Snow and Ice Far-Infrared Spectral Emissivity Retrievals from FORUM-like Measurements

C. Belotti, M. Barucci G. Bianchini
B. Cluzet[1,2], F. D'Amato, G. Di Natale
F. Pratesi, M. Ridolfi, S. Viciani
L. Palchetti

CNR – INO, Italy
[1] UGA, UT, Météo-France,
CNRS, CEN, France
[2] now at: WSL, SLF, Switzerland

24 November 2021

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

Motivation

- In high-elevation locations and polar regions where the dry and cold atmosphere is not opaque in the far-infrared (FIR), part of the surface emission can escape to space
- In the FIR, snow surface emissivity shows considerable spectral variation
- The impact of modelled FIR surface emissivity was studied by Chen et al. 2014 and Feldman et al. 2014; Huang et al. 2016 compiled a database of surface spectral emissivity
- There is only a handful of retrievals of infrared spectral surface emissivity reaching the far-infrared
- Bellisario et al. 2016 and Murray et al. 2020 exploited observations taken by TAFTS during an airborne campaign over Greenland

FORUM

ESA-DEVELOPED EARTH OBSERVATION MISSIONS
esa
2010
2015
2020
2025
2030
ERS-1
ERS-2
MetOp-A
Envisat
Proba-1
SMOS
GOCE
CryoSat
Meteosat 10 (MSG)
MetOp-B
Swarm
Proba-V
Sentinel-1A
Meteosat 11 (MSG)
Sentinel-1B
Sentinel-2A
Sentinel-2B
Sentinel-3A
Sentinel-3B
Sentinel-5P
MetOp-C
Sentinel-6 Michael Freilich
Sentinel-1C
Sentinel-2C
Sentinel-3C
Aeolus
ALTIUS
EarthCARE
Biomass
Sentinel-1D
FLEX
ESP-MACCS
HydroGNSS
TRUTHS
FORUM
Harmony
Earth Explorer-11
Sentinel-2D
Sentinel-6B
Sentinel-3D
MTG-I1
Sentinel-5A MetOp-SG-A1
Arctic Weather Satellite
MetOp-SG-B1
CO2M-A
Sentinel-4A MTG-S1
MTG-I2
CO2M-B
CO2M-C
CRISTAL-A
CIMR-A
ROSE-L-A
LSTM-A
CHIME-A
CHIME-B
LSTM-B
CRISTAL-B
CIMR-B
ROSE-L-B
Sentinel-4B MTG-S2
MTG-I3
Sentinel-5B MetOp-SG-A2
MetOp-SG-B2
Sentinel-1
Sentinel-2
Sentinel-3
Sentinel-6
Continuation of Sentinel Next Generation Missions
Science
esa
Copernicus
Meteorology
EUMETSAT

FORUM

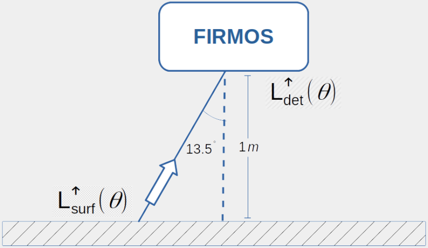
- FTS, 100—1600 cm^{-1} (6.25—100 μm), spectral resolution is 0.5 cm^{-1}
- One of FORUM objectives is the retrieval of FIR surface emissivity
- Excellent sampling at high latitudes (sun-synch 98.7° orbit)
- Uncertainty of 0.01 in 300—600 cm^{-1}, 50 cm^{-1}

FIRMOS

- FORUM demonstrator
- FTS, 100—1000 cm^{-1}, $\Delta\nu = 0.3$ cm^{-1} ground-based, balloon
- Zugspitze campaign (German Alps, 3000 a.m.s.l)

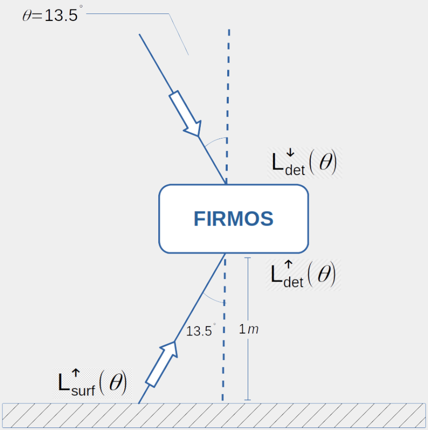
FIRMOS

- FORUM demonstrator
- FTS, 100—1000 cm^{-1}, $\Delta\nu = 0.3$ cm^{-1} ground-based, balloon
- Zugspitze campaign (German Alps, 3000 a.m.s.l)
- Upwelling radiance @13.5 degree off-nadir

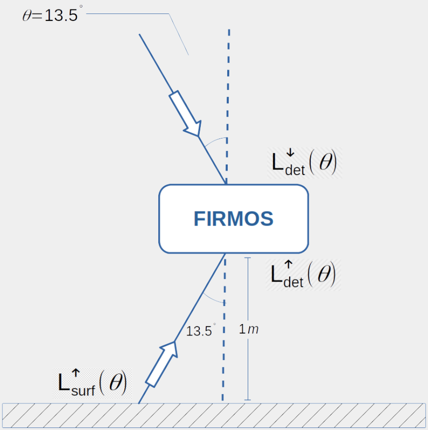


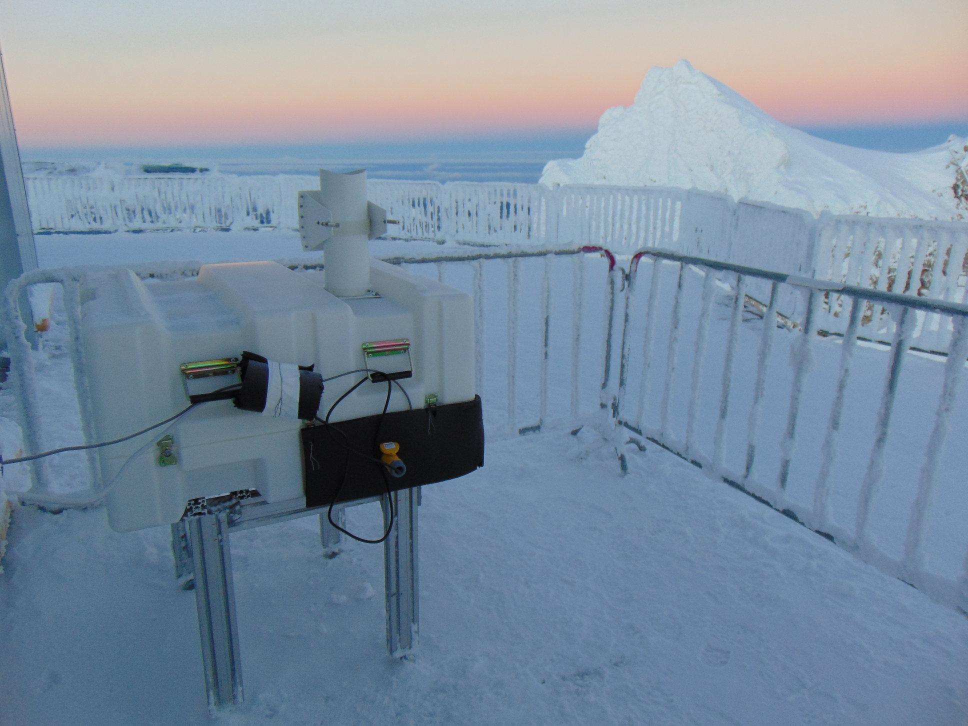
FIRMOS

- FORUM demonstrator
- FTS, 100—1000 cm^{-1}, $\Delta\nu = 0.3$ cm^{-1} ground-based, balloon
- Zugspitze campaign (German Alps, 3000 a.m.s.l)
- Upwelling radiance @13.5 degree off-nadir
- Downwelling radiance @13.5 degree viewing zenith angle



- FORUM demonstrator
- FTS, 100—1000 cm^{-1}, $\Delta\nu = 0.3$ cm^{-1} ground-based, balloon
- Zugspitze campaign (German Alps, 3000 a.m.s.l)
- Upwelling radiance @13.5 degree off-nadir
- Downwelling radiance @13.5 degree viewing zenith angle
- 9 samples characterised by snow grain type, density (kgm^{-3}), and specific surface area (SSA, m^2kg^{-1})

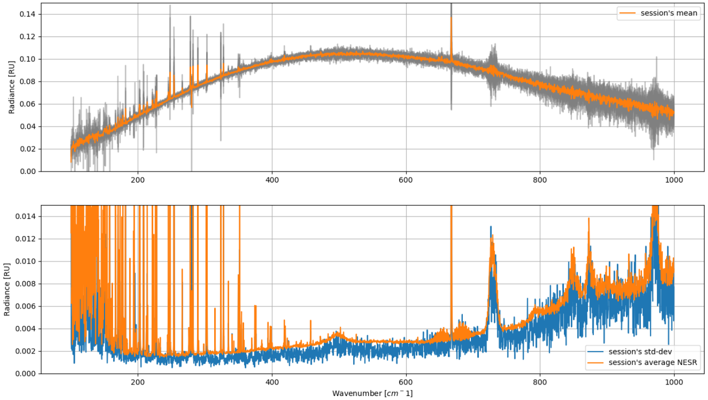


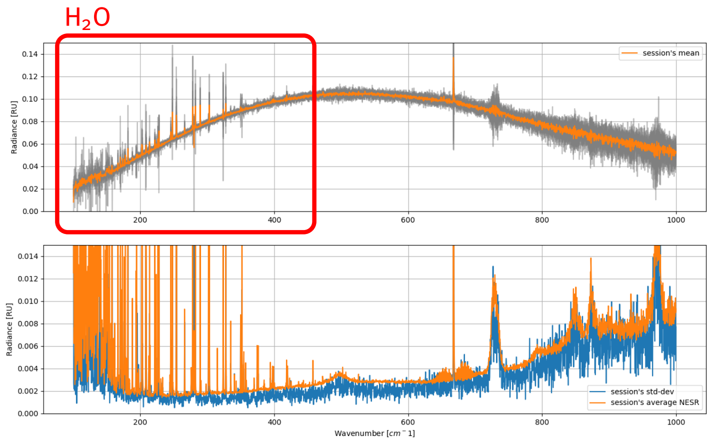


Snow characterisation

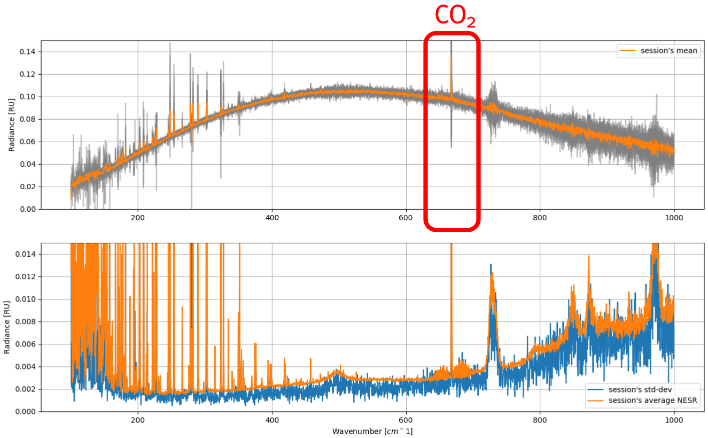
id	name	description	spectra	mins
17:30 - d1	SKY		1*	8
17:51	ICE	Ice	10	79
19:38	FS	Fresh snow	12	95
21:36	ACC30	Accumulated 30cm snow	11	87
23:42	SKY		1*	8
06:19 - d2	SKY		1*	8
06:44	DH	Depth hoar snow	13	103
09:01	DHRUG	Depth hoar snow with grooves	12	95
10:52	RGREF	Melted forms snow	7	56
12:13	SKY		1*	8
13:00	MFREF	Refrozen snow - natural case	14	111
15:00	SKY		1*	8
16:20	SKY		1*	8
16:31	DS	Dense slab snow	14	111
18:48	ACC100	Accumulated (100 cm) snow	13	103
21:00	ACC70	Accumulated (70 cm) snow	12	95

MEASUREMENTS, $L^{\uparrow}$

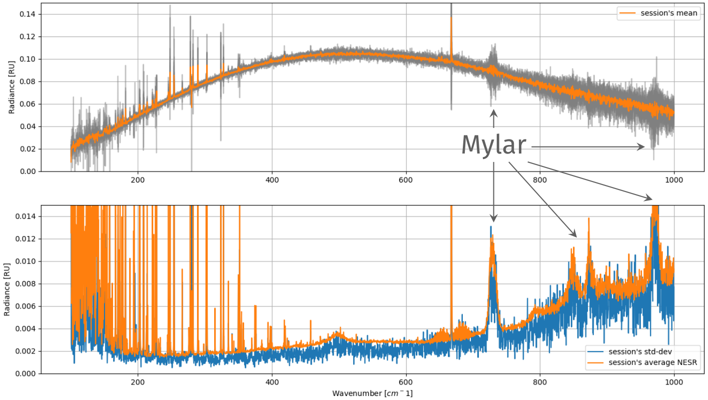



H_2O
session's mean
Radiance [RU]
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
200
400
600
800
1000
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
session's std-dev
session's average NESR
Wavenumber [cm⁻1]

MEASUREMENTS, $L^{\uparrow}$

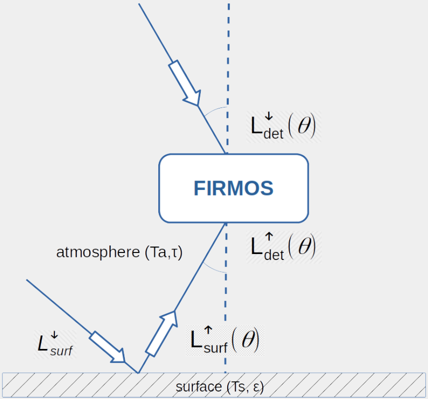


Measurements, $L^{\uparrow}$



$$L^{\uparrow}_{det} = \left[\epsilon B(T_s) + (1-\epsilon)L^{\downarrow}_{surf}\right]$$

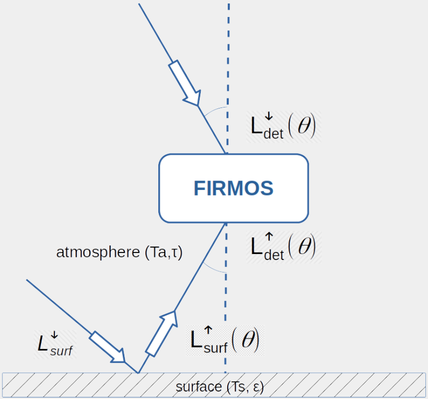
- ϵ_ν surface spectral emissivity
- $B_\nu(T_s)$ Planck emission at surface temperature (T_s)
- $L^{\downarrow}_{\nu,surf}$ atmospheric downwelling radiance at the surface



Modelling of the Problem

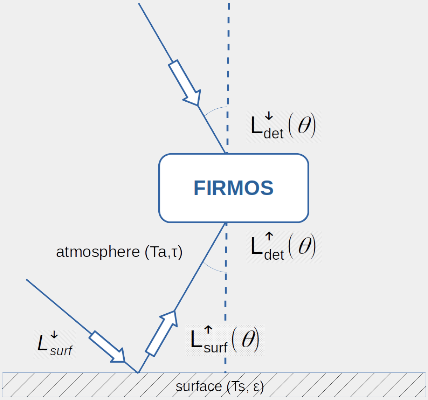
$$L_{det}^{\uparrow} = \left[\epsilon B(T_s) + (1 - \epsilon) L_{surf}^{\downarrow}\right] \tau$$

- ϵ_ν surface spectral emissivity
- $B_\nu(T_s)$ Planck emission at surface temperature (T_s)
- $L_{\nu,surf}^{\downarrow}$ atmospheric downwelling radiance at the surface
- τ_ν atmospheric spectral transmission



$$L_{det}^{\uparrow} = \left[\epsilon B(T_s) + (1-\epsilon)L_{surf}^{\downarrow}\right]\tau + E^{\uparrow}$$

- ϵ_ν surface spectral emissivity
- $B_\nu(T_s)$ Planck emission at surface temperature (T_s)
- $L_{\nu,surf}^{\downarrow}$ atmospheric downwelling radiance at the surface
- τ_ν atmospheric spectral transmission
- E_ν atmospheric path upwelling radiance



Modelling of the Problem (2)

$$L_{det}^{\uparrow} = \left[\epsilon B(T_s) + (1-\epsilon)L_{surf}^{\downarrow}\right]\tau + E^{\uparrow}$$

- Together with the upwelling radiance measured by the detector we need knowledge of the atmospheric downwelling radiance $L_{surf}^{\downarrow}$
- If the surface is specular reflector we can use the measurement made by the instrument $L_{surf}^{\downarrow} \simeq L_{det}^{\downarrow}$

Modelling of the Problem (2)

$$L^{\uparrow}_{det} = \left[\epsilon B(T_s) + (1-\epsilon) L^{\downarrow}_{surf,eff}\right] \tau + E^{\uparrow}$$

- Together with the upwelling radiance measured by the detector we need knowledge of the atmospheric downwelling radiance $L^{\downarrow}_{surf}$
- If the surface is specular reflector we can use the measurement made by the instrument $L^{\downarrow}_{surf} \simeq L^{\downarrow}_{det}$
- But snow reflection is Lambertian, we model the downwelling radiance at a single effective angle (55°, Bellisario et al. 2017) using the state of the atmosphere retrieved from the sky observations
- $L^{\downarrow}_{surf,eff} = RT(T, wv, \ldots, \theta = 55^{\circ})$

Inversion

$$L^{\uparrow}_{det} = F\left(\epsilon, T_s, T_a, wv_a, L^{\downarrow}_{surf,eff}\right)$$

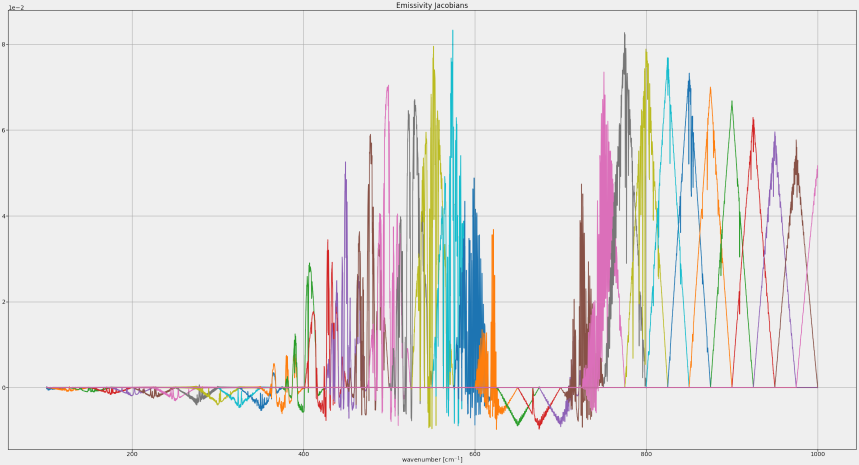
We use OE to find an optimal solution $\hat{x}$ given the observation and prior information using an iterative process

$$x_{i+1} = x_a + (S_a^{-1} + K_i^T S_y^{-1} K_i)^{-1} K_i^T S_y^{-1} [y - F(x_i) + K_i(x_i - x_a)]$$

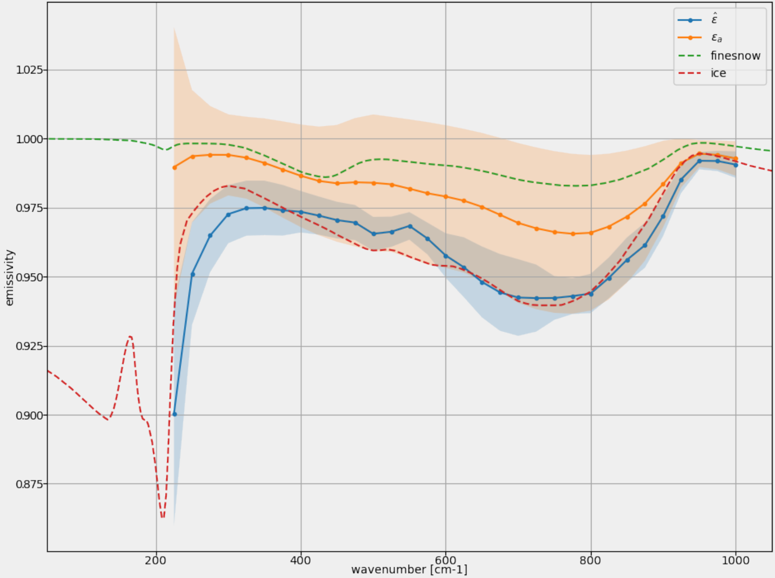
$$S_i = (S_a^{-1} + K_i^T S_y^{-1} K_i)^{-1}$$

- x state (emissivity, surface T, air humidity and T)
- x_a, S_a prior information
- $K = \frac{\delta y}{\delta x}$ Jacobian matrix to linearise F
- y, S_y observations

- a-priori - courtesy of X. Huang, same as Huang et al. (2016) but at FIRMOS' viewing angle
- Jacobians

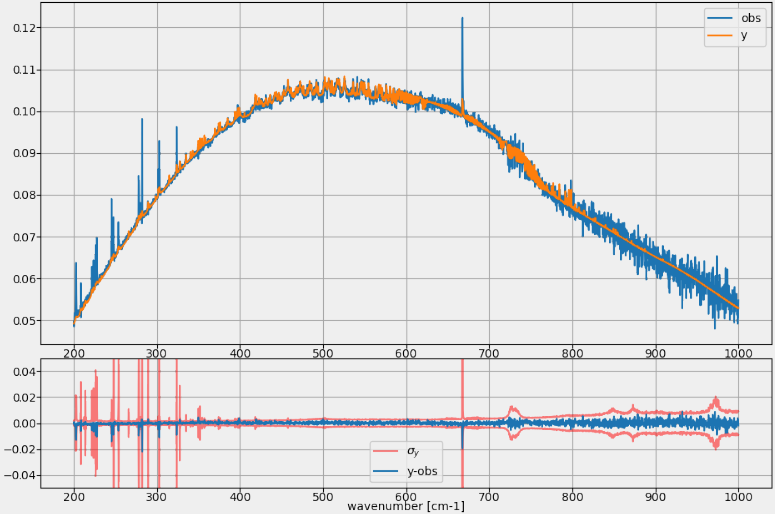


Results, ICE



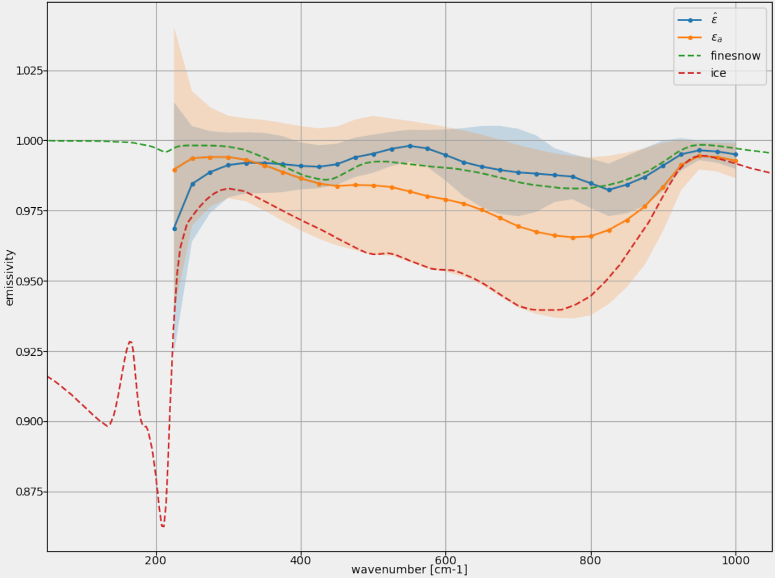
$\hat{\varepsilon}$
ε_a
finesnow
ice
1.025
1.000
0.975
0.950
0.925
0.900
0.875
emissivity
200
400
600
800
1000
wavenumber [cm-1]

Results, ICE

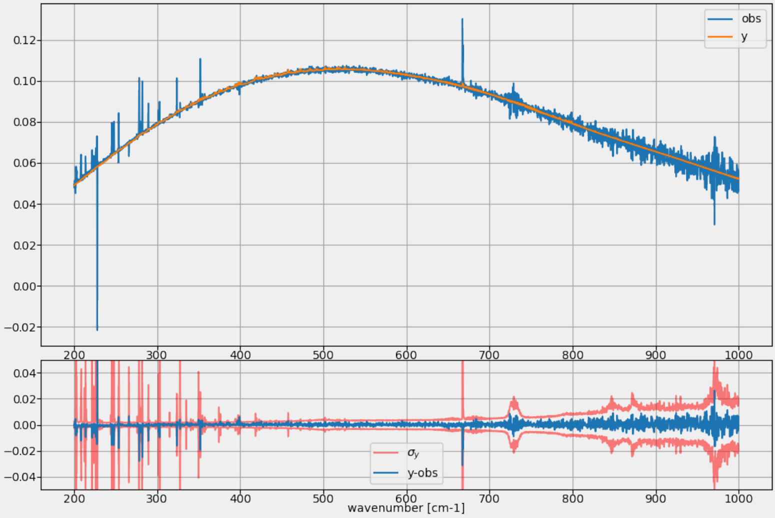


obs
y
0.12
0.11
0.10
0.09
0.08
0.07
0.06
0.05
200
300
400
500
600
700
800
900
1000
0.04
0.02
0.00
−0.02
−0.04
σ_y
y-obs
wavenumber [cm-1]

Results, snow ACC100



Results, snow ACC100



DISCUSSION

- The retrieval of snow surface emissivity from FIRMOS shows promising results
- There is good sensitivity in the 400-600 cm^{-1} range
- The origin of the dip in the 200-400 cm^{-1} range is unclear
- Work is in progress to exploit the snow samples characterisation
- in future campaigns the measurements should alternate between surface and atmosphere

Thank you