Home Exam Passive

FYS-3001 Physics of remote sensing

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Tromsø - Norway
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Fundamentals

In this section of the home exam, we will take a look at the fundamentals, thermal sensing and practical surface sensing regarding passive remote sensing.

Task 1:

Electromagnetic (EM) radiation is the information that is transmitted from an object to a sensor. The information collected can be encoded in the frequency content, intensity, and polarization of the electromagnetic wave.
The usefulness of using EM radiation in remote sensing from satellites has many reasons, but we will mention some of them. By using EM radiation we have a wavelength diversity, that spans a wide range of wavelengths from radio waves to gamma rays.
This diversity enables us to sense a variety of different phenomena and materials on Earth's surface. For example, shorter wavelengths (e.g. ultraviolet and visible light) are useful for imaging features like vegetation, urban areas, etc, while longer wavelengths (e.g. infrared, microwaves, and radio waves) can penetrate clouds and temperature variations, moisture, and underground features.
As different wavelengths of the EM spectrum have different penetration and reflection characteristics, hence interact differently with Earth's atmosphere and surface. As microwave band covers the wavelength span from 1 mm to 10 cm, it can penetrate through clouds, vegetation, snow, and also some types of soil. This allows us to observe the surface regardless of the weather of time of day. On the other hand, we have the infrared and the visible band ranging from 1mm to 0.4 μm. At these wavelengths, we have strong effects from the weather and atmospheric conditions. These differences in penetration and reflection characteristics, enable remote sensing satellites to gather data under different environmental conditions.
Satellites equipped with remote sensing instruments can provide global coverage of Earth's surface, and also remote areas which are hard to reach e.g. deserts, jungles, oceans, and polar regions. This enables us to have a wide coverage for monitoring and analyzing environmental changes, natural disasters, and other changes.

Task 2:

The equation is sometimes referred to as an energy balance equation for a surface.

$$\epsilon = \tau = 1 - \rho \tag{1}$$

In the equation we have ϵ that represents surface emissivity, which is the ratio of the energy emitted of the surface to the energy emitted of blackbody at the same temperature. τ represents a fraction describing the ratio of the energy transmitted through the surface (interface) to the incident energy. At last we have the fraction ρ, which represents the surface reflectivity, so the ratio of the energy reflected by the surface to the incident energy.
Overall the equation states that the sum of ϵ (emissivity), τ (transmissivity), and ρ (reflectivity) equals one. This holds under the assumption of energy conservation, which means all incident is either absorbed, transmitted, or reflected by the surface/interface.

Task 3:

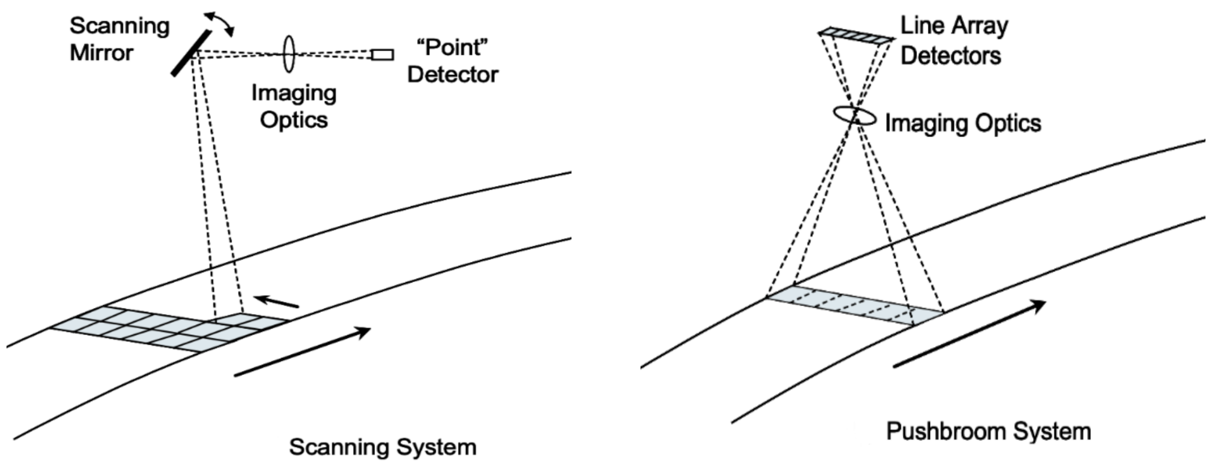
BRDF stands for *Bi-directional Reflectance Distribution Functions*, it describes the reflectance of a target as a function of illumination geometry and viewing geometry. In simpler terms, it describes how much light is reflected in different directions when light hits the surface at an angle. It is crucial for Earth observation from satellites, for several reasons e.g. surface characterization, atmospheric correction, climate, and environmental monitoring by using the BRDF we can do this under any lighting conditions. In surface characterization, the BRDG gives valuable data on the reflectivity of Earth's surface, which includes the composition, structure, and condition (e.g. Figure 1). Satellite sensors measure the radiation reflected or emitted by Earth's surface, these signals are often/can be distorted by the atmosphere like scattering or absorption. With help from the BRDF models, we can make corrections to this. The BRDF data, is also great for monitoring changes in land and surface properties over time. The reason for this is also seen in the image below in figure 1, it's giving the image a better contrast.

Figure 1: Image from lecture notes, "FYS3001_MJ24_Chapter3a.pdf".

Task 4:

The scanning system uses a scanning mirror that projects the image of one surface resolution element (the squares in figure 2) on a single detector, shown in figure 2a. To produce an image, an *across-track* scanning is used, to cover the imaged swath across the track. This method have only one swath. The other method called *whiskbroom* uses a mechanical platform that carries the imaged swath along the track (scanning back and forth). The whiskbroom has a low detection or dwell time for each pixel.
The Pushbroom system, on the other hand, doesn't use this mechanism instead it uses a linear array of detectors to cover all the pixels in the across-track dimension at the same time, shown in figure 2b. This allows for a longer dwell time for each detector on each surface element, which allows for higher sensitivity and a narrow bandwidth of observation. As for moving parts, it will be preferable to use the pushbroom system, as it leaves fewer

things to fail and it will have a longer life expectancy than the scanner. Another bonus for the pushbroom is that a fixed geometry results in higher geometric accuracy in the line directions, this simplifies the image reconstruction and processing. But it have the disadvantage, that more detectors need to be calibrated. The advantage of using the scanning systems, is it a simple detector, a narrow field-of-view optics, wide sweep capability and can be used with multiple wavelengths.



(a) (b)

Figure 2: Figures from Introduction to the Physics and Techniques of Remote Sensing, p.89, [1].

Task 5:

Spectral resolution, is describing the ability of sensor to distinguish between different wavelengths or bands of electromagnetic radiation. High spectral resolution means the sensor can distinguish between narrow bands of wavelengths, providing more detailed information about a target.

Spatial resolution, refers to the level of detail or sharpness in a image captured. It measures the number of pixels in a given area, and is often expressed in meters per pixel. A higher spatial resolution means smaller pixel sizes, which will give a more detailed image of the target.

Usually, there is a trade-off between spectral and spatial resolution. Increasing the spectral resolution will affect the spatial resolution, and vice versa. This trade-off comes from the limitations in sensor technology today. E.g. sensors with high spectral resolution may have fewer pixels on the ground, leading to lower spatial resolution.

Also, different applications have different needs. If we want to monitor land cover or some vegetation, a high spectral resolution is preferable for distinguishing between different surfaces and vegetation types. If we want to use remote sensing for urban planning or to look at a disaster that have happened, a high spatial resolution is preferable as it is better for identifying and analyzing small-scale futures or changes in the landscape.

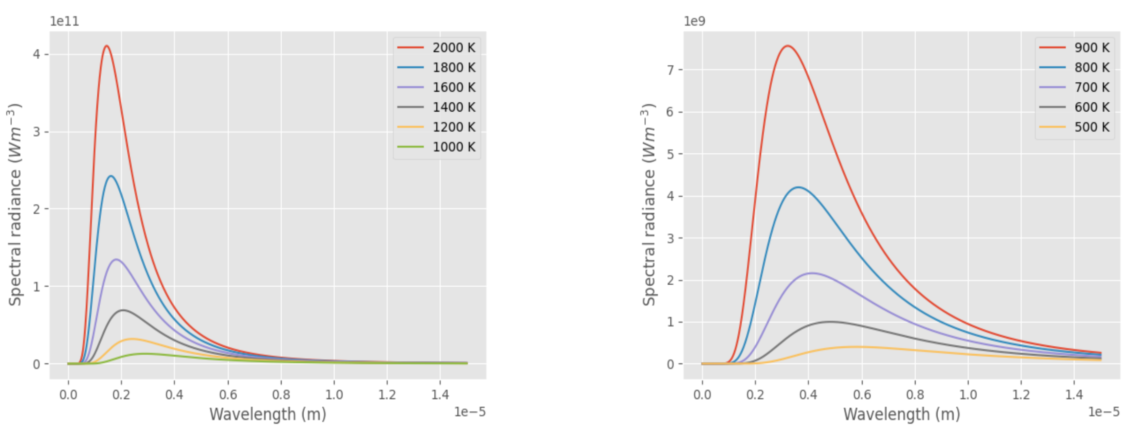
Thermal sensing

Task 1:

Planck's blackbody formula ($S(\lambda)$) describes a blackbody's spectral emittance, which transforms energy into radiant energy at the maximum rate permitted at a fixed temperature as a function of wavelength.

$$S(\lambda) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{ch/\lambda kT}-1} \qquad \left[\frac{W}{m^3}\right] \tag{2}$$

Where h is Planck's constant, k is the Boltzmann constant, c is the speed of light, λ is the wavelength and T is the absolute temperature in Kelvin. The formula describes the distribution of energy emitted from a blackbody at different wavelengths, it shows that at any given temperature a blackbody emits radiation across a continuous spectrum of wavelengths. We can see in figure 3 in the plots, that as the temperature increases the peak of the spectral radiation curve shifts to the shorter wavelength. Hence, a shift towards higher energy radiation. In other words, as the temperature increases more energy is emitted, as seen when comparing the plot for temperatures between 1000 K and 2000 K in figure 3a with the plot for temperatures between 500 K and 900 K in figure 3b. By taking this formula into use, we can study land surface temperature, and detect thermal anomalies, environmental changes, etc.



(a) (b)

Figure 3: Spectral radiance emittance of a blackbody at different temperatures. Plots inspired from figure 2-12, book of remote sensing [3].

Task 2:

As we know not all energy is reflected directly from the Earth, the reason for this is that around the world we have a lot of different materials either if it's man-made, environmental or the atmosphere where the two last gives the biggest effect. The energy which is not reflected is absorbed or scattered, by particles in the atmosphere. Whether it is absorbed, reflected,

or scattered is mainly dependent on the frequency of the wave. As the waves interfere with materials their electrons, molecules, or nuclei are put into motion. As the energy can't just disappear, we have an exchange of energy between the wave and the material. This excitation The two most important material properties that regulate the reflection, absorption, and scattering, are what we call *albedo* and *emissivity*.
Albedo describes the fraction of incident light sunlight/energy that is reflected by a surface, hence it is a measure of surface reflectivity. The scale ranges from 0 to 1, where 0 is total absorption and 1 indicates total reflection. Different surfaces have different albedo, depending on numerous properties such as composition, texture, and color. e.g. snow and ice have high albedo values, while oceans or asphalt have low albedo.
Emissivity is a measure of how efficiently a surface radiates energy compared to an ideal blackbody at the same temperature, wavelength, and viewing conditions. Its quantity ranges from 0 to 1, where 0 indicates perfect reflection and 1 indicates perfect emission. Emissivity varies with the material properties, surface roughness, and temperature. Hence, a surface with high emissivity radiates energy more effectively, while a surface with low emissivity radiates less energy. Emissivity often increases with surface roughness and temperature. So Rough surfaces with irregularities and micro-structures have higher emissivity due to the increased surface area for radiation emission. As for the temperature increase of an object, its emissivity will also increase.

Task 3:

Planck's equation only describes radiation from a black body, which has the highest efficiency of converting thermal energy into electromagnetic energy. All natural objects have a lower efficiency, for compromising this we can use the *spectral emissivity factor* $\epsilon(\lambda)$.

$$\epsilon(\lambda) = \frac{S'(\lambda, T)}{S(\lambda, T)} \tag{3}$$

So how do all these natural objects differ from a blackbody, here we have different factors like surfaces, temperature variations, material properties, and environmental factors. As all surfaces on Earth is non-ideal surfaces, they have varying levels of reflectivity, absorption, and emissivity which is depending on factors such as surface texture, color, and composition. While Planck's equation assumes a perfect absorption and emission of energy radiation (blackbody), real surfaces may reflect, transmit or scatter the incident energy radiation. Planck's equation also assumes uniform temperature across the emitting surface. But as we know, real objects have temperature variation across their surface due to uneven heating or thermal properties. These temperature variations can affect the spectral radiance emitted by an object, which can introduce deviation from the predicted behavior. We also have material properties, which include factors such as thermal conductivity and heat capacity. These factors can influence the thermal behavior and the emission characteristics.

Task 4:

The term of brightness temperature which was introduced with Rayleigh-Jean's equation, is defined as.

$$B(\nu) = \frac{2kT}{c^2}\nu^2 \tag{4}$$

Where $B(\nu)$ is the surface brightness, c is the speed of light, ν is the frequency of the radiation, k is the Boltzmann constant, and T is the physical temperature. Equation 4 for brightness temperature describes the temperature of a blackbody emitting radiation with the same intensity as the observed radiation at a specific wavelength or frequency. So the Rayleigh-Jeans law provides an approximation for the brightness temperature T_B based on the physical temperature (T) and the wavelength (λ) of the radiation. This is a useful concept as it provides a simple way to interpret thermal infrared data. As it allows us to quantify the temperature of objects or surfaces based on the intensity of radiation emitted. However, as the brightness temperature is a measure of the intensity of the radiation it will not give the true temperature. But it relates to the true temperature, as a temperature emits radiation. The temperature of the object is often either lower or higher [4], which comes from the fact that it can be influenced by surface emissivity, roughness or atmospheric conditions (e.g. clouds).

Practical Surface Sensing

Task 1:

The Advanced Microwave Scanning Radiometer 2 (AMSER-2) sensor, is what we often call a microwave imaging radiometer [5]. Where one of its most useful applications is land ice and sea ice mapping, and monitoring. The big advantage of using microwave radiometry is the fact it is capable of recording data all the time, as the microwave region sees through cloud cover or during the dark winter seasons, hence preferable in the polar regions. By taking into consideration the large emissivity difference between the ice (*dielectric:* $\epsilon = 3$, *reflectivity:* $\rho = 0.07$) and open water (*dielectric:* $\epsilon = 81$, *reflectivity:* $\rho = 0.64$), we get a strong contrast in the received radiation that allow us to separate between sea ice and open water. As the water has higher reflectivity it will look cooler ($T_s \approx 50K$) compared with the sea ice ($T_i \approx 272K$), which would give a difference of $\Delta T_{obs} = \Delta\rho(T_s - T_i) \approx 127K$ that is easy to detect. But we know that ice ages and deforms with time, where salinity and roughness of the ice will change ϵ_{ice} hence our observed ice reflectivity and temperature will change. AMSER-2 has different sensors working at different frequencies which have different penetration properties, lower microwave frequencies penetrate deeper, and higher frequencies are more sensitive to surface conditions. With the properties of aging and deforming, and with the AMSER-2 instrument working with different frequencies the ice composition is also detectable regarding new ice and multi-year ice.
Important factors to consider when using passive microwaves to derive sea ice information are frequency and polarization. As frequencies are sensitive to different sea ice properties. We mentioned that lower frequencies (e.g. 10.7GHz) are more sensitive to sea ice concentration and composition as ice layers, and higher frequencies (e.g. 89.0GHz) are more sensitive to the surface and thinner ice.
When using passive microwave sensors we often measure the polarization properties of microwave radiation emitted by a surface. When speaking about polarization we refer to the orientation of the electric field vector of the electromagnetic wave. Polarization in sea ice context, it often used for distinguishing between surface types, sea ice edges, and ice properties. When working with polarization we have vertical- and horizontally polarization, as the vertical polarization is orthogonal to the horizontal polarizations [3]. The vertical polarization shows often the open water with a higher brightness temperature than the horizontal polarization, this comes from the fact that horizontal polarization is more sensitive to the surface roughness and not penetrate as deep as vertical polarization [9].

Task 2:

Figure 4 shows the brightness temperature in kelvin, at three different frequencies 18.7GHz, 36.5GHz, and 85.0GHz. Where we have focused on an area centered over Svalbard, with the coordinates 75°N-85°N and 20°W-40°E. One thing that stands out first, is that the resolutions get increasingly better with the frequency. This comes from the fact that the, higher frequencies don't penetrate as deep as the lower frequencies but are more affected by the surfaces. Hence, more of the surface is more detailed with a spatial resolution of about a few kilometers but is more sensible for clouds and atmospheric influence which one of the factors is the scattering mechanisms [6]. Including this and that the 85.0GHz is more sensitive to emissivity changes, we see the brightness temperature of the open water is higher for the 85.0GHz plot. As for the lower frequencies, they will penetrate deeper into the sea ice and will not be as affected by the surface hence the plot does not look as detailed. But it reveals the "secrets" within the sea ice, by comparing the plot for 18.7GHz and 36.5GHz we see that the 36.5GHz plot is to some extent affected by the surfaces.

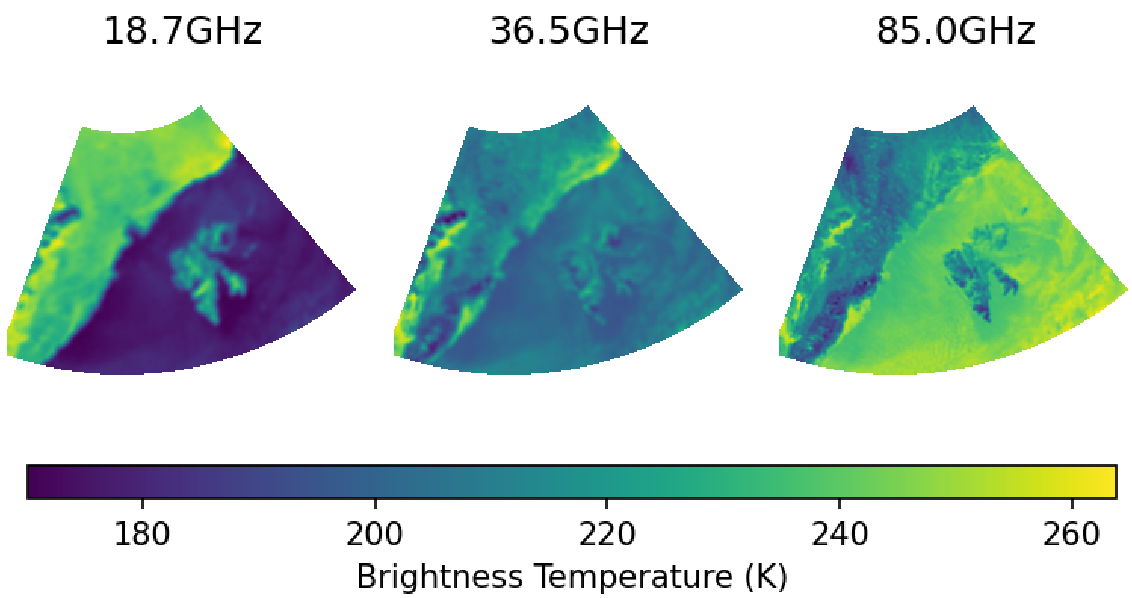


Figure 4: Plot of the brightness temperature at three difference frequencies 18.7GHz, 36.5GHz and 85GHz at a location with coordinates 75°N-85°N and 20°W-40°E. Data retrieved from ASMR-2 12/11/2018.

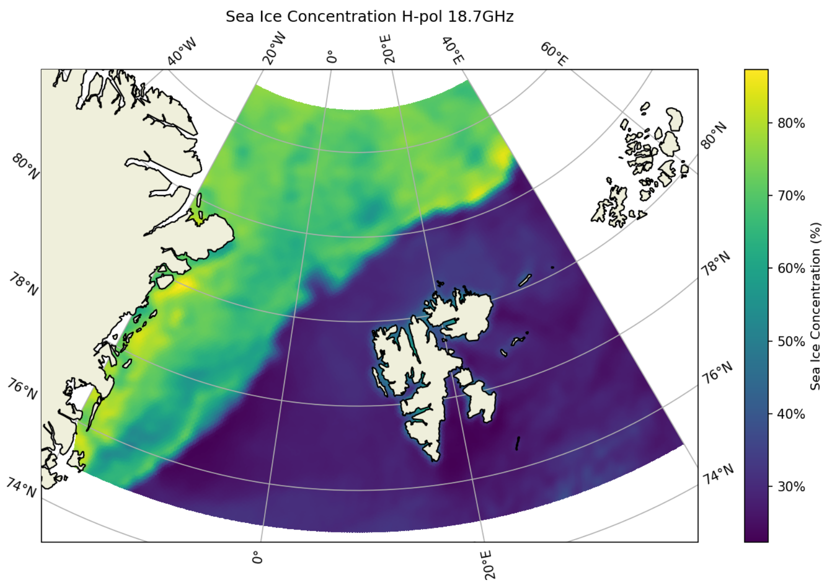
Task 3:

Now we are going to derive the sea ice concentration from the ASMR-2 image, for this we are given the relation between the brightness temperature and sea ice concentration.

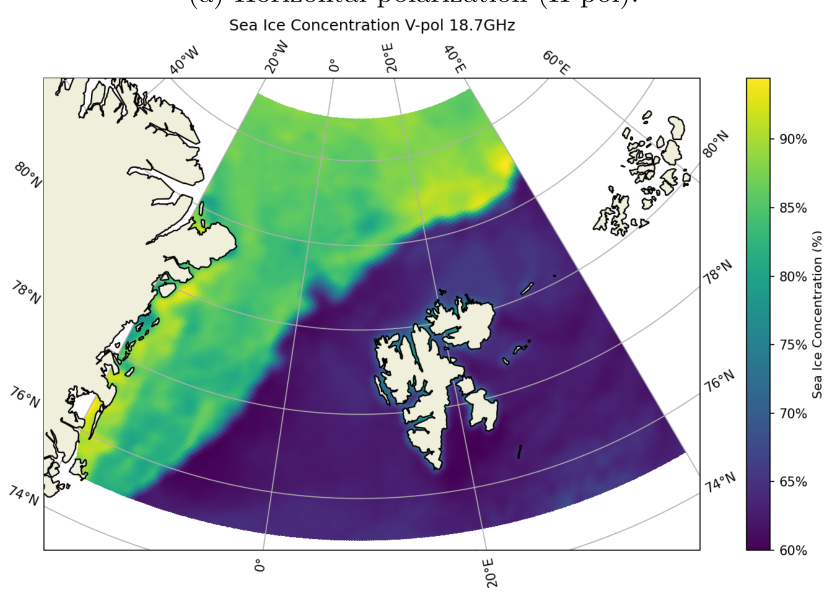
$$T_b = T_i C_I + T_O(1 - C_I) \qquad \Longrightarrow \qquad C_I = \frac{T_b - T_o}{T_i - T_o} \tag{5}$$

Where C_I is the sea ice concentration, T_b is the observed brightness temperature, T_i is the brightness temperature of 100% sea ice and T_o is the brightness of open water. The reason for this approach to deriving the sea ice concentration, is that the brightness temperature is influenced by the temperature and emissivity. As the sea ice has different properties compared with the open water, we have a difference in brightness temperature. As a result, by comparing the observed brightness temperature with reference values for the sea ice and the open water, we can estimate the proportion of sea ice.
The 89GHz channel is more sensitive to smaller-scale surface features, which allows for more detailed information about the surface characteristics of the observed area and can improve the accuracy of sea ice concentration calculations. It can be especially useful in regions where

we have thin or fragmented ice cover. But comes with a downside regarding atmospheric influence (e.g. clouds), and can also be affected by the snow cover over the sea ice.
Figure 5 shows the sea ice concentration over Svalbard with a frequency of 18.7GHz. Additionally, we have also included separate plots for the horizontal- 5a and vertical polarization 5b. This is done as the two different polarizations have different angle of incidence (according to Figure 5-2 [5]), giving different radiometric temperatures. The horizontal polarization gives a bigger variation in radiometric temperatures, than the vertical polarization. This results in the plots being different, and the sea ice concentration using horizontal polarization having a more variable sea ice concentration seen in figure 5a.



(a) Horizontal polarization (H-pol).



(b) Vertical polarization (V-pol).

Figure 5: Sea ice concentration using the 18.7GHz channel, including horizontal - and vertical polarization.

Task 4:

By using passive microwave sensors, we are also able to make maps of where we have open water, new ice, and older ice areas also including the the edge between the sea ice and water. To be able to calculate this, we rely on the polarization ratio (PR) and the spectral gradient ratio (GR).
As the brightness temperature varies with the polarization and frequency, figure 9.5 [6] confirms this difference for a surface emissivity at different polarizations and frequencies. Which states that we can use this to discriminate sea ice from water. This difference is expressed as follows.

$$PR = \frac{T_{BV} - T_{BH}}{T_{BV} - T_{BH}} \tag{6}$$

Which includes the brightness temperature at different polarizations. Then for detecting the sea ice edge, we set a span for where we have sea ice and water both for the 18.7GHz and 36.5GHz. To retrieve the span values, we look at Figure 9 in *Global Sea Ice Edge and Type Algorithm Theoretical Basis Document V2* [2] (also displayed in appendix figure 10) and see where sea ice and open water cross paths which for 18.7GHz is approximately at 0.20 and for 36.5 will be at approx 0.12. As this data is from AMSR-2 in 2015, it gives good results for where the sea ice edge is shown in Figure 6.

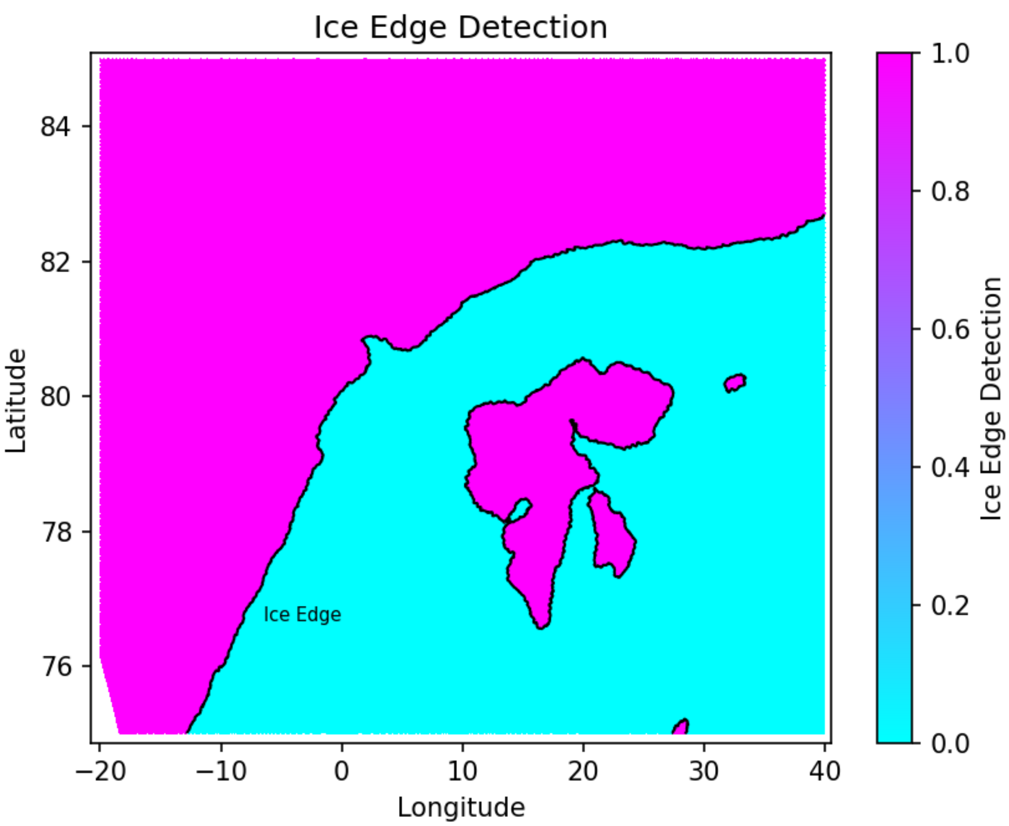


Figure 6: Sea ice edge detection, using the 18.7GHz and 36.5GHz channels. The black line shows where approximately the sea ice edge is.

Now for the map where we can see the open water, new ice, and multi-year ice, we have used the spectral gradient ratio (GR). As radiometric backscattering is different for different ice types (salinity, temperature, surface, etc.), which will affect the brightness temperature (T_B). We use GR to make up for these different properties, hence the reason for the GR expressed in equation 7 includes the 18.7GHz and 36.5GHz channels.

$$GR_{36.5,18.7} = \frac{T_B(36.5V) - T_B(18.7V)}{T_B(36.5V + T_B(18.7V)} \tag{7}$$

From Sea Ice [6], we know that first-year ice has a GR close to zero, and for multi-year ice, we have a negative GR. Further, the exam paper has given us that $GR(36.5V, 18.7V) > 0.05$ and $GR(36.5V, 18.7V) > -0.02$, which we can include into our span for the map 7 showing open water, new ice ($<$ 1year) and multi-year ice ($>$ 1year). In figure 7 we have also included the ice edge calculated from the PR, which is not exactly the same but pretty close.

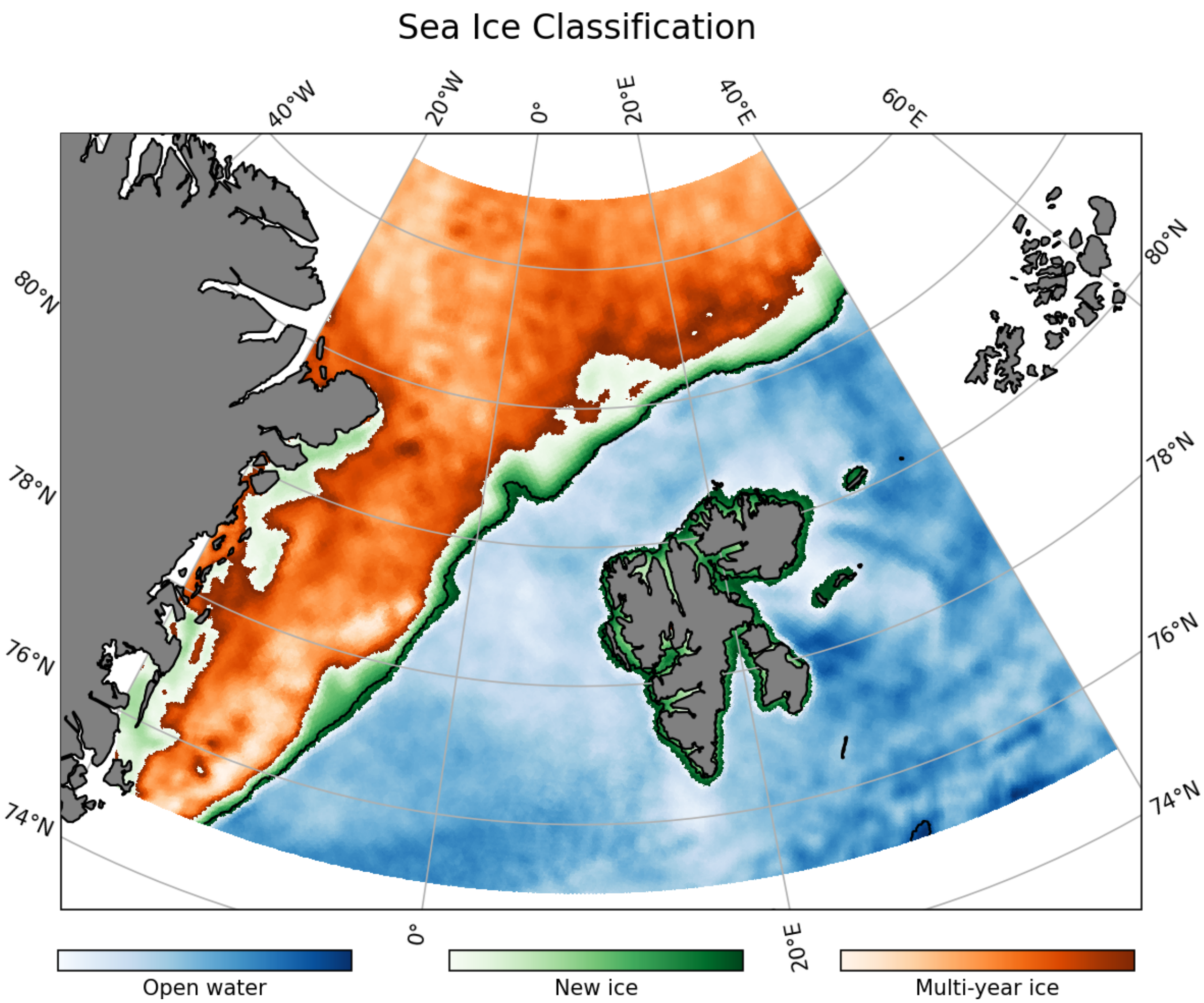


Figure 7: Sea ice classification, open water, new ice ($<$ 1year) and multi-year ice ($>$ 1year). The black line indicates where the ice edge is. Channel 18.7GHz and 37.5GHz.

In figure 7, we can see that a big region of the sea ice is dominated by multi-year ice to which extent this is true is uncertain when we don't have a lot to go after. But by doing some research sea ice age images from NOAA [7] and NSIDC (National Snow and Ice Data Center) [8], it look's like it could be a possibility for this to be correct. As we use 18.7GHz and 37.5GHz which will not include the fractionated sea ice, that could include valuable data about how the region is. So if an area is dominated by fractionated sea ice, it will look like that the whole area is multi-year ice, it becomes clear that in a lot of the sea ice classification on the internet, a higher frequency range is used. So to do a comparison, we have plotted a sea ice classification map in figure 8 by using 85.0GHz and 37.5GHz in equation 7. This gives a more realistic image of the amount of new ice and multi-year ice, and now our sea ice edge also fit better besides not using 85GHz in our calculations of PR. Also stated in *Sea Ice* [6] and *introduction to the physics and techniques of remote sensing* [5] higher frequencies likes 85GHz is more sensitive to thinner ice and surface roughness.

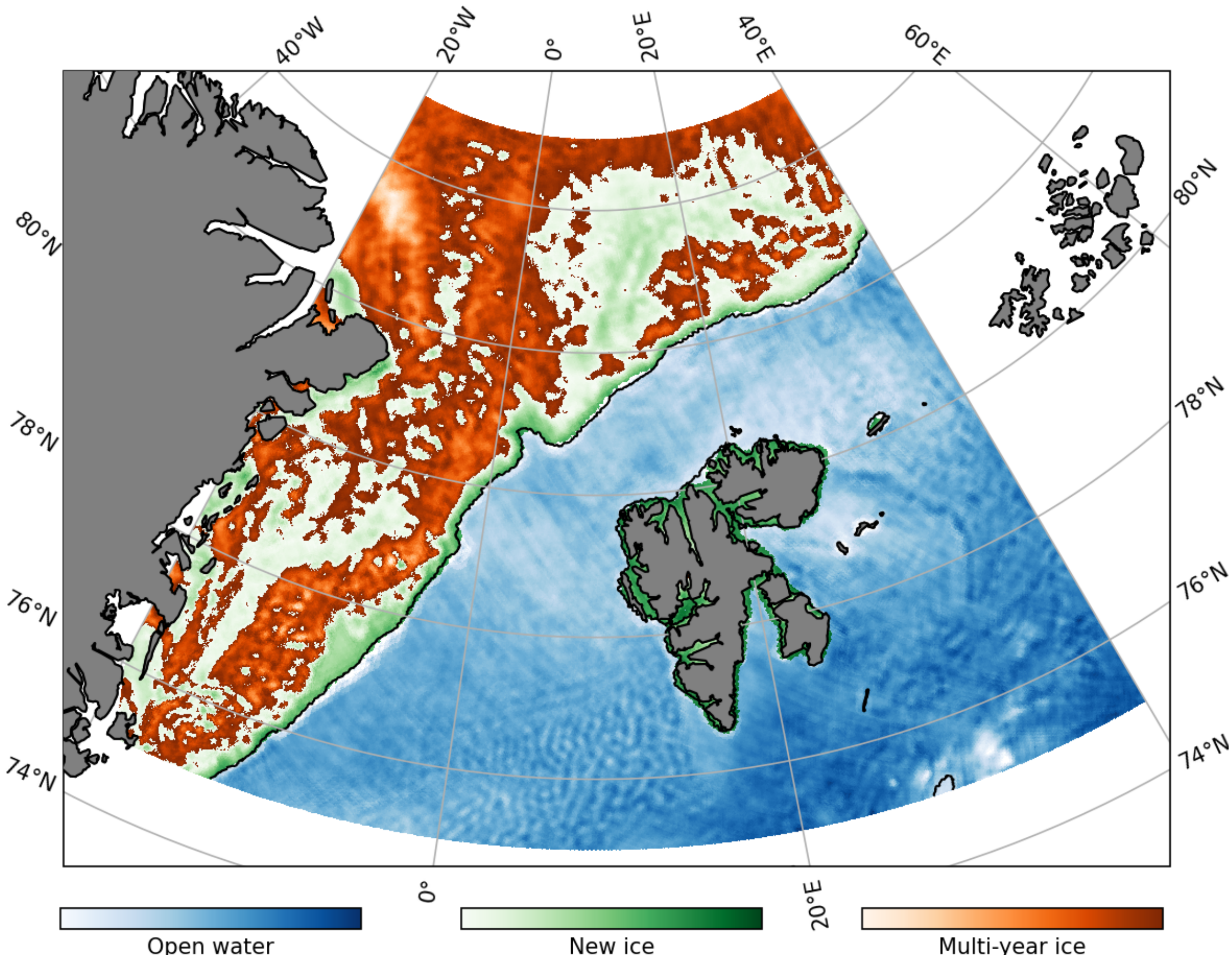


Figure 8: Sea ice classification, open water, new ice (< 1year) and multi-year ice (> 1year). The black line indicates where the ice edge is. Channel 37.5GHz and 85.0GHz.

We use the range 0-15% for the sea ice concentration, as this range corresponds to the transition zone between open water and sea ice. In the artics this transition does not happen abruptly, but gradually over a range from sea ice and open water. In this range, sea ice is typically fractioned sea ice or thin ice cover where we have open water floating in between. Also for a sea ice concentration below 15%, the difference in emission between open water and sea ice is relatively small.

Task 5:

By using the relationship estimates (e.g. Fig 11) in Cho et el, 2024, for sea ice thickness below 5cm. We are able to plot the areas with sea ice thickness below 5cm, shown in figure 9. Where approximately it cover 20% of the sea ice, which i think may be a little bit high if we compare it with the sea ice classification map 8. I would think that the multi-year ice would be thicker, and we would have more of the areas with new ice and the sea ice edge to have a ice thickness of less than 5cm.

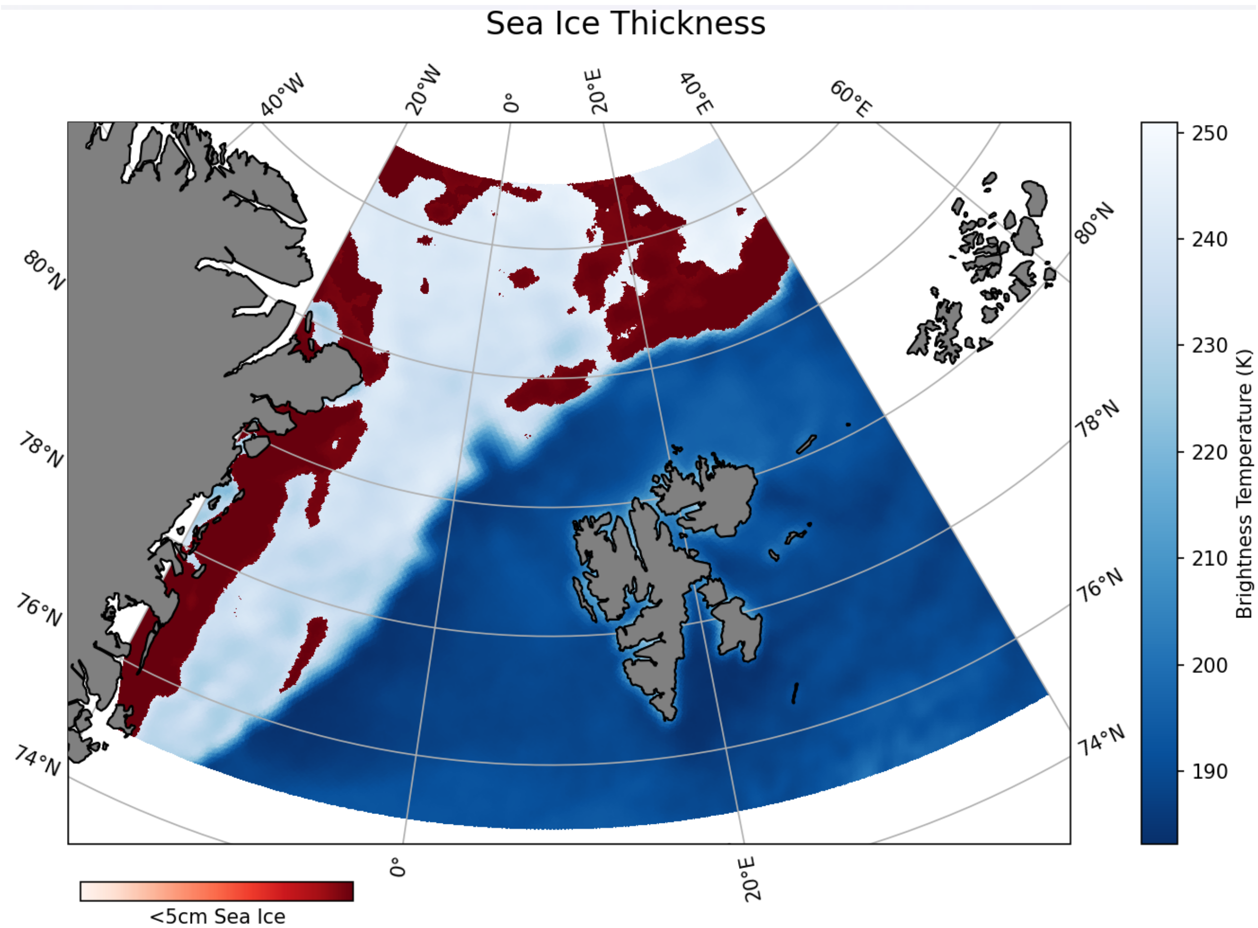
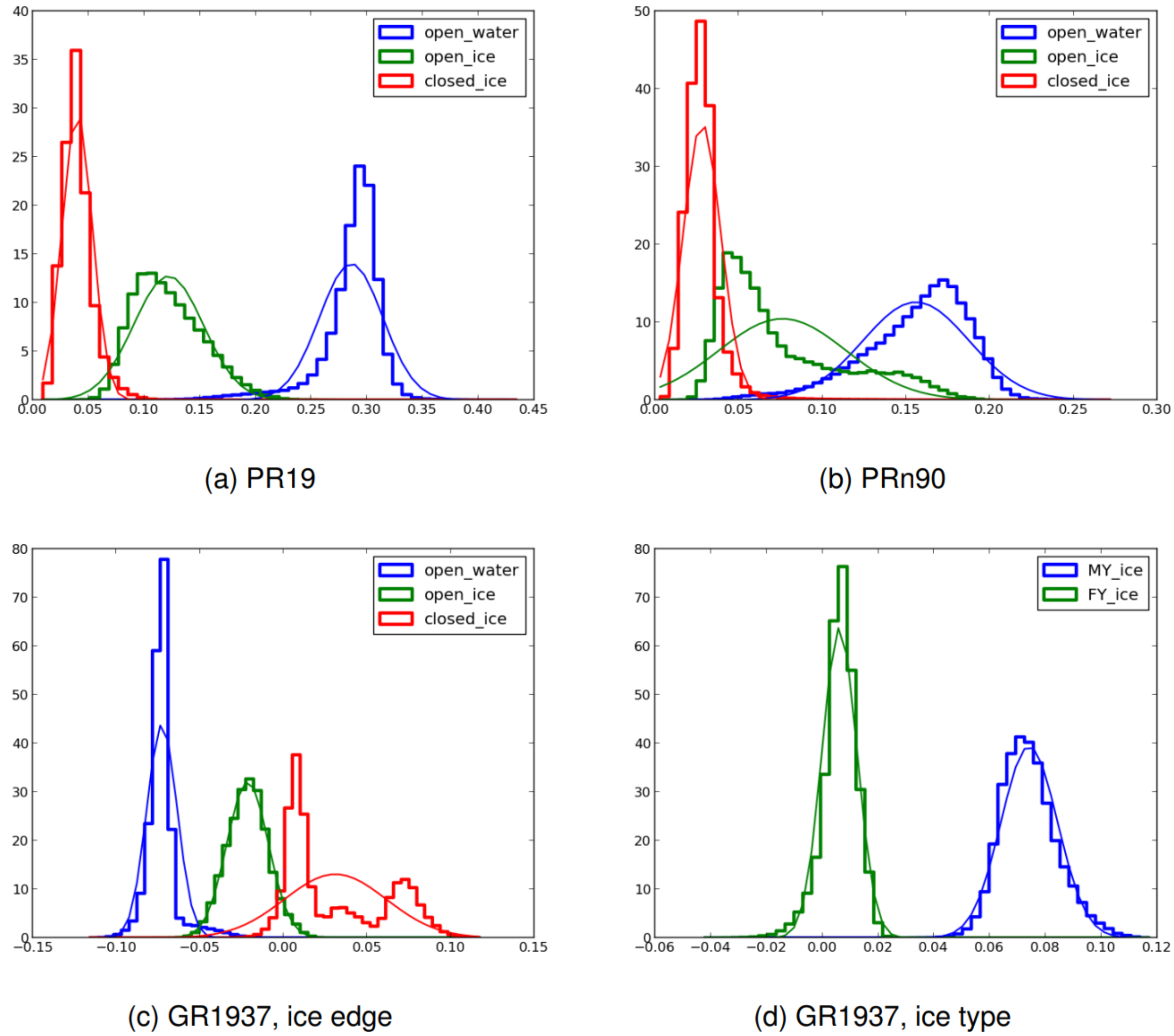


Figure 9: Sea ice thickness map, showing ice with thickness less than 5cm in red.

Appendix

External data and figures

Figure 10 and figure text, is from Global Sea Ice Edge and Type Algorithm Theoretical Basis Document delivered by Ocean & Sea Ice SAF in collaboration with Norwegian Meteorological Institute [2].



(a) PR19

(b) PRn90

(c) GR1937, ice edge

(d) GR1937, ice type

Figure 10: Density plot for the SSMIS parameters: (a) PR19, (b) PRn90 and (c) GR1937cfor sea ice edge classes closed ice (red), open ice (green) and open water (blue), and (d) GR1937 for sea ice type classes first-year ice (green) and multi-year ice (blue). Data are collocated from F18, December 2015. The stair plots show the data and the thin lines show the corresponding Gaussian fit to the data. [2]

References

[1] *Solid Surfaces Sensing in the Visible and Near Infrared*, chapter 3, pages 44–120. John Wiley Sons, Ltd, 2021.

[2] Lars-Anders Breivik Signe Aaboe and Steinar Eastwood. *Global Sea Ice Edge and Type Algorithm Theoretical Basis Document*, pages 1–56. Norwegian Meteorological Institute, 2016, V2.

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[4] brightness temperature, Oxford Reference, April 2024. [Online; accessed 7. Apr. 2024].

[5] *Solid-Surface Sensing*, chapter 5, pages 159–189. John Wiley Sons, Ltd, 2021.

[6] Gunnar Spreen and Stefan Kern. *Methods of satellite remote sensing of sea ice*, chapter 9, pages 239–260. John Wiley Sons, Ltd, 2017.

[7] sea ice age 1984 vs. 2018 (large), April 2024. [Online; accessed 16. Apr. 2024].

[8] May | 2018 | Arctic Sea Ice News and Analysis, April 2024. [Online; accessed 16. Apr. 2024].

[9] *Solid-Surface Sensing*, chapter 6, pages 190–333. John Wiley Sons, Ltd, 2021.