Spectral Emissivity Retrieval from Far-Infrared Field Observations of Snow and Ice

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1. The instrument: FIRMOS-B

The Far-Infrared Radiation Mobile Observation System (FIRMOS, Belotti et al. 2023) is an FTS measuring the 100–1600 cm^{-1} spectral range with a resolution of 0.4 cm^{-1}. It has been employed to provide measurements that support the design concepts and methods during the FORUM mission preparatory phase.

2. The WHAFFFERS campaign

WHAFFFERS (W-band, HiSRAMS, AERI, FIRR-2, FINESSE, and FIRMOS Experiment on Remote Sensing) was an international field campaign held in Canada during January–February 2025. Its primary goal was to intercompare advanced radiometers designed for future satellite missions such as **FORUM** and **HAWC**. One of the campaign's objectives was to investigate the **emissivity of snow and ice surfaces**.

In the far-infrared (FIR), part of the surface emission can escape to space when the atmosphere is cold and dry enough (high-elevation locations and polar regions). Modelled emissivity for snow and ice shows considerable spectral variation in the FIR (Huang et al. 2016).

FIR surface emissivity will be one of the objectives of FORUM (ESA Earth Explorer 9, Palchetti et al. 2020). The mission will have an excellent sampling at high latitudes and the expected requirements for the retrieval are an uncertainty of 0.01, in the 300–600 cm^{-1} range, with 50 cm^{-1} resolution.

Figure 1. FIRMOS-B (on the left, mounted on the tilted platform) and FINESSE measuring the snow surface at the Gault Nature Reserve site (Mont-Saint-Hilaire, QuébeC, Canada), February 2025.

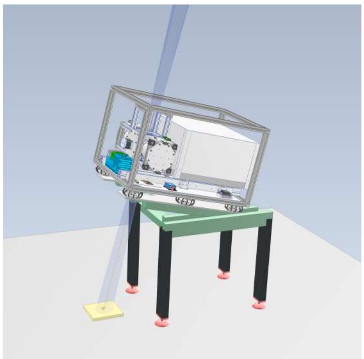


Figure 2. Schematic of FIRMOS illustrating the observation towards a surface sample and the atmosphere.

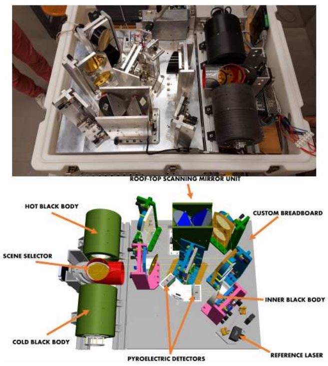
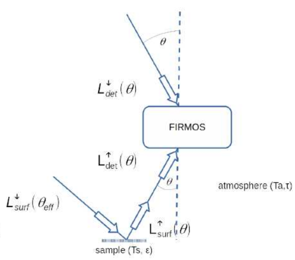


Figure 3. FIRMOS components and subsystems.

3. Modelling and Retrieval

$$L^{\uparrow}_{\nu,det}(\theta) = \tau_{\nu}(\theta)\left[\epsilon_{\nu}(\theta)B_{\nu}(T_s) + (1-\epsilon_{\nu}(\theta))L^{\downarrow}_{\nu,surf,eff}\right] + E^{\uparrow}_{\nu}(\theta)$$

- ϵ, **sample emissivity**
- $L^{\uparrow}_{det}$ **upwelling radiance** measured by FIRMOS-B
- τ, transmissivity of the atmosphere
- $B(T_s)$ radiance emitted by the sample at temperature T_s – according to Planck law;
- $L^{\downarrow}_{surf}$, **downwelling** atmospheric **radiation** at the surface
- $E^{\uparrow}$, radiance emitted by the atmosphere



θ is the viewing angle, the subscript ν denotes the spectral dependence of all the terms.

An Optimal Estimation iterative scheme is used to retrieve **spectral emissivity** and **Ts**. Air **temperature** and **humidity** are also retrieved and used to model τ and $E^{\uparrow}$. Depending on the sample behaviour (specular, Lambertian) $L^{\downarrow}_{surf}$, can be measured directly or modelled, either entirely or partially (e.g. a normalized measurement).

4. Level1 data

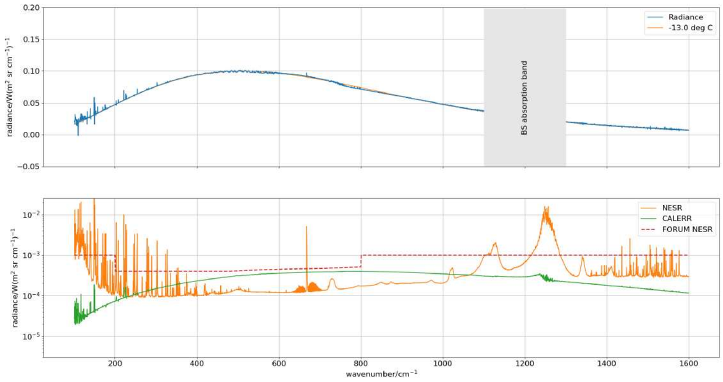


Figure 4. Example of a FIRMOS-B spectrum measured while observing the ice sample. The spectrum shown is the average of four consecutive measurements. Top panel: Upwelling radiance (blue) and Planck emission at -13 °C (orange). Bottom panel: NESR (orange) and calibration error (green).

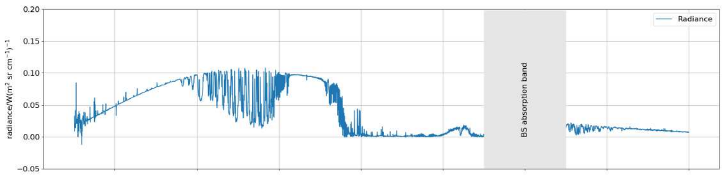


Figure 5. Downwelling radiance measured by FIRMOS-B observing the atmosphere at a viewing zenith angle of 13°.

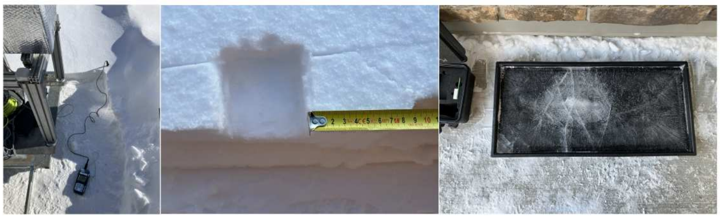


Figure 6. Campaign details: from left to right — monitoring snow temperature, sampling snow to measure density, and an ice sample prepared from de-ionized water.

5. Results

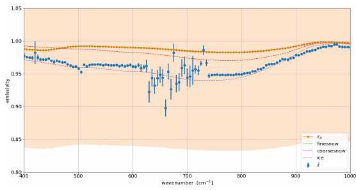


Figure 7. Retrieved spectral emissivity for the ice sample.

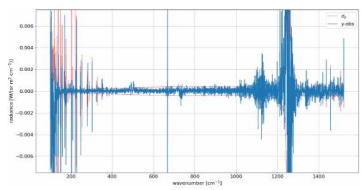


Figure 8. Simulations-observations for the ice sample.

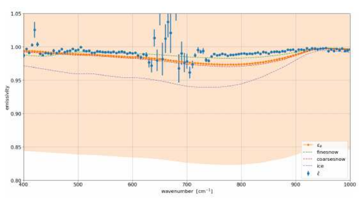


Figure 9. Retrieved spectral emissivity for the snow sample.

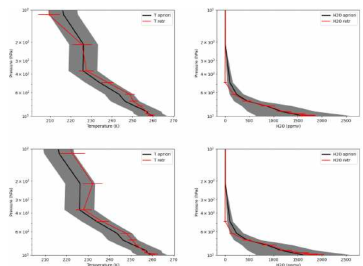


Figure 10. Retrievals of the atmospheric temperature and water vapor profiles.

Figures 7 and 9 show the retrieved spectral emissivity for the measured samples. The blue dots ($\hat{\epsilon}$) and blue bars represent the retrieved emissivity and its uncertainty. The orange dots (ϵ_a) and orange shading indicate the a priori values and their uncertainty, respectively. The dashed lines correspond to the modeled values from Huang (2016) for the viewing angle used in the measurements, courtesy of X. Huang. Figure 8 shows the difference between simulated and observed values (in blue) relative to the measurement uncertainty (in red). Figure 10 shows the atmospheric state (retrieved by a different algorithm) used for normalizing the downwelling radiance reflected by the surface, see Bellisario et al. (2017).

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