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Sensitivity of radiance simulations over snow for satellite-based remote sensing of carbon dioxide


Image: OHB-System

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Abstract

To meet the climate change mitigation targets, global greenhouse gas emission monitoring is needed. In the Arctic and boreal regions, continuous monitoring can inform on the expanding anthropogenic activities and their emissions as well as the changing carbon cycle and natural CO2 uptake in the changing climate. However, in the high latitudes there are numerous properties making observations difficult: large solar zenith angles, frequent cloud cover and snow.

Observing the carbon dioxide from a satellite is an ill-posed inverse problem. The solar radiation reflected from the Earth surface is measured by a satellite instrument and the amount of CO2 is inferred from the attenuation. Parameters, such as other absorbing atmospheric gases, scattering from air molecules and aerosols and the reflectivity of the Earth's surface also need to be estimated.

ESA SNOWITE is a feasibility study funded by European Space Agency for examining how to improve satellite-based remote sensing of CO2 over snow-covered surfaces. Snow surfaces are very dark in the near infrared bands used in CO2 observations, but they have a considerable forward-reflecting peak. This supports the fact that improvements could be attained with modified observation geometry.

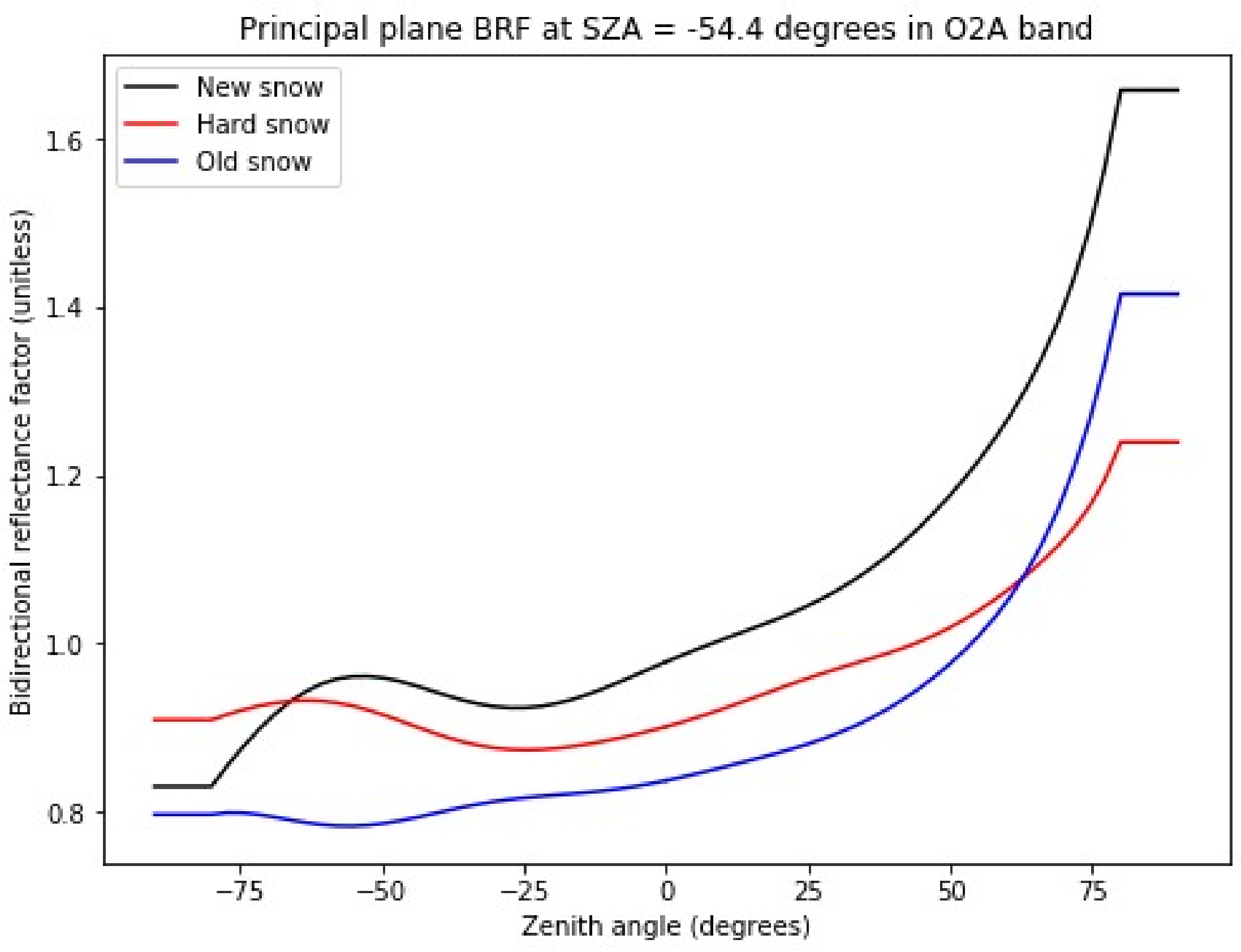
Snow BRDF models

In this study, we examined if more sophisticated modeling of snow reflectivity could improve the reconstruction of CO2 from satellite-based spectral measurements over snow-covered land surfaces.

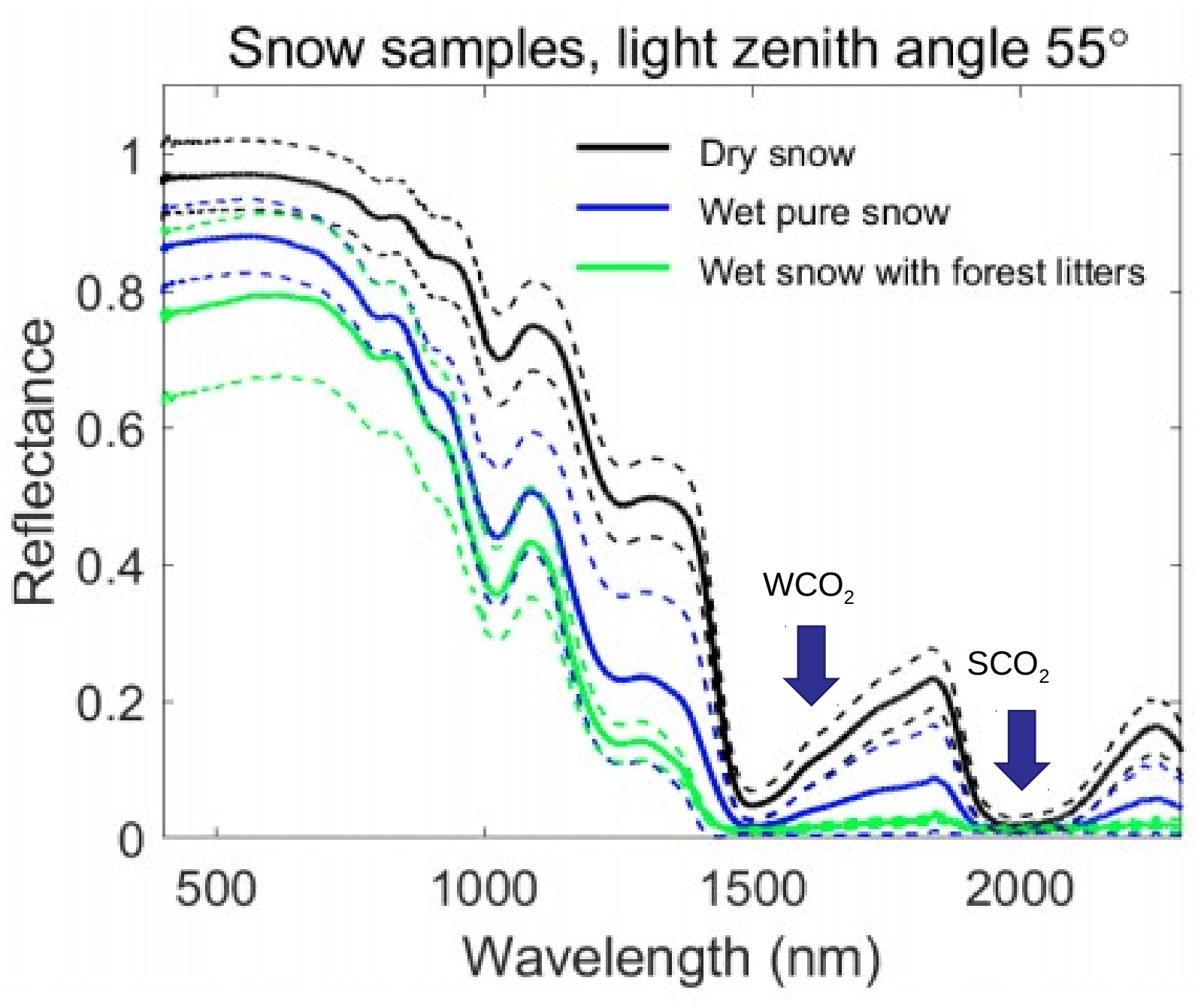
Three bands of interest in CO2 remote sensing are the O2 A-band (~765 nm), weak CO2 band (~1650 nm) and strong CO2 band (~2050 nm). In general, the snow surfaces are highly reflective in the O2 A-band, but they tend to be quite dark in the CO2 bands. However, snow surfaces exhibit a strong reflectance into the forward direction in each of these bands.

The snow reflectivity is modeled as bi-directional reflectance distribution function. It is a function of incident zenith angle, reflected zenith angle, the azimuth angle difference and the wavelength, i.e. $R = R(\theta_{in},\theta_{out},\Phi,\lambda)$. Traditionally land surfaces are only modeled as wavelength-dependent.

Jouni Peltoniemi from Finnish Geospatial Research Institute has measured snow reflectivity using a field goniospectrometer for about two decades in Finland, the Arctic and Greenland. From this data, three rough distinctions of snow based on the reflectivity was found: new snow, hard snow and old snow. New snow is snow with an age of maximum of two days from the snowfall. New snow is transformed into hard snow after packing due to e.g. wind. Old snow is partially melted and it is the dominant snow type in the Spring.



Reflectance measured at nadir geometry



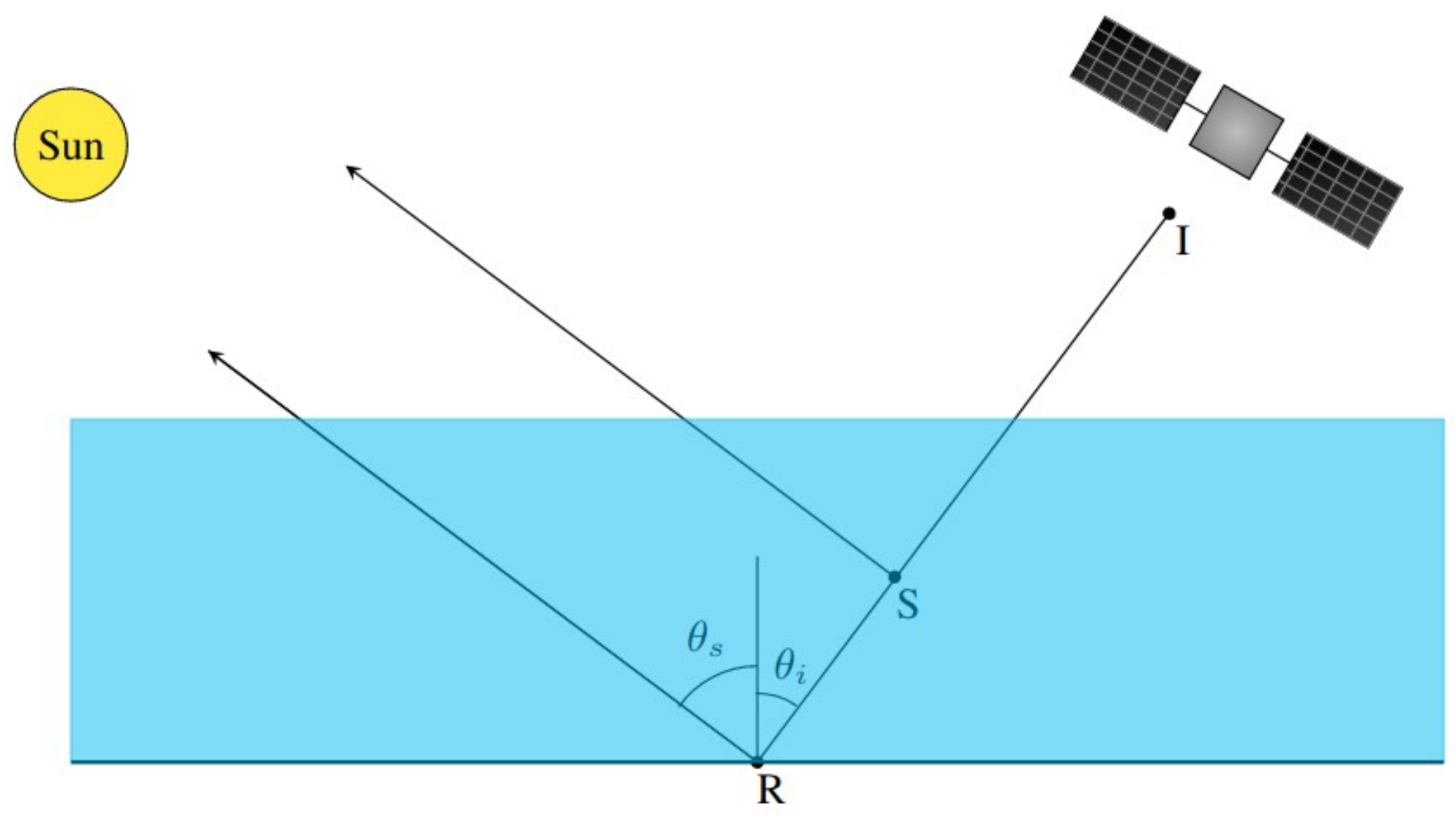
Hannula et al. (ESSD, 2020)

The inverse problem

Our simplified aim is to obtain the atmospheric CO2 profile using the spectral measurement from a satellite. In actuality this requires a reconstruction of about 50 different parameters such as atmospheric aerosols, water vapour, surface reflectance and atmospheric surface pressure.

The altitude information can be obtained from the pressure and temperature dependent absorption cross-sections of CO2.

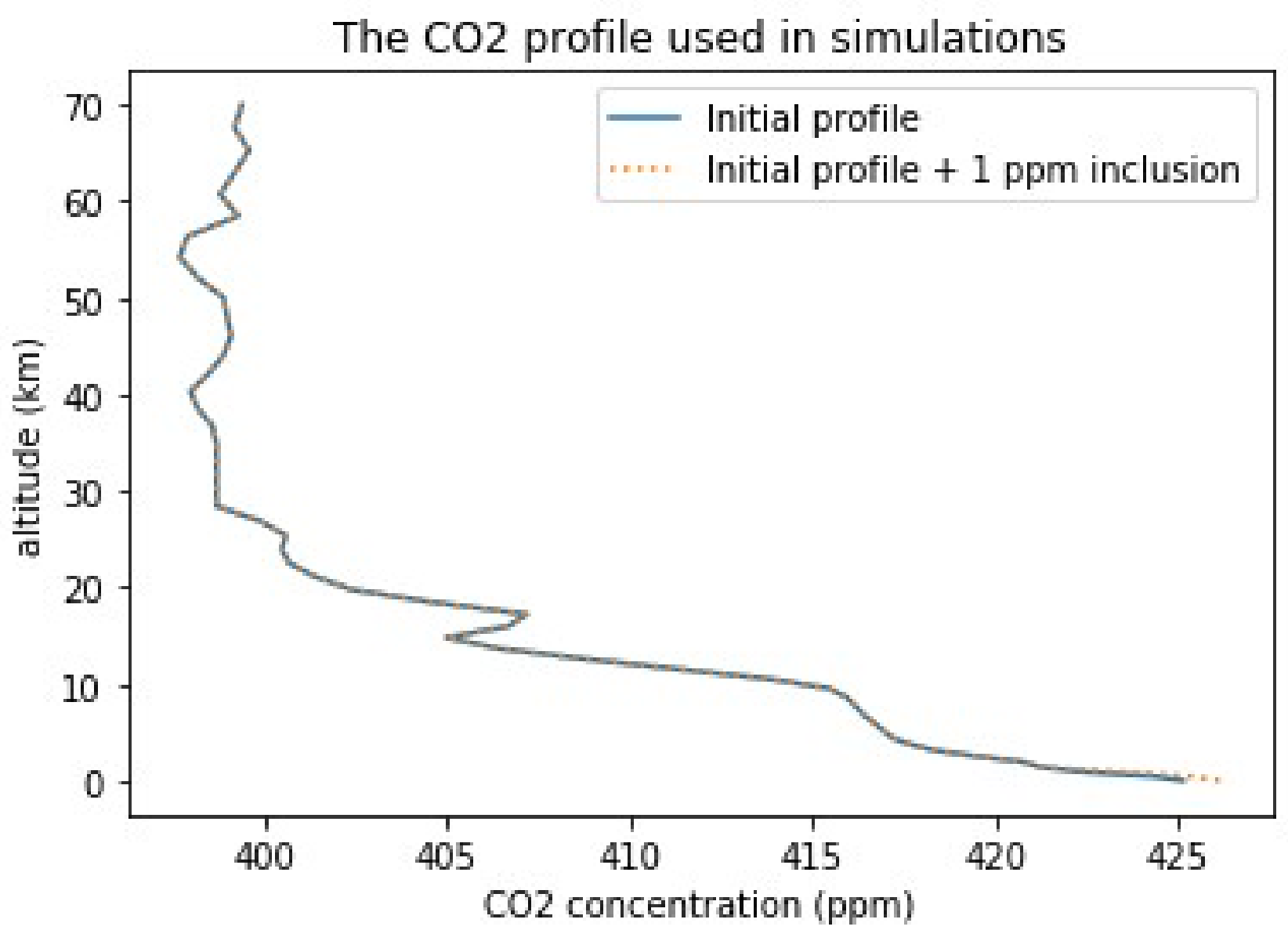
One motivation for reconstructing the atmospheric CO2 profile is to detect and quantify emission sources at the surface. An average increase of 1 ppm in a full atmospheric column above a ground pixel of a size 1.3 km x 2.3 km could correspond to a moderately sized point source, such as a coal power plant.

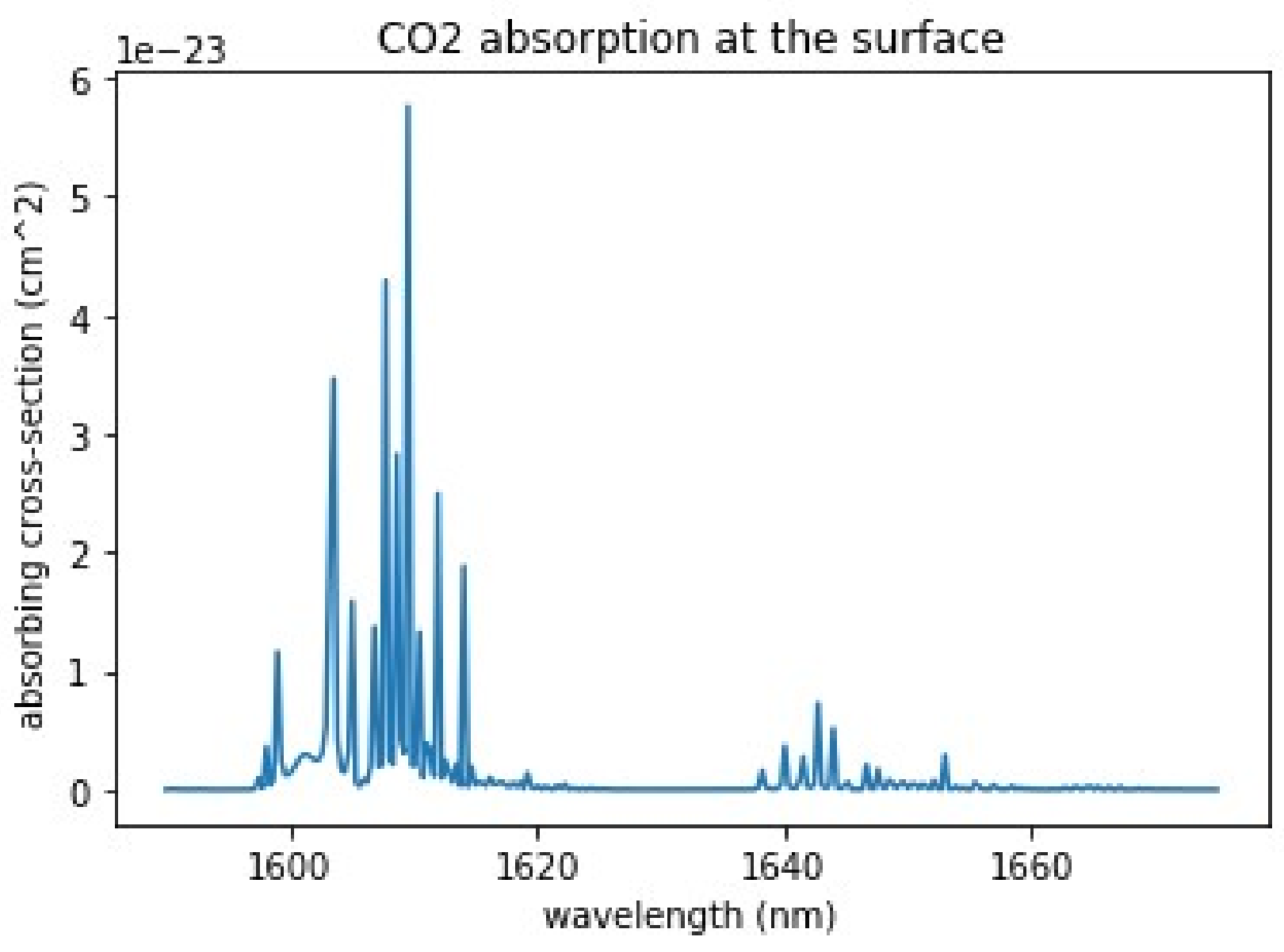


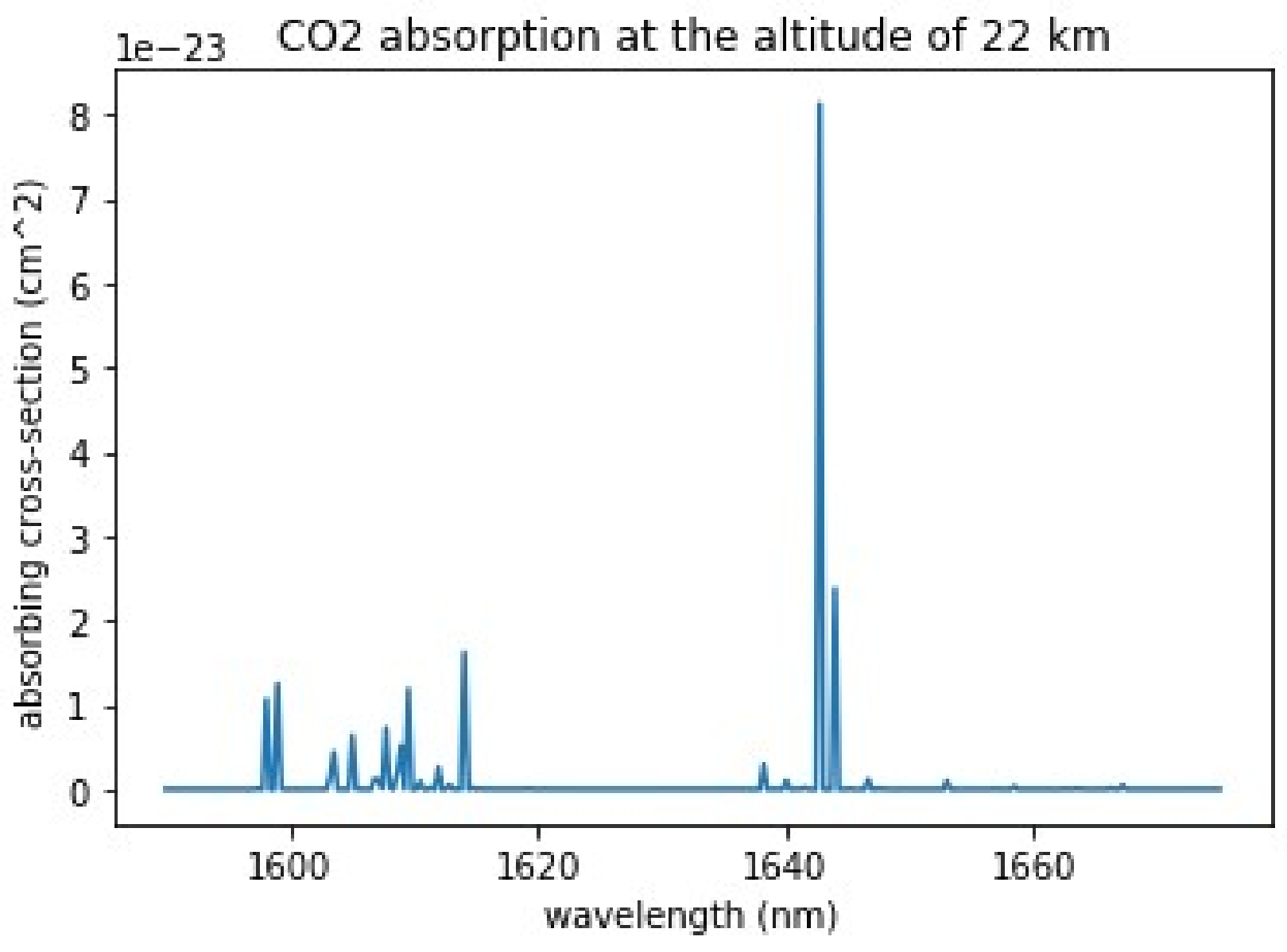
Observation geometry and the forward model

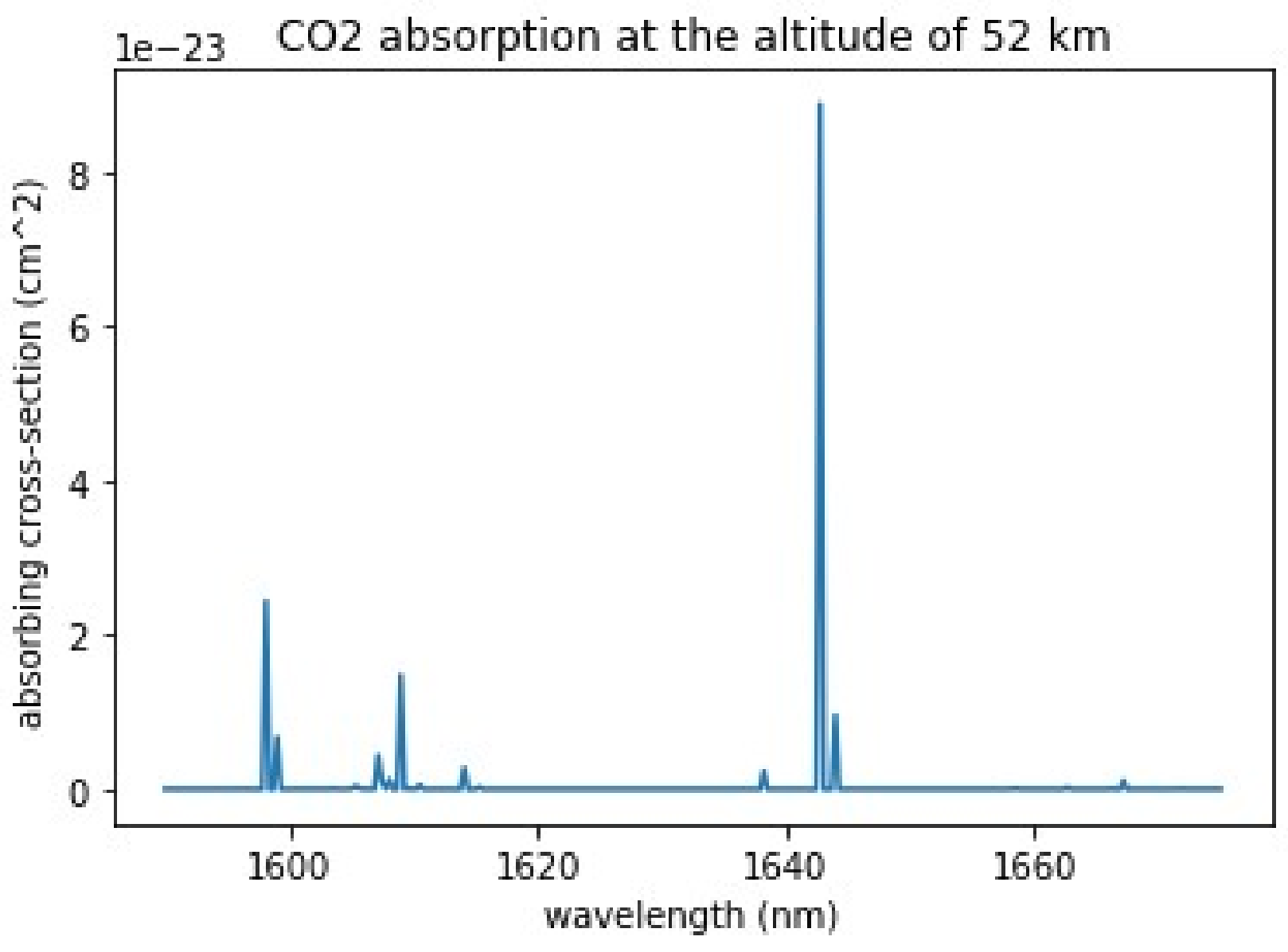
Remote sensing of the atmosphere can be done by observing solar radiation reflected off the planetary surface. The factors contributing to the propagation of the radiation are the absorbing gases in the atmosphere, the reflectivity of the of the surface *R* and the atmospheric scattering *S*. The radiative transfer is modeled with an approximation of the radiative transfer equation, which we compute along discrete 1D lines through the atmosphere. This is appropriate when the medium is not very scattering and when we are interested in the radiation observed at a single point and direction. The RTE is then comparable to the Beer-Lambert-Bouger attenuation law.

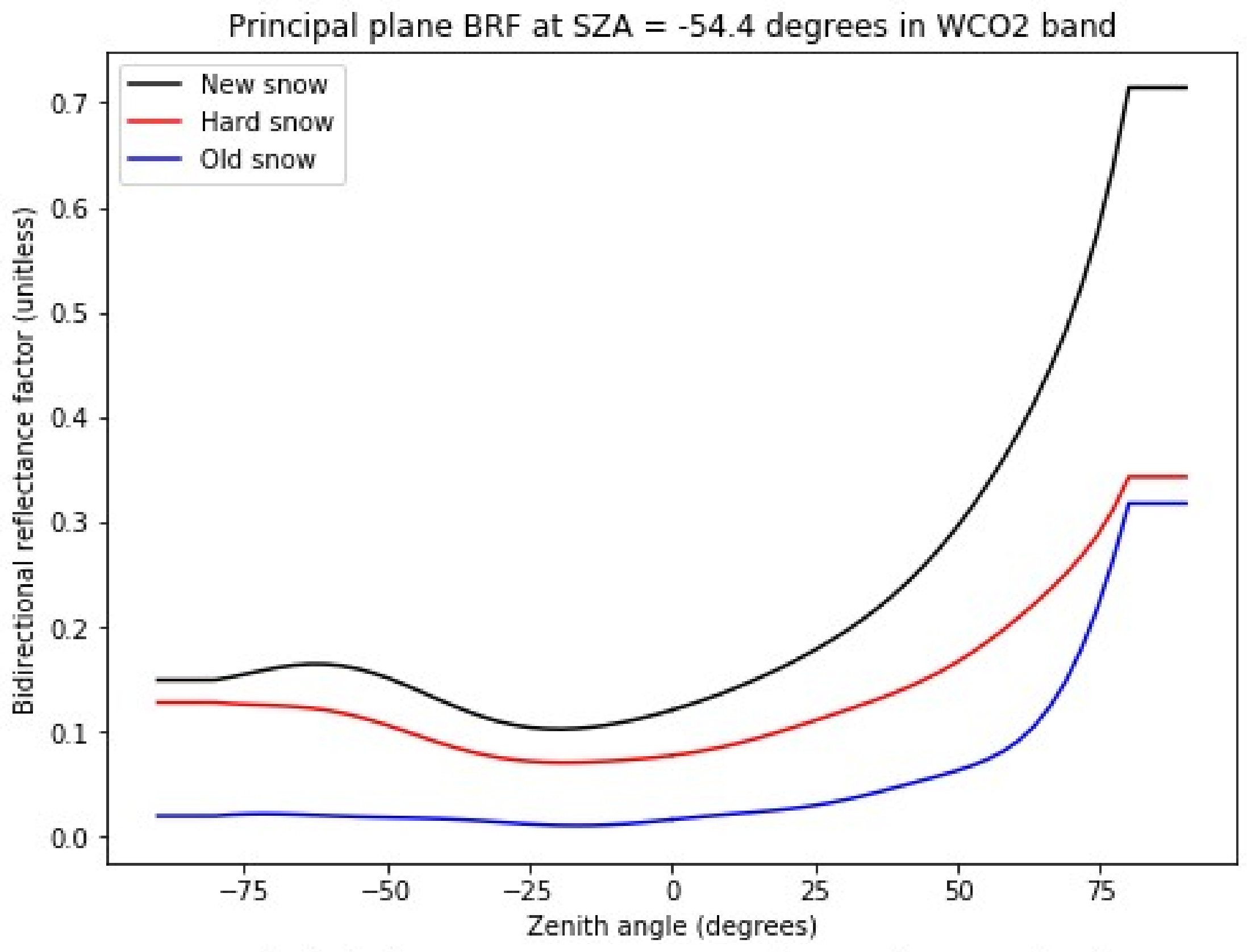
In remote sensing of greenhouse gases, two main modes of observation are nadir and glint. In nadir mode, the instrument is observing directly downwards ($\theta_i = 0$). In glint mode, the instrument is observing the point of mirror-like reflectance ($\theta_i = \theta_s$).

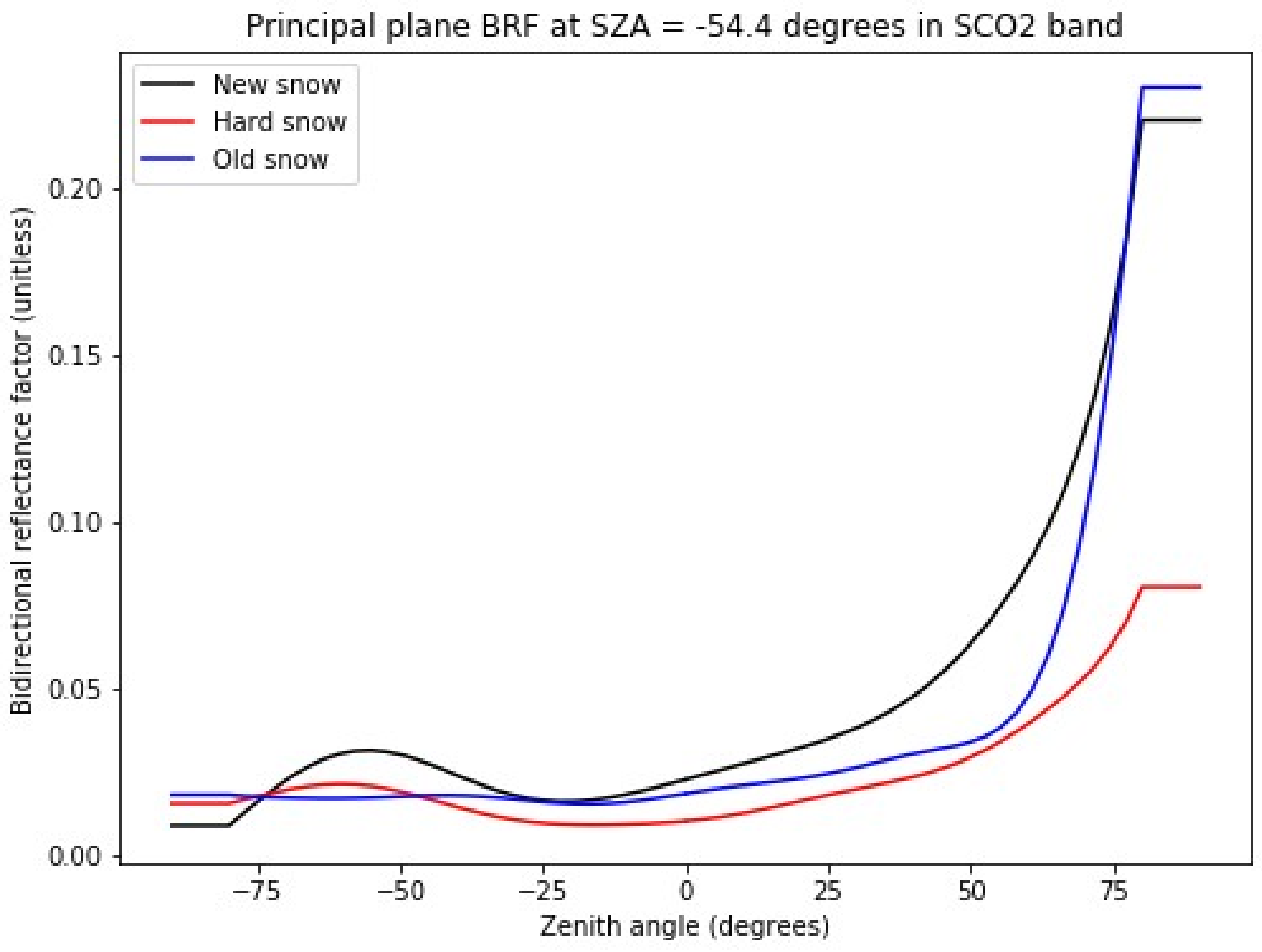












The sensitivity analysis

One way to estimate the information content of the data is to perturb the parameters and observe what effects do they have on the simulated data.

The atmosphere was divided into 10 different layers and a 1 ppm increase of CO2 was introduced into each of those separately. The difference between these and the original spectra are plotted below for each of the altitudes. It appears that the greatest effect can be observed in the 6 – 11 km layer.

It can be seen that the sensitivity to the perturbations is qualitatively quite similar between the observation modes, which might be a result from the low spectral dependence of the snow surface reflection. The scale of the sensitivity is about three times greater in glint mode and thus larger changes in the profile will be visible. This is not entirely obvious from the surface reflectivity because glint geometry has an increased optical path length compared to nadir geometry.