Ground-Based Hyperspectral and Spectro-Directional Reflectance Characterization of Arctic Tundra Vegetation Communities

- Field Spectroscopy and Field Spectro-Goniometry of Siberian and Alaskan Tundra in Preparation of the EnMAP Satellite Mission -

The Arctic tundra, covering approx. 5.5 % of the Earth's land surface, is one of the last ecosystems remaining closest to its untouched condition. Increased tundra productivity, which is thought to be mainly a response to climate warming, and anthropogenic impacts on the physical environment lead to major implications for this ecosystem. Consequently, detailed information about the status of Arctic tundra ecosystems is needed to effectively monitor human impacts and to evaluate the influence of climate change as recommended by the Kyoto Protocol from 1997. Remote sensing is able to provide information at regular time intervals and large spatial scales on the structure and function of Arctic ecosystems. Specifically, reflectance data in the optical light spectrum can be related to biophysical plant parameters which are important input parameters for models. But almost all natural surfaces reveal individual anisotropic reflectance behaviors, which can be described by the bidirectional reflectance distribution function (BRDF). This effect can cause significant changes in the measured surface reflectance depending on solar illumination and sensor viewing geometries.

The aim of this thesis is the hyperspectral and spectro-directional reflectance characterization of important Arctic tundra vegetation communities at representative Siberian and Alaskan tundra sites as basis for the extraction of vegetation parameters, and the normalization of BRDF effects in off-nadir and multi-temporal remote sensing data. Moreover, in preparation for the upcoming German EnMAP (Environmental Mapping and Analysis Program) satellite mission, the understanding of BRDF effects in Arctic tundra is essential for the retrieval of high quality, consistent and therefore comparable datasets. Because hyperspectral or multi-angle satellite and aerial data are not operationally available for tundra regions, the research in this doctoral thesis is based on field spectroscopic and field spectro-goniometric investigations of representative Siberian and Alaskan measurement grids belonging to the Greening-of-the-Arctic program.

Performing ground-based spectro-directional measurements with currently available spectro-goniometer instruments is impractical in the Arctic due to the environmental and logistical challenges. Therefore, the first objective of this thesis was the development of a lightweight, transportable, and easily managed field spectro-goniometer system which nevertheless provides reliable spectro-directional data. I developed the *Man*ual *T*ransportable *I*nstrument platform for ground-based *S*pectro-directional observations (ManTIS). The ManTIS can be equipped with various sensor systems and allows spectro-directional measurements with up to 30° viewing zenith angle by full 360° viewing azimuth angles, in unison with a high angular accuracy and fast execution of the measurements. The developed data processing chain in connection with the self-programmed software for the semi-automatic control provides a reliable method to reduce temporal effects during the measurements. Another outcome of the thesis is that the innovative design and operation mode of the ManTIS was nationally and internationally registered for patent (patent publication number: DE 10 2011 117 713.A1).

The second objective of this thesis is the hyperspectral characterization of Arctic tundra. The outcome of the field spectro-radiometrical measurements at the Low Arctic study sites along important environmental gradients (regional climate, soil pH, toposequence, and soil moisture) show that the different plant communities can be distinguished by their nadir-view reflectance spectra. For this purpose, spectral metrics, including the averaged reflectance and absorption-related metrics, were investigated with respect to "greenness", biomass, vegetation height, and soil moisture regimes. The results especially reveal separation possibilities between the different tundra vegetation communities in the visible (VIS) blue and red wavelength regions. Additionally, the near-infrared (NIR) shoulder and NIR reflectance plateau, despite their relatively low values due to the low structure of tundra vegetation, are still valuable information sources and can separate communities according to their biomass and vegetation structure. The main spectro-radiometrically-based differences among these communities are: (i) southern sites along the climate gradient have taller shrubs and greater overall vegetation biomass, which leads to higher reflectance in the NIR; (ii) vegetation height and surface wetness have opposing effects that balance each other out with respect to the NIR reflectance along the toposequence and soil moisture gradients; (iii) moist acidic tundra (MAT) sites have "greener" species, more leaf biomass, and green-colored moss species that lead to higher absorption by photosynthetic pigments compared to moist non-acidic tundra (MNT) sites. The regression analyses with biomass indicate the possibility of separating out MAT and MNT vegetation via hyperspectral vegetation indices (VI), such as the narrowband Normalized Difference Vegetation Indices (NDVI); these communities have not been previously separable in such a good way using broadband data. Nevertheless, the field spectroscopy also exhibits some universal reflectance characteristics for tundra vegetation. In general, all different tundra plant communities show: (i) low maximum NIR reflectance; (ii) a weakly or nonexistent visible green reflectance peak in the VIS spectrum; (iii) a narrow "red-edge" region between the red and NIR wavelength regions; and (iv) no distinct NIR reflectance plateau.

These common nadir-view reflectance characteristics are essential for the understanding of the variability of BRDF effects in Arctic tundra. For the third objective – the investigation of the spectro-directional reflectance characteristics of tundra vegetation communities – the spectro-goniometry was performed at solar noon in order to gain comparable datasets. None of the analyzed tundra communities showed an even closely isotropic reflectance behavior. In general, tundra vegetation communities: (i) usually show the highest BRDF effects in the solar principal plane; (ii) usually show the reflectance maximum in the backward viewing directions, and the reflectance minimum in the nadir to forward viewing directions; (iii) usually have a higher degree of reflectance anisotropy in the VIS wavelength region than in the NIR wavelength region; and (iv) show a more bowl-shaped reflectance distribution in longer wavelength bands (>700 nm). The explanation for these findings is that tundra communities form an overall more erectophile canopy, and that the dense moss and lichen mats in the understory exclude soil BRDF effects. The fourth objective of this thesis is the analysis of the influence of high sun zenith angles on the reflectance anisotropy. Therefore, spectro-goniometry was carried out at varying sun zenith angles ranging from 46° to 68°. The results show that with increasing sun zenith angles, the reflectance anisotropy changes to azimuthally symmetrical, bowl-shaped reflectance distributions with the lowest reflectance values in the nadir view position.

The fifth objective of this thesis is the investigation of the variability in remote sensing products for Low Arctic tundra environments that is attributable to changes in the illumination-target-sensor geometry. The spectro-directional analyses show that remote sensing products such as the NDVI or relative absorption depth products are strongly influenced by BRDF effects, and that the anisotropic characteristics of the remote sensing products can significantly differ from the observed BRDF effects in the original reflectance data. The results show that in relative absorption depth products the off-nadir values can deviate with increasing sensor view zenith angle up to 25 % from the nadir value. But the results further show that the NDVI can minimize view angle effects relative to the contrary spectro-directional effects in the red and NIR bands. For the researched tundra plant communities, the overall difference of the off-nadir NDVI values compared to the nadir NDVI value increases with increasing sensor viewing angles, but on average never exceeds 10 %.

In conclusion, this study shows that changes in the illumination-target-viewing geometry directly lead to an altering of the reflectance spectra of Arctic tundra communities according to their object-specific BRDFs. Since the different tundra communities show only small, but nonetheless significant differences in the surface reflectance, it is important to include spectro-directional reflectance characteristics in the algorithm development for remote sensing products. In preparation of the upcoming EnMAP satellite mission, (i) the availability of ground-based multi-angular and hyperspectral data, (ii) the possibility of measuring with a field-adapted, resistant and light-weight spectro-goniometer such as the developed ManTIS, and (iii) the understanding of the BRDF effects in low-growing tundra biomes are crucial for the normalization of off-nadir remote sensing data as well as the potential derivation of vegetation structure parameters for tundra and permafrost landscapes.