Coupled Retrieval of the Three Phases of Water from Spaceborne Imaging Spectroscopy Measurements

Niklas Bohn[1], Theres Kuester[1], Karl Segl[1], Luis Guanter[2], and Rene Preusker[3]

[1]Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences
[2]Polytechnic University of Valencia
[3]Free University of Berlin

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Abstract

Measurements of reflected solar radiation by imaging spectrometers allow to quantify water in different states (solid, liquid, gas) thanks to the discriminative absorption lines in the solar spectrum. We developed a retrieval method to quantify the amount of water in each of the three states from spaceborne imaging spectroscopy data, such as those from the German EnMAP mission. Our retrieval couples atmospheric radiative transfer simulations from the MODTRAN5 radiative transfer code to a surface reflectance model based on the Beer-Lambert law. The model is inverted on a per-pixel basis using a maximum likelihood estimation formalism. Based on a unique coupling of the canopy reflectance model HySimCaR and the EnMAP end-to-end simulation tool EeteS, we performed a sensitivity analysis by comparing the retrieved values with the simulation input leading to an R2 of 0.991 for water vapor and 0.965 for liquid water. Furthermore, we applied our algorithm to airborne AVIRIS-C data to demonstrate the ability to map snow/ice extents as well as to a CHRIS-PROBA dataset for which concurrent field measurements of canopy water content were available. The comparison between our retrievals and the ground measurements showed an overall R2 of 0.80 for multiple crop types and a remarkable clustering in the regression analysis indicating a dependency of the retrieved water content from the physical structure of the vegetation. In addition, our algorithm is able to produce smoother and more physically-plausible water vapor maps than the ones from the band ratio approaches used for multispectral data, since biases due to background reflectance are reduced. The demonstrated potential of imaging spectroscopy to provide accurate quantitative measures of water from space will be further exploited using upcoming spaceborne imaging spectroscopy missions like PRISMA or EnMAP.

Coupled Retrieval of the Three Phases of Water from Spaceborne Hyperspectral Measurements

Niklas Bohn[1,2]*, Theres Kuester[2], Karl Segl[2], Luis Guanter[2,3], René Preusker[4]

[1] Visiting Research Scholar, Jet Propulsion Laboratory, California Institute of Technology
[2] GFZ German Research Centre for Geosciences, Section 1.4, Remote Sensing and Geoinformatics, Potsdam, Germany
[3] School of Telecommunications Engineering, Universitat Politecnica de Valencia, Spain
[4] Freie Universität Berlin, Germany
* niklas.n.bohn@jpl.nasa.gov; nbohn@gfz-potsdam.de

Introduction

Imaging spectroscopy makes it possible to identify and quantify water in different states due to the presence of sufficient narrow bands in the near-infrared (NIR). The use of spaceborne measurements enables new possibilities in mapping local and global trends of water vapor, liquid water and ice. On the one hand, it is essential for evaluating plant physiological status and health. On the other, it supports the prediction of snow melt rates and the availability of fresh water. We developed a coupled three phases of water retrieval for spaceborne hyperspectral measurements such as DESIS, PRISMA or the upcoming EnMAP, CHIME and SBG missions. Our method is based on a maximum likelihood estimation and integrated in an atmospheric correction procedure by linking the MODTRAN radiative transfer code to a surface reflectance model based on the Beer-Lambert law. We evaluate the performance of the algorithm through a sensitivity analysis on simulated EnMAP spectra and use CHRIS-PROBA data as a proxy for future satellite missions to compare the retrieval results with ground-based measurements. Confirmatory of previous studies, we additionally show results from airborne AVIRIS-C data.

Methods

Approach

Discriminative absorption lines of water vapor, liquid water and ice

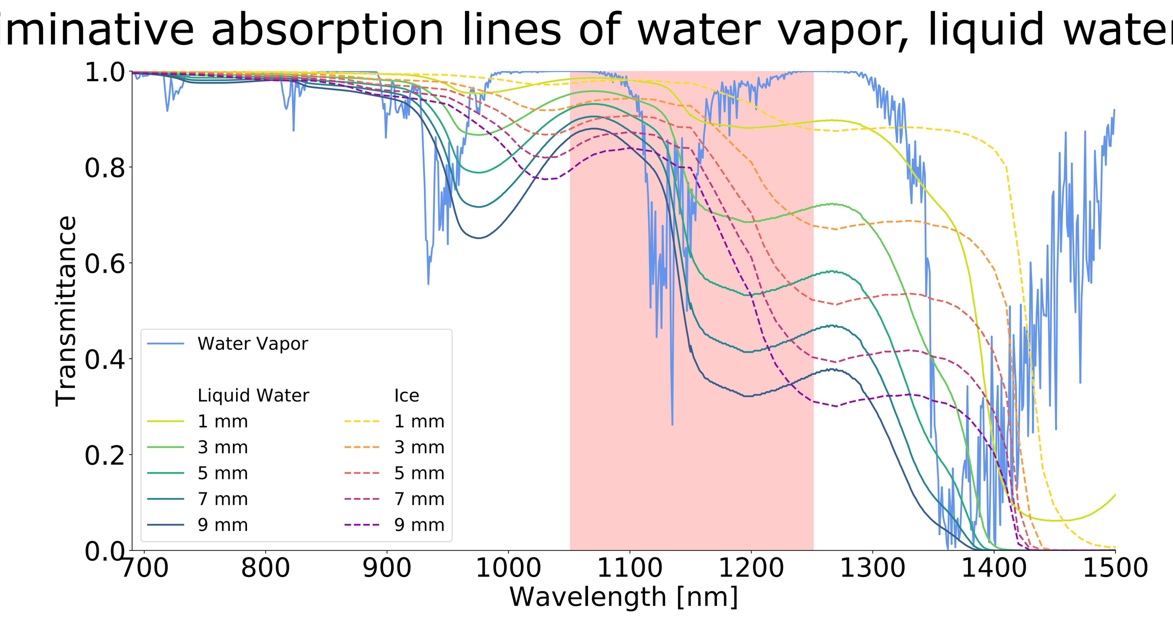


Fig. 1: Overlapping transmittance spectra of water vapor, liquid water and ice. Water vapor: 5 mm precipitable water. Liquid water and ice: five different path lengths from 1 to 9 mm. The absorption window used for spectral fitting is displayed in light red.

1. Modeling of TOA radiance using radiative transfer simulations:

$$L_{TOA} = L_0 + \frac{1}{\pi} * \frac{\rho_{s,\lambda}(E_{dir}\mu_{sun} + E_{dif})T_{\uparrow}}{1 - S\rho_{s,\lambda}} \quad (1)$$

with surface reflectance model based on Beer-Lambert-law:

$$\rho_{s,\lambda} = (a + b\lambda)e^{(-d_w\alpha_{w,\lambda} - d_i\alpha_{i,\lambda})} \quad (2)$$

2. Inversion of forward model (Eq. 1) using maximum likelihood estimation:
   - Matching simulated and measured spectra within spectral fitting window evaluated by pre-defined cost function
   - Calculation of correlation errors and retrieval uncertainties

Conclusion

Our coupled retrieval infers CWV and CWC from simulated EnMAP TOA radiances showing very high R^2 of 0.99 and 0.96, respectively. Moreover, CWC retrieved from CHRIS-PROBA data features an R^2 of 0.80 compared with ground-based measurements. Despite the high correlation, CWC is systematically overestimated. This is caused by multiple scattering within the canopy, which largely depends on canopy structural parameters such as LAI and height. Since the Beer-Lambert law actually has to be applied to non-scattering media, our surface reflectance model needs to be improved by additional terms, e.g., based on the directional area scattering factor (DASF) or spectral invariants, as part of future research. Nevertheless, our method leads to improvements in atmospheric correction procedures by producing smoother and more plausible CWV maps since biases due to background reflectance are reduced. It also delivers a promising basis for future EnMAP-based snow parameter retrievals.

Data

- **Simulated EnMAP TOA radiances**
  - **PROSPECT** + Hyperspectral Simulation of Canopy Reflectance system (**HySimCaR**) + EnMAP end-to-end Simulation tool (**EeteS**)
- **CHRIS-PROBA (CP) measurements, Barrax, Spain, 07/14/2003 (ESA SPARC'03 campaign)**
- **AVIRIS-C data, Sierra Nevada, CA, 02/24/2015**

Results

Sensitivity analysis on simulated EnMAP radiances

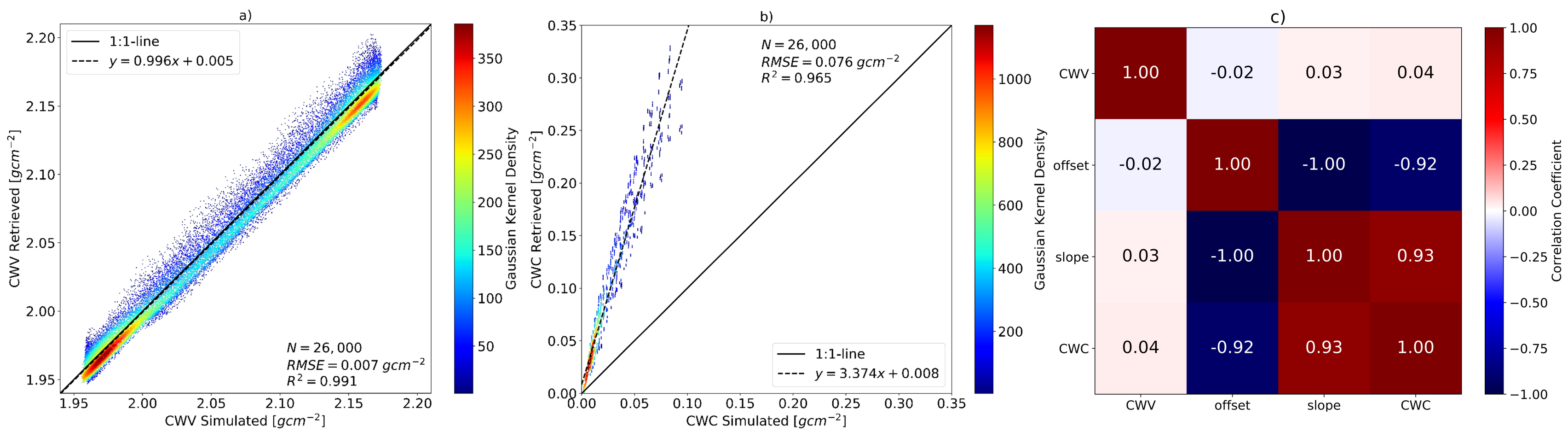


Fig. 2: a) and b) Comparison of derived water vapor (CWV) and canopy water content (CWC), respectively, with the simulation input. c) State vector correlation error matrix.

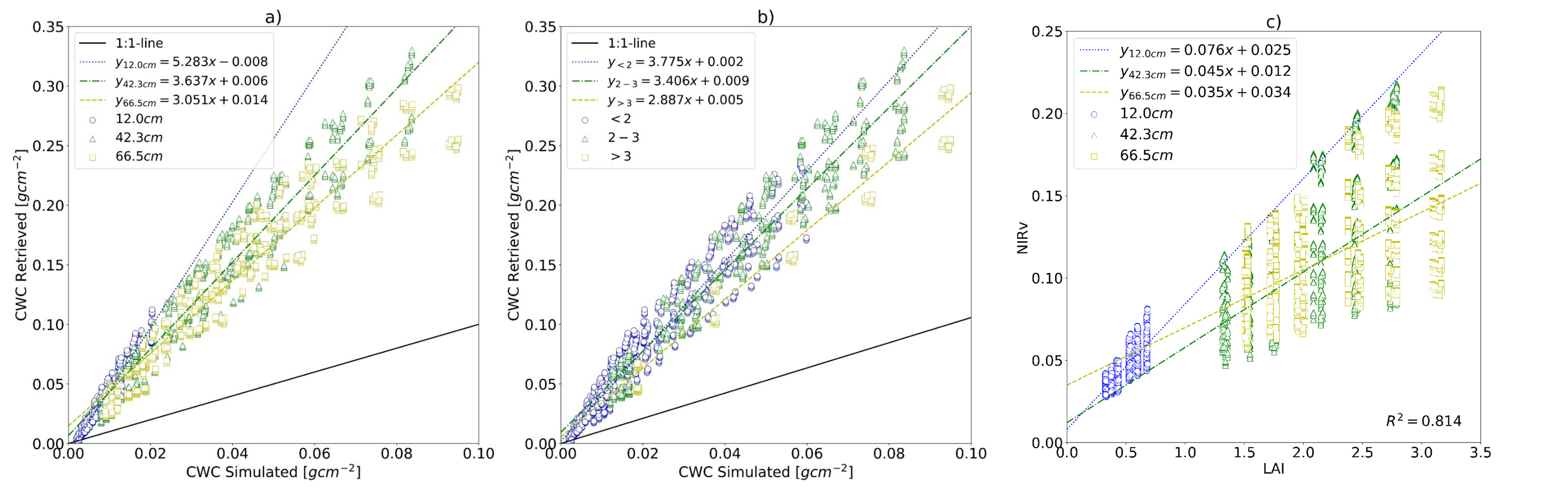
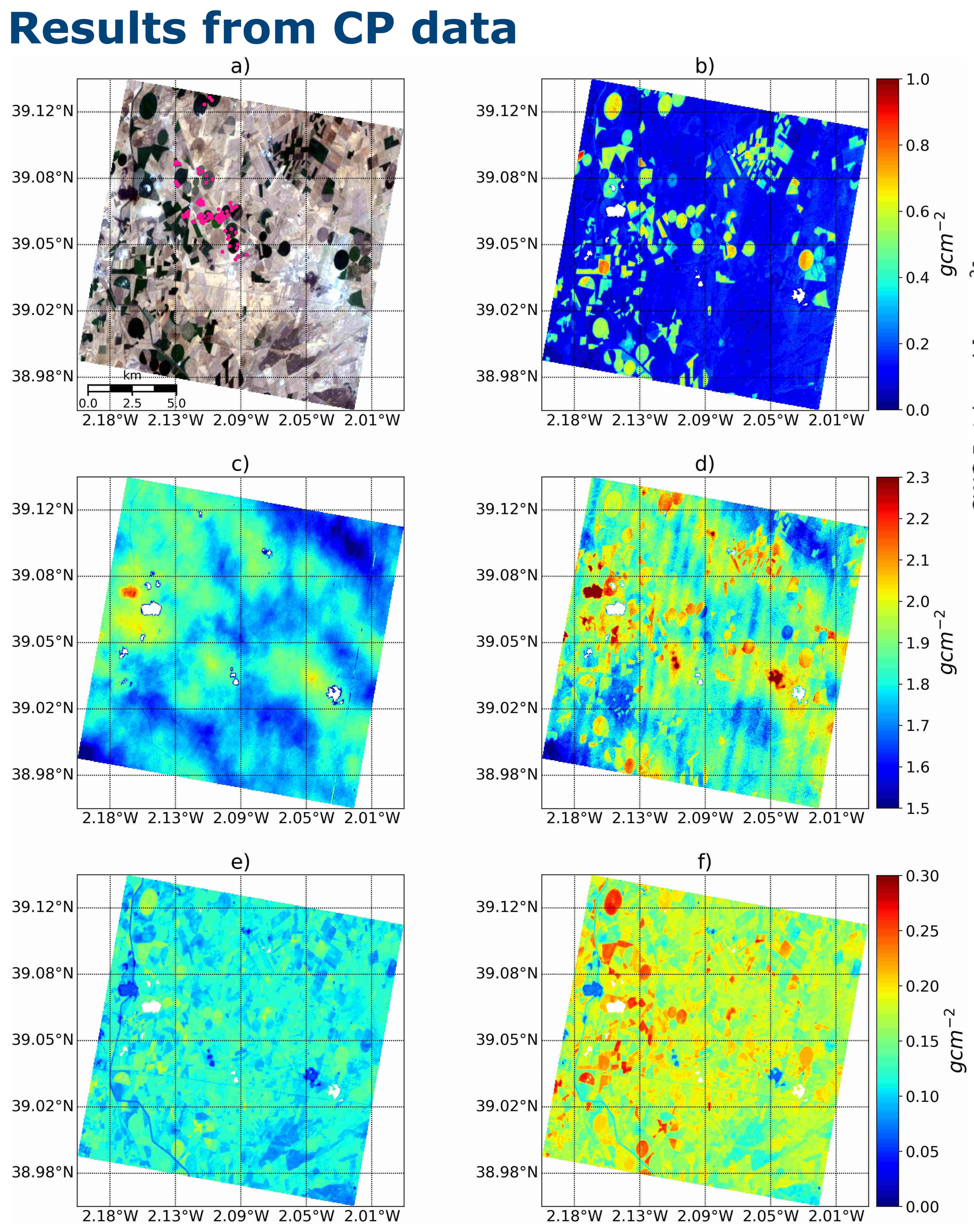


Fig. 3: Comparison of retrieved with simulated CWC as a function of a) mean canopy height, and b) LAI. c) Comparison of NIRv with LAI for different mean canopy heights.

Results from CP data



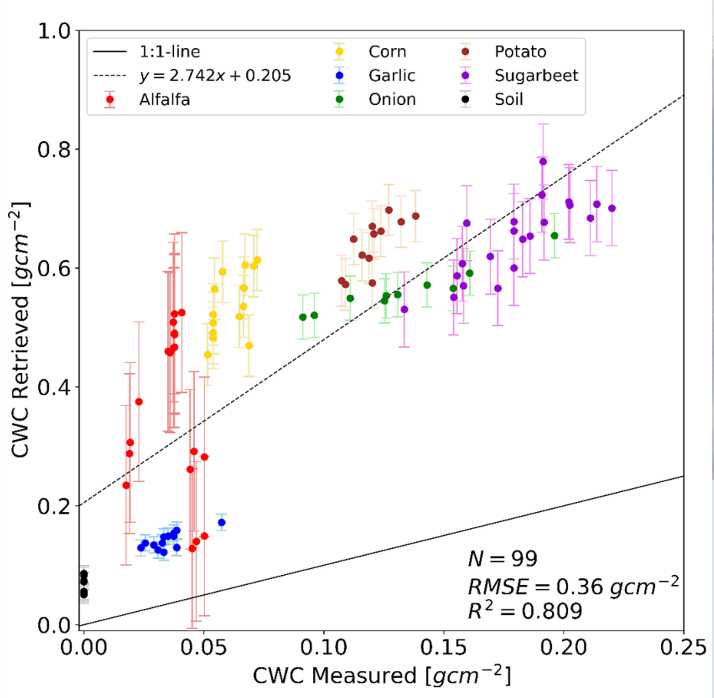


Fig. 5: Comparison of retrieved CWC with field measurements of CWC for different crop types.

Fig. 4: a) True-color image with pink colored points representing locations of field measurements (RGB: 653/563/481 nm). b) CWC map derived from the coupled retrieval. c) CWV map derived from the coupled retrieval. d) CWV map derived from a band ratio retrieval. e) CWV and f) CWC uncertainties for the coupled retrieval. White colored pixels indicate masked clouds.

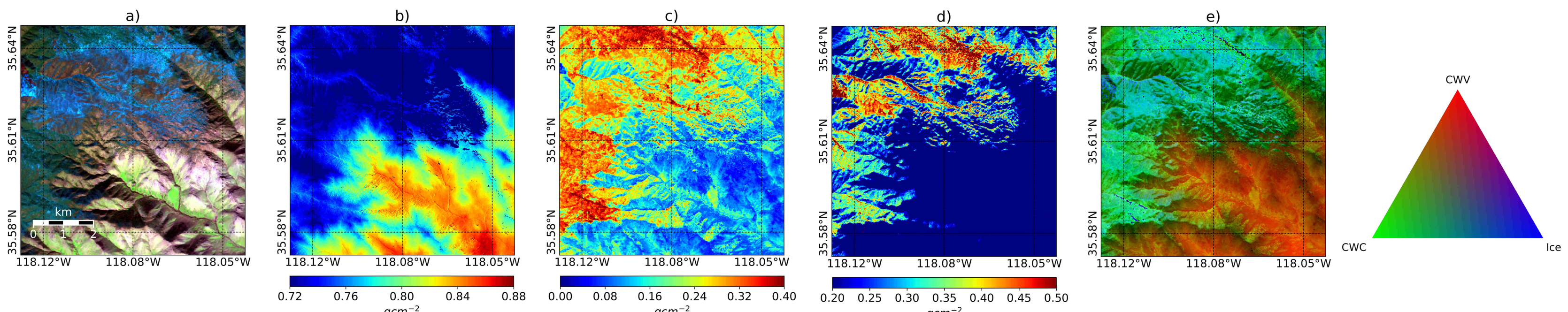


Fig. 6: Results from AVIRIS-C data. a) False-color image (RGB: 1602/870/560 nm). b) CWV map. C) Liquid water map. d) Ice map. e) Combined three phases map (RGB: CWV/Liquid/Ice).

Acknowledgments

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