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# Simulations of Improved Carbon Dioxide Observations over Snow

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Satellite observations of greenhouse gases over the Arctic and boreal regions are important for a better understanding of the changing natural carbon cycle and monitoring anthropogenic emissions. However, high latitudes pose significant challenges to reliable space-based observations of carbon dioxide ($CO_2$). In addition to large solar zenith angles and frequent cloud coverage, snow-covered surfaces absorb strongly in the near-infrared wavelengths that are used for retrievals of $CO_2$. Because of the resulting low radiances of the reflection measured by the satellite in nadir geometry, the retrievals over snow may be less reliable and are typically filtered or flagged for potentially poor quality.

We present the results of a feasibility study for examining how to improve satellite-based remote sensing of $CO_2$ over snow-covered surfaces. Our primary goal is to support the development of the upcoming Copernicus Anthropogenic $CO_2$ Monitoring Mission (CO2M). CO2M is planned to be operational in 2025 and it will provide quantitative information of anthropogenic $CO_2$ emissions from cities and large production facilities to help meet the carbon emission reduction targets agreed in the Paris Agreement. Our findings are also applicable to other missions that retrieve $CO_2$ from reflected sunlight, for example OCO-2 and TanSat.

As a part of the feasibility study, extensive radiative transfer (RT) simulator development is also undertaken. RaySca, a novel RT simulator aims to be a computationally fast model of polarized radiation within planetary atmospheres in visual, near-infrared and shortwave-infrared wavelength bands. Modeling the polarization of the radiation will enable further research of atmospheric remote sensing with planetary surfaces and atmospheric aerosols with complex reflection and scattering properties. Within the ESA Dragon co-operation, we plan to continue the research and development of atmospheric RT models in the context of further improving greenhouse gas retrievals from space, specifically in polluted conditions.

## Measurement-based snow BRDF model

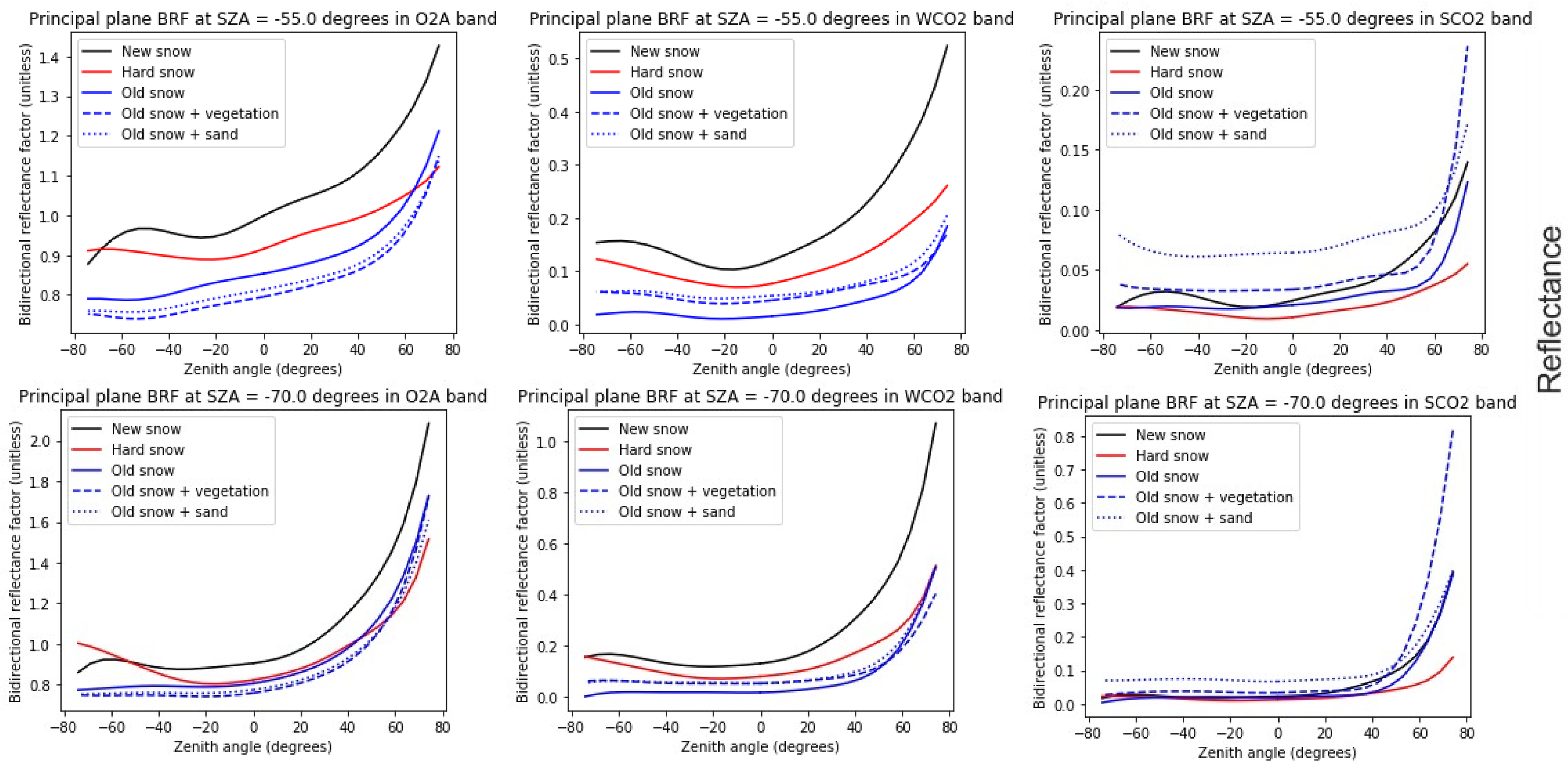
Snow surface reflectivity is modeled after field goniometer measurements various Earth surface bidirectional reflectance factors (BRF) carried out by Jouni Peltoniemi of Finnish Geospatial Research Institute using the FIGIFIGO instrument (Peltoniemi et al. 2020). Peltoniemi's archives of snow BRF measurements 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

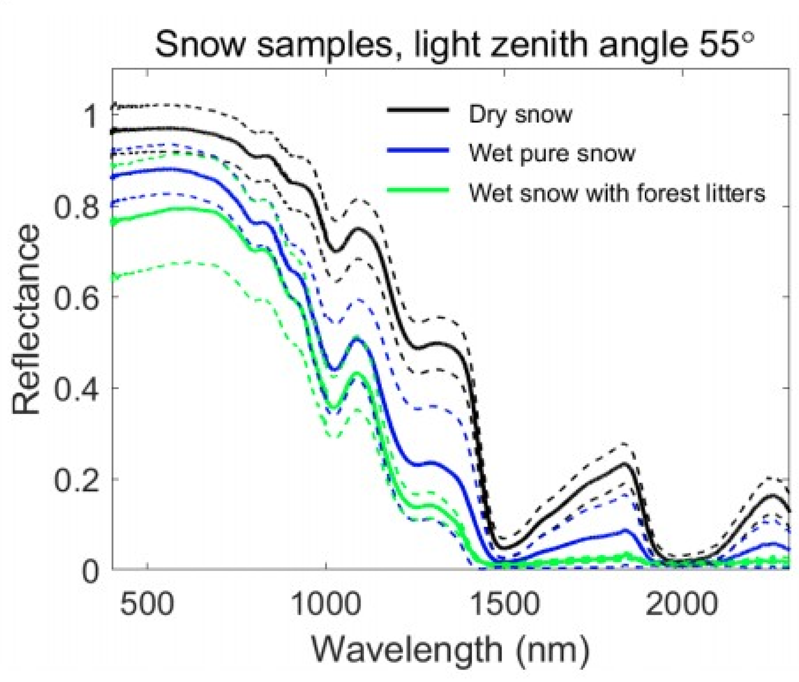
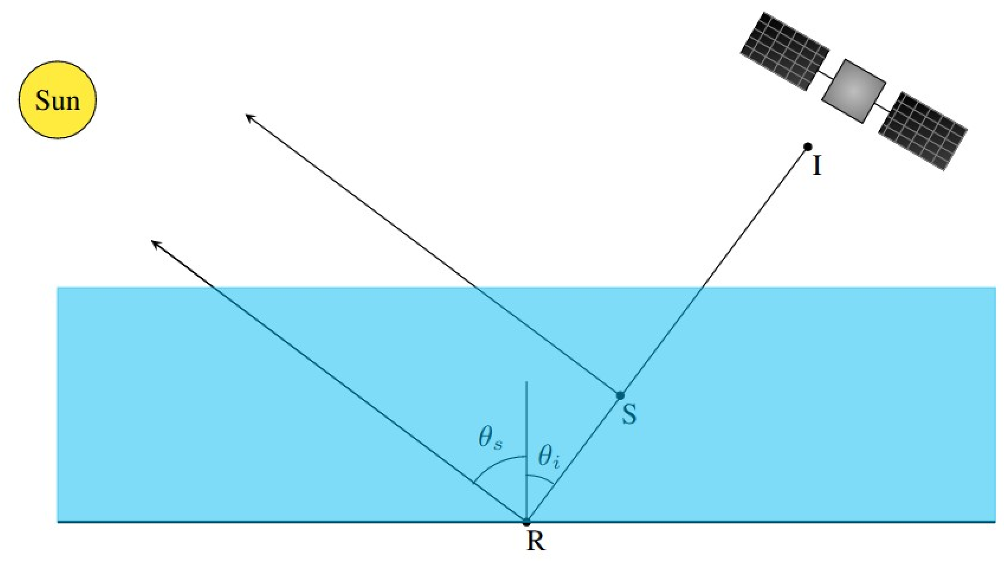



Figure: Hannula, H.-R., Heinilä, K., Böttcher, K., Mattila, O.-P., Salminen, M. and Pulliainen, J.: Laboratory, field, mast-borne and airborne spectral reflectance measurements of boreal landscape during spring, Earth Syst. Sci. Data, 12, 719–740, 2020.




## 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 currently 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.

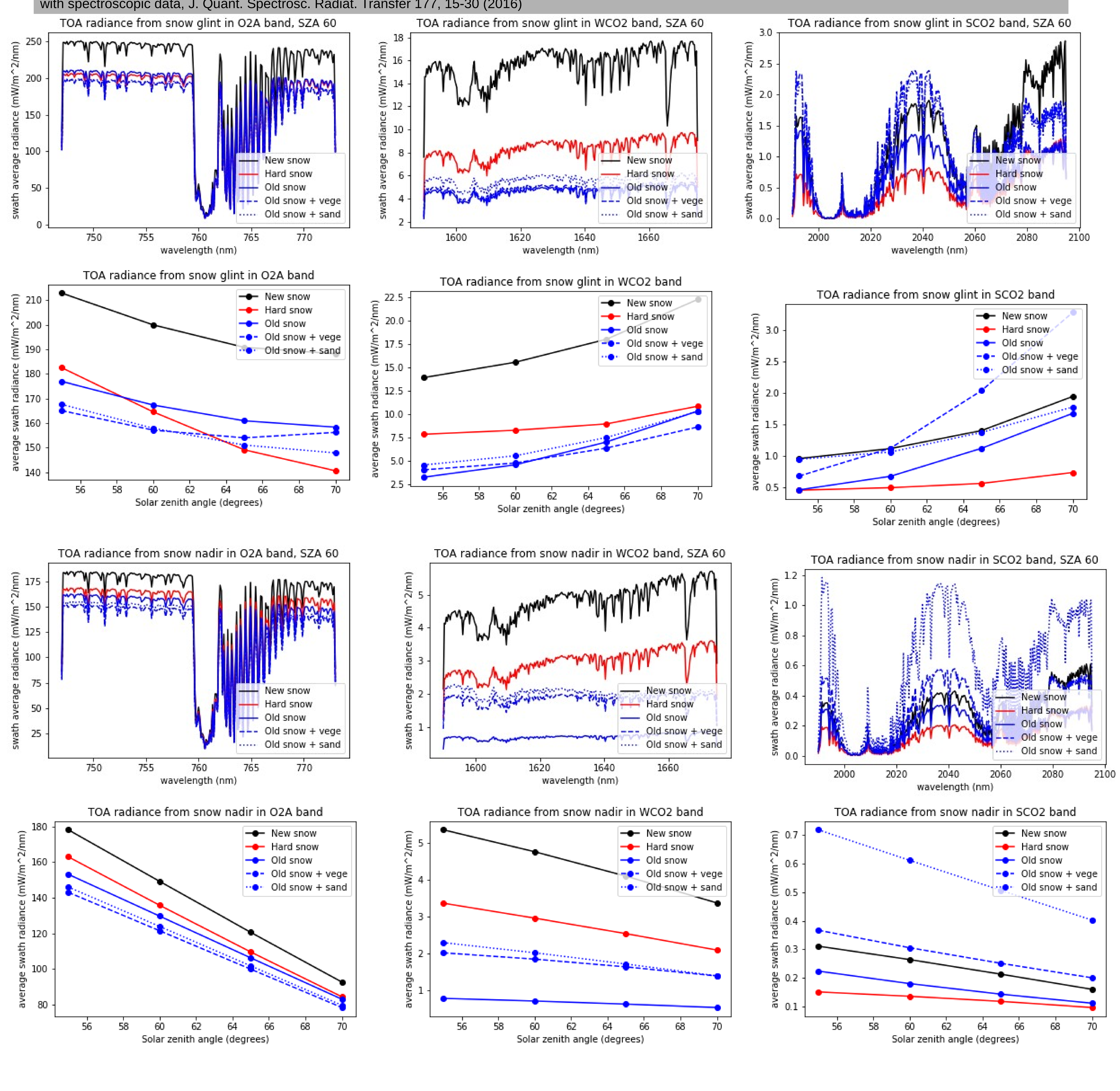
Mikkonen A, Lindqvist H, Peltoniemi J, Tamminen J: The non-Lambertian snow surface reflection models for simulated atmospheric transmittances in the NIR and SWIR wavelengths, JQSRT, (2022, in preparation)

## 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 $O_2$ 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)

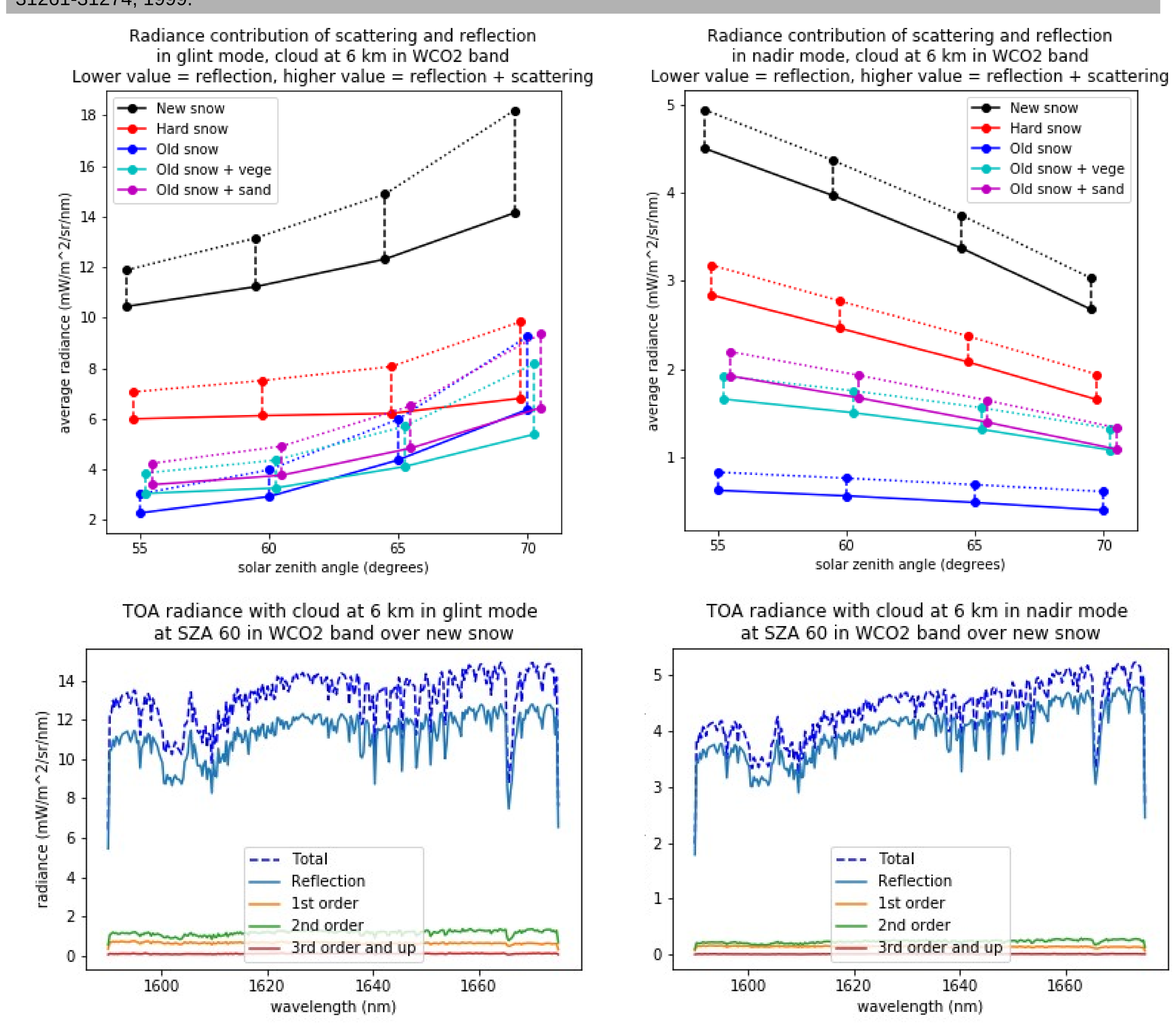



## Cirrus clouds over snow

One potential problem in the northern high latitudes is frequent cloud cover. The cloudy pixels are screened with a cloud filtering algorithm, but we suspect that sufficiently high and thin ice crystal cloud might be undetectable over snow surfaces. Thin ice clouds and aerosols may cause significant biases in $CO_2$ retrievals if not taken properly into account. We used a backward Monte Carlo RT model Siro (Oikarinen et al., 1999) to simulate the effect of high Cirrus clouds over snow surfaces. The hexagonal ice crystals (d = 70µm) formed a thin cloud with an optical depth of 0.05 at an altitude of 6 km.

Below are presented the effects in the weak $CO_2$ band in glint and nadir observation modes. The thin ice cloud causes significant scattering, especially in the glint mode. Due to the increased scattering and similarities in the spectral response, the presence of the ice cloud is difficult to deduce especially if the underlying snow type is unknown based on this study alone.

Oikarinen L, Sihvola E, Kyrölä E, Multiple scattering radiance in limb-viewing geometries, J. Geophys. Res.: Atmos., 104-D24, p. 31261-31274, 1999.




## Conclusions

There are four 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.
- The atmospheric scattering by ice crystal clouds over snow is greater in glint mode than in nadir mode and that could complicate the retrieval process.
- (Not shown in this poster) 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.