., 2014). Today EO satellites are one of the strongest tool for users who wish to carry out classification on large areas. Because of the huge open data library (e.g., Landsat, MODIS, and in future Sentinel-2/3) times series back in time are possible. EO satellites with medium spatial resolution as Sentinel-2 and Landsat-8 are today capable to derive accurate land cover classes by classification (Topaloğlu et al., 2016), but because of the medium temporal resolution, day to day land cover classification, is more feasible using instruments such as MODIS on the satellite Aqua and Terra or the new ESA satellite Sentinel-3, both with high temporal resolution, but with low spatial resolution. A shift in data availability is seen today as users are getting hands on unmanned aerial vehicles (UAVs). With UAVs, users can make a land cover classification when it is needed.
at most, with very high spatial resolution and because of the low flight height, classification of
land cover under light cirrus clouds is feasible, which can be a challenge with satellite imagery.

4.4.2 Image Classification

The overall objective of image classification procedures is to automatically group all pixels in an
image into land cover classes (Lillesand et al., 2007). It exist different ways to classify an image,
spectral pattern recognition is well known and much used and «historically, spectral approaches
have formed the backbone of multispectral classification activities» (Lillesand et al., 2007, p. 546),
but other methods exist too (e.g., object-oriented classification and decision tree).

Spectral pattern recognition is based on using the multispectral information using the digital
number (DN), each spectral band attempts to classify each individual pixel based on DN (Lille-
sand et al., 2007). The approach of classifying the image is treated in three different ways:

- Supervised classification.
- Unsupervised classification.
- Hybrid unsupervised/supervised classification.

These methods are described below and in this thesis the focus are on hybrid classification.

4.4.3 Supervised Classification

Supervised classification is based on two essential steps, (i) training stage and (ii) classification
stage. In the training stage, the analyst acquires a set of training pixels for each class of interest,
and desirably for all classes in the image (Richards, 2013). The training pixels can emerge from
either the image itself or reference data such as aerial photographs, maps with class information,
or in situ observations. The amount of training data will often be less than 1-5% of the image
pixels (Richards, 2013), and therefore the process requires an accurate training and labelling of
pixels. Next step is the classification stage; each pixel in the image is categorized into land cover
classes it most closely resembles (Lillesand et al., 2007). The output of the classification typically
consists of a thematic map of class labels, often with an error matrix indicating the user’s and
the producer’s accuracy. The key point of the classification stage is the classification algorithm
which is used, and several algorithm exist for this purpose, although not all of the algorithm
has remote sensing in focus (Richards, 2013). The most used and traditional algorithms for
supervised classification are listed below:

- Minimum-Distance to the Mean-Classifier (MD), is one of the simpler classification algo-
  rithms and is based on the evaluation of mean values in each band for each class to assign a
  pixel to one of them, according to the minimum values of Euclidian distance (Lasaponara
  & Masini, 2012).
- Maximum Likelihood Classifier (MLC), is one of the most common supervised classification
  algorithms used in remote sensing (Richards, 2013) «which is based on the evaluation of
variance and co-variance for each class to assign a pixel to one of them according to the highest probability» (Lasaponara & Masini, 2012, p. 76). The algorithm assumes the distribution of the cloud of points forming the category training data is Gaussian (normally distributed) (Lillesand et al., 2007). «The assumption of normality is generally reasonable for common spectral response distributions» (Lillesand et al., 2007, p. 554), so given the assumption, the distribution of a class pattern can be completely described by the mean vector and the covariance matrix. With the values in the mean vector and the covariance matrix estimated from the training data, the statistical probability of a given pixel value could be computed to land cover class (Lillesand et al., 2007).

- The parallelepiped classifier is a very simple algorithm, and uses the upper and lower DN in each band, and the range of each training class appears as a multidimensional box or parallelepiped (Lillesand et al., 2007; Richards, 2013).

4.4.4 Unsupervised Classification

Unlike supervised classification, unsupervised classification requires minimal amount of input values. By applying an unsupervised classification: (i) the process is automatic, only a few input parameters are required; (ii) classes are not needed to be defined before the result; «new» classes or unknown classes may be found (Lasaponara & Masini, 2012). For the supervised classification several classification algorithms exist, but the two most used are the K-means Clustering and the ISODATA Clustering (Iterative Self-Organizing Data Analyst Technique), and both of them are quite similar.

Both of the K-mean and ISODATA are clustering algorithms, which try to identify pixels in an image that are spectrally similar. The analyst chooses how many clusters the algorithm should try to find, and how many iterations the algorithm should run over. A strategy to use the unsupervised classification is to choose a rather high number of clusters, and then after the cluster algorithm has been applied, the analyst could aggregate similar classes.

4.4.5 Hybrid Classification

There exist multiple hybrid classification, but the hybrid classification which is used and focused on in this thesis are on combining the unsupervised and supervised classification, by taking the advantage in unsupervised classification of identifying classes which the analyst would maybe not identify because not all of the spectral classes are used e.g., users choose to only train their classes using the RGB bands (Rees & Williams, 1997; Kueblerle et al., 2006). After an unsupervised classification the analyst could then train classes on areas which are spectral difference and perform the supervised classification algorithm with much more confidence (Kueblerle et al., 2006).

4.4.6 Classification Accuracy Assessment

After a classification is applied on a satellite image, the accuracy of classified data has to be assessed, as it is essential to demonstrate the quality of the product (Cihlar, 2000; Foody, 2002;
Gómez et al., 2016). Although there is no standard method to assess the accuracy of a classification result creating an error matrix or often called confusion matrix is a common way to do it (Gómez et al., 2016) as it provides an evident foundation for accuracy assessment (Foody, 2002). An error matrix is a cross-tabulation of the numbers of classified labels against the reference data (ground truth) sampled at specific locations (Foody, 2002).

The reason the error matrix are being used a lot as an accuracy assessment is because it represents the map accuracy in the way the «individual accuracies of each category are plainly described along with both the errors of inclusion (commission errors) and errors of exclusion (omission errors) present in the classification» (Congalton & Green, 2008, p. 58), simplified, a commission error is «simply defined as including an area in a category when it does not belong to that category» (Congalton & Green, 2008, p. 58), while an omission error is «excluding an area from the category to which it belongs. Each and every error is an omission from the correct category and a commission to a wrong category» (Congalton & Green, 2008, p. 58).

Using the error matrix, the user is also capable of measuring the overall accuracy, user’s accuracy and producer’s accuracy as described below, and illustrated in Figure 4.4:

- **Overall accuracy:** Computed by dividing the total number of correctly classified pixels (i.e., the sum along the major diagonal, as shaded grey in Figure 4.4) by the total number of reference pixels in the entire error matrix (Lillesand et al., 2007).
- **User’s accuracy:** Computed by dividing the total number of correctly classified pixels in a column, by the total numbers of reference pixels in a column (Lillesand et al., 2007). User’s accuracies are often just calculated for each class, but could also be averaged to one user’s accuracy (Lillesand et al., 2007).
- **Producer’s accuracy:** Computed by dividing the total number of correctly classified pixels in a row, by the total numbers of reference pixels in a row (Lillesand et al., 2007). Producer’s accuracies are often just calculated for each class, but could also be averaged to one producer’s accuracy (Lillesand et al., 2007).

After an error matrix has been generated, several analysing techniques can be performed, one of them is the *Kappa* analysis. The Kappa analysis was much used in sociology and psychology literature for many years, before it was first introduced in classification accuracy assessment analysis in a remote sensing journal in 1983 by Congalton et al. (1983), and since then the Kappa
analysis has become a standard component of classification accuracy assessment (Congalton & Green, 2008).

The Kappa analysis is a statistic measure of the difference between the actual agreement between reference data and the classified data (i.e., as indicated by the major diagonal in the error matrix) and the chance of agreement between the reference data and a random classified data (i.e., as indicated by the row and columns in the error matrix) (Lillesand et al., 2007; Congalton & Green, 2008). The statistic provides an indicator of the extent to which the percentage correct values of an error matrix are due to «actual» agreement versus «chance» agreement (Lillesand et al., 2007). The $\hat{K}$ range between 1 (actual agreement) and 0 (chance agreement), and a $\hat{K}$ of 0 indicate that a random classified pixel could belong to any random class.

Conceptually $\hat{K}$ can be defined as given by Equation 4.6.

$$\hat{K} = \frac{p_o - p_c}{1 - p_c}$$

(4.6)

Where:

$p_o = $ actual agreement

$p_c = $ chance agreement

Equation 4.6 could translate to Equation 4.7 for computational purposes as proposed by Lillesand et al. (2007, p. 590-591):

$$\hat{K} = \frac{N \sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r} (x_{i+} \cdot x_{+i})}{N^2 - \sum_{i=1}^{r} (x_{i+} \cdot x_{+i})}$$

(4.7)

Where:

$r = $ number of rows in the error matrix

$x_{ii} = $ number of observations in row $i$ and column $i$ (on the major diagonal)

$x_{i+} = $ total of observations in row $i$ (shown as marginal total to right of the matrix)

$x_{+i} = $ total of observations in row $i$ (shown as marginal total at bottom of the matrix)

$N = $ total number of observations included in matrix
Chapter 5

Methods

This chapter starts to present the methodology used for the geometric performance followed by
the ice velocity. Both use the same principal to derive the terrain displacement between two
satellites acquisitions, but differ from each other when doing the post-processing. Further the
land cover classification methodology using a hybrid methodology of combining supervised and
unsupervised classification to derive a land cover map is presented.

5.1 Geometric Performance

For the geometric performance test, the image correlation software CIAS was used to compute
the displacements between the two satellite orthoimages acquired at different times. For the
calculation, eight inputs (variables) are required:

1. Input file of orthoimage time 1.
2. Input file of orthoimage time 2.
3. Measure with or without co-registration (yes/no).
4. Usage of algorithm, as either NCC or orientation correlation.
5. Measurements of point’s method (single points, polygons or XY-file).
7. Size of the search area (in pixels).
8. Grid distance (the raster resolution of measurement points).

The file format of the input file requires either GeoTIFF or TIFF-World format, meaning all
Sentinel-2 files which are delivered in the JPEG2000 format need to be formatted. The formation
from JPEG2000 to GeoTIFF is done with the *Raster to other format* tool in ArcMap from the Esri
ArcGis software. The process of measuring displacement with CIAS is presented in a flowchart
in Figure 5.1.
CHAPTER 5. METHODS

Figure 5.1: Flowchart of how the measurement of displacement is done between two Sentinel-2 images. Rectangles represent processes, while parallelograms represent input-output data. CIAS inputs includes also the choice of algorithm, measurement of points method, size of reference block, search area and grid distance.

The strategy of calculating the displacements of co-registration of two acquisitions of the same tile using CIAS is for the first time to draw the polygon to cover the entire tile, then for repeating tests within the same tile with different input files, the first result is used as the XY-file input instead of drawing the polygon for an exact match of the same grid. The size of the reference block is set to 15 pixels, size of search area is set to 20 pixels, and the grid distance is set to 150 m for all of the geometric performance tests, in order to cover all possible displacements.

5.1.1 Post-processing

To filter the lowest correlated points, the correlation coefficient \( R \) is used as a threshold for the matching result and set to minimum 0.7 (where 1 is the maximum). The filter has also set a maximum displacement of 70 m so if the point was not filtered by the correlation coefficient threshold any unrealistic displacements is also removed. This is often due cloud cover, cloud cover shadow, mountain shadow, water, or when ice on water disappears.

5.1.2 DEM Accuracy Assessment

In order to measure the accuracy of the DEM used for ortho-rectification for Sentinel-2, statistics are calculated for the vertical differences \( \Delta h \) between the reference DEM applied from Kartverket, and the DEM used for ortho-rectification of Sentinel-2 images, PlanetDEM90. Different approaches are combined together for the accuracy assessment, some basics statistics such as mean, standard deviation (std), median and RMSE. Because the vertical differences do not always follow the frequently applied Gaussian distribution, robust statistics of which the normalized median absolute deviation (NMAD), skewness and kurtosis were also calculated as suggested by Höhle & Höhle (2009). The NMAD is an alternative approach to estimate the scale of \( \Delta h \) distribution when the difference distribution has a high amount of outliers, (Höhle & Höhle,
Simplified, NMAD is a sort of standard deviation, where the influence of the outliers is minimized, the NMAD follows Formula 5.1.

\[
NMAD = 1.4826 \cdot \text{median}_j(|\Delta h_j - m_{\Delta h}|)
\] (5.1)

Where:

- \( j \) are the indices \( j = 1, \ldots, n \)
- \( \Delta h_j \) is the height difference of individual errors \( j \)
- \( m_{\Delta h} \) denotes the median of the errors

However, before any statistics is assessed, outliers needs to be dealt with by applying a threshold. Different approaches exist to apply the threshold, and the method used for this thesis follows the same approach as suggested by (Höhle & Potuckova, 2006), and outliers is removed be applying the threshold calculated in Formula 5.2, and removed by following \(|\Delta h_j| > \text{Threshold}\).

\[
\text{Threshold} = \pm 3 \times \text{RMSE}
\] (5.2)

### 5.2 Ice Velocity

For the ice velocity measurements, the same method was used as for the geometric performance test, but while the grid distance was set relatively large for the geometric performance test, the distance was set to 20 m for the ice velocity measurements in Norway because of a much smaller AOI.

The method highly depends on good co-registration between the matched data, and the highest matching accuracy is possibly achieved when the matching images which is co-registered before matching (Paul et al., 2015). The strategy of calculating the ice velocity is to do it as simple as possible, and skip the co-registration part, but rather do some point correlation on stable points, and add them to the error budget of the displacements.

#### 5.2.1 Post-processing

The same post-processing step is applied to the ice velocity measurements as for the geometric performance test, while the maximum velocity filter is changed for each study area, as listed below:

- Engabreen: 0.7 m/d
- Nigardsbreen: 2.33 m/d
- Rembesdalskåka: 0.7 m/d
- West coast of Greenland Ice sheet: 20 m/d
In addition to filtering out wrong displacements measurements, 20 points of stable ground on each study site was selected manually for testing the accuracy of co-registration between the matching images. The displacements was added to the error budged of measured velocity.

### 5.2.2 Greenland Ice Sheet Reference Velocity Product

The horizontal velocity by the reference data used for the Greenland Ice Sheet is calculated by using Equation 5.3 of the easting (vx) and northing (vy) velocity [m/d] product, delivered by Greenland Ice Sheet CCI Project (Nagler et al., 2015).

\[
    \text{Velocity}_h = \sqrt{\text{Easting}^2_{vx} + \text{Northing}^2_{vy}} \quad (5.3)
\]

### 5.3 Land Cover Classification

The methodology of generating a classification from the satellites include several steps and several different software’s are applied as either open source: GDAL library (GDAL Development Team, 2016), SNAP (Sentinel Application Platform) and Sen2Cor, or commercial software: PCI Geomatica (v.2016) and ArcMap (v.10.3.1) from the Esri ArcGis software. The process of classifying land cover is further described below, and simplified in a flowchart in Figure 5.2.

1. **L2A generation**: For the Sentinel-2 the L2A product was generated from the L1C using the Sen2Cor engine.

2. **Resampling**: Resampling the bands with the open source library GDAL (GDAL Development Team, 2016), using the bilinear interpolation technique. Bands 8, 10 and 11 are resampled to 30 m spatial resolution for the Landsat-8 scenes, while for Sentinel-2, band 1,5,6,7,8A,9,10,11,12 are resampled to 10 m spatial resolution.

3. **Layer stacking**: For each, scene the respective bands are stacked and exported as PCIDSK (.pix) file format using the PCI Geomatica engine, as the supervised classification requires this format.

   Each Sentinel-2 scene was also layer stacked to the GeoTIFF (.tif) format using GDAL, for the unsupervised classification.

4. **Unsupervised classification**: For each Sentinel-2 scene, an unsupervised classification was applied using 25 cluster and 30 iterations with the K-Mean algorithm in the SNAP engine and aggregated to 7 distinct classes in PCI Geomatica.

5. **Definition of training data**: Using the aggregated unsupervised classification and the layered RGB scene, polygon were made on each respective class with ArcMap. For a most fair comparison between the Landsat-8 and Sentinel-2, it was ensured that the training polygon covered similar class representation. The training data is exported as a shapefile (.shp). Because of large land cover change between August and October, two training sets were applied for the respective data time.

6. **Supervised classification**: With the PCI Geomatica engine the respective PCIDSK and shapefile is loaded, and the supervised classification is performed with the MD algorithm.
In order to do a temporal comparison between the two periods, the normalised difference vegetation index (NDVI) was calculated with the Formula 5.4. For a most fair NDVI comparison between the two satellites, the NIR band of Sentinel-2 8A was chosen, as it is closer to the NIR
band 5 of Landsat-8, from the radiometric point of view (Mandanici & Bitelli, 2016).

\[ \text{NDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}} \]  

(5.4)

### 5.3.1 Post-processing

After the classification, error matrices are calculated by using the training polygons as reference data versus the classified data of each product. From each error matrix, the overall, producer’s and user’s accuracies is derived.
Chapter 6

Results

In the following, the results derived about geometric performance, ice velocity and land cover classification are presented.

6.1 Geometric Performance

By using image matching, co-registration displacements between two Sentinel-2A satellite orthoimages have been tested at different regions with different topography. The topography is ranging from flat tundra landscape, to high mountain landscape. All tests are above 60° north, were it is assumed to have higher offset due to the DEM used for ortho-rectification (outside of SRTM coverage) (Kääb et al., 2016). All test regions have been tested with one reference image, the image with least cloud cover, against images at either similar or different relative orbits at different time.

Last subsection of Section 6.1.1 display other biases, like stripe pattern and satellite jitter, as these errors were found when the overall displacement was low. Results, which is present in statistics tables, but not displayed in this chapter are found in Appendix A.

6.1.1 Flat Tundra

Tile 51WWR, which is located in the northern Siberia, has a flat tundra landscape, and the geometric performance is expected to be high, as the DEM likely does not change very much (elevation ranging from approximately sea level to 300 m). Tile 51WWR is covered by the relative orbits, R018, R061 and R104, and it is the satellite scene from 28.06.2016 (R018) that are used as the reference image, and the tile is located left on the swath edge of the relative orbit (see Figure A.11 in Appendix A). Table 6.1 shows the key statistic values from the correlation files.
Table 6.1: The mean \([m]\), std. \([m]\), median \([m]\), SNR and mean direction \([\circ]\) of each co-registration test of flat tundra area, covering tile 51WWR. (i) and (ii) mark the difference between the two equal relative orbit tests. All dates are in the year 2016.

<table>
<thead>
<tr>
<th>Date and relative orbits</th>
<th>Mean</th>
<th>Std.</th>
<th>Median</th>
<th>SNR</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>08.06 - R018 (i) and 28.06 - R018</td>
<td>13.733</td>
<td>4.366</td>
<td>12.748</td>
<td>2.771</td>
<td>183</td>
</tr>
<tr>
<td>14.06 - R104 and 28.06 - R018</td>
<td>3.509</td>
<td>2.855</td>
<td>2.795</td>
<td>2.925</td>
<td>150</td>
</tr>
<tr>
<td>21.06 - R061 and 28.06 - R018</td>
<td>4.150</td>
<td>2.53</td>
<td>3.953</td>
<td>2.942</td>
<td>167</td>
</tr>
<tr>
<td>28.06 - R018 and 02.09 - R104</td>
<td>4.263</td>
<td>4.782</td>
<td>3.536</td>
<td>2.561</td>
<td>212</td>
</tr>
<tr>
<td>28.06 - R018 and 16.09 - R018 (ii)</td>
<td>5.217</td>
<td>6.911</td>
<td>3.536</td>
<td>2.209</td>
<td>206</td>
</tr>
</tbody>
</table>

6.1.1.1 Equal Relative Orbits - R018-R018 (i)

The two images from the equal relative orbit R018 acquired on 08.06.2016 (i) and 28.06.2016 (ii) have different processing algorithms for each product, image (i) has the processing algorithm identifier known as 02.02 while image (ii) has the 02.04 processing algorithm identifier. The tile is for both orbits located at the left edge of the Sentinel-2 swath, (as displayed in Figure A.11 in Appendix A). Displacements between the two images are increasing from approximately east to west in the cross-track direction as displayed in Figure 6.2 on the order of 5-30 m. The displacement has a strong direction indication to the south as seen in Figure 6.1 and in Table 6.1.

A visual inspection of the RGB composite of the two images (not shown) indicates little changes in the biophysical terrain that could lead to low correlation, but the ice in the largest ponds in scene (i) has melted before the acquisition of scene (ii), and has resulted in low correlation between the two images. The grass has slightly increased closer to some ponds, mire and rivers.
and results in a minor increase in displacement because of this. For all water bodies, the lack of signal variance between the two matched images leads to low correlation, this are applied to all followed matched scenes that contains water bodies.

Figure 6.2: Displacement (in m) between the two scenes 08.06.2016 and 28.06.2016, having equal relative orbits. The displacement has increasing magnitude from approximately east to west in the cross-track direction.
6.1.1.2 Different Relative Orbits - R061-R018

The images used in the test with different relative orbits are acquired on 21.06.2016, R061 (i) and on 28.06.2016, R018 (ii). Because ESA changed their processing algorithm the 15.06.2016 (Clerc & MPC-Team, 2017), both images have the same new algorithm identifier 02.04. The tile 51WWR is covered in the centre of the relative orbits R061 swath, in contrast to R018, which covers the tile at the left swath edge (Figure A.11 in Appendix A). The result of the image matching offset is on the order of 2.5 m, as displayed in Figure 6.4 and in table 6.1. From the direction diagram in Figure 6.3 and Table 6.1 the direction of the offset is in a south direction.

![Direction diagram of displacements between the two scenes 21.06.2016 and 28.06.2016, having different relative orbits.](image)

For tests on the tile 51WWR, the correlation between (i) and (ii) have the shortest baseline (days between acquisition) of 7 days, and as assumed the correlation is high, as very little biophysical terrain change has occurred. The only place with low correlation is in the bottom right corner given the appearance of clouds. The distinctive stripe pattern in the figure are further investigated in Section 6.1.1.4.
Figure 6.4: Displacement (in m) between the two scenes 21.06.2016 and 28.06.2016, having different relative orbits. Three stripes are clearly visible on the displacement measurement.

6.1.1.3 Equal Relative Orbits - R018-R018 (ii)

The second set obtained with equal relative orbits which could be used for measure the displacement are acquired on 28.06.2016 (i) and 16.09.2016 (ii), and this time both images have the same processing baseline of 02.04, in contrast to the test result in Section 6.1.1.1. The result is displayed in Figure 6.6, and from Table 6.1 the mean and standard deviation of displacement is rather high compared against the result with lower baseline between the acquisition of images
CHAPTER 6. RESULTS

matched, while the median stays as low as other results for this tile. The mean direction in Table 6.1 and direction diagram in Figure 6.5, shows how the direction mostly ranges from north to south (counter-clockwise).

Figure 6.5: Direction diagram of displacements between the two scenes 28.06.2016 and 16.09.2016, having equal relative orbits.

The second set of displacement measurements between the equal relative orbits R018 covering the tile 51WWR have the longest baseline between the two acquisitions (80 days). The long baseline has resulted in a much lower correlation close to water surfaces. As image (ii) is captured close to winter time the physical biomass is lowered, and has resulted for some places in a much lower correlation in the displacement measurement.

6.1.1.4 Jitter and Stripe Pattern

The result from the test between the relative orbits R061 and R018 (Section 6.1.1.4) has one of the lowest deviations and displacements, and because of this, further investigation for stripe pattern and potential satellite jitter is performed, as these errors were found by Kääb et al. (2016) on the commissioning and ramp up data (not shown). In contrast to Kääb et al. (2016) which display these errors on similar relative orbit data, the result of stripe pattern and jitter are calculated on measurements from different relative orbit, simply because the equal relative orbit test R018-R018 (ii) had too large biophysical changes, and is therefore not comparable between the two studies. Other measurements showing stripe pattern are found in Figure A.13 in Appendix A.
Figure 6.6: Displacement (in m) between the two scenes 28.06.2016 and 16.09.2016, having equal relative orbits. Due to large change in the biophysical terrain between the two acquisitions, the deviation is rather high.

Figure 6.7 displays signs of satellite jitter when displaying the west-east component of the displacement measurement, the figure shows a jitter with a ~ 2 km wavelength in flight direction. In the same figure, increasing displacement from the R018 nadir to the swath edge is displayed. In Figure 6.8 a distinctive stripe pattern is found. The line pattern are in flight direction (southwest) and has a distance of 25 km from each other.
Figure 6.7: West-east component of displacements between the two scenes 21.06.2016 and 28.06.2016, which have different relative orbits. The image are showing jitter with $\sim 2$ km wavelength in flight direction, in addition to increasing displacement from nadir to the swath edge on the west-east component.
Figure 6.8: Displacements between the two scenes 21.06.2016 and 28.06.2016, which have different relative orbits. Image are displaying stripe pattern. The length between the stripes are ~ 25 km in width in flight direction.
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6.1.2 Hilly and Mountainous Landscape

Tile 32VMQ covers the central western part of Norway, and the terrain located in the tile is represented as hilly mountain landscape. The elevation of the terrain changes from sea level to approximately 1700 m a.s.l. and because the tile is located north of 60°N and outside the SRTM coverage, displacement between two scenes with different relative orbits is assumed to have high errors, because of vertical DEM errors. Following sections display the result of an accuracy assessment of the DEM difference, and the displacement measured by using image matching techniques.

The tile is covered by the relative orbits R051, R094 and R137, and it is the satellite scene obtained on 04.10.2016 with the relative orbit R137 that are chosen as the reference scene. The 32VMQ tile is located at the right swath edge of the reference orbit scene (see Figure A.16 in Appendix A). Table 6.2 shows the key statistics from the correlation files of the different image matchings.

Table 6.2: The mean [m], std. [m], median [m], SNR and mean direction [°] of each co-registration test of the hilly and mountainously landscape in the 32VMQ tile. All dates are in the year 2016.

<table>
<thead>
<tr>
<th>Date and relative orbits</th>
<th>Mean</th>
<th>Std.</th>
<th>Median</th>
<th>SNR</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>04.10 - R137 and 08.10 - R051</td>
<td>6.467</td>
<td>7.030</td>
<td>4.507</td>
<td>2.300</td>
<td>146</td>
</tr>
<tr>
<td>04.10 - R137 and 11.10 - R094</td>
<td>7.166</td>
<td>7.060</td>
<td>5.303</td>
<td>2.242</td>
<td>174</td>
</tr>
<tr>
<td>04.10 - R137 and 14.10 - R137</td>
<td>4.183</td>
<td>7.660</td>
<td>1.768</td>
<td>2.303</td>
<td>169</td>
</tr>
</tbody>
</table>

6.1.2.1 Accuracy Assessment of DEM

By differencing the Kartverket and PlanetDEM90 DEMs (Δh) covering the 32VMQ tile, a substantial amount of outliers were detected, as displayed in Figure 6.9, and the DEM differences maximum is 458.6 m and the minimum is -449.5 m. After calculating the threshold by Equation 5.2, the upper and lower threshold is defined as ±57.1 m, symbolized as green vertical lines in Figure 6.9, and further statistics is based on the data inside the threshold, and are listed in Table 6.3. The histogram calculated after the threshold is applied, is displayed in Figure 6.10.

Table 6.3: Statistics (in m) calculated on the Δh before and after thresholding. Table abbreviations: AT = After thresholding, Skewn = Skewness, Kurt = Kurtosis and 95 Q = The 95% quantile.

<table>
<thead>
<tr>
<th>Δh</th>
<th>Mean</th>
<th>Std.</th>
<th>Median</th>
<th>RMSE</th>
<th>NMAD</th>
<th>Skewn.</th>
<th>Kurt.</th>
<th>95 Q</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.269</td>
<td>19.021</td>
<td>0</td>
<td>19.023</td>
<td>9.637</td>
<td>-0.131</td>
<td>16.196</td>
<td>39.900</td>
</tr>
<tr>
<td>Δh_{AT}</td>
<td>0.273</td>
<td>15.071</td>
<td>0</td>
<td>15.074</td>
<td>9.340</td>
<td>-0.016</td>
<td>5.151</td>
<td>34.600</td>
</tr>
</tbody>
</table>

Most water surfaces and large flat areas have little or no difference between the two DEMs, while when the terrain change to hilly and mountainously, the differences get larger, as displayed in Figure 6.11. A visual inspection of the PlanetDEM90 from Figure 3.2, displays difference artefacts, which also are visible in the DEM differencing in Figure 6.11. Typically, these artefacts are present as distinctive horizontal and vertical lines in the DEM from PlanetDEM90, and could arise from the course pixels size of the DEM. The displacement measurements, of the same extent as the DEM differencing in Figure 6.11 shows the typically southward direction of displacement between the R137 (04.10.2016) and R094 (11.10.2016) orbits, see Section 6.1.2.4. The measured
displacement is larger in the higher elevated areas, but also less well correlated in the same area because of change in snow cover between the two acquisitions.

Assuming the DEM from Kartverket as ground truth and the minimum and maximum pixels $\Delta h$ of respective -449.5 m and 458.6 m, the values could according to Formula 4.3 translate to a potential worst case horizontal maximum offset of $d_{\text{max}(S2)} \approx 166.5$ m or $d_{\text{max}(S2)} \approx 169.9$ m on the respective minimum and maximum pixel of on two wrongly orthoprojected Sentinel-2 scenes in the orbit swath edge.
Figure 6.11: **Top:** $\Delta h$ between the two DEM Kartverket and PlanetDEM90, located at the same extent in bottom of Figure 3.2. **Bottom:** Displacement (in m) with direction vectors for same extent as above. Displacement measured between the R137 (04.10.2016) and R094 (11.10.2016) orbits, see Section 6.1.2.4.

### 6.1.2.2 Equal Relative Orbits - R137-R137

The displacement measured by the two scene of equal relative orbits R137, acquired on 04.10.2016 (i) and 14.10.2016 (ii) is displayed in Figure 6.13. The calculated direction diagram in Figure 6.12 and the mean direction of 169° shows how the displacement has a south direction.
Because the displacement is measured between a short baseline of 10 days, the biophysical ground cover has changed very little, but the snow cover of the highest mountains had melted between the two scenes, especially snow facing in the direction of the second and third quadrant (90°–270°). The largest differences between the two images is how the sun cast the shadows from the high mountains, which has resulted in a much lower correlation value in this areas between the two images.
Figure 6.13: Displacement (in m) between the two scenes 04.10.2016 and 14.10.2016, having equal relative orbits.
6.1.2.3 Different Relative Orbits - R137-R051

The test of displacement between the two scenes with different relative orbits and the shortest baseline of tile 32VMQ are acquired on 04.10.2016 (i) and 08.10.2016 (ii). Both of the scenes are at the outermost swath edge of the relative orbit, R137 (i) has the tile at the right edge, and orbit R051 (ii) has the tile at the left edge (Figure A.16 in Appendix A), and because of this, the size of the correlated scenes is rather small as displayed in the displacement calculation in Figure 6.15. The calculated direction diagram in Figure 6.14, and the mean direction of 146° indicate the displacement is in a southeast direction, and it seems the displacement is shifted towards the R051 orbit.

Figure 6.14: Direction diagram of displacements between the two scenes 04.10.2016 and 08.10.2016, having different relative orbits.

Despite short baseline, the mean and median of displacement is rather high. As for the test with equal relative orbit, a change of snow-cover has affected the correlation between the scenes. Except from the snow, very little biophysical changes could explain the high displacement, other than it mainly stems from horizontal offset due to vertical errors in the DEM used for orthoprojection.
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Figure 6.15: Displacement (in m) between the two scenes 04.10.2016 and 08.10.2016, having different relative orbits.
6.1.2.4 Different Relative Orbits - R137-R094

Displacement measured on the second test with different relative orbits R137-R094 of the 32VMQ tile, stems from the scenes acquired on 04.10.2016 (i) and 11.10.2016 (ii). Tile 32VMQ is covered by the relative orbit R094 swath in centre (Figure A.16 in Appendix A). The calculated direction diagram in Figure 6.16, and the mean direction of 174° indicate the displacement is in a south direction. The displacement as displayed in Figure 6.17 and the calculated mean 7.2 m and median 5.3 m (Table 6.2), indicate the highest displacement of tests in the 32VMQ tile.

Figure 6.16: Direction diagram of displacements between the two scenes 04.10.2016 and 11.10.2016, having different relative orbits.

As for all tests within the tile 32VMQ, the biophysical terrain changes between (i) and (ii) are rather low and the main change on the surface is a melting of snow-cover in the highest mountains. Change in mountain shadows is also present in this test.
Fig. 6.17: Displacement (in m) between the two scenes 04.10.2016 and 11.10.2016, having different relative orbits.
6.1.3 Flat and Hilly

Tile 51WXS is located between the Lena River and the foot of the Verkhoyansk Range. The tile is a perfect site for proving the horizontal displacement due to vertical DEM errors used for orthoprojection, as it contains flat tundra landscape (ranging from 100 m to 300 m), which is assumed to have very low vertical DEM error, and high mountain landscape (ranging from 300 m to 1200 m), which is assumed to have high vertical DEM errors. The tile is covered by four different relative orbits: R018, R061, R104 and R118, where it is the scene acquired on 16.09.2016 on the relative orbit R018 which is used for the reference scene. The tile is covered by the reference orbit middle of the left edge and centre of the orbit swath, as displayed in Figure A.17 in Appendix A. Key statistic values from the different tests between equal and different relative orbits are listed in Table 6.4.

Table 6.4: The mean [m], std. [m], median [m], SNR and mean direction [°] of each co-registration test of tile 51WXS. All dates are in the year 2016.

<table>
<thead>
<tr>
<th>Date and relative orbits</th>
<th>Mean</th>
<th>Std.</th>
<th>Median</th>
<th>SNR</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.08 - R061 and 16.09 - R018</td>
<td>9.695</td>
<td>7.182</td>
<td>8.385</td>
<td>2.046</td>
<td>193</td>
</tr>
<tr>
<td>02.09 - R104 and 16.09 - R018</td>
<td>5.001</td>
<td>6.661</td>
<td>2.795</td>
<td>2.286</td>
<td>195</td>
</tr>
<tr>
<td>03.09 - R118 and 16.09 - R018</td>
<td>7.028</td>
<td>7.857</td>
<td>5.000</td>
<td>1.991</td>
<td>217</td>
</tr>
</tbody>
</table>

6.1.3.1 Equal Relative Orbits - R018-R018

Scenes used for the equal relative orbits test on the 51WXS tile have the longest baseline of 60 days, compared to other tests within the same tile. The displacement stems from the two scenes acquired on 18.07.2016 (i) and 16.09.2016 (ii). Measured direction of the displacement is displayed in Figure 6.18, and from the figure and the mean calculated vale of 243° (Table 6.4), the direction is very much between the third and fourth quadrant (180-360°).

Given the long baseline and the high amount of cloud cover of (i), the mean and median displacement is low compared to other tests of tile 51WXS, as seen in Table 6.4 and in Figure 6.19. Apart from the clouds, the displacement as in Figure 6.19 is very much affected by changes of the mountain shadow as a function of the solar seasonally changing, this gives huge areas of low correlation between the two images.

The biophysical terrain has also changed a lot, from a high amount of biophysical elements at the flat tundra in (i), lowering much between the period of (ii), as the season is getting closer to winter. Between the two acquisitions, small patches of snow in the V-valleys (i) have melted while the acquisition of the (ii) scene lowered the correlation of image matching for these areas.
Figure 6.18: Direction diagram of displacements between the two scenes 18.07.2016 and 16.09.2016, having equal relative orbits.
Figure 6.19: Displacement (in m) between the two scenes 18.07.2016 and 16.09.2016, having equal relative orbits. The displacement measurement are inaccuracies because of large changes of the biophysical terrain on the flat area, and cloud cover in the higher mountains in the two acquisitions.
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6.1.3.2 Different Relative Orbits - R118-R018

Test with different relative orbits of R118-R018 have the shortest baseline of 13 days of tests within the 51WXS tile. Scenes used for the displacement measurements are acquired on 03.09.2016 (i) and 16.09.2016 (ii). Tile 51WXS is only half covered by the R118 orbit as it is in the outermost edge of the relative orbit (Figure A.17 in Appendix A). Direction of the measured displacement is displayed in Figure 6.20, and from the figure and the mean direction of 217° (Table 6.4) the direction is very much in the third quadrant (180-270°).

![Figure 6.20: Direction diagram of displacements between the two scenes 03.09.2016 and 16.09.2016, having different relative orbits.](image)

The calculated displacement using image matching is displayed in Figure 6.21. The displacement has a mean of 7 m and a median of 5 m, and most of the higher displacement is found in the higher mountains and in the rivers. As the test with equal relative orbit, the displacement calculation between (i) and (ii) are also affected by the clouds in the reference image (ii). The difference between (i) and (ii) in biophysical terrain is very low, and apart from some snow patches in (i) in the upper mountain had melted between the (ii) scenes, and the clouds in the reference image, the displacement probably stems from horizontal shift given vertical DEM errors.
Figure 6.21: Displacement (in m) between the two scenes 03.09.2016 and 16.09.2016, having different relative orbits. Cloud cover are present in the upper right corner on the image from 16.09.2016.
6.1.3.3 Different Relative Orbits - R104-R018

The second test with different relative orbits on the til 51WXS is between the relative orbits R104-R118, of were the scenes are acquired on 02.09.2016 (i) and 16.09.2016 (ii). The time between the two scenes is very short, only one day longer than test of R118-R018 (14 days), see section 6.1.3.2. As the other test with different relative orbits on the tile 51WXS, the orbit R104 covers only half of the working tile, but this time the coverage is in the right edge of the orbit swath (see Figure A.17 in Appendix A). Direction diagram of the measured displacement is displayed in Figure 6.22 and from the direction diagram, the direction spreads mostly through the second and third quadrant (90-270°).

![Figure 6.22: Direction diagram of displacements between the two scenes 02.09.2016 and 16.09.2016, having different relative orbits.](image)

The measured displacement between (i) and (ii) is displayed in Figure 6.23. The matched area covers both the flat tundra, but also high mountain. Scene (i) is covered by clouds and cirrus, left in the scene, at the flat tundra area, while this time the clouds in the reference image (ii) is outside the coverage of R104 and does not affect the matching this time. The displacement has the lowest mean of 5 m and median of 2.8 m, probably due to the matched area cover less high mountain areas compared to other tests of the tile 51WXS.
Figure 6.23: Displacement (in m) between the two scenes 02.09.2016 and 16.09.2016, having different relative orbits. Cloud cover is present left in the scene on 02.09.2016, and lowering the amount of well correlated measurements in this area.
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6.2 Ice Velocity

The result of measuring the ice velocity of the three glacier at Norway (Engabreen, Nigardsbreen and Rembesdalskåka) and the western coast of the Greenland Ice Sheet have followed the same procedure as for the geometric performance tests, but on a much smaller AOI, and thereby the grid distance are lowered from 150 m to 20 m. In order to avoid the horizontal shift because of vertical DEM errors, only scenes with equal relative orbits were chosen for the ice velocity measurements.

For each site, basic statistics was calculated, were the calculation stems from points inside the following image extent of the result, in addition to be inside the glacier basin. The statistic from each glacier complex are listed in Table 6.5.

Table 6.5: Key statistics for each glacier velocity measurement of the displacement (m). The statistics originate from points inside the image extent of the following result images and inside the glacier complex. Last three columns show the mean of the measurements.

<table>
<thead>
<tr>
<th>Glacier</th>
<th>Mean</th>
<th>Std.</th>
<th>Median</th>
<th>SNR</th>
<th>Direction [°]</th>
<th>Velocity [m/d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engabreen</td>
<td>10.900</td>
<td>4.913</td>
<td>11.319</td>
<td>8.683</td>
<td>288</td>
<td>0.363</td>
</tr>
<tr>
<td>Nigardsbreen</td>
<td>15.611</td>
<td>9.397</td>
<td>14.252</td>
<td>7.280</td>
<td>128</td>
<td>0.520</td>
</tr>
<tr>
<td>Rembesdalskåka</td>
<td>2.960</td>
<td>2.481</td>
<td>1.768</td>
<td>7.244</td>
<td>265</td>
<td>0.148</td>
</tr>
<tr>
<td>Greenland Ice Sheet</td>
<td>32.323</td>
<td>44.495</td>
<td>22.256</td>
<td>14.180</td>
<td>250</td>
<td>1.616</td>
</tr>
</tbody>
</table>

For each ice velocity measurement, 20 stable points were measured using the same correlation tool used for measure the displacement, to measure how well the correlated scenes were co-registered. The points were tried to be evenly spread out, but were restricted to not be on ice, snow and water bodies. The mean of the measured co-registration displacement and direction are listed in Table 6.6 for each site.

Table 6.6: Mean of displacement (m) and direction of 20 stable points around each measured glacier.

<table>
<thead>
<tr>
<th>Glacier</th>
<th>Displacement [m]</th>
<th>Direction [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engabreen</td>
<td>5.626</td>
<td>171</td>
</tr>
<tr>
<td>Nigardsbreen</td>
<td>5.068</td>
<td>134</td>
</tr>
<tr>
<td>Rembesdalskåka</td>
<td>5.872</td>
<td>87</td>
</tr>
<tr>
<td>Greenland Ice Sheet</td>
<td>2.465</td>
<td>194</td>
</tr>
</tbody>
</table>

6.2.1 Engabreen

The displacement measured at Engabreen using the image matching tool CIAS, was operated at the two scenes 23.07.2016 and 22.08.2016 (30 days). Glacier velocity (m/d) were calculated from the displacement measurements and are displayed in Figure 6.24. As for the post-processing part, direction vectors was chosen from the theoretical glacier flow, following vectors inside the $<= 359^\circ$ and $>= 190^\circ$ direction constrain. The calculated direction diagram is found in Figure 6.25.

The measured co-registration between the two images that were found when measuring 20 stable points, were calculated to a mean $\pm 5.6$ m and a mean direction of 171° as displayed in Table 6.6.
The co-registration error translates to ±0.19 (m/d) given the 30 days baseline and thereby the measured ice velocity using Sentinel-2 images is significant.

Figure 6.24: Velocity vectors on Engabreen from image matching of the 23.07.2016 and 22.08.2016 Sentinel-2A satellite scenes.

From the measured velocity vectors at Engabreen (Figure 6.24) a high amount of well correlated points were found in the outlet of the glacier. The highest velocity (∼0.7 m/d) and highest amount of correlated points were found in the largest crevasses, and the steepest slopes. Of the total area inside the glacier basin, the mean velocity were found to be 0.36 m/d.
Figure 6.25: Direction diagram of velocity vectors at Engabreen glacier. The vector direction are constrained between $\leq 359^\circ$ and $\geq 190^\circ$.

### 6.2.2 Nigardsbreen

The glacier velocity measured at Nigardsbreen, displayed in Figure 6.26, were derived from the correlation of the two scenes 04.09.2016 and 04.10.2016 (30 days). Velocity vectors are constrained to be between $\leq 190^\circ$ and $\geq 50^\circ$ direction, see Figure 6.27 for measured direction diagram.

Mean velocity (Table 6.5) was calculated to be 0.52 m/d, while the co-registration error were calculated to be $\pm 5.068$ m, which translates to $\pm 0.17$ m/d given the 30 days baseline.
Figure 6.26: Velocity vectors on Nigardsbreen from image matching of the 04.09.2016 and 04.10.2016 Sentinel-2A satellite scenes.
Figure 6.27: Direction diagram of velocity vectors at Nigardsbreen glacier. The vector direction are constrained between $\leq 190^\circ$ and $\geq 50^\circ$. 
Of the velocity vectors, a high amount of well correlated measurements were found, especially close to the glacier tongue, but also in the steepest crevasses, which also has the highest velocity ($\sim 2$ m/d). Low correlation between the two correlated scenes were found in the lowermost horizontal drainage, close to the green field, because appearance of mountain shadow between the two acquisitions.

### 6.2.3 Rembesdalskåka

The ice velocity vectors measured at Rembesdalskåka are displayed in Figure 6.28, which stems from the correlation between the two scenes acquired on 18.09.2016 and 08.10.2016 (20 days). The velocity vectors is constrained to be between $<= 330^\circ$ and $>= 210^\circ$, following the assumed glacier velocity flow, direction diagram is found in Figure 6.29.

Mean velocity of the Rembesdalskåka is calculated to be 0.15 m/d, while the co-registration error between the two correlated scenes is found to be $\pm 5.87$ m with a mean direction of $87^\circ$. The co-registration error could translate to a velocity error equal $\pm 0.294$ m/d, given the 20 days baseline.

Figure 6.28: Velocity vectors on Rembesdalskåka from image matching of the 18.09.2016 and 08.10.2016 Sentinel-2A satellite scenes.

Between the two acquisitions, new-snow on the scene from 08.10.2016 has affected the result very much, and has lowered the amount of correlated points to only be on the most defined crevasses, and hardly any correlated points are found on the glacier tongue. The measured velocity are rather questionable because the co-registration error are higher than the measured mean displacement.
6.2.4 Greenland Ice Sheet

Glacier velocity measured at the west coast of the Greenland Ice Sheet, in the Sermeq Kujalleq area, north of Jakobshavn glacier, is displayed in Figure 6.30. The velocity is measured from correlation from the two Sentinel-2 scenes on 14.07.2016 and 03.08.2016 (20 days). The velocity vectors is constrained to be between $<\leq 359^\circ$ and $\geq 180^\circ$, in order to filter out vectors which does not follow the assumed direction towards the coast. The direction diagram of the velocity vectors is displayed in Figure 6.31.

From the velocity vectors in Figure 6.30 the figure shows that close to where the ice sheet is calving, some of the highest ice speed is reached, and as high as $\sim 20$ m/d is measured, the mean velocity (Table 6.5) is calculated to be 1.616 m/d. The measured co-registration error between the two correlated scenes were measured to $\pm 2.47$ m, in the mean direction of 194°. The length of the co-registration displacement translates to a mean velocity error of $\pm 0.12$ m/d, given the 20 days baseline.

Between the two matched scenes, Figure 6.30, the process of finding correlated points worked well, but between Sermeq Avannarleq and Sermeq Kujalleq (top in the figure) the correlation has resulted in fewer points, and wrong velocity and direction for some vectors. This is due to a much brighter snow in this area of the 14.07.2016 scene. The water bodies on the matched areas is also changing, while some lakes decreases, others increases, but an overall decrease is seen (not shown), and thereby the water bodies edge are measured wrong between the two acquisitions.

The black line superimposed in Figure 6.30 is used to compare the velocity against the Greenland Ice Sheet CCI project 2016/2017 winter campaign (Nagler et al., 2015), using the SAR
Figure 6.30: Velocity vectors at west coast of Greenland Ice Sheet. The vectors stems from image correlation between the two Sentinel-2A satellite scenes of 14.07.2016 and 03.08.2016. Black line indicate the velocity profile, shown in Figure 6.32.

Figure 6.31: Direction diagram of velocity vectors of the west coast of Greenland Ice Sheet. The vector direction are constrained to be between $\leq 359^\circ$ and $\geq 180^\circ$. 
Sentinel-1A/B satellites against the Sentinel-2A, the result are displayed in Figure 6.32. The profile comparison is displaying good agreement between the two measurements, but a slightly higher difference is found close to the calving ice, this is probably due to the Sentinel-1 profile is from the winter mapping campaign 2016/2017 and the Sentinel-2 is from an early 2016 summer period.

Figure 6.32: Comparison of ice velocity along the black profile in Figure 6.30 from Sentinel-2A in an early 2016 summer period and a Sentinel-1A/B ice velocity map in the 2016/2017 winter campaign (Nagler et al., 2015).

6.3 Land Cover Classification

Both Sentinel-2 and Landsat-8 images were classified using the MD algorithm to create land cover maps on a Sentinel-2 granule size of the study region both in August and October. This resulted in eight different land cover classifications maps. The four maps for each period of August and October follows: Landsat-8 using all bands, Sentinel-2 using all bands, Sentinel-2 using Landsat-8 «similar» bands and Sentinel-2 using L2A bands. An example of full extent of the result is shown in Figure 6.33 and 6.34, and zoomed in on the location as illustrated in the red extent (AOI) in Figure 3.3 are shown in Figure 6.35 to 6.38.
Figure 6.33: Classification of the Landsat-8 scene in 14.08.2016. Clouds has wrongly been classified as plowed agriculture and the clouds shadow as water. North is up.
Figure 6.34: Classification of the Sentinel-2 scene using Landsat-8 «similar» bands in 16.08.2016. Clouds has wrongly been classified as plowed agriculture and the clouds shadow as water. North is up.

From the full extent of the classification results in Figure 6.33 of the Landsat-8 and 6.34 of the Sentinel-2 using Landsat-8 «similar» bands, they both clearly show the dominant class cover of the forest, grass, water and open fields. Both classifications includes clouds, and in both scenes the clouds are classified as plowed agriculture fields and the cloud shadow are classified as water.

In the zoomed in location (AOI) close to the location Sander in the Sør-Odal municipality in the Hedmark county, for the August period as displayed in Figure 6.35 and for the October period in Figure 6.36 all classes as applied from the training is labelled. The Landsat-8 compared to all of the other Sentinel-2 classifications differ in the way it contains much more barren vegetation, where the Sentinel-2 scenes classifies the barren vegetation with either urban, asphalt or felled area. None of the product covers the asphalt road centred in the extent very well, but the Sentinel-2 maps classifies the road in the upper right as urban, whereas Landsat-8 classifies the asphalt road as a mainly a combination between felled area and barren vegetation but it also
Figure 6.35: AOI in August (Landsat-8, 14.08.2016 and Sentinel-2, 16.08.2016): (a) Landsat-8 pansharpen RGB composite. (b) Sentinel-2 RGB composite. (c) Classification result of Landsat-8. (d) Classification result of Sentinel-2 using Landsat-8 «similar» bands. (e) Classification result of Sentinel-2 using all bands. (f) Classification result with use of the Sentinel-2 L2A bands.
Since August, the agriculture land cover has changed allot, with fields with high biomass level changed to low between the two acquisitions. For the October period (Figure 6.36) the difference between Landsat-8 and Sentinel-2 is smaller. The Landsat-8 does not label any pixels with the
urban class in the extent. In the upper right corner the two satellites differ in the classification of the open field (close to the road). Landsat-8 classifies the area as a combination between open field and felled area, whereas Sentinel-2 classifies it as mire and open field (high bio).

The land cover classification AR5 by NIBIO combined with an orthoimage and the NDVI from the Landsat-8 and Sentinel-2 is displayed in Figure 6.37.

Mean spectral values (DN) from all of the bands of the different classes for the Sentinel-2 satellite is displayed in Figure 6.38. The Figure clarifies bands that are spectral difference or similar for each class, and for Sentinel-2 in August, band 1, 2 and 10 highlights as the most spectral unlike for this period.

Accuracy assessment were carried out for the Landsat-8 and Sentinel-2 using Landsat-8 «similar» bands for the August and October period, using the training areas as the reference for each calculated error matrix, see Table 6.8 and 6.9. The accuracies of; overall, producer’s user’s, and the Kappa value are presented in Table 6.7.

Table 6.7: Calculated accuracies (in %) and Kappa values from each error matrix presented in Table 6.8 and 6.9. Abbreviations: OA= Overall Accuracies, PA = Producer’s Accuracies and UA = User’s Accuracies.

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<th>OA</th>
<th>PA</th>
<th>UA</th>
<th>Kappa</th>
</tr>
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<td>70.31</td>
<td>72.07</td>
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<tr>
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<td>67.0</td>
<td>70.02</td>
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<td>Sentinel-2 05.10.2016</td>
<td>94.4</td>
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<td>0.944</td>
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Figure 6.37: AOI: (a) Classes from the AR5 land cover classification by NIBIO. Source: Geovekst/kommunene. (b) Aerial orthophoto of the AOI, lower part is acquired on 23.09.2011 while the upper part is acquired on 26.04.2015, both from the Norwegian mapping authority - Kartverket published by Geodata AS. The following sub figures ranging from (c-f) is the NDVI from: (c) Landsat-8 in 14.08.2016. (d) Sentinel-2 in 16.08.2016. (e) Landsat-8 in 01.10.2016. (f) Sentinel-2 in 05.01.2016.
Figure 6.38: Mean spectral values (TOA) of all of the training polygons for each class used for classification of Sentinel-2 in 16.08.2016.
Table 6.8: Error matrix for (a) Landsat-8 and (b) Sentinel-2 (with Landsat-8 «similar» bands) classification in October using MD. * Abbreviations: OA = Overall Accuracies, PA = Producer’s Accuracies and UA = User’s Accuracies.

(a) Error matrix of classified Landsat-8. *OA = 93.70, PA = 64.84 and UA = 69.77

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<th>Fresh water</th>
<th>Evergreen</th>
<th>Mire</th>
<th>Felled area</th>
<th>Open field</th>
<th>Urban</th>
<th>Asphalt</th>
<th>Barren Veg.</th>
<th>Grass (h. bio)</th>
<th>Grass (l. bio)</th>
<th>Agriculture (p.)</th>
<th>Open field (h. bio)</th>
<th>Totals</th>
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Producer’s Accuracies Totals: 22777/22781 1658/2036 277/329 85/374 38/159 138/141 405/450 188/292 564/587 101/333 292/603 133/343 KAPPA = 0.816

(b) Error matrix of classified Sentinel-2 with Landsat-8 «similar» bands. *OA = 94.40, PA = 62.68 and UA = 69.99

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<th>Felled area</th>
<th>Open field</th>
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<th>Asphalt</th>
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<th>Grass (l. bio)</th>
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Producer’s Accuracies Totals: 206877/207100 1468/15120 2406/3083 437/2741 287/2920 446/582 3566/4800 2643/3741 5092/5243 1693/3413 2461/4678 1087/3341 KAPPA = 0.944
Table 6.9: Error matrix for (a) Landsat-8 and (b) Sentinel-2 (with Landsat-8 «similar» bands) classification in August MD. * Abbreviations: OA = Overall Accuracies, PA = Producer’s Accuracies and UA = User’s Accuracies.

(a) Error matrix of classified Landsat-8. *OA = 95.54, PA = 70.31 and UA = 72.07

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<th>User’s Accuracies</th>
<th>Totals</th>
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<td>0</td>
</tr>
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<td>0</td>
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<td>Barren Veg.</td>
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</tr>
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<td>0</td>
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Producer’s Accuracies

(b) Error matrix of classified Sentinel-2 with Landsat-8 «similar» bands. *OA = 95.40, PA = 67.00 and UA = 70.02

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<th>User’s Accuracies</th>
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Producer’s Accuracies

KAPPA = 0.869

KAPPA = 0.954
Chapter 7

Discussion

This chapter aims to discuss the results presented in Chapter 6, for each case objective as presented in Chapter 1. To do this, each objective are compared to similar measurements studies, or similar instruments, as e.g., Landsat-8.

7.1 Geometric Performance

Measuring the horizontal displacement between two ortho-rectified Sentinel-2A satellites scenes, as either equal or different relative orbits, was calculated with the use of NCC matching technique in different topography, in order to quantify orthoprojection errors due to vertical DEM errors. Results from the different topography has shown that on large surfaces of which the topography change very little, similar to the flat tundra in the northern Russia Siberia has none or little horizontal displacement, whereas on the mountainously topography similar to the mountains in southwestern Norway and the western Verkhoyansk Range has a higher displacement distributed in their steepest slopes and highest elevated areas. Each site with different topography is further discussed below.

7.1.1 Flat Tundra

Displacement measurements performed on the flat tundra landscape in the northern Russia Siberia (see Section 6.1.1), has for each test shown very little displacement, except from the measurements using equal relative orbits with different processing algorithm, see Figure 6.2. Since all other displacement tests in this tile are below the median of 4 m, even the scene from 14.06.2016, which has the same processing algorithm of 02.02, it is reasonable to suggest the 08.06.2016 scene has been wrong processed, and incorrectly uploaded by ESA on the Copernicus download hub. The Sentinel-2 Data Quality Report by Clerc & MPC-Team (2017) could report a few products with the 02.02 processing algorithm having anomalies related to geolocation and miss-registration errors, and Gascon et al. (2016) could report products produced before the 02.04 processing algorithm suffered from a yaw bias correction anomaly, distinctly visible in the edge of the swath. Despite that other scenes using older processing algorithm than the 02.04 having reported anomalies, the Copernicus download hub report claim the «Geometric quality» tag as
CHAPTER 7. DISCUSSION

passed for the 08.06.2016 scene, and the product is still available for downloading regardless of having larger error than repeat orbit accuracy should have (Drusch et al., 2010), see Table 4.1.

The displacement pattern of the 08.06.2016 scene does not follow any other displacement measurements results, as it has a strong pattern of increasing displacement from east to west in the cross-track direction of the satellite, and given the distinctive pattern, the displacement could stem from the two other error budget terms as proposed in section 4.1, (i) overall scene offset and (ii) higher-order offsets patterns.

Despite promising results of all other tests in the 51WWR tile with displacement below a half of pixels size, small effects of jitter and stripe pattern were found in Figures 6.7 and 6.8, similar to tests on the commissioning ramp up phase data by Kääb et al. (2016). Small differences in jitter wavelength were found between the two studies, while Kääb et al. (2016) displays wavelengths of \( \sim 7 \pm 8 \) km, wavelength of \( \sim 2 \) km were found using different relative orbit, displayed in Figure 6.7. Notice the calculations by Kääb et al. (2016) stems from co-registration of equal relative orbit, while results found in Figure 6.7 stems from different relative orbit.

Both of the studies display jitter as an overlay between correlated images, not the jitter of individual scenes (Kääb et al., 2016). Thereby if the jitter stems from only one of the correlated images this will also be the jitter which is measured, but because the combination between the two correlated jitter pattern is a result of an increase and decrease of the two images jitter amplitude, the jitter is thereby impossible to distinguish from which image it origins from (Kääb et al., 2016). While we cannot distinguish which image has jitter, if the jitter is present in both images, the jitter has the chance of been zeroed out if one of the matched image jitter is following the other images jitter with a half wavelength, given equal amplitude (Kääb et al., 2016), but it is also in risk of been doubled following the same principle, when having matching frequency.

From Figure 6.8 three stripes is clearly visible and in Figure A.13 in Appendix A also two stripes is visible. The stripes indicate the orbit direction, and stems from «misalignments in the overlap areas of the 12 adjacent pushbroom modules that cover the 290 km swath» (Kääb et al., 2016, p. 8). Similar stripes were also found in the study by Kääb et al. (2016), but these were found when correlating similar relative orbits.

The fact that the nearly all displacement measurements on the flat topography of the tundra terrain in Russia Siberia, shows how the PlanetDEM90 cope the DSM representation of the terrain very well in this type of topography, probably because the change of elevation does not change as rapid as the mountainously terrain as represented in the two following sites.

7.1.2 Hilly and Mountainous Landscape

Displacement measured in the southwestern Norway, has from calculated statistics very low displacement, and most of the results is lower than a median of 5 m. The test of equal relative orbit has the lowest measured median of all displacement tests, 1.8 m. Even though it shows promising statistics, the Figures 6.12 to 6.17, show the displacement having higher values in the mountain regions, compared to the flat tundra in the Siberia. This is also displayed in the Figure 6.11, which compare the DEM differencing and the measured displacement between the two orbits R137 and R094.

Similar to the displacement measurements, the DEM used for ortho-rectification of Sentinel-2 scenes has a higher difference from the «ground truth» in the steepest elevations and slopes. It
seems that the PlanetDEM90 have larger errors in steep regions with high elevation differences, due to the low resolution of the DEM. Gascon et al. (2016) could report the elevation accuracy of the PlanetDEM90 to be 16 m at the 2σ, while from Table 6.3 the 2σ after the threshold filtering calculates to 30.1 m, almost the double of the accuracy by Gascon et al. (2016), but the two DEMs accuracy assessments should not simply be compared against each other as the size and location on the assessed data differ, as it is unknown which areas the calculation from Gascon et al. (2016) stems from, possible from regions or subsets inside the SRTM coverage.

If the two elevations accuracies are used with the Equation 4.3, the assumed maximum displacement of one pixel in the swath edge between two different relative orbits is for the accuracy of $\Delta h = 16$ m approximately equal to $d_{\text{max}(S2)} \approx 5.926$ m and for accuracy of $\Delta h = 30.142$ m approximately equal to $d_{\text{max}(S2)} \approx 11.164$ m.

A study performed by Gjertsen et al. (2014) compared the original SRTM below 60° north in an inland area of Norway, with the same type of dataset from Kartverket as used in this thesis. Results from the assessment could report the maximum deviation as high as 610 m, mean of -2.162 m, median -1.949 m and a std. 7.257 m, and considered the large area they assessed the comparison on, 75 % of SRTM fell within 7 m and 1.4 % of tested points have a larger deviation than 20 m (Gjertsen et al., 2014).

In the Figure 6.11, the typically larger flat areas has lower displacement compared to the higher elevated areas, which are also represented in the DEM differencing. The same figure shows how hard it is to measure well-correlated points in a changing terrestrial landscape, as seen in the higher snow-covered mountains, the change in snow-cover between the two acquisitions leads to low correlation in this areas. The same type of errors were found in edge of the mountain shadow, which leads to wrongly estimated displacement measurements.

From the two DEM assessments of the PlanetDEM90, there is possible to concludes the DEM used for ortho-rectification suffer from poor recognition of the topography in high elevated areas and steep slopes, and thereby Sentinel-2 ortho-rectified pixels is in risk of having wrong geo-location as shown in the displacement measurements, due to vertical errors in the DEM used for ortho-rectification. The PlanetDEM90 compared to the SRTM assessment shows also a much higher standard deviation when each assessment are compared against equal dataset (Kartverket).

### 7.1.3 Flat and Hilly

Tests performed on the flat and hilly terrain close to the Verkhoyansk Range, displayed in Figures 6.18 to 6.23, quantify how horizontal displacement are related to the accuracy of the DEM used for orthoprojection of the Sentinel-2 satellite scenes. The tile covers areas which has little and a high amount of displacement, given the two different topography types. From the DEM accuracy assessment, we know that in regions similar to the mountains located in the southwest Norway have large errors, which we can assume is the same for the mountains located close to the foot of Verkhoyansk Range. Thereby given the different topography and the measured displacement, horizontal errors is because of the vertical DEM errors. This is because if the displacement were given the two other error budget terms of (i) and (ii) it would be displayed in the flat area, which it does not. This is perhaps best illustrated in Figure 6.23 that on the flat area has displacement below 10 m, except on areas affected by clouds, while in the mountain topography, the displacement is $\sim 20$ m, which translates an $\Delta h \sim 54$, when applying the measured distance to formula 4.3. Notice the formula excepts the maximum distance in the swath edge, which is
not applied in this case, probably a lower $\Delta h$ is more reasonable.

### 7.2 Ice Velocity

When measuring the ice velocity from the three glaciers in Norway and western coast of the Greenland Ice Sheet, the same displacement technique were used as for the geometric performance tests. For all sites, except for Rembesdalskåka a high amount of velocity vectors were found, and all four glaciers sites are further discussed, and compared with other studies of ice velocity measurements (Table 3.4).

#### 7.2.1 Engabreen

The ice velocity measured at Engabreen were calculated to a mean of 0.36 m/d (Figure 6.24), with an error-estimation of $\pm 0.19$ m/d in a south direction, given imperfect co-registration of the two correlated scenes. The displacement of co-registration most likely affected the ice velocity result as the mean direction of measured displacement was in the south direction, almost the opposite direction of assumed and measured direction flow (Figure 6.25). Because of two distinct icefalls that is noticeable at the largest crevasses, the velocity speed changes down the glacier fall. The speed decrease before the icefall, where the surface is less steep, and speed-ups again in the icefall, were the surface is steeper.

The glacier have been measured previously with different techniques and data (Table 3.4). Jackson et al. (2005) used two aerial photographs of Engabreen and calculated the velocity using the NCC algorithm. For validation of the ice velocity from the repeat aerial photographs, stake measurements with GNSS were conducted in the study of Jackson et al. (2005), and of areas that felled inside both measurements, a good agreement were found. The velocity result measured by Jackson et al. (2005) when correlating aerial images is found in Figure 7.1. The velocity calculated by Jackson et al. (2005) in the Figure 7.1 shows several locations with good agreement between velocity generated from correlation of aerial photographs and Sentinel-2, as e.g., the distinctive circle of high velocity as displayed between the B and C mark in the figure is also found in the velocity measured using Sentinel-2 in Figure 6.24, approximately at the intersecting 7396000 m northing coordinate line. The sudden increase in velocity is due to an icefall. Other similarities is found on several other locations compared to Jackson et al. (2005) and the Figure 7.1, but while the highest velocities found in the contour velocity map in Figure 7.1 has the highest velocities outside the largest crevasses, (looks similar to a horseshoe), the velocity generated from Sentinel-2 has the highest velocities in the crevasses itself. The difference shows also a $\sim 0.2$ m/d slowdown at the glacier tongue between the studies, which could be a response of the surface mass balance (Kjøllmoen et al., 2016), as seen in other mountain regions (Paul et al., 2015). However, the measured annual surface mass balance on Engabreen in 2015 was positive (0.61 m w.e.), the annual surface mass balance was measured for 2013 and 2014 to be -1.86 m w.e. and -0.97 m w.e. respectively (Kjellmoen et al., 2016). Because there is a time lag between positive surface mass balance respond to increasing ice velocities, the later measurements should be taken into consideration. The velocity slowdown at the glacier tongue by the Sentinel-2 could also stem from different timing between the two measurements.

From the report series of glaciological investigations in Norway by Kjøllmoen et al. (2016) GNSS stake measurements were used to measure annually velocity by five stake locations (not shown). By the five stakes measurements, just stake E17 were found inside the Sentinel-2 velocity mea-
Figure 7.1: Contour map of velocity by Jackson et al. (2005) on the Engabreen outlet correlated from two aerial orthophotos acquired on 20.08.2002 and 10.09.2002. Velocity contours values in cm/d.

measurements (Figure 6.24). The E17 stake is located approximately in the intersecting northing coordinate line 7396500 m on the glacier tongue in Figure 6.24. The mean stake velocity for this stake is for the period measured by Kjollmoen et al. (2016) to be:

\[
\begin{align*}
2000-2003 &= 0.45 \text{ m/d} \\
2007-2009 &= 0.35 \text{ m/d} \\
2013-2015 &= 0.23 \text{ m/d}
\end{align*}
\]

While for Sentinel-2:

\[
2016 \approx 0.2-0.3 \text{ m/d}
\]

Of other techniques and data used for ice velocity measurements, Messerli & Grinsted (2015)
CHAPTER 7. DISCUSSION

Figure 7.2: Annually mean surface velocity measurements at Engabreen by Messerli (2015), correlated from Landsat-8 with the NCC algorithm.

used time-lapse camera and Messerli (2015) used Landsat-8 to calculated the annually mean velocity using the NCC algorithm for correlating the images, see Figure 7.2 for annually velocity measurements for 2013 and 2014 using Landsat-8. In contrast to measurements from Sentinel-2, Messerli & Grinsted (2015) measure velocities up to 1 m/d in the lower icefall in 2013 using correlated time-lapse images, compared to Sentinel-2 derived velocity of 0.7 m/d in the same area. The velocity difference could stem from the difference timing of the measurements, the maximum velocity pair by using the correlated time-lapse images were reported during a spring-speed up event (Messerli, 2015). Good agreement between the 2013 Landsat-8 mean velocity (Figure 7.2a) and the calculated velocity by Sentinel-2 were also found (Figure 6.24).

7.2.2 Nigardsbreen

Off glacier measured in Norway using the Sentinel-2 satellite, Nigardsbreen were measured to have the highest velocity of the three Norwegian glaciers, of $\sim 1.33-1.66$ m/d in the steepest icefall, and a mean velocity of 0.52 m/d. The mean co-registration error were measured to be 0.17 m/d in a southeast direction, and thereby the ice velocity at Nigardsbreen are significantly higher than the co-registration error between the two correlated images.

The measured velocity at Nigardsbreen using Sentinel-2 seems to match other studies using the same image matching software CIAS (but with older version) as assessed by Wangensteen et al. (2006), using aerial photos for images. Wangensteen et al. (2006) could report a mean ice velocity of 0.56 m/d, when measuring on a slightly less area of the glacier, see Figure 7.3 compared to the mean 0.52 m/d using Sentinel-2 (Figure 6.26). Small differences between the maximum measured velocity in the icefall are found between the two studies, Wangensteen et al. (2006) measured velocity of 1.34 m/d in the icefall, whereas velocity derived by Sentinel-2 measured velocity up to 1.46 m/d. Notice the different timing between the two studies, which affects the comparison. The study by Wangensteen et al. (2006) calculated the velocity using images from August, while velocity calculated using Sentinel-2 were from images between the September-October periods.
The GNSS measurements used for validate the result from image matching in the Wangensteen et al. (2006) study, reveals good agreement between the two measurements methods, as the difference is only 0.01 m/d. At similar GNSS stake measurements points from Wangensteen et al. (2006) (not shown), the Sentinel-2 generated velocity falls within the 0.33 velocity range in Figure 6.26. While Wangensteen et al. (2006) measure lower velocity on the glacier snout late summer using GPS, similarly the measurements from Sentinel-2 that were measured from a period later in the season, has lower velocity on the same area. Wangensteen et al. (2006) correlate the slow-down because of a drop in the subglacial water pressure gives less surface melting in this period. The correlation between the subglacial water pressure and ice velocity are well known from earlier studies by Iken & Bindschadler (1986). The slowdown could also stem from the same reason as suggested happened at Engabreen, a decrease of annual surface mass balance the later year (Kjøllmoen et al., 2016), as seen in Figure 7.4.
Figure 7.4: Nigardsbreen annually mass balance for the period 1962-2015. Figure by Kjøllmoen et al. (2016).

7.2.3 Rembesdalskåka

The ice velocity vectors measured at the Rembesdalskåka glacier is not significant, given the inaccuracies of the co-registration between the two matched images are larger than the mean derived velocity. Ice velocities measured using GPS stake measurements by Kjøllmoen et al. (2016) displays velocities of ice at 0.156 m/d just north to the area that are covered by mountain shadow in Figure 6.28, and speed up to 0.192 m/d in the approximately intersecting easting coordinate line 408500 m in the figure.

The measured co-registration error between the two correlated scenes was calculated to ±0.29 m/d which is higher than measured mean using Sentinel-2 and measured velocity using stake GNSS (Kjøllmoen et al., 2016). Assuming the highest velocity measured by Kjøllmoen et al. (2016) by 0.192 m/d, required baseline for measuring this velocity is ~ 30 days, only then the co-registration error is equal the assumed highest velocity. It is possible other correlated data-scenes have lower, but also higher co-registration errors.

When assuming the co-registration is perfect, and assuming a velocity between ~ 0.15 and ~ 0.2 is the reasonable value at the glacier tongue as «ground truth» measurements, all measurements in Figure 6.28 higher than 0.2 is possible incorrect measurements. The measurements close to the glacier basin indicator is especially questionable, and could stem from either mountain shadow or snow-fall between the two images acquisitions.

Ice velocity measurements at Engabreen, shows the need for another satellite, as Sentinel-2B (in-commissioning), in order to double the temporal resolution and thereby possible lower the amount of scenes with cloud cover, but also the need for improving the DEM used for ortho-rectification, which will allow using different overlapping relative orbits. As shown in the Figure 2.1, the potential temporal resolution of Sentinel-2 above the Arctic Circle will be overlapped three times within the ten day temporal resolution for on satellite, and doubled for two.
7.2.4 Greenland Ice Sheet

In contrast to velocities measured at the Norwegian glaciers, the ice velocity at the west coast of the Greenland Ice Sheet, is considerably higher, as the calculated mean is $1.616 \text{ m/d}$, over three times higher the mean of Nigardsbreen. The co-registration measured at Greenland is also the lowest of all measured glaciers, measured to $\pm 0.12 \text{ m/d}$ given the 20 days baseline.

The profile comparison between the Sentinel-1A/B and Sentinel-2A satellites in Figure 6.32 is showing overall good agreement, and suggest synergy of the two satellites as a possible solution for future velocity measurements. Kääb et al. (2016) constructed similar comparison in the study of comparing the Greenland Ice Sheet CCI Products annual ice velocity from Sentinel-1 between January and March 2015 period (Nagler et al., 2015), against Sentinel-2 in the August and September 2015 period. Kääb et al. (2016) also discovered a slightly higher velocity close to the calving ice, but also an overall good agreement between the two satellites was found. The increase in speed closer to the glacier terminus measured in this thesis could be because of the different timing for each product, while the Sentinel-1 profile is from the winter mapping period, the line from Sentinel-2A is from an early summer period. As glaciers tend to have higher velocity in the summer compared to the winter, due to the change of subglacial meltwater (Bartholomew et al., 2010).

As the result using Sentinel-2 is rather promising, and has a good agreement with the Sentinel-1 satellite, future acquisitions from both of the satellites could further investigate relation of summer/winter ice velocity and their relation to the subglacial environment and how they are affected by the surface meltwater as over 95% of the available meltwater enters the englacial drainage system (Koziol et al., 2017).

The potential to measure ice velocity on the Greenland Ice Sheet with the synergy of Sentinel-1A/B and Sentinel-2A/B is huge, and because Greenland is located as far north, overlapping relative orbits (Figure 2.1) making annual velocity investigations more feasible, because the potential of lowering amount of scenes with cloud cover and Sentinel-1 could fill the data gap in the winter time when Sentinel-2 can not acquire any imagery due to the low solar elevation (polar night). In the future, both satellites ice velocities products should continue to deliver measurements to the Greenland Ice Sheet CCI project, which let EO users and scientists investigate this remote ice sheet fast and effective for a long comparable time.

7.3 Land Cover Classification

As a result of Sentinel-2 and Landsat-8 was classified using the MD algorithm, in order to create a land cover classification covering the southeastern Norway and eastern Sweden. Four classification maps for each period in August and October were created (see Table 3.2 for individual dates): Landsat-8 using all bands, Sentinel-2 L1C using all bands, Sentinel-2 using Landsat-8 «similar» bands, and Sentinel-2 using L2A bands. The different bands combination of Sentinel-2 were created to distinguish differences between the Sentinel-2 and Landsat-8, and differences between the difference producing level of Sentinel-2 L1C (TOA) and Sentinel-2 L2A (BOA).

This thesis discussion are about the land cover classification results as displayed in Section 6.3 and are divided into three points:

1. Differences between the Landsat-8 and Sentinel-2 using Landsat-8 «similar» bands.
2. Differences between the Sentinel-2 L1C (TOA) and Sentinel-2 L2A (BOA).
3. Seasonal differences.

Both point 1 and 2 discuss the different result within each season, as the different classification consist of one result in August and October, see Table 3.2 for specific dates.

Of factors that shows inconsistencies, when comparing classifications are:

(i) Different spatial resolution.
(ii) Different spectral configurations.
(iii) Different dates of acquisitions.
(iv) Different illumination.
(v) Geo-location accuracy.
(vi) Reflectance variations, as either TOA or BOA.

While (i), (ii), (iii), (iv) and (v) is the most important factors to know about when discussing differences between Landsat-8 and Sentinel-2 using Landsat-8 «similar» bands (point 1), the (vi) is the dominant factor when discussing differences between the Sentinel-2 L1C and Sentinel-2 L2A (point 2), and (iii) and (iv) is the most important factor to discuss when comparing differences in seasonal classified result (point 3). Other important factors as differences in soil moisture could give different spectral differences between the different acquisitions (J. R. Jensen, 1983; Singh, 1989), and thereby affect each classification map.

A drawback of all resulting accuracy assessment (i.e., error matrices), is the lack of reference data. From all calculated error matrices and Kappa values, the reference data used is equal to the data used for training pixels, and thereby break all assumptions of independence and biases the assessment in the approval of a final classification result (Congalton & Green, 2008). Even though the error matrices in Tables 6.7 to 6.9 is estimated without the optimal use of reference data, they will further be discussed, and treated as «correct» further below, as they illustrates how an accuracy assessment should be conducted and assessed.

7.3.1 Comparison of Landsat-8 and Sentinel-2 Using Landsat-8 «Similar» Bands

When classifying a land cover map, the spatial scale must be considered (i), as a land cover classification used for climate models, depends less on high resolution in order to have a reasonable computation time, whereas a land cover classification used for agriculture usages should have a high as possible resolution, in order to distinguish different land cover and biophysical levels. Example of where the high resolution of Sentinel-2 does not matter are displayed in Figure 6.34 which when displayed on a Sentinel-2 tile (100 × 100 km), disparities between this classification and the Landsat-8 classification (Figure 6.33) is not possible to distinguish visually from each other. In contrast when displaying a typical agriculture extent of ~ 3 × 3 km as seen in the two Figures 6.35 and 6.36 the pixel resolution of 30 m for Landsat-8 clearly limits the fully potential of an agriculture classification at this level of extent.

When comparing results of land cover classification between the Landsat-8 and Sentinel-2 using «similar» Landsat-8 bands within the same month, differences of pixel resolution is one of many
variables which affect a direct comparison between the two products, other variables which affect the classification results is differences in the two satellites spectral configuration (ii). The classification of Landsat-8 compared to the classification Sentinel-2 using Landsat-8 «similar» bands, displayed as c) and d) in Figure 6.35 and 6.36, are showing large discrepancies in type of land cover which has been classified within each season. Even though the classifications were classified with shortest possible baseline between the two acquisitions, and bands were simulated to match each others configurations, differences are visible as difference land cover representation by the two different sensors.

The differences probably stems from small changes in the spectral configuration (ii), which in turn would translate to different recorded radiometric values. As presented in the Satellite Overview in Section 2 and Table 2.1 the spectral position and bandwidths of each band differ between all bands, except band 1 between the two sensors. Figure 7.5 simply displays the differences that are expected in the spectral response relative to radiance between the two NIR bands B8 and B8A for Sentinel-2 and B4 and B5 for Landsat-8. Disparities in the relative spectral response in NIR-and other used bands matter for comparison when we are classifying every images using equal training dataset and different sensors, but is likely less important when classifying separately using independent training dataset (Lu et al., 2004; Mandanici & Bitelli, 2015, 2016).

![Figure 7.5: Total spectral response (normalized to 1) for Band 8 and 8A for Sentinel-2 and for Landsat-8 band 4 and 5 relative to radiance. Superimposed in the figure is the lawn spectral reflectance curve. Figure by Mandanici & Bitelli (2016).](image)

From visual inspection, large differences were found in the August period in contrast to the October period. For the August period, differences as marked in Figure 6.35, shows how different classifications in areas of where plowed agriculture is wrongly classified (arrow number 1, 2, 3, 5 and 6) by both classifications, as barren vegetation for Landsat-8 and urban and felled area for Sentinel-2 using Landsat-8 «similar» bands. Finding out which band is the reason is a difficult process and possible an own study of itself, but from the spectral overview in Table 2.1 one solution could be the difference of VNIR and NIR bands which is used in the two classifications,
see Figure 7.5, as the bands include an import heritage of vegetation (Lillesand et al., 2007). Small changes in the spectral configuration would turn into variation in the recorded radiometric values, which in turn is what matter when classifying based on spectral response.

The two datasets used for each period (August and October) are captured at different date/time and under different solar conditions (iii and iv), see Table 3.2 for specific solar elevation and Azimuth angle in addition to time of day the scene is captured. The classification were conducted with as short baseline between the two acquisitions as possible, but still the classification is in risk of being slightly different for each month because of inconsistency sun angle and scene capture time (Singh, 1989). Differences for satellites sensors within same month as displayed in Table 3.2, has very little change in sun angle and time, but still there is a difference which could be effective enough to change the land cover reflectance with this short time period.

Because different illumination between the two seasons, shadowing from large groups of trees at different locations (not shown) was for the unsupervised classification and for some of the supervised classification classified as water, and as displayed in the error matrix of Landsat-8 in October, see Table 6.8a, the user’s accuracies show that 1.5% of all pixels claimed to be in the water class was actually classified as evergreen. This type of error were not encountered in the August period, probably because of a much higher solar elevation as displayed in Table 3.2 in contrast to the October period.

When going through the classification methodology (Section 5.3) the plan was first to assess the classification in August, and then for the October period, just change the respective training polygon class if change between the two seasons were noticed from either the RGB visual or the unsupervised classification. But because of the Sentinel-2 scene acquired in October had shifted about one pixel, between the scene from August (v), small training pixels of e.g., urban, asphalt, mires and open field, had to be moved, and changed in size in order to overcome the criteria of the training pixel should cover both the Landsat-8 scene and the Sentinel-2 scene. The changes would affect the comparison between Landsat-8 and Sentinel-2 using Landsat-8 «similar» bands (point 1 and 2) in a positive way, because each training pixel probably represents each class more correctly if not changed position and size but just adjusted the class.

Despite all meta-data geometric quality tags of the Sentinel-2 were tagged as «Passed», the pixels shifts were measured by flicking between the two different Sentinel-2 scenes (in August and October). The reason for the shift is probably not the same as revealed in Section 6.1 as horizontal shift due to DEM errors, because both Sentinel-2 datasets has equal relative orbits and in theory the horizontal shift, due to DEM errors will be present in both, and thereby be eliminated (Kääb et al., 2016). The shift must thereby stem from one of the two other horizontal bias categories (see Section 4.1), as either overall scene offsets (i) or higher-order offset patterns (ii). The error could stem from errors or inaccuracies in spacecraft attitude e.g., on-board star tracker or on-board GPS receiver.

The solution to this problem is the under development GRI (see Section 4.1.2) which aim to use cloud free ortho-rectified Sentinel-2 images, and based on tie-points and GCPs between the cloud free image (reference image) and the working image (as of it is in the L1B stage), it will be adjusted to match the GRI image by applying bundle block adjustment (Baillarin et al., 2012; Gascon et al., 2016). Thereby all future and readjusted images are adjusted by the same set of GRI, and in the future the same set will be used to adjust Landsat-8, as the miss-registration could be expected as high as 38 m between the two sensors (Storey et al., 2016). Both sensors using the same GRI, would improve the synergy between the two satellites, while meantime, the users is advised to manually/automatically pick tie-points and apply the bundle adjustment from one image to the another (Storey et al., 2016).
From the calculated error matrices the overall accuracies, producer’s accuracies, user’s accuracies and Kappa were calculated for each period, for the Landsat-8 and Sentinel-2 using Landsat-8 «similar» bands, see Table 6.7. Even though the overall accuracies is high as 95 % in August and 94% in October, because it is an average weighted value it does not show any large distribution biases between classified classes, and classes which has low accuracy, i.e., low user’s or producer’s accuracies. Beside the calculated accuracies, the Kappa value of all classified data is above 0.8 and translates to strong agreement (Landis & Koch, 1977).

Example of classes which does not represent the high value of overall accuracies is e.g., the urban class for Landsat-8 for the August period. The urban class has been correctly identified as urban 87.2% (Table 6.9a), but only 57.3% of the areas classified as urban on the map are actually urban on the ground. Similar example is found between e.g., the barren vegetation class. The error goes also the other way, as e.g., the felled area claims to be actually classified 73.5% accurate but of produced pixels of felled areas, it has only been labelled correctly 26.0%.

If looking into the three classes: barren vegetation, urban and felled area, as these three classes represents classes which is highly difference visually between the two classifications results. Of barren vegetation, which Landsat-8 classify wrongly on large plowed agriculture areas (c) in Figure 6.35 and 6.36, the producer’s accuracies is high as mentioned earlier for Landsat-8, but even higher for Sentinel-2, 95.5% , but of actual classified pixels, the accuracy is low as 49.1%. The urban class differ even more between the two classifications producer’s accuracies in both August and October period. The urban producer’s accuracies in the October period is high as 97% for Landsat-8, and a high user’s accuracies of 77.1%, while Sentinel-2 using Landsat-8 «similar» bands has a low producer’s accuracies as 54.0% and an even lower user’s accuracies of 28.0% in the October period. The reason for urban producer’s accuracies is so low for Sentinel-2 using Landsat-8 «similar» bands differ for the two periods August and October. While the reason for August is high values from felled area and asphalt, the reason for October is truly grass with low biomass, but visually urban were more wrongly classified in August, in Figure 6.35.

A visually error which goes through all classifications is the poor representation of correctly classified asphalt. From the Figures in the AOI (see Figure 6.35 and 6.36), both classifications struggle to map the asphalt which is represented in the AR5 classification from NIBIO as the transport class, see a) in Figure 6.37. For the October period, Landsat-8 has almost none pixels classified as asphalt. In both seasons, the Sentinel-2 manage to distinguish the road north of the lake, as represented as arrow number 4 in August and arrow number 5 in October, but in both periods it has been wrongly classified as urban, but still a better representation than the Landsat-8, mapped as barren vegetation and felled area.

From the error matrices, the mixing of urban and asphalt is strong, and while there probably is multiple reasons for the mixing, it could for instance be the fair spatial resolution but more likely it is because urban and asphalt classes may share the same spectral response (Myint et al., 2011). The problem stems from how we humans distinctly class urban and asphalt as distinctly difference classes while in the spectral response they are very similar (Myint et al., 2011), this is well illustrated in Figure 6.38 which show how spectral similar the urban and asphalt classes is for each band, notice that band 6, 7 and 8 was not used in the classification of Sentinel-2 using Landsat-8 «similar» bands. By looking at the figure, the similarity is visible, and is truly a problem for the different algorithms that is based on spectral differences, as those mentioned in Section 4.4.3. A solution to overcome the inaccuracies of urban and asphalt classification is to use objective classification as it are demonstrated to be a significantly better approach than the classification algorithms which is based on spectral inconsistencies are (Myint et al., 2011), such as the MD-algorithm used in this land cover classification.
7.3.2 Differences Between the Sentinel-2 L1C (TOA) and Sentinel-2 L2A (BOA)

Comparing of the two different classifications using the same Sentinel-2 datasets as either L1C or L2A, differences in the TOA and BOA spectral representation became visible. The BOA product is in contrast to the TOA representing the surface reflectance after an atmospheric correction has been applied (Gascon et al., 2016) and thereby influence the spectral depended classification because of possible different spectral values from the BOA. Visually differences between the TOA and BOA displayed in Figure 6.35 and 6.36.

Locations in the Figure 6.35 as pointed out as arrow number 2, 4, and 5 in the August period is location where the two classifications differ, mostly for the urban and asphalt classes. For the October period as in Figure 6.36 arrow number 6 and 7 is location where the classification differ in the October period, but this time it is the difference between the barren vegetation and urban which they two classification mixes up. The road north of the river marked as arrow number 4 in 6.35 and 5 in 6.36 is in both seasons classified better in the BOA classification as a line of single pixels of asphalt. Other locations as arrow number 5 in Figure 6.35 both classifications has classified the plowed agriculture area as urban and asphalt, but the BOA classification has a larger area of asphalt. Of the scene from October, the largest disparities between the two classification is in the plowed areas where both classification struggles and classify areas as barren vegetation, but the BOA classification map some areas as urban in addition, as seen in arrow number 4. The Sentinel-2 BOA classification is for the October period, classifying some canopy shadow as water, in the October period, as seen as arrow number 3 and 8 in Figure 6.36.

From the two figures (6.35 and 6.36), classes of which contain a high vegetation index, as illustrated in Figure 6.37, the change between TOA and BOA is very small, and both classifications manage to represent areas with high amount of chlorophyll very well. Where both classifications struggle is in areas with low chlorophyll content and it is in this locations where the different classifications differs.

7.3.3 Seasonal Differences

Because of the relative short temporal resolution for Sentinel-2 of 5 days when Sentinel-2B is fully operationally, and the possibility of an even shorter temporal resolution when combined with Landsat-8 overlapping relative orbits, will for users who wish to monitor biomass change through season be more feasible when combining different EOS datasets for land cover classification and change detection, given the possibility of clouds in an image drops when using a higher amount of images. By using only two different acquisitions the seasonal and anthropogenic changes is clearly visible between the two seasonal classifications in August (Figure 6.35) and October (Figure 6.36) after comparing the two classifications visually.

Finally as the spectral response has changed between the two acquisitions in turn of changes of seasons or anthropogenic changes as of plowing the cultivated land, differences in the chlorophyll content changes, as visible in the NDVI in Figure 6.37. By the mapped calculated NDVI (Figure 6.37) the change of season which is illustrated as a more soft biomass change, see arrow number 3 and 4 in the figure, is distinct differently from the anthropogenic changes as plowing as pointed out in arrow number 1. When it comes for the visual differences between the Sentinel-2 and Landsat NDVI comparison, the spatial resolution has an impact of distinguish small elements which has none chlorophyll content, e.g., houses and roads, as an index close to -1 for Sentinel-2,
but for Landsat-8 because of the poor spatial resolution, the index varies around 0, see arrow number 2 and 5. None of the classified maps has any well representation of urban areas as the single houses which are well represented in the NDVI calculation in Figure 6.37 indicated as low index.
Chapter 8

Conclusions

This thesis focus was on testing the geometric performance on the Sentinel-2A satellite imagery, and how this affected the geolocation for repeating orbits. Secondly, Sentinel-2A sensor was tested in this work on two geoscience applications: land cover classification and measuring ice velocity on glaciers. The conclusion from this thesis are summarized below for each category.

8.1 Geometric Performance

The geometric performance were tested at three different test locations with different topography, such as flat tundra, hilly and mountainous, and flat and hilly. The conclusions are:

- The horizontal displacements measured between Sentinel-2A data from repeat orbits were typically less than the pixel size of the Sentinel-2 (10 m).
- When horizontal displacement were measured between Sentinel-2A data using different relative orbits, the offsets increase between the matched images, as it is highly affected by vertical DEM errors used for ortho-projection of the images. The vertical DEM errors stems from a poor surface representation of the Russian maps, the DEM was based upon in the northern Scandinavia and Russia.
- Horizontal displacement in the west-east components of approximately ~ 2 m was found, caused by jitter.
- The sensor clearly shows signs of stripe pattern in orbit direction, most likely caused by misalignments in the detector overlap of the pushbroom sensor.
- The horizontal displacements measured in the west-east direction were found to be larger in the swath edge, due to larger geometric distortions caused by the large swath of 290 km.
- A product with large anomalies is still available for download at the Copernicus data hub, even after the calibration and validation team readjusted their processing algorithm and scheduled a reprocessing of scenes with anomalies.
CHAPTER 8. CONCLUSIONS

8.2 Ice Velocity

The Sentinel-2 sensor was used to calculate ice velocity at three glaciers in Norway and four glacier at the Greenland Ice Sheet, and the conclusions were:

- Results using the 10 m Sentinel-2 data shows that ice velocity dynamics is possible to measure, and has proven to detect similar glacier dynamics when measured with much higher spatial resolution e.g., aerial photographs and time-lapse cameras.
- The ice movement needs to be larger the co-registration error, between two satellite imageries used, which is a limitation when deriving ice velocity from Sentinel-2.
- The Sentinel-2 has shown similar, but also different velocity measurements at the Greenland Ice Sheet as the SAR satellite Sentinel-1A/B due to seasonal differences. When using both satellites in synergy, one could better understand ice sheet behaviour and seasonally differences.
- Improving the DEM used for ortho-rectification will allow use of different relative orbits for calculating ice velocity, and thereby increase the number of potential useful images for ice velocity calculation. Today, when deriving ice velocity from different relative orbits it has to large co-registration error.

8.3 Land Cover Classification

An agricultural region in southeast Norway and eastern Sweden has been classified using the Landsat-8 and Sentinel-2A satellite. By using a simple variant of hybrid classification, of combining unsupervised and supervised classification, the work has resulted in four different classifications in two different seasons, in order to distinguish differences between sensors with different band combination, processing level and seasonal changes, from this work the conclusions are:

- Both Landsat-8 and Sentinel-2 using Landsat-8 «similar» bands classification has very similar results compared to each other. However because of differences in their spectral representation, small changes were found, typically the anthropogenic land classes dominated these classes.
- A proper classification accuracy assessment were set back by the lack of proper reference data. When using the training pixels as the reference data, overall accuracy was measured as high as 95%, however from the error matrices, distinct classes shows low accuracy, typically classes which share similar spectral response, as e.g. urban, asphalt, felled areas and open field.
- Differences between the two sensors spatial resolution (Landsat-8, 30 m and Sentinel-2, 10 m) are highly visible when comparing the two sensors classification results. The lower spatial resolution for Landsat-8, limits the truly potential to reflect the true classes at the surface, as e.g., asphalt and smaller urban surfaces.
- High similarity between the classified L1C (TOA) and L2A (BOA) processing products. However, while L2A has larger error of classifying canopy shadow as water, it has also the best representation of the asphalt class.
- Classes which is poorly represented in all classifications, is the urban and asphalt class, because their share similar spectral response and are limited by spatial resolution.
• Both satellite sensors and the different processing levels by Sentinel-2, represents the seasonal differences very well, as both anthropogenic and biomass change is detected between the two classified periods.

• Finally, between the two Sentinel-2A scenes used for classifying, a shift of one pixel was registered, due to the inaccuracies geometric performance, in contrast to Landsat-8 which were stable between the two seasons.

Overall, the quality of the Sentinel-2 sensor has shown well performance and the sensor will be an important tool for future applications and provide datasets which could be used for monitoring essential climate variables for a long time. However, there are some constrains which should be given before using the large dataset archive, for instance using different relative orbits on topography which is poorly represented by the digital surface model used for the ortho-rectification should be taken into consideration. Many EO applications will be constricted to use repeat orbit, but future improvement of the DSM used for ortho-rectification will perhaps resolve this issue.
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Appendix A

This thesis appendix displays information, as e.g., swath coverage for the difference orbit for each tile in the geometric performance test, and meta-data for satellite scenes used in this thesis, in addition to figures which was not essential for drawing a conclusion, but which has been calculated in difference statistics tables.

A.1 Geometric Performance

A.1.1 Flat Tundra
Figure A.11: The difference relative orbits swath covering the 51WWR tile. Source: Google Earth.

A.1.1.1 Different Relative Orbits - R104-R018 (i)
Figure A.12: Direction diagram of displacements between the two scenes 14.06.2016 (i) and 28.06.2016, having different relative orbit.
Figure A.13: Displacement (in m) between the two scenes 14.06.2016 and 28.06.2016, having different relative orbit. A distinct stripe pattern is visible on the image.
A.1.1.2 Different Relative Orbits - R104-R018 (ii)

Figure A.14: Direction diagram of displacements between the two scenes 02.09.2016 (ii) and 28.06.2016, having different relative orbit.
APPENDIX A.

Figure A.15: Displacement (in m) between the two scenes 02.09.2016 (ii) and 28.06.2016, having different relative orbit.

A.1.2 Hilly and Mountainous Landscape
Figure A.16: The difference relative orbits swath covering the 32VMQ tile. Source: Google Earth.

A.1.3 Flat and Hilly
Figure A.17: The difference relative orbits swath covering the 51WX5 tile. Source: Google Earth.

A.1.3.1 Different Relative Orbits - R061-R018
Figure A.18: Direction diagram of displacements between the two scenes 20.08.2016 and 16.09.2016, having different relative orbit.
APPENDIX A.

Figure A.19: Displacement (in m) between the two scenes 20.08.2016 and 16.09.2016, having different relative orbit. The larger displacement on the flat terrain is due to cirrus and large biophysical changes between the two acquisitions.
A.2 List of Data

A.2.1 Geometric Performance

Used imagery for flat tundra area,
S2A_OPER_PRD_MSIL1C_PDMC_20160608T082616_R018_V20160608T032541_20160608T032541,
S2A_OPER_PRD_MSIL1C_PDMC_20160614T091822_R014_V20160614T034537_20160614T034537,
S2A_OPER_PRD_MSIL1C_PDMC_20160621T112603_R061_V20160621T033833_20160621T033833,
S2A_OPER_PRD_MSIL1C_PDMC_20160628T083634_R018_V20160628T032538_20160628T032538,
S2A_OPER_PRD_MSIL1C_PDMC_20160902T220222_R104_V20160902T034532_20160902T034534,
S2A_OPER_PRD_MSIL1C_PDMC_20160917T055736_R018_V20160916T032532_20160916T032532

Used imagery for flat and hilly area,
S2A_OPER_PRD_MSIL1C_PDMC_20160904T194734_R018_V20160718T032542_20160718T032540,
S2A_OPER_PRD_MSIL1C_PDMC_20160821T141452_R061_V20160820T033542_20160820T033537,
S2A_OPER_PRD_MSIL1C_PDMC_20160902T220222_R104_V20160902T034532_20160902T034534,
S2A_OPER_PRD_MSIL1C_PDMC_20160905T185631_R118_V20160903T031542_20160903T031539,
S2A_OPER_PRD_MSIL1C_PDMC_20160917T055736_R018_V20160916T032532_20160916T032532

Used imagery for hilly and mountainous landscape,
S2A_OPER_PRD_MSIL1C_PDMC_20161004T181150_R137_V20161004T110912_20161004T110942,
S2A_OPER_PRD_MSIL1C_PDMC_20161008T190153_R051_V20161008T105022_20161008T105022,
S2A_OPER_PRD_MSIL1C_PDMC_20161011T183000_R094_V20161011T105952_20161011T10223,
S2A_OPER_PRD_MSIL1C_PDMC_20161014T212250_R137_V20161014T111012_20161014T111009

A.2.2 Ice Velocity

Used imagery for Engabreen,
S2A_OPER_PRD_MSIL1C_PDMC_20160724T052607_R094_V20160723T105623_20160723T105623,
S2A_OPER_PRD_MSIL1C_PDMC_20160823T200335_R094_V20160822T105652_20160822T105653

Used imagery for Nigardsbreen,
S2A_OPER_PRD_MSIL1C_PDMC_20160905T215913_R137_V20160904T110652_20160904T110817,
S2A_OPER_PRD_MSIL1C_PDMC_20161004T183809_R137_V20161004T110912_20161004T110942

Used imagery for Rembesdalskåka,
S2A_OPER_PRD_MSIL1C_PDMC_20161013T114437_R051_V20160918T105022_20160918T105022,
S2A_OPER_PRD_MSIL1C_PDMC_20161008T183203_R051_V20161008T105022_20161008T105022

Used imagery for the Greenland Ice Sheet,
S2A_OPER_PRD_MSIL1C_PDMC_20160714T223352_R111_V20160714T152910_20160714T152910,
S2A_OPER_PRD_MSIL1C_PDMC_20161018T235720_R111_V20160803T152912_20160803T152910

A.2.3 Land Cover Classification

Used imagery for land cover classification,
S2A_OPER_PRD_MSIL1C_PDMC_20160817T201311_R008_V20160816T104022_20160816T104025,
S2A_OPER_PRD_MSI1C_PDMC_20161005T201135_R008_V20161005T104022_20161005T104018,
LC81970182016227LGN00,
LC81970182016275LGN00