Detection of Landslides

By Satellite Remote Sensing

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TBA 4510 – Geotechnical Specialization Project
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Abbreviations and Symbols

EWS	Early Warning System
ESA	The European Space Agency
NVE	The Norwegian Water Resources and Energy Directorate (Norges Vassdrag og Energidirektorat)
NGI	Norwegian Geotechnical Institute (Norges Geotekniske Institutt)
NDVI	The Normalized Difference Vegetation Index
NDSI	The Normalized Diffference Snow Index
NDWI	The Normalizd Difference Water Index
NIR	Near Infrared
SWIR	Short Wave Infrared
DEM	Digital Elevation Model
NDSI*	The Normalized Difference Soil index

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1 Introduction

A larger part of the globe experiences some level of landslide activity. On average, about 1000 human lives, and hundred of millions of dollars of damage per year are lost due to landslides worldwide (Clague and Stead, 2012).

In Norway, the topography and morphology, together with the climatic conditions contribute to frequent landslide activity. Debris avalanches, rock falls, and snow avalanches are all common hazards that cause monetary losses, or even loss of life. Along the Norwegian road network in the period 2000-2009 in the range of 1500-2000 events of sliding activity were recorded per year (Bjordal et al., 2011). Since 2004, there has been five fatalities due to landslides in soils, and it is estimated that about 125 fatalities have occurred over the past 150 years (Colleuille et al., 2017).

With changing climatic conditions and more extreme weather patterns, we are likely to see an increase of such events. Understanding the triggers and mechanisms behind these events is crucial for accurate forecasting and risk mitigation.

As part of the research program “Klima 2050”, research is being conducted to address the problem of rainfall induced landslides, for the purpose of building resilience to the adverse effects of climate change in Norway. With a higher frequency of extreme weather events, Early Warning Systems (EWS) are a possible cost effective approach for risk mitigation. A key aspect of a landslide EWS is accurate forecasting, which involves identifying locations vulnerable to landslide activity and understanding the conditions in which landslides are triggered. Freely available satellite imagery may be a useful source of information to complement ground-based instrumentations to understand more about the occurrence of landslides, particularly in a country with low population density, such as Norway.

1.1 Background

For the purposes of identifying locations vulnerable to landslide activity and predicting future landslides, one would typically look to a record of historic events to see where landslides have happened in the past. The documentation of landslide events in Norway is mainly completed by the road and railroad network authorities who are responsible for clearing the transport routes after landslides occur. The events are stored in the landslide database (www.skrednett.no) maintained by NVE (Devoli, 2017). However, this makes the database of events biased, as few events that happen away from roads or railways are recorded. Additionally, the information about the events is rather limited; the landslide type may be misclassified (e.g. debris flows recorded as rock fall), and little or no information is provided about the timing of initiation or potential causes. Therefore, much filtering is needed in order to do statistical analyses using this the database (Devoli, 2017). A more complete database, would possibly be a basis for obtaining more knowledge about these events' causes and their mechanisms, and ultimately contribute to more accurate forecasting.

Norway has an operational forecasting system for landslides, which defines different hazard levels based on hydrological thresholds which triggered events in the past (Colleuille et al., 2017). It can be hypothesized that remote sensing techniques and satellite data can be used in combination with ground-based observations to detect landslides, by providing supplementary information about the earth's surface. The European Space Agency (ESA) is developing and operating a series of "public" satellites, which are designed to monitor different aspects of our planet; atmospheric, oceanic and land monitoring[1]. The satellites improved technical specifications, wider spatial coverage and publicly available data may provide valuable information regarding natural hazards and landslide activity.

ESA's Sentinel-1 and 2 missions will be used as basis for this project. The first satellites were launched in 2014 and 2015, and have higher spectral and temporal resolution than previously launched public satellites. The Sentinel-1 mission comprises of two polar-orbiting radar satellites, designed for land and ocean monitoring, while the Sentinel-2 mission comprises of two polar-orbiting satellites with optical instruments, designed for land monitoring. The two satellites acquire data in different spectra, which will provide a wider range of data that can be utilized for investigations.

1.2 Problem Description and Objectives

The purpose of the KLIMA 2050 research on EWS, is to allow automatic detection of landslides, to improve records, and to provide further information about causes and triggers, so that this information can be used to predict landslides and provide warnings when people are at risk from landslides.

The main aim of this project is to contribute to the KLIMA 2050 research, by investigating how remote sensing data from ESA's Sentinel-1 and 2 public satellites can be utilized to detect new landslide events in Norway.

This project will focus on the basic principles and methods of satellite remote sensing, and the physical properties of landslides that can be detected by the means of remote sensing. Norwegian conditions are of interest, predominantly landslides in soil. The main tasks of this project are therefore:

- Define Norwegian conditions, with respect to landslide activity.
- Characterize different landslides and their triggers.
- Obtain theoretical and practical knowledge of satellite remote sensing.
- Identify characteristics of landslides that can be detected from satellites.
- Identify relevant parameters that can be detected from satellites.

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[1] As described in "Sentinel missions overview", available from https://sentinels.copernicus.eu/web/sentinel/missions.

- Identify limitations and strengths of the different Sentinel satellite spectra, with respect to landslide detection in Norway.
- Provide a recommendation for further research

2 Methods

The main approach for the tasks listed in the above section is to conduct a literature review, summarizing relevant information from similar studies where satellite remote sensing has been used for landslide detection or surveillance. This will include:

- General theory about basic principles regarding satellite remote sensing.
- Norwegian literature regarding landslides.
- Research available information about the Norwegian landslide database.
- Research work done with satellite remote sensing data and geohazards.
- Case studies to investigate approaches and techniques for satellite remote sensing.
- Propose an outline for further work, based on findings.

3 Landslide Theory

In this section, background theory about landslides, Norwegian conditions, is summarized, with reflections of the relevance for this project.

3.1 Landslide classification

To be able to investigate which types of landslides may be possible to detect using satellite data, more specific classification and characteristics are needed. “Landslide” is a broad term, which describes a variety of processes. A common definition is *“the failure and movement of a mass of rock, sediment, soil or artificial fill, under the influence of gravity”* (Clague, 2013). More specific definitions may be used to communicate the characteristics of different types of landslides. These definitions are mainly based on how the displaced mass is moving, and what type of material the displaced mass is comprised of.

3.1.1 Landslide types

Landslides can be classified into different types, dependent on the characteristics. A widely used classification system is the Varnes (1978) classification system, which divides the type of mass movement into five classes. The movement type, in combination with the type of material is used to classify the event. The type of material is given as either rock, debris or earth (Sidle and Ochiai, 2006).

Material type is a key aspect of landslide characterization. “Debris is not a geotechnical term, but has been established as a term for this type of events throughout the years. From a geotechnical point of view, debris is a mixture of sand, gravel, cobbles and boulders. The mix often also contains varying portions of the smaller fractions such as clay and silt (Hungr et al., 2014). Whereas “earth” is described in the Varnes classification system as soil, in which 80 percent or more of the grains are smaller than 2mm in diameter (Keefer and Johnson, 1983). To make the characterization of the classification system up to date, and compatible with geotechnical terminology (Hungr et al., 2014) proposed an updated version of the system. The five basic types of mass movement, and their general characteristics are described, along with material types after the updated system, in Table 3.1. The information and terms are obtained from the U.S. Geological Survey landslide handbook by (Highland and Bobrowsky, 2008), and (Hungr et al., 2014).

Table 3.1 - Landslide types

Falls	Detachment of a mass of soil or rock from a steep slope. There is little or no shear displacement along the failure surface before the detachment. The material will mainly descend by falling, bouncing or rolling. **Types:** Boulder/Debris/Silt fall
Topple	A mass of soil or rock, forward rotating around a point or axis below its center of gravity. **Types**: Gravel/sand/silt topple
Slide	A mass of soil or rock moving downslope on surfaces of rupture, or thin regions of intense shear displacement. Movement of the entire mass does not occur simultaneously. It enlarges from its local point of origin, mobilizing a larger volume along its path. **Types**: Clay/silt rotation/translational/compound slide, Gravel/sand/debris slide
Spread	An extending mass of soil or rock mass, subsiding into a softer underlying material. May result from the liquefaction or flow of the underlying material. **Types**: Sand/silt liquefaction spread, Sensitive clay spread
Flow	A continuously moving mass, behaving like a viscous liquid. The shear surfaces are closely spaced, short lived and usually not preserved. **Types**: Sand/silt/debris dry flow, Sand/silt/debris flow slide, Debris flow, Mud flow, Debris flood, Debris avalanche, Earthflow, Peat flow.

The terms “debris” is still commonly used in geology and landslide science and is used as defined above. Note that the event earthflow here refers to a “flow-like movement of plastic, clayey soil”, that move slowly and intermittently. Classification is important with respect

Classification of landslides is essential for distinguishing the types and processes of a landslide, as well as accurate communication. The snow and rock type of materials are not included, as the satellite remote detection is in the respect focused in soil-type slides.

3.2 Norwegian conditions

The soil cover in Norway predominantly originates from the last glaciation, about 10, 000 years ago. Most of Scandinavia was covered by a thick sheet of ice. Gradually the ice retracted, and various processes have continued to contribute to the soil cover we have today. The different types of soils possess different type of material properties. These material properties may reflect how some of these soils become unstable and explain some of the mechanics and of a landslide, as well as triggering factors.

3.2.1 Soil cover

The soil cover is often classified according to how it was deposited. NGI has in their book about landslides (Høeg et al., 2014) summarized the common types of soil deposits in Norway, and their origin. The following information is an abbreviated summary of their description:

The characteristics of the Norwegian soil cover is to a large degree correlated to glacial processes. Marine sediments occur above today’s sea level due to land heave. These sediments are typically in the clay fraction, and may exhibit quick behavior.

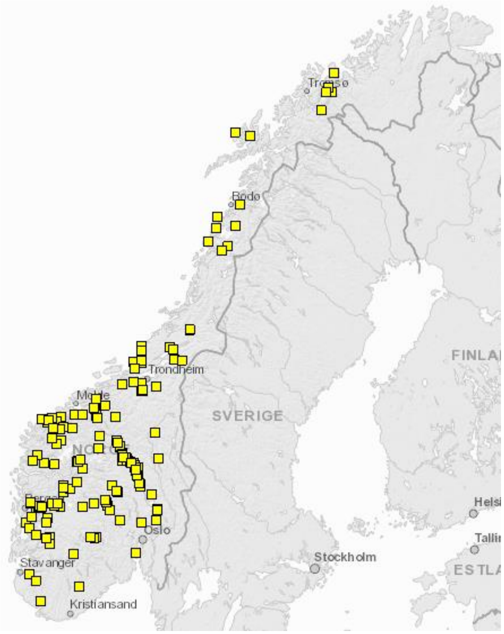
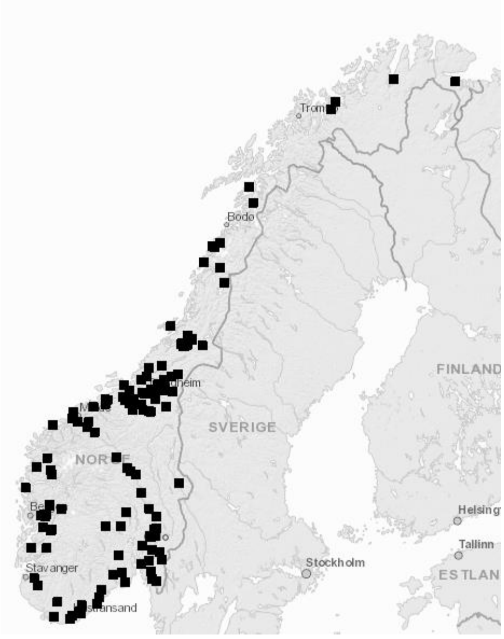
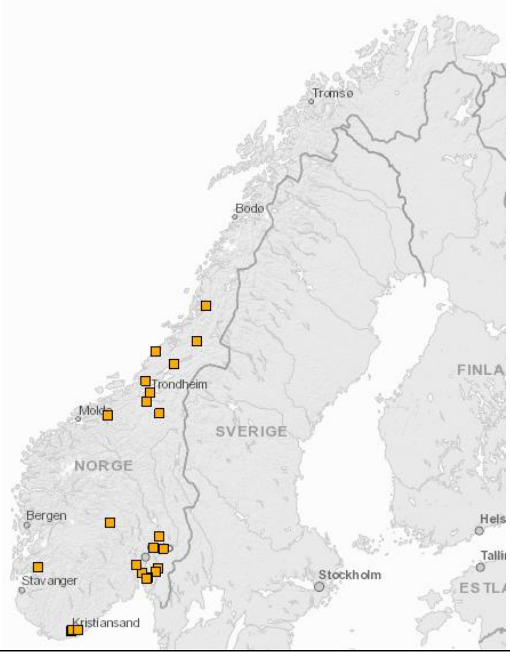
The most common type of soil above the marine limit is moraine. The moraine was deposited directly by the moving glacier. Typically the material is poorly graded, with a clay/silt content of 5-15 %. A large number of the debris flows and avalanches that occur in the Norwegian valley sides, occur in moraine material. Rivers, streams and lakes have contributed much of the materials in the sand and gravel fractions. Their origin may be due to melting glacier ice, or in natural water systems after the last glaciation.

3.2.2 Landslide activity in Norway

Norway is exposed to frequent landslide activity. NVEs national landslide database is publicly available. It shows the geographical location of events, type of slides, along with varying additional information about the incident. The database contains historic events from several hundred years ago, but mostly events that have inflicted the road or railroad network in recent time.

As shown in Table 3.2, debris flows and debris avalanches are the most frequent registered slide events in soil over the past five years. They occur more frequently under wet conditions, typically in periods with high precipitation and/or snowmelt. Coastal Norway typically experiences large amounts of rainfall in the late fall and early winter, which are the months when debris flows and debris avalanches are most frequent. Inland Norway experiences the highest frequency of these types of slides in the spring, when the snowmelt and thaw sets in (Høeg et al., 2014).

Table 3.2 - Landslide events from the national landslide database

<table>
<tr><th colspan="2">Registered landslide events in soils in Norway, in the period 16.11.2012 – 16.11.2017[2]</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td><i>Flomskred</i> – Debris flows</td><td><i>Jordskred</i> – Debris avalanche/Soil slides</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td><i>Utglidning</i> – Shallow slides/Rotational slide</td><td><i>Leirskred</i> – Clay slide (Not quick clay)</td></tr>
</table>

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[2] All screenshots from https://www.skredregistrering.no/, acquired 16.11.2017

It should be noted that the landslide terminology used in the national landslide database differs somewhat from that of the international literature. In general, the events are differentiated by their material; rock, snow or soil. NVE and the Norwegian Landslide Forecasting Service – *Jordskredvarslingen* – define the terms:

Table 3.3 – Terminology defined by NVE. As described by (Colleuille et al., 2017)

Jordskred	Rapid displacements of saturated soils in steep slopes, with no clearly defined water channel. **Coincides with the English terms:** Debris avalanches, debris slides, soil slides, translational slides, shallow slides.
Utglidning	Slow mass movement along a distinct flat or spoon-shaped failure surface. The term is also used for general movement of mass in a slope, and for the initial fracture in a *jordskred.* May be translated to “slipping” **Coincides with the English terms:** Soil slides, rotational slides, shallow slides.
Flomskred	High velocity flow-like slides along defined channels and streams. Can occur in channels where it normally is no running water. The moving mass can entrain large amounts of sediments, boulders, trees and vegetation. **Coincides with the English terms:** Debris flows, debris floods.

3.3 Physical characteristics of landslides

Understanding the conditions in which landslides occur, is relevant to determine where to search for landslides in the satellite data, and identify areas prone to landslides or areas that can be excluded. Physical properties of landslides that may be detected post-failure using satellite data are also described.

3.3.1 Material characteristics

Natural soil slopes are deposited with inclinations close to the internal friction angle of the material. Many slopes in their natural state will thus have a low factor of safety. The slopes are adapted to their normal conditions. External forces such as earthquakes and extreme weather events will be able to destabilize the slope and cause sliding events (Høeg et al., 2014).

Flow like slides in soil, occur in slopes with inclinations steeper than 25^{o}. They may also occur in gentler slopes if pore pressures are able to build up. In high permeability soils there is normally no danger of excess pore pressures. Slopes of this kind of material are usually stable at inclinations lower than 37^{o}, unless they are influenced by external forces from an earthquake or intense rainfall (Høeg et al., 2014).

Slopes with a high content of clay and silt will normally be more prone to sliding activity. The smaller fractions are able to build up excess pore pressure, which will decrease the critical slope inclination (Høeg et al., 2014). In the clay/silt fraction, capillary forces act on the grain skeleton if the material is wet. These forces act as extra binding, and will stabilize the material. If the material is completely dry, or completely saturated these forces disappear (Høeg et al., 2014).

Layers with differing permeability may destabilize a slope. Wetting/drying processes, roots, freeze-thaw cycles and biological activity affect the upper part of the soil, giving it a porous and permeable structure. Underlying layers with low permeability may cause a pore pressure build-up, and destabilize the soil (Høeg et al., 2014).

Vegetation may have a positive effect on the slope stability, as roots will reinforce the layer by binding the soil. During growth season, the root uptake removes water from the soil, which contributes to lower pore pressure build-ups. Large and relative dense forest has best stabilizing effects. Deforestation will lead to root decay, and may cause cavities in the soil after the roots have rot (Myrabø et al., 2014).

The inclination required for a debris flow to develop varies, dependent on the hydrological conditions. A slope steeper than 15o is normally required for the water to reach high enough velocities to erode and entrain material along its channel (Myrabø et al., 2014). At intense periods of rainfall, debris flows may occur in slopes with inclinations down to 10^{o} (Høeg et al., 2014). Available material the water can entrain along its channel is a precondition for a debris flow to develop. Channels along bedrock will be less prone to developing debris flows due to the lack of loose material. Steep slopes leading into the debris flow channel may add material by separate sliding events, adding large volumes of water and material to the debris flow. The characteristics of the watershed is also an factor, as debris flows are more prone to occur in steep watersheds, with relatively thin soil cover and a quick response to water inflow (Myrabø et al., 2014).

3.3.2 Triggering and contributing factors

The following description of triggering and contributing factors is summarized from (Høeg et al., 2014) and NVE’s factsheet in (Colleuille et al., 2017).

Water is a major component of landslide triggers. Intense precipitation, prolonged rainfall and snowmelt affect the soil and its natural condition. Water infiltration may cause pore pressure build-ups in susceptible materials and reduce capillary suction, causing a destabilizing effect. Large water input events will increase river flows, which increases the sediment transport. Ultimately, this may initiate debris flows if the river erosion gets sufficiently large. The finer fractions, silt/sand, are more exposed to the river erosion than coarser material, such as gravel. River erosion may also undercut slopes and cause instabilities. Temporary blockage of channels and streams may occur. A sudden burst of this natural dam may initiate sliding events, as a large volume of water is introduced into the surroundings. Glacial melt water can similarly be dammed, by ice, and cause the same effect.

Artificial changes that alter the normal conditions of slopes may cause instabilities. Human activity, buildings and constructions may possibly change the natural surrounding waterways. Rerouting of water into slopes may cause higher pore pressure build-ups and erosion, which could trigger sliding events. Malfunctioning of artificial drainage systems may cause the same effect. A clogged culvert could reroute the water into a slope and eventually initiate a sliding event. Road cuts work as gutters, collecting water from upslope. If any of the drainage systems established along the road were to malfunction, this could cause an increased water flow downslope. Logging and deforestation may also contribute to destabilization, as less vegetation leads to less root uptake. More water in the soil will be available for possible excess pore pressure. The roots binding effect will also disappear.

Earthquake of a certain magnitude will initiate landslide activity. In Norway this is generally not a problem, due to the low magnitude earthquakes that occur. Other avalanche activity, such as rockfalls may initiate other types of slides. The falling material may hit saturated material, causing a sudden increase of pore pressure and initiate a successive slide in soil material.

3.3.2 Topographic features and characteristics

Traditional mapping of landslides is done using aerial photographs. Terrain features and their photographic characteristics visible in aerial photography are listed in Table 3.4. The table is reproduced from (Jakob and Hungr, 2005).

Table 3.4 - Topographic features of debris avalanches and debris flows, and their photographic characteristics

Terrain feature	Relation to slope stability	Photographic characteristics
Semicircular backscarp and steps	Head part of slide with outcrop of failure plane	Light-toned scarp, associated with small slightly curved lineaments
Hummocky and irregular slope morphology	Microrelief associated with shallow movements or small retrogressive slide blocks	Coarse surface texture, contrasting with smooth surroundings
Berms or levees parallel to a stream channel in a gully or canyon	Microrelief associated with the deposition of debris during a debris flow.	Raised ridges immediately adjacent to and on one or both sides of a stream
Concave/convex slope features	Landslide scar and associated deposit	Concave/convex anomalies in stereo-model
Lack of vegetation immediately below breaks in slope	Removal of vegetation by translational sliding at debris avalanche headscarps	Light-toned elongated areas at the head of gullies or just below breaks in slope
Irregular linear swaths of denuded vegetation or new regrowth	Slips surface of debris avalanches and the path of debris flows	Light toned elongated areas at the head of gullies or just below breaks in slope
Areas of stagnated drainage	Landslide hollow, back-tilting landslide blocks, and hummocky landslide topography	Tonal differences and darker tones associated with ponds of wet areas
Seepage and springs in hillslope hollows	Naturally wet areas on slopes sometimes naturally occur at debris slide headscarps	Dark patches in hollows sometimes enhanced by differential vegetation
Interruption in drainage lines	Drainage anomaly caused by a headscarp.	Drainage line abruptly broken by a break in slope
Anomalous drainage pattern	Streams curing around the lobe of a debris deposit	Stream disruption by a debris fan deposit

The features of landslides used previously in aerial photo analysis can be transferred and potentially improved upon using alternative light spectrums, as will be discussed further.

4 Remote sensing

Obtaining data of the earth's surface without being in direct contact with it, is the basic principle of remote sensing. In general, the term implies that measurements are made indirectly. When done by satellites, they rely on emitted or reflected electromagnetic radiation. Different approaches will also qualify as remote sensing. Geophysical investigations, utilizing e.g. detection of sonic waves from a distance, or laser scanning techniques also qualify as remote sensing. However, over the past few decades', satellite and aircraft data analysis is more closely associated with the term and is the focus of this project. (Emery et al., 2017)

4.2 Electromagnetic Radiation and the Electromagnetic Spectrum

Electromagnetic radiation behaves according to fundamental physical properties, which makes it possible to describe its behavior mathematically. The radiation can be described as a magnetic and electric field travelling at the speed of light, propagating as waves. The fundamental characteristics of these waves are described with the parameters; wavelength and frequency. Wavelength, typically denoted as λ, has a unit of distance, whilst frequency is measured as cycles per second - Hertz (Hz).

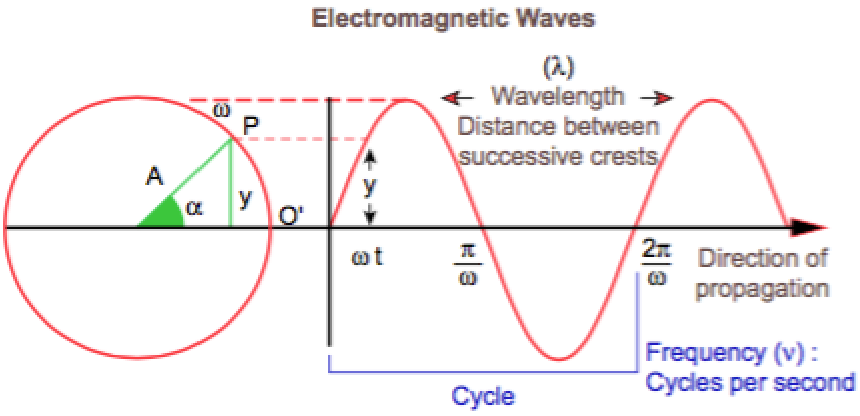

Figure 4.1 - Electromagnetic waves. From (Emery et al., 2017).

Electromagnetic radiation, can be arranged in a spectrum depending on the wave characteristics. The spectrum ranges from the radiation with short wavelengths, and high frequency to the radiation with longer wavelengths and lower frequencies.

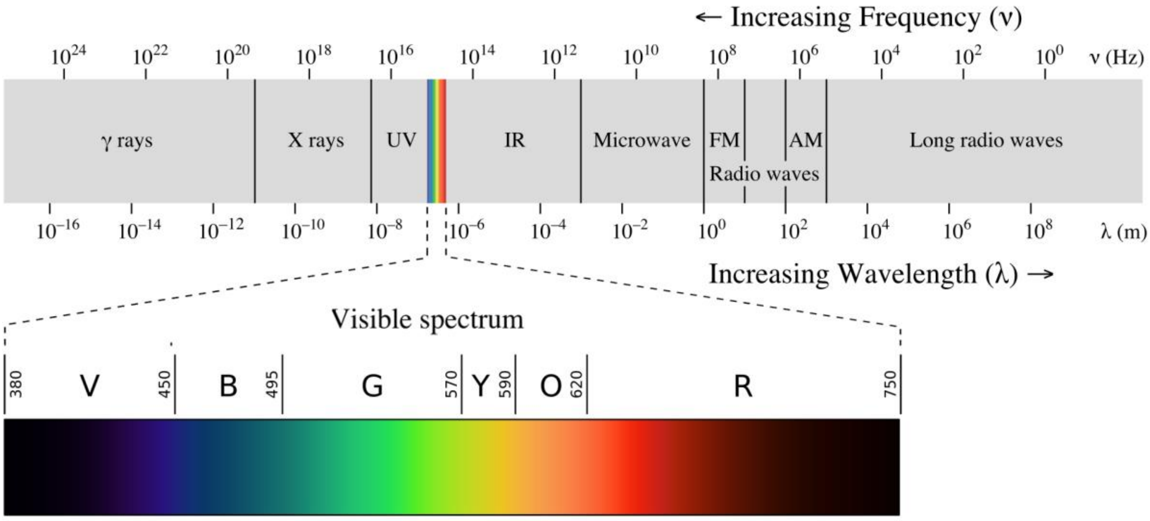

Figure 4.2 - The electromagnetic spectrum. Figure by Philip Ronan, Gringer[3].

Our human senses are adapted to see a small portion of the electromagnetic spectrum – the visible light. It ranges from about 0.4 micrometers to 0.7 micrometers. We can sense other parts of the spectrum, for example the UV-portion by getting sunburnt.

4.3 Satellite remote sensing

Some satellites are designed to detect electromagnetic radiation. They are equipped with sensors, which can register electromagnetic radiation of different wavelengths. However not all ranges of the electromagnetic spectrum are detectable in space. Radiation from the sun is reflected from the earth's surface and must pass though the earth's atmosphere before reaching the satellites sensor. Particles and gases in the atmosphere interact with the electromagnetic radiation, and will absorb the radiation to different degrees depending on the wavelength. Figure 4.3 shows the degree of transmission for different wavelengths. Visible light, UV and the microwave spectrum pass through the atmosphere into space, while portions of the IR-light as well gamma and x-rays are absorbed by particles in the atmosphere. Due to these atmospheric windows where the electromagnetic radiation is able to pass through the atmosphere, visible light, UV and the microwave spectrum are hence the most interesting wavelengths for remote sensing purposes (Observation, 2013).

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[3] Available from https://en.wikipedia.org/wiki/Electromagnetic_radiation#/media/File:EM_spectrumrevised.png

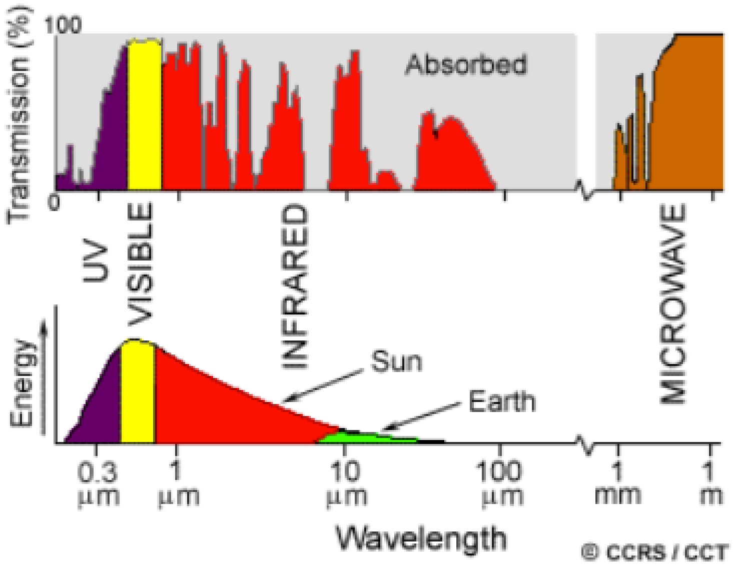

Figure 4.3 - Atmospheric windows. From (Observation, 2013).

4.3.1 Optical Satellites

Optical remote sensing spans the range of electromagnetic wavelengths from the visible to the thermal infrared (Emery et al., 2017). A passive sensors rely on an external source of energy for remote sensing. For the most part, this energy is reflected sunlight. This energy can only be sensed when the sun is illuminating the objects to be sensed. Nighttime, cloud cover and "blind spots" will shadow the reflectance of solar energy. Passive sensors can sense naturally emitted energy, e.g. thermal infrared, if the energy is large enough. (Observation, 2013)

When the sunlight hits a target, the radiation will be absorbed, transmitted and reflected. The interaction between the radiation and the objects will vary dependent on the objects *spectral signature.*

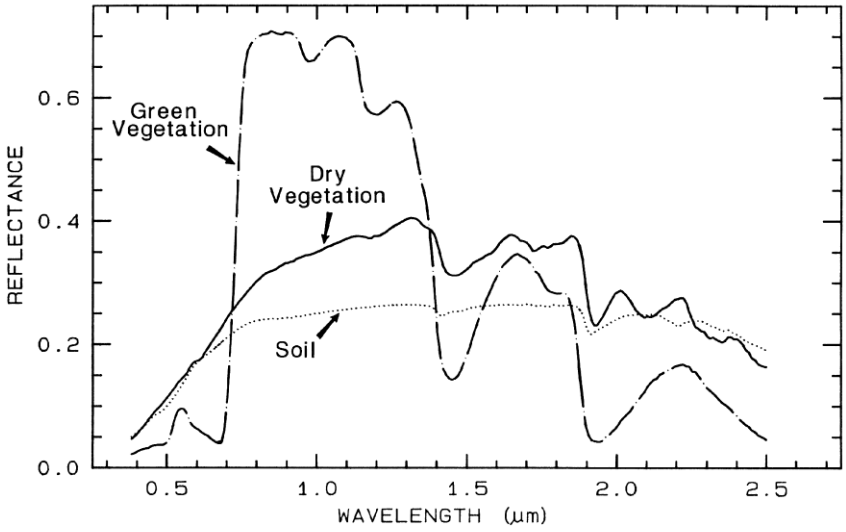

Figure 4.4 - Reflectance properties of different surfaces. From (Clark, 1999)

As shown in Figure 4.4, the reflectance properties of soil, green vegetation and dry vegetation differs in different wavelengths. Green vegetation has a high reflectance in the infrared portion of the spectra, whilst it absorbs more of the radiation in the narrower portion. By comparing the spectral response of different objects, it may be possible to distinguish features from each other based on the reflected energy.

Some technical characteristics are commonly used to describe the satellite instruments. The size of the smallest feature that can be detected is referred to as *spatial resolution.* The time it takes between data acquisition of the same area is referred to as *temporal resolution.* The range of wavelength the instrument records electromagnetic radiation is referred to as bands. The narrower the band, the finer is the *spectral resolution* of the instrument (Observation, 2013).

4.3.2 RADAR Satellites

Microwaves are the portion of the electromagnetic spectrum with wavelength in the range of 1 cm to 1 meter. This property is important for satellite remote sensing, due to the fact that the longer wavelengths can penetrate through cloud cover, haze and dust. Passive sensors can detect naturally occurring microwaves in the same manner as sunlight, but because of the long wavelengths, the energy available is small compared to the optical wavelengths (Observation, 2013).

Rather than relying on external energy, active sensors will emit their own energy. A well-known application for this in the microwave region is RADAR. In principle, the active sensor transmits a microwave signal and the intensity of the return signal is recorded.

The microwave part of the electromagnetic spectrum is wider than the visible and infrared parts. There are several bands in this range that are commonly used in RADAR applications, where the C-band is common on many space borne systems (Observation, 2013).

Table 4.1 - Radar bands. From (Emery et al., 2017).

Band	Wavelength range	Frequency range
P-Band	30 – 100 cm	0.3 – 1 GHz
L-Band	15 – 30 cm	1 – 2 GHz
S- Band	7.5 – 15 cm	2 – 4 GHz
C-Band	3.75 – 7.5 cm	4 – 8 GHz
X-Band	2.4 – 3.75 cm	8 – 12.5 GHz
Ku – Band	1.67 – 2.4 cm	12.5 – 18 GHz
K-Band	1.1 – 1.67 cm	18 – 26.5 GHz

The radar bands interact differently with natural objects. The lower frequency bands will penetrate objects such as forests, snow, ice and dry soil. The higher frequency bands are used for surface remote sensing, as they to do not penetrate natural surfaces (Emery et al., 2017).

4.3.3 Sentinel-1

The sentinel-1 mission[4] comprise of two identical satellites, Sentinel 1-A and 1-B. They have a near polar, solar synchronous orbit, meaning that the satellite orbit close to the poles, and revisit the same location approximately at the same time at every passing.

Table 4.2 - Sentinel-1 specifications.

Sensor	SAR – Synthetic aperture radar
Band	C-band
Temporal resolution	6 days revisit time at equator. At northern latitude, close to 2 days depending on location.
Spatial resolution	Varying depending on mode of acquisition. Full resolution: 10m.

4.3.4 Sentinel 2

The sentinel-2 mission[4] comprise of two identical satellites, Sentinel 2-A and 2-B. They have a solar synchronous orbit, meaning that the satellite revisit the same location approximately at the same time at every passing.

Table 4.3 - Sentinel-2 specifications

Sensor	Optical
Band	13 bands, see Table 4.4.
Temporal resolution	5 days revisit time. At northern latitude, close to 2 days depending on location, but with different viewing angles.
Spatial resolution	Varying depending on band. Full resolution: 10m.

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[4] All information obtained from «Sentinel Missions Overview». Available from https://sentinel.esa.int/web/sentinel/missions;jsessionid=61353E1F7851E2257253257D8AF4751B.jvm1

Table 4.4 - Sentinel-2 bands and applications

Band	Application	Spatial Resolution (m)	Central Wavelength(nm)
1 – Blue	Atmospheric correction	60	443
2 – Blue	Vegetation senescing, carotenoid, browning and soil background. Atmospheric correction.	10	490
3 – Green	Green peak, total chlorophyll in vegetation.	10	560
4 – Red	Maximum chlorophyll absortion.	10	665
5 – NIR	Position of red edge, consolidation of atmospheric corrections / fluorescence baseline.	20	705
6 – NIR	Position of red edge, atmospheric correction, retrieval of aerosol load.	20	740
7 – NIR	Leaf area index, edge of the NIR plateau.	20	783
8 – NIR	Leaf area index	10	842
8a – NIR	NIR plateau, sensitive to total chlorophyll, biomass, LAI and protein; water vapour absorption reference; retrieval of aerosol load and type.	20	865
9 – NIR	Water vapour absorption, atmospheric correction.	60	945
10 – SWIR	Detection of thin cirrus for atmospheric correction.	60	1375
11 – SWIR	Sensitive to lignin, starch and forest above ground biomass. Snow/ice/cloud separation.	20	1610
12 – SWIR	Assessment of Mediterranean vegetation conditions. Distinction of clay soils for the monitoring of soil erosion. Distinction between live biomass, dead biomass and soil, e.g. for burn scars mapping.	20	2190

5 Case studies

Some case studies are presented below, where primarily remote sensing data from satellites have been used to detect different types of sliding activity. There are many approaches on how to best identify sliding activity from remote sensing data, these studies highlight two interesting techniques.

5.1.1 Detection of slush flows using satellite radar data

Slush flow events may be initiated when large amount of water are added to snow. The Northern research institute *Norut* has shown that snow avalanches successfully can be detected using satellite radar data (Eckerstorfer and Malnes, 2015). Radar backscatter analysis is used to detect the avalanche debris. The authors show that the radar backscatter signal increase from the debris, mostly due to the increased surface roughness. This makes it possible to differentiate the snow avalanche surface, from the undisturbed snow surface.

The same methodology is applied to slush flows by (Malnes et al., 2016). Using radar data from three different satellite sensors, a total of 25 known events are investigated with satellite data. A summary of their results is shown in Table 5.1.

Table 5.1 - Satellite information and detection rate

Satellite	**Spatial resolution**	**Polarization**	**Events investigated**	**Events detected***
Envisat ASAR	75 m	VV, HH	9	8 (5)
Radarsat-2	3 m and 25 m	HH, VH, VV	3	3 (2)
Sentinel 1-a	10 m	VV, VH	13	7 (1)

*Figures in parenthesis are detected events with 50% or higher confidence

The key results/discussion points the authors did in this study:

- The backscatter signature of most of the investigated slush flows is indistinct due to impurities in the debris.
- Slush flow debris contains large amounts of water. C-band SAR does not penetrate wet snow, and a higher backscatter signal can be assumed.
- Slush flows will normally flow along channels, which can be hard to detect with spatial resolution > 10m. They will typically have an elongated shape, and can be a few meters wide and hundreds of meters long, which can make it difficult to detect using low-resolution images.
- Slush flows often shave the snow cover, and erode the terrain. Loose material, soil and rock is entrained in the flow, which make it hard to distinguish the backscatter signals from the slush flows, from the surrounding terrain.

The authors conclude, and show that it is possible to manually detect slush flows using radar data, with medium to high resolution, provided that the exact location is known. The size of the flow must be approximately as wide as it is long, and the debris should be mostly snow, water and ice as soil and rock diffuse the signal.

5.1.2 Detection of landslides using optical data

It has been shown that optical satellite data can be used for landslide detection. Both (Frauenfelder et al., 2005) and (Ma et al., 2016) utilize the fact that a landslide event will significantly alter the spectral signal of the earth's surface.

(Frauenfelder et al., 2005) successfully detected landslides in Pakistan after a major earthquake event, using optical ASTER data. The Aster data is acquired with a spatial resolution of 15-90 meters, depending on mode of acquisition. (Frauenfelder et al., 2005) applied three different approaches for detecting landslides in their study area. "Simple band thresholding", "Band ratios" and "Spectral change detection".

The pixels in the satellite image are assigned a value, based on the detected electromagnetic energy. By defining thresholds on pixel values, the pixels could be categorized into classes based on the spectral signature. A pixel could be classified accordingly as "landslide" or "not landslide". The authors defined thresholds for pixel values in the green and red band, in their simple band thresholding approach.

Pixel values may also be quantified by indices. Known spectral responses of surfaces in different bands, make it possible to use indices for identification of a specific surface type. The normalized difference vegetation index, NDVI, is commonly used to detect vegetation. It utilizes the fact that chlorophyll has a high reflectance in the NIR-wavelengths, and a low reflectance in red wavelength. A ratio between bands in these wavelengths, as shown in Table 5.2. , is used to detect vegetation. Pixels with a high value is likely to contain vegetation, whilst a cell with low value will probably not contain green vegetation. (Frauenfelder et al., 2005) used the NDVI along with similar indices for snow and water to detect landslides. Threshold values were also her defined, where pixel values below these thresholds were considered as potential landslides. This was used in combination with elevation data for the area. A digital elevation model (DEM) was used to set a slope criteria, where areas with inclinations between 0^{o} and 15^{o} where classified as non-landslide.

Table 5.2 - Indices and thresholds used by (Frauenfelder et al., 2005).

Index	**Band Ratios**	**Thresholds**
NDVI	$\frac{NIR - RED}{NIR + RED}$	≤ -0.05
NDSI	$\frac{NIR - \text{SWIR}}{NIR + \text{SWIR}}$	< 0.4
NDWI	$\frac{GREEN - NIR}{GREEN + NIR}$	< 0.4

A final approach was a change detection technique, were a pre-earthquake image and post-earthquake image were compared, and checked for change in spectral signature in the same band in both images.

The main experiences the authors gain from the study is that the three approaches detects and classifies the visually discernible landslides in their imagery, at different accuracies.

(Ma et al., 2016) use partly a similar approach for their automated landslide detection. As part of an algorithm, several indices are applied to identify landslide pixels in their satellite imagery. They use high resolution satellite data of an area in China. The data is acquired from the optical satellite Worldview 2, with a spatial resolution of 2.0 meters.

The authors approach for detection is to identify the geometrical and spectral characteristics of the landslide area. The authors identify landslide affected areas as bright spots in their remote sensing imagery. The soil brightness index were used to distinguish the brightness information of the soil efficiently. In addition the inverse NDVI were used. Meaning that vegetated areas will be suppressed in the image, as cells with vegetation will get a low value. These indices will hence highlight bare soil areas, and suppress vegetated areas.

Table 5.3 - Indices used by (Ma et al., 2016).

Index	**Band Ratios**
NDVI*	$1 - \frac{NIR - RED}{NIR + RED}$
NDSI*	$\frac{GREEN - BLUE}{GREEN + BLUE}$

Satellites with high number of bands may result in a high correlation between the band information. First principal component analysis, a statistical procedure, were used to obtain a higher variance in the datasets. The authors apply a shadow index, derived from the first principal component, to account for shadow effects in the landslide scar. This shadow effect may affect the precision of the results in high resolution remote sensing images.

Further, the authors used criterions to eliminate areas in the image, not likely to be a landslide. A DEM for the area were applied, with inclinations between 20^o and 50^o defined as possible landslide terrain. A smallest area parameter is applied. The minimum landslide area that can be identified from visual interpretation is 20 to 25 times its spatial resolution, as proposed by (Shi and al, 2008), cited in (Ma et al., 2016). Areas smaller than 40-50 m^2 identified as potential landslides is hence removed. Finally a geometric parameter is applied, related to the length-width ratio of landslide events, and how this ratio typically differ from that of roads or other infrastructure. The ratio is taken as the square root of the area, divided by the perimeter. The authors managed to get a high detection percentage in their algorithm, but stresses the fact that the selected thresholds/parameters are in many cases uncertain and may cause both over- and undershooting of detected pixels.

6 Discussion and Conclusions

6.1 Landslide Characteristics

The size of a landslide is of significance when it comes to satellite detection. The event must be equally large, or larger than the satellite instruments spatial resolution to be registered by the satellite. A key characteristic of a landslide is the events altering of the terrain surface. Depending on the surrounding environment, this alteration may be registered by satellite sensors. If the slide happens in vegetated areas, the slide may denude the vegetation and create a distinct signature in the landscape. If the sliding event happens in coarser unsorted material, it might be difficult to detect, due to the lack of contrast to its surrounding material. Debris flows follow channels, which will typically be long and narrow. If the flow follows an existing channel, it will not be altered by the terrain, and possibly go undetected. Key features for visual identification of landslide events are that of *Table 3.4 - Topographic features of debris avalanches and debris flows, and their photographic characteristics*. The characteristics are described for aerial photography, but may just as well be applied for spaceborn optical instruments, as long as the feature is larger than the spatial resolution.

By incorporating DEMs into the analysis, the topography can be evaluated. Areas with inclinations too gentle/steep can be masked out of the satellite imagery. Quaternary geology maps provide information about soil types, and their extent, and may possibly be incorporated into the analysis. Vegetation, or lack of vegetation may be detected as shown by both (Frauenfelder et al., 2005) and (Ma et al., 2016), where they both used the lack of vegetation as a criteria for possible slides. The thickness of the soil cover would be difficult to detect by satellite remote sensing, but one might could get an idea by identifying the spectral signature of bare rock compared to different soils.

Triggering events would be hard to detect via satellite imagery. Satellite data could however be used to survey contributing factors, such as snow, glacial damming, roads and deforestation.

6.2 Norwegian conditions

One great limitation with regards to satellite remote sensing, is the Norwegian weather condition. Frequent cloud cover disrupts the temporal resolution of the optical satellites, as it will “block” its view. This may result in many datasets without useful information, and a lower temporal resolution, due to the fact that the satellite will be dependent on weather windows. The seasons will also play a vital role, as the passive satellites rely on sunlight as a source of energy. The high latitudes of Norway ensure short windows of daylight during the winter season, and no sunlight at all in the northernmost regions. This renders a passive sensor practically useless in winter time.

The active satellite sensors do not rely on an external source of energy, and are not affected by the lack of sunlight. Combined with the fact that the microwave wavelengths used in RADAR sensors can penetrate cloud cover, this makes an advantage when it comes to the degree of coverage in Norwegian conditions. It should also be noted that large features, such as steep mountains might influence the signals, as it can shadow the electromagnetic waves. This is valid for both active and passive sensors.

6.3 Satellite remote sensing with Sentinel satellites

The availability of the new Sentinel satellites results in huge amount of data that can be processed an analyzed for different purposes. A temporal resolution of 4-5 days in the northernmost regions ensure large spatial coverage, and the possibility of frequent surveillance over the same areas.

Different approaches can be used for landslide detection, as shown by the case studies presented in chapter 4. Sentinel-1, with radar instrumentation is well suited for Norwegian conditions, as it does not rely on the sun as a source of energy. The drawback is however, the interaction between the radar backscatter signal and soil. As shown by (Malnes et al., 2016), there is no clear contrast between avalanche debris containing soil compared to the surrounding terrain. This method is therefore not applicable for detecting landslides in soil.

The optical instruments on the Sentinel-2 satellites are specifically designed for land monitoring. The bands are adapted for land-use classification, and may be used to detect parameters relevant for landslide activity, such as vegetation, or type of soil. With a spatial resolution of 10 m, it may obtain relatively small events. Different types of indices, as used by both (Frauenfelder et al., 2005) and (Ma et al., 2016) should also be investigated for Norwegian conditions.

The general approach for optical analysis that could be used; Initially, indices are used to highlight possible slide areas. Further identify areas that are *not* likely slide areas, by i.e slope criterias, or areal parameters as demonstrated by (Ma et al., 2016).

7 Outlook

A recommended approach for further work is to get more into the specifics of detection in Norwegian conditions. The background for this project is to possibly improve the current database, by enabling detection of landslides that otherwise not would have been recorded or even detected. Looking past limitations, such as cloud cover or difficult conditions, a main objective would be to successfully detect a landslide in Norwegian conditions.

This may be done by identifying 3-4 known events, and research the best possible ways to detect them with satellite remote sensing data.

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