The potential and feasibility of improved glint observations over snow for CO2M

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High latitudes pose significant challenges to reliable space-based observations of carbon dioxide. In addition to large solar zenith angles and frequent cloud coverage, snow-covered surfaces absorb strongly in the near-infrared wavelengths. Because of the resulting low radiances of the reflection measured by the satellite, the retrievals over snow may be less reliable and are typically filtered or flagged for potentially poor quality. Snow surfaces are highly forward-scattering and therefore the traditional nadir-viewing geometries over land might not be optimal and instead the strongest signal could be attainable in glint-like geometries. In addition, the contributions from the SWIR-1 (1.6 um) and SWIR-2 (2.0 um) CO2 absorption bands need to be evaluated over snow.

In this presentation, we will focus on the examination of the effects of a realistic, non-Lambertian surface reflection model of snow based on snow reflectance measurements on simulated top-of-atmosphere radiances in the wavelength bands of interest. The radiance simulations were carried out with various different viewing geometries, solar angles and snow surfaces.

There are three main findings of the simulation study. Firstly, snow reflectivity varies greatly by snow type, but the forward reflection peak is present in all examined types and wavelength bands. Secondly, glint observation mode was found to be more reflective than nadir observation mode over snow surfaces across all the examined wavelengths bands and geometries. Thirdly, a simple information content analysis shows that glint-viewing geometries are significantly more informative than nadir-viewing geometries and that the SWIR-2 band is more informative than the SWIR-1 band over snow surfaces.

The study presented is part of the ESA SNOWITE project. The primary aim of the project is to support the development of the upcoming Copernicus CO2 Monitoring Mission (CO2M).

Measurement-based snow BRDF model

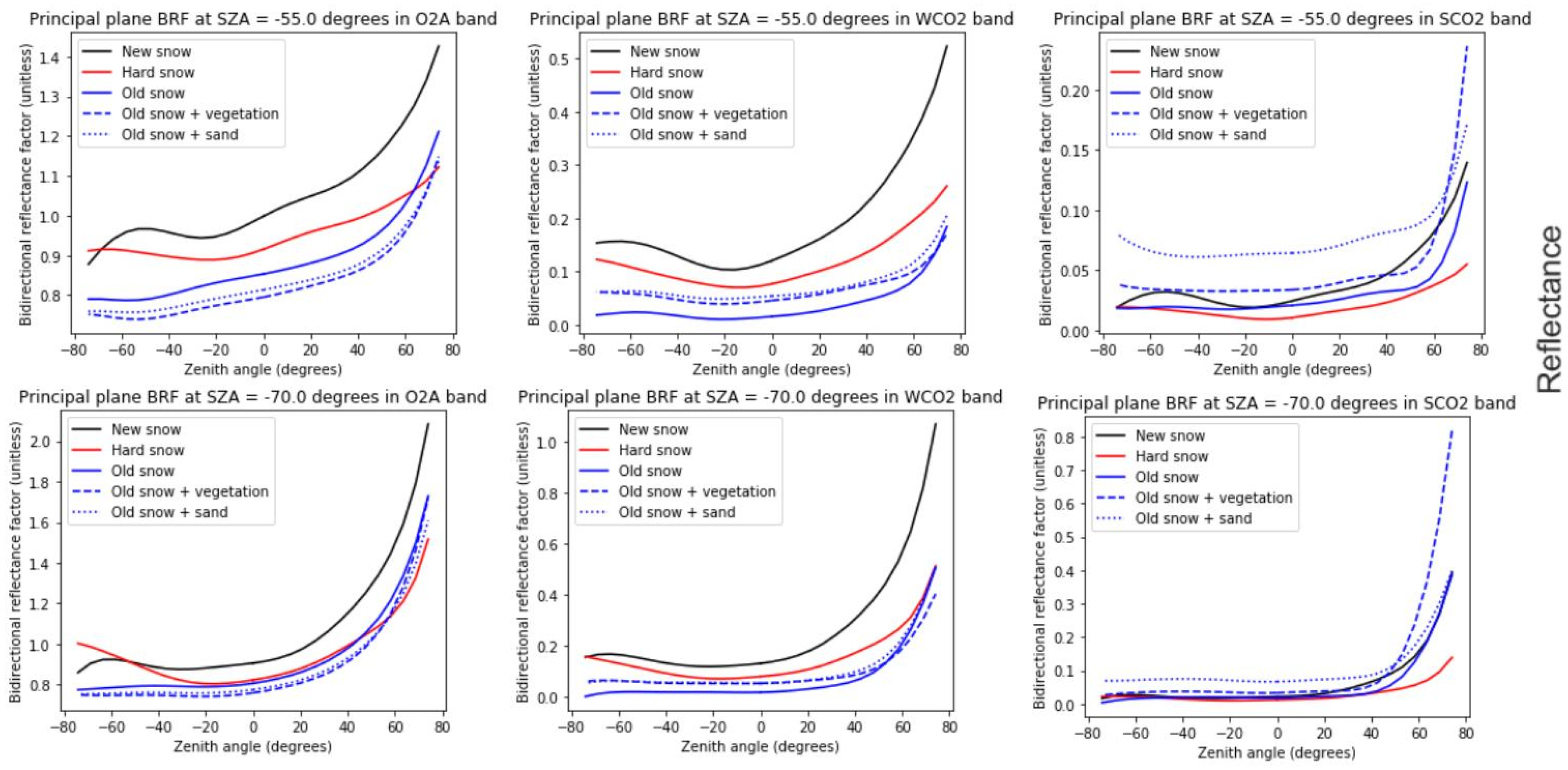
Snow surface reflectivity is modeled after field goniometer measurements various Earth surface bidirectional reflectance factors (BRF) carried out by Jouni Peltoniemi of Finnish Geospatial Research Institute using the FIGIFIGO instrument (Peltoniemi et al. 2020). Peltoniemi's archives of snow BRF measurements span more than 20 years and three rough categories of snow were identified from there:

- New snow: Fresh snowfall, at most 48 hours old.
- Hard snow: Wind-packed snow, main type of snow found in Greenland.
- Old snow: Partially melted snow, most common type in the Spring months.

Two mixed types were also examined: 90 % old snow + 10 % vegetation and 90 % old snow + 10 % sand to observe the effects of further melting of the snow.

The snow reflectivity is very high in the O_2 A-band, but almost non-existent in the CO_2 absorption bands. However, almost all of the bands and snow types exhibit a strong forward reflecting peak, which could indicate higher top-of-atmosphere radiance values in the forward direction.

Peltoniemi, J. I., Gritsevich, M., Markkanen, J., Hakala, T., Suomalainen, J., Zubko, N., Wilkman, O. and Muinonen, K.: A COMPOSITE MODEL FOR REFLECTANCE AND POLARISATION OF LIGHT FROM GRANULATE MATERIALS, ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., V-1-2020, 375–382, 2020.



Reflectance measured at nadir geometry

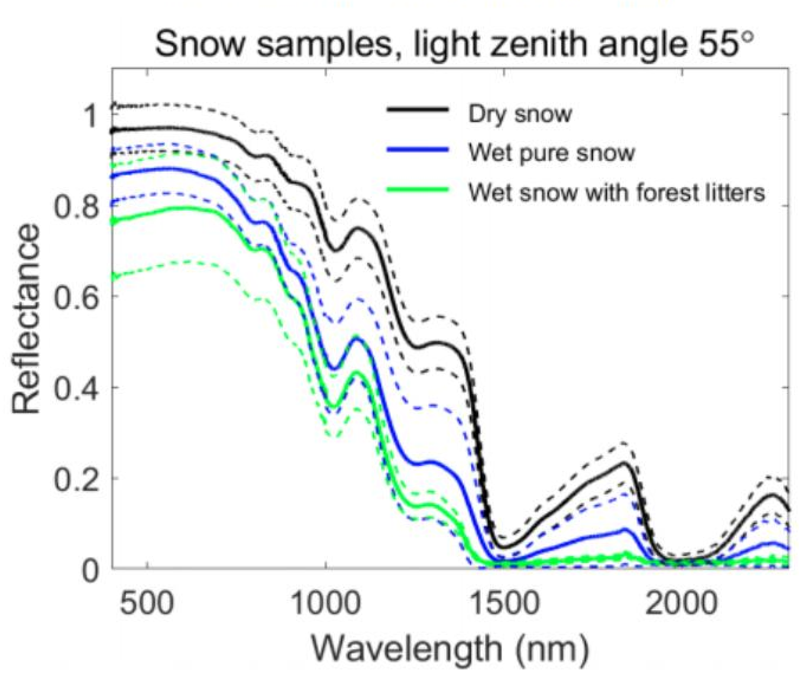
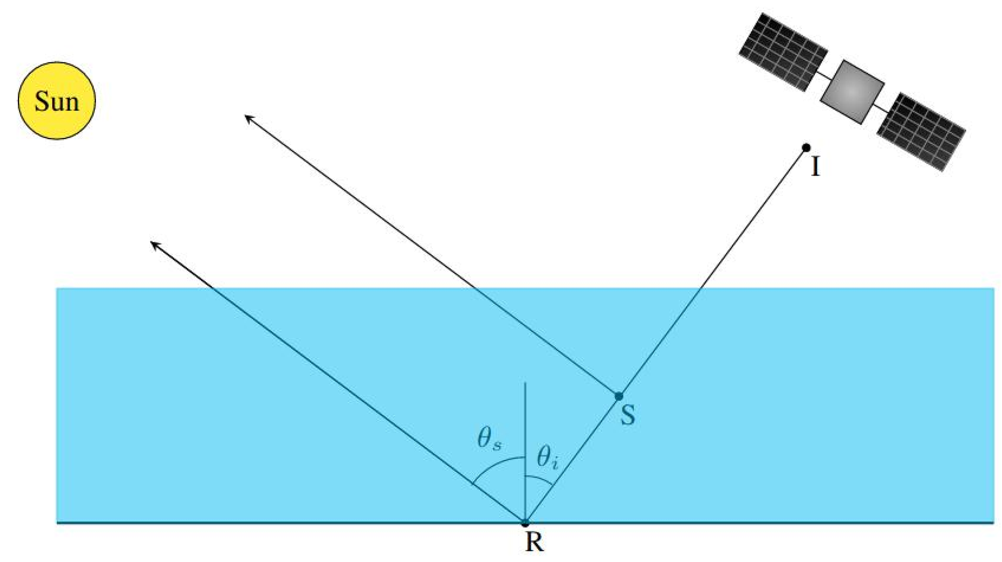


Figure: Hannula, H.-R., Heinilä, K., Böttcher, K., Mattila, O.-P., Salminen, M. and Pulliainen, J.: Laboratory, field, mast-borne and airborne spectral reflectance measurements of boreal landscape during spring, Earth Syst. Sci. Data, 12, 719–740, 2020.



Radiative transfer (RT) modeling and observation geometries

In this work, we utilized RaySca, a novel radiative transfer code developed at the Finnish Meteorological Institute (Mikkonen et al, 2022, in preparation). The code aims to be fast polarized RT code for atmospheric NIR-SWIR radiation. RaySca is capable of simulating fully 3D atmospheres, with varying atmospheric absorbing and scattering cross-sections and arbitrary planetary surface BRDFs. However, its atmospheric scattering is only limited to the first order scattering, which constrains the atmosphere to be relatively aerosol-free and the wavelength region of sufficiently accurate simulations.

In this study, we compared nadir ($\theta_i = 0$) and glint ($\theta_i = \theta_s$) observation modes for observing CO_2 over snow-covered surfaces. The optimal observation angle could be something else, but it would be unfeasible from mission operation point-of-view.

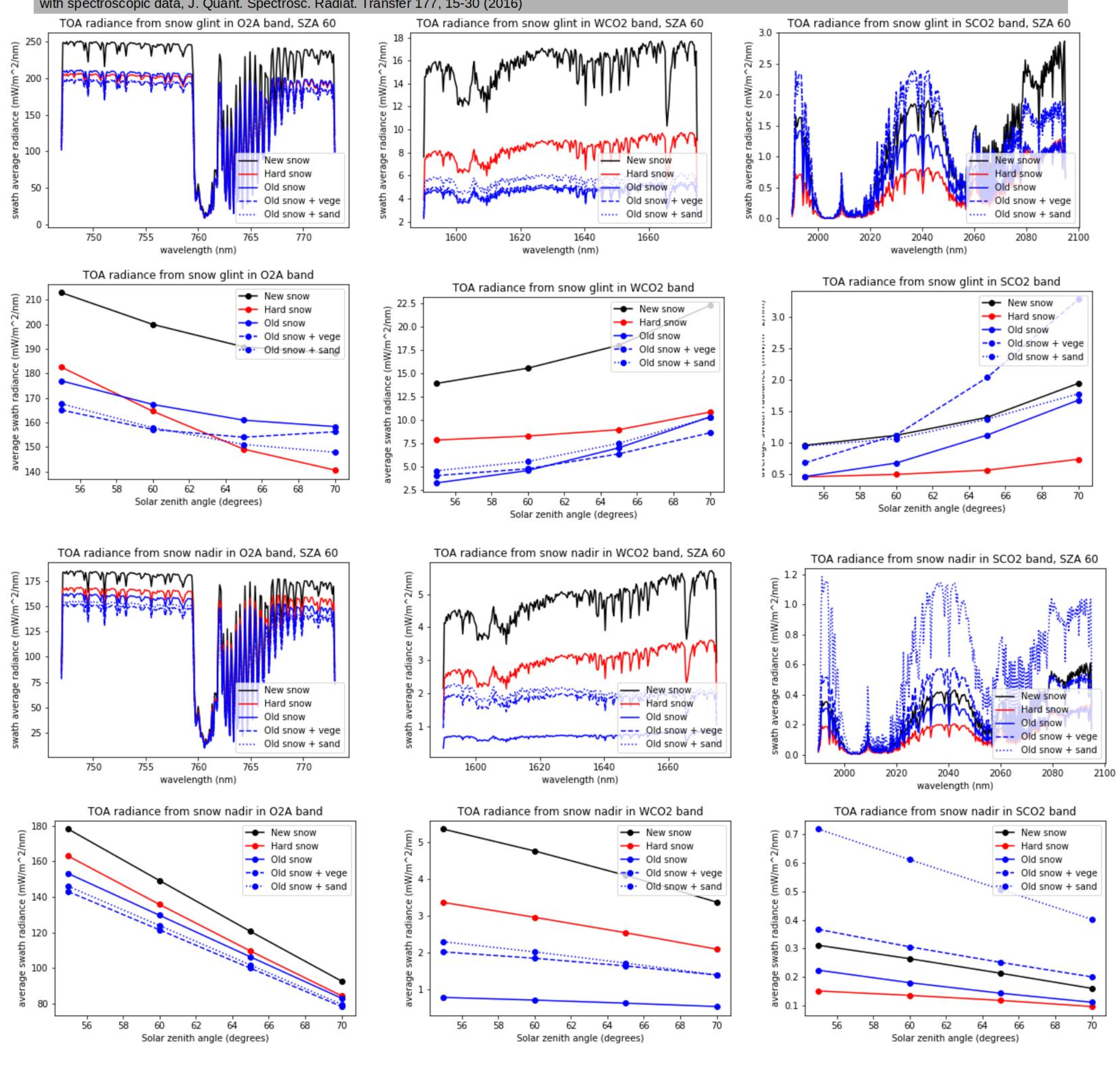
Mikkonen A, Lindqvist H, Peltoniemi J, Tamminen J: The non-Lambertian snow surface reflection models for simulated atmospheric transmittances in the NIR and SWIR wavelengths, JQSRT, (2022, in preparation)

Top-of-atmosphere radiance spectra over snow-covered surfaces in nadir and glint mode

Radiance simulations of reflected solar radiance by snow surfaces were carried out. The whole CO2M swath was simulated, but no spectral variation along the swath was observed. The radiance spectra were averaged over the swath pixels. Solar zenith angles of 55 to 70 degrees were found to be representative of the high latitude spring season. The atmosphere is based on TCCON/GGG2020 in April at Sodankylä, Finland which is a usual atmosphere in the boreal region. The absorption cross-sections of the gases in different atmospheric altitudes and the instrument function were computed using HITRAN API (Kochanov et al., 2016). Only the Rayleigh scattering of the atmosphere was considered.

It can be seen that while in nadir observation mode, the measured radiances decrease with the increasing solar zenith angle. However in the glint mode, the radiance levels increase with the increasing solar zenith angle, but only in the CO_2 bands. This is likely due to the fact that the snow surface is highly forward reflecting and that in the CO_2 bands, the extinction due to the atmospheric Rayleigh scattering is significantly smaller than in the O2 A-band. The increased radiance levels are observable with all the snow surface types and it could indicate preference of glint mode observation over snow.

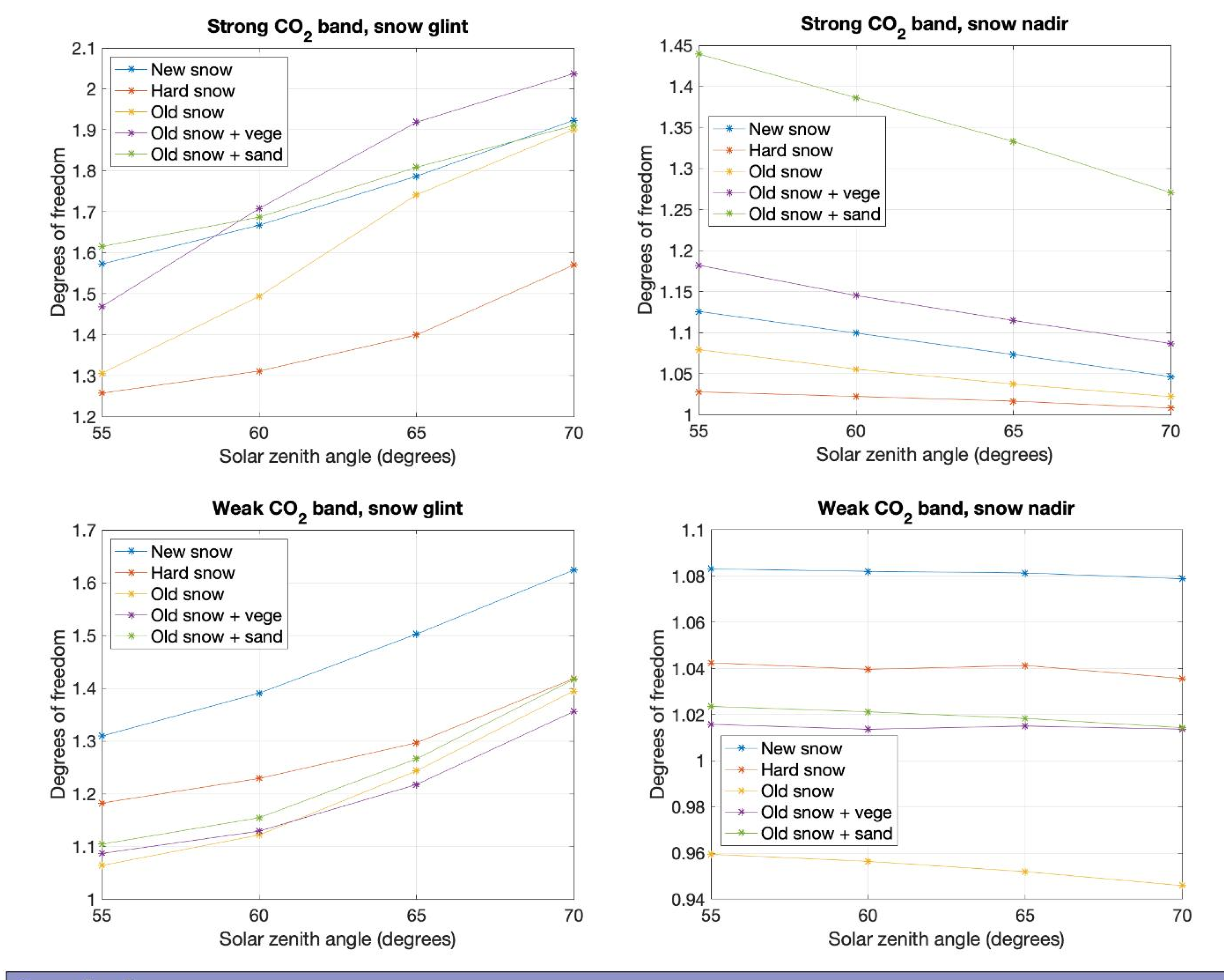
R.V. Kochanov, I.E. Gordon, L.S. Rothman, P. Wcislo, C. Hill, J.S. Wilzewski, HITRAN Application Programming Interface (HAPI): A comprehensive approach to working with spectroscopic data, J. Quant. Spectrosc. Radiat. Transfer 177, 15-30 (2016)



Information content analysis

A simple scheme was employed to analyze the information content of the simulated spectra. The CO_2 content of the atmosphere was varied in 10 different layers to obtain a finite difference Jacobian matrix of the measurement. This Jacobian was combined with a CO_2 prior profile and prior covariance matrix similar to those used in OCO-2 ACOS retrievals and the estimated error levels of the CO2M instrument to obtain the degrees of freedom (DoF) the signal provided for the CO_2 profile. DoF over one indicates that the signal contains some profile information.

The analysis shows that glint observations carry significantly more information compared to nadir observations in both CO2 bands over all examined surface types. The effect is strengthened with the increasing solar zenith angle. The strong band was shown to be more informative than the weak band in all examined cases.



Conclusions

There are three main findings of the simulation study:

- Snow reflectivity varies greatly by snow type, but the forward reflection peak is present in all examined types. The snow reflectivity model is also expressible in kernel modality and it has been delivered to several retrieval development teams.
- Glint observation mode was found to be more reflective than nadir observation mode over snow surfaces across all the examined wavelengths bands and geometries and the glint geometries convey significantly more information in the CO_2 bands compared to nadir geometries.
- Although the weak CO_2 band had systematically greater radiances than the strong CO_2 band which could indicate a greater significance in retrievals over snow, the information content of the strong CO_2 signal was considerably larger than in the weak CO_2 signal.