Accessible remote sensing of water

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English summary

Water is all around us. We use it to drink, wash, play, fish, sail, and much more. Natural waters, like streams, rivers, lakes, seas, and oceans, are full of life and interesting chemistry. Because of its importance, we need to study water intensively, measuring the various compounds and life forms that inhabit it. This way, we can better understand the world around us, our impact on it, and its impact on us.

Oceans and inland waters contain many different *constituents*. These include various chemical compounds, particles, phytoplankton, and pollution. Each constituent in a water body plays a role in its chemistry and biology. For example, phytoplankton produces half of the organic carbon and oxygen in the world, which are vital for all other life forms. By studying the concentrations and properties of constituents in a water body, we can understand its ecosystem. This knowledge has inherent value and also allows us to intervene against pollution, climate change, and other harmful events.

Concentrations and properties of constituents are traditionally measured by taking samples and analysing them in a laboratory. However, this method faces three important challenges. First, it requires expensive equipment and trained personnel, which are not available everywhere nor to everyone. Second, it is difficult to scale these measurements up in time and space. Studying global processes like climate change requires global coverage, but the funds and personnel required to sample every water body regularly are not available. Studying local processes requires speed and local access, which are also not readily available. Third, there is limited standardisation in sampling and analysis protocols between researchers. This causes a large uncertainty on results and makes it difficult to compare results from different groups or locations.

Remote sensing, measuring the light reflected by water, enables global measurements with rapid response times and high consistency. Using different wavelengths and polarisation states, we can determine the concentrations and properties of various constituents. For example, the phytoplankton concentration can be estimated by comparing the reflectance at blue vs. green wavelengths. There is a wide variety of remote sensing instruments on satellites, aeroplanes, ships, and stationary platforms. Recently, consumer cameras like those on drones and smartphones have become popular for low-cost remote sensing.

Citizen science involves non-professionals in the scientific process by taking measurements, interpreting results, and thinking of new research. This provides opportunities to reduce cost and improve scalability by increasing the accessibility of water research. Citizens provide many data and local knowledge that, in collaboration with professional researchers, can lead to new possibilities, shared insights, and tailored local interpretation. At the same time, the citizen scientists learn more about their environment by conducting their own research and they are socially and politically empowered as stakeholders.

The aim of this thesis is to investigate and improve accessibility and uncertainty in remote sensing and citizen science, so that these techniques can better deliver the desired improvements to cost, scale, and reproducibility of water research. *Accessibility* here means the degree to which people can create, use, and interpret data, without being limited by physical ability or financial status. *Uncertainty* refers to the spread in measured values caused by random effects and to errors caused by known or unknown systematic effects.

Chapter 2. Citizen science with colour blindness: A case study on the Forel-Ule scale. Many citizen science projects depend on colour vision, but up to 1 in 11 participants are colour blind. We simulate the impact of various forms of colour blindness on measurements with the Forel-Ule scale, which is used to measure water colour by eye. We find that colour blindness decreases the ability to distinguish between Forel-Ule colours. This reduces the precision and accuracy of citizen science data and the motivation of participants. These issues can be addressed by including uncertainty estimates in data entry forms and discussing colour blindness in training materials. These conclusions and recommendations apply to colour-based citizen science in general, including other classification and monitoring activities. Being inclusive of the colour blind increases both the social and scientific impact of citizen science.

Chapter 3. Standardised spectral and radiometric calibration of consumer cameras. Consumer cameras, particularly onboard smartphones and UAVs, are now commonly used as scientific instruments. However, their data processing pipelines are not optimised for quantitative radiometry and their calibration is more complex than that of scientific cameras. The lack of a standardised calibration methodology limits the reproducibility between devices and, in the ever-changing market, ultimately the lifespan of projects using them. We present a standardised methodology and database (SPECTACLE) for spectral and radiometric calibrations of consumer cameras. The methodology is applied to seven popular cameras to characterise their performance and quantify uncertainties. Through calibration and the use of RAW data, we lay the groundwork for using consumer cameras to perform professional-grade spectroradiometry.

Chapter 4. Accuracy and reproducibility of above-water radiometry with calibrated smartphone cameras using RAW data.
In this chapter, we apply the results and recommendations from Chapter 3 to above-water radiometry. We measure R_{rs} and water colour on and around Lake Balaton, Hungary, with two smartphones and two hyperspectral reference instruments for validation. We quantify the uncertainty, reproducibility, and accuracy of the resulting data and compare these to professional spectroradiometers and existing citizen science approaches. We find that smartphone cameras perform similarly to professional instruments in terms of uncertainty, accuracy, and reproducibility. Based on these results, we offer practical recommendations for using consumer cameras in professional and citizen science.

Chapter 5. Biases from incorrect reflectance convolution.
Reflectance measurements from different instruments are converted and compared through spectral convolution. This is done to combine time series, validate instruments, and apply retrieval algorithms. However, convolution is often done incorrectly, with reflectance itself convolved rather than the underlying (ir)radiances. We quantify the resulting error for simulated and real instruments and find biases up to 5%. Based on these results, we suggest that this error was partially responsible for uncertainties found in previous work and recommend that future work apply spectral convolution correctly.

Chapter 6. A universal smartphone add-on for portable spectroscopy and polarimetry: iSPEX 2.

We present a new smartphone spectropolarimeter, iSPEX 2. It succeeds the original iSPEX add-on for citizen science measurements of atmospheric aerosols. The optical design is presented and the manufacturing process is detailed. Through universal smartphone support and a data processing pipeline based on Chapter 3, we aim to improve the accessibility and data quality compared to the original. An initial validation measurement is presented as a proof of concept. Finally, we suggest possible applications of iSPEX 2 for professional and citizen science.

Chapter 7. General discussion and future outlook.

In this chapter, we synthesise the overall findings of Chapters 2–6 and discuss them relative to the current state and future direction of the field. Research in remote sensing of water is focused on obtaining higher-dimensional data by including more wavelengths and polarisation, on automation, and on more in-depth analysis of uncertainty and information content. Citizen science has experienced a boom in the last twenty years, but much work remains to be done. Improvements to equity, diversity, and inclusion will increase the social and scientific impact of citizen science. Further social and technological research is necessary to attain these improvements. Additionally, this chapter contains the initial findings from a follow-up project on spectropolarimetry of floating debris. We observe various types of debris, mostly plastics, in a wave basin under realistic conditions. We find a significant polarisation signal for several types of debris, suggesting that polarisation can be used to detect debris in nature.