Clouds detection and properties from FORUM mission measurements

Tiziano Maestri, Rolando Rizzi, William Cossich, Iacopo Sbrolli
University of Bologna, DIFA, Physics and Astronomy Department, Bologna, Italy

and the FORUM Team

FORUM Phase A and related Activities

FORUM E2E Simulator

End to End Simulator for FORUM Earth Explorer Fast-Track Mission

- main tasks: SGM, contribution to L2M, ATBD

FORUM Aircraft Study

Testing models and retrieving cloud properties from aircraft observations of cirrus

- Machine learning algorithms for cloud identification from TAFTS measures

Antarctic campaigns

- PRANA research project (REFIR-PAD continuous measures since 2013)

- FIRCLOUDS measures of mixed phase and precipitating clouds

Motivations and Goals

Clear sky

- Evaluate the state-of-the-art simulation accuracy in *under-explored* spectral region
- Estimate clear sky *simulation biases* in window channels

Cloud identification and classifications

- Implement a new cloud *identification/classification* algorithm for high spectral resolution FIR-MIR satellite data
- Evaluate the added *information content* in the FIR

Cloud properties and retrieval

- Identify the radiance *sensitivity* to ice cloud properties in the FIR
- Exploit the FIR part of the spectrum to *derive cirrus cloud properties*

Dome Concordia station: 1-year dataset (2013)

REFIR-PAD Interferometric data (Palchetti and Bianchini)

- Operates 24h/day to provide spectrally-resolved zenith-sounding radiance measurements in the 100-1400 cm^{-1} range with a 0.4 cm^{-1} resolution.
- REFIR-PAD is a fast scanning spectro-radiometer with signals acquired in the time-domain and re-sampled in post-processing at equal intervals in optical path difference.
- Each single atmospheric observation lasts about 5 min and is the result of the average of eight atmospheric spectra (four for each output port). The repetition rate is 12 min, including the calibration measurements and some mechanical delays.

[*Palchetti et al.,* 2015]

Ancillary data (Del Guasta)

- LIDAR system: tropospheric profiles of backscattering and (linear) depolarization signal (532 nm) with a vertical resolution of 7.5 m from 30 to 12 000 m, every 5 min, 24/24 h. 2013 is the first full year available [Ricaud et al., 2017]
- Radiosonde: A Vaisala WXT520 weather station is available. Routine radiosondes observations are performed at the station every day at 12 UTC by Vaisala RS92 sondes (from 2006) [climantartide.it]

Features selection for the Clear sky spectra identification

A **Linear discriminant analysis method** is used to select the features important for describing the observations and for classification purposes [*Bishop*, 2006].

The selection is made to:

- lead to a minimum classification error
- avoid redundant information.

The selection criteria for features representing data are:

1. The interclass distance (defined by Fisher) is maximized:

$$d_{12} = \frac{(\mu_{\text{clear}} - \mu_{\text{cloud}})^2}{s^2_{\text{clear}} - s^2_{\text{cloud}}}$$

2. The minimum correlation among the features is found.

[Rizzi et al. 2016]

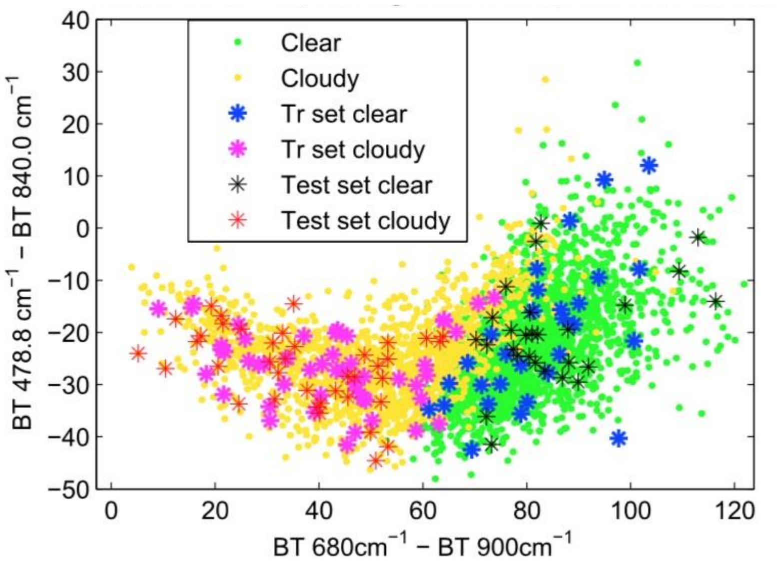
Most Recurrent **Features Selected** to Discriminate Clear to cloudy cases

Interval at	Interval at	Occurrences	Type
680.0	840.0	73	CO_2-WIN
531.2	680.0	56	FIR-CO_2
680.0	900.0	44	CO_2-WIN
680.0	870.0	41	CO_2-WIN
559.2	680.0	28	FIR-CO_2
573.2	840.0	27	FIR-WIN
478.8	840.0	27	FIR-WIN
464.4	840.0	25	FIR-WIN
522.4	680.0	24	FIR-CO_2
531.2	840.0	22	FIR-WIN
381.2	680.0	21	FIR-CO_2

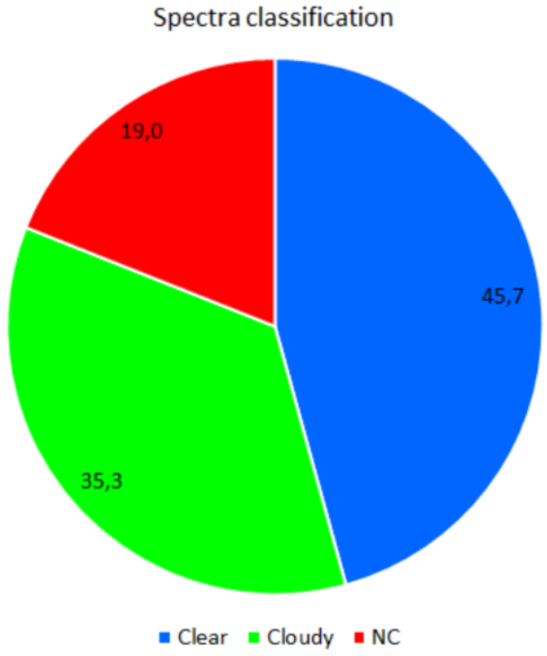
The feature selection algorithm is run 10 times for 24 different combinations of months. 8 out of 11 most recurrent combinations include FIR channels

Clear sky spectra identification and case study selection

Clear/cloud identification
The full data set (described by means of the selected features only) is passed to a **support vector machine** (SVM) code and, using a linear kernel, an identification is performed.



The SVM classification algorithm is applied to the whole 2013 dataset (13500 REFIR-PAD spectra)



Clear sky are predominant:

- 52% in the austral summer
- 47% in winter.

Clouds are identified in the:

- 34% of the cases during summer
- 36% in winter months.

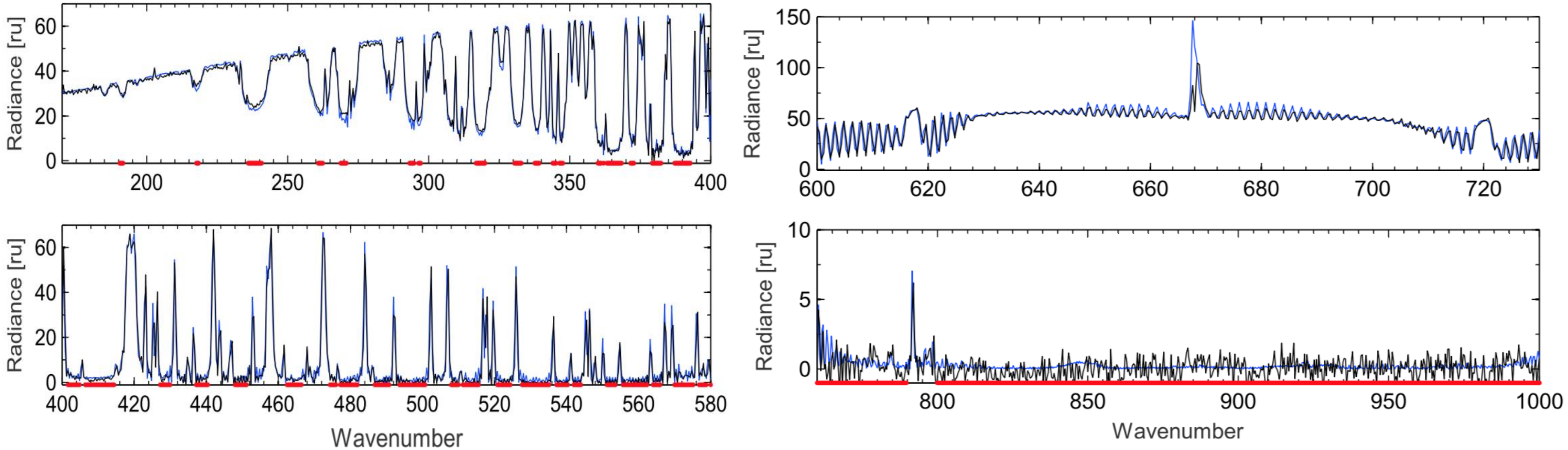
Clear sky spectra identification and case study selection

Clear Sky case study Dataset

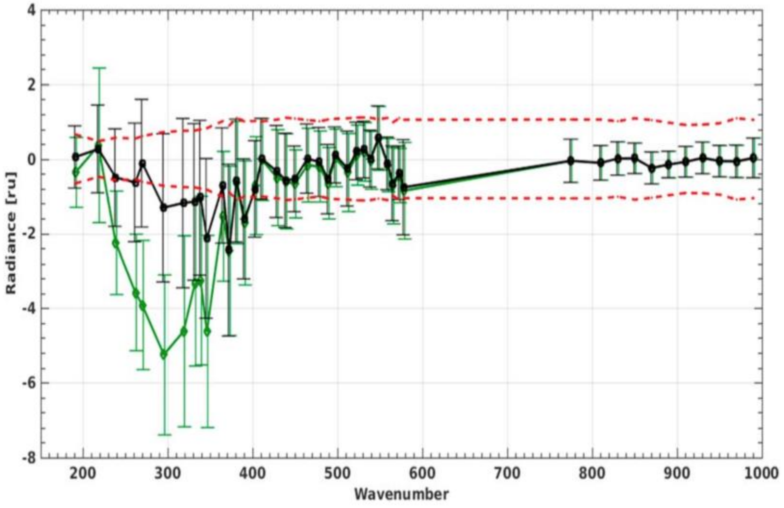
Data cover 66 days in all seasons (more than 6 consecutive spectra for each day) and stable conditions.

RS profile data are available up to at least 5 km asl and a sequence of at least 4 clear REFIR-PAD measurements are available within 70 minutes from 12 UTC.

Simulations are performed using LBLRTM, [Clough et al., 2005] and input data from RS and ECMWF re-analysis only.

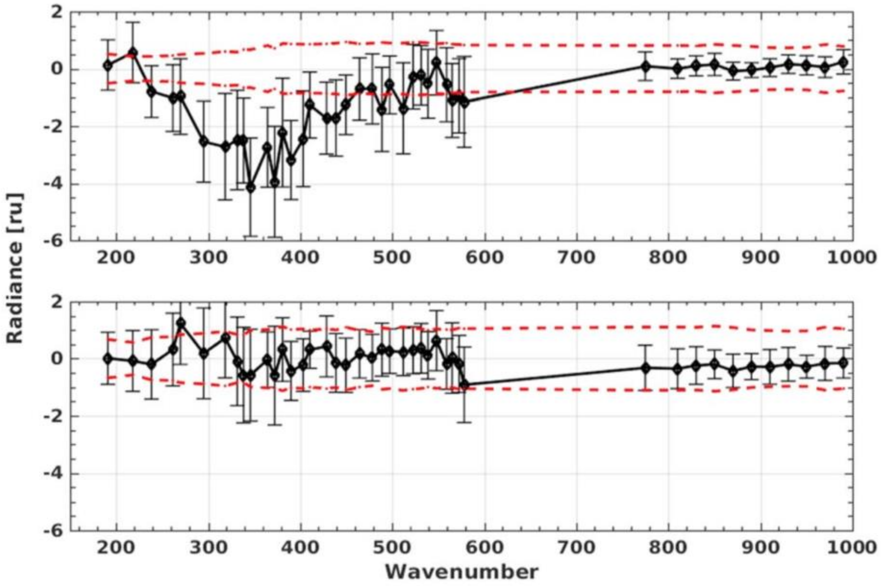


Clear sky analysis and results

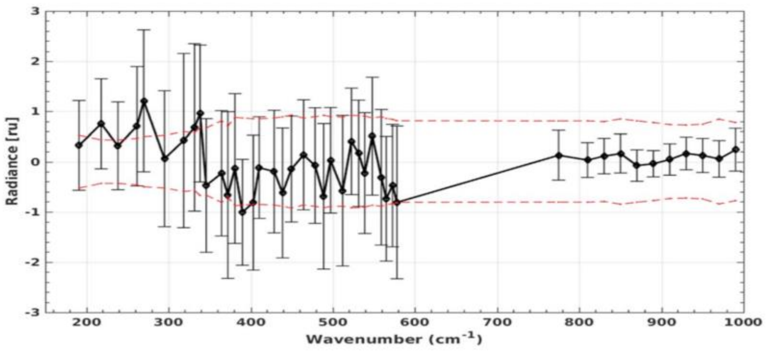


Annual mean residuals (for selected micro-windows) between simulated and measured radiances.
Green:LBLRTM v12.2, aer v3.2 and MT-CKD v2.5.2
Black: LBLRTM v12.7, aer v3.5 and MT-CKD v3.0

Upper panel: mean spectral residuals for Austral Summer (20 days and 127 spectra).



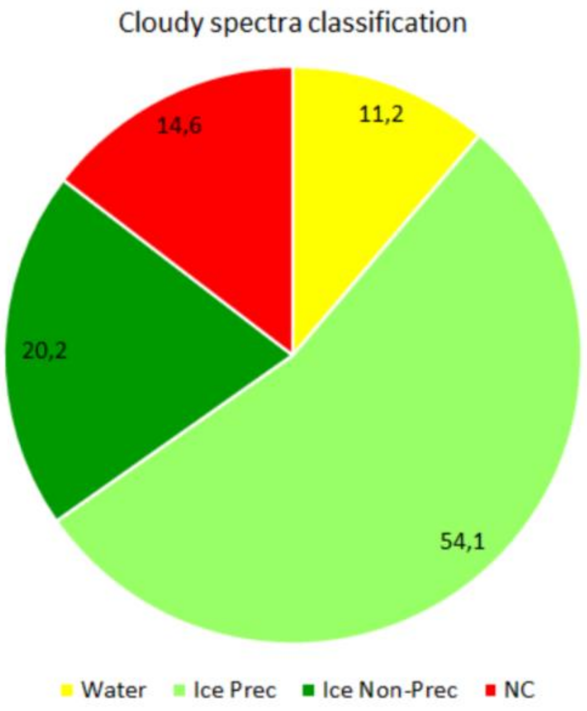
Lower panel: mean spectral residuals for Austral Winter (17 days and 111 spectra)



Annual mean residuals after a new set of simulations is performed to quantify a correction to be applied to the water vapor concentration profile for all summer days to minimize the dry bias effect.
An increase of 14.7% of the water vapor concentration profile reduces the residuals below the error level.

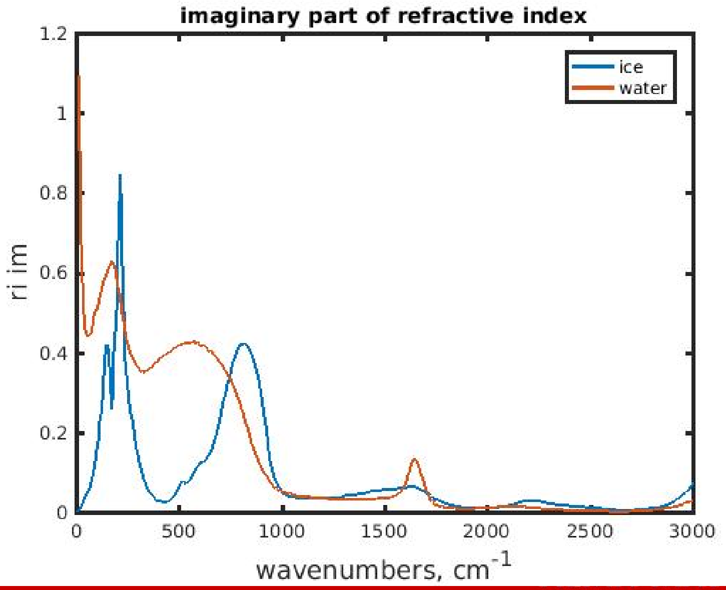
Vertical bars are one standard deviation around the yearly (or seasonal) mean;
Red dashed lines connect the values of the total spectral measurement uncertainty in each microwindow [Rizzi et al. (2018)].

Clouds classification



ice – liquid water clouds

Interval at $[cm^{-1}]$	Interval at $[cm^{-1}]$	Occurrences	Type
840.0	900.0	40	WIN-WIN
381.2	390.0	27	FIR-FIR
573.2	870.0	20	FIR-WIN
438.4	478.8	16	FIR-FIR
573.2	840.0	14	FIR-WIN
410.4	449.6	10	FIR-FIR



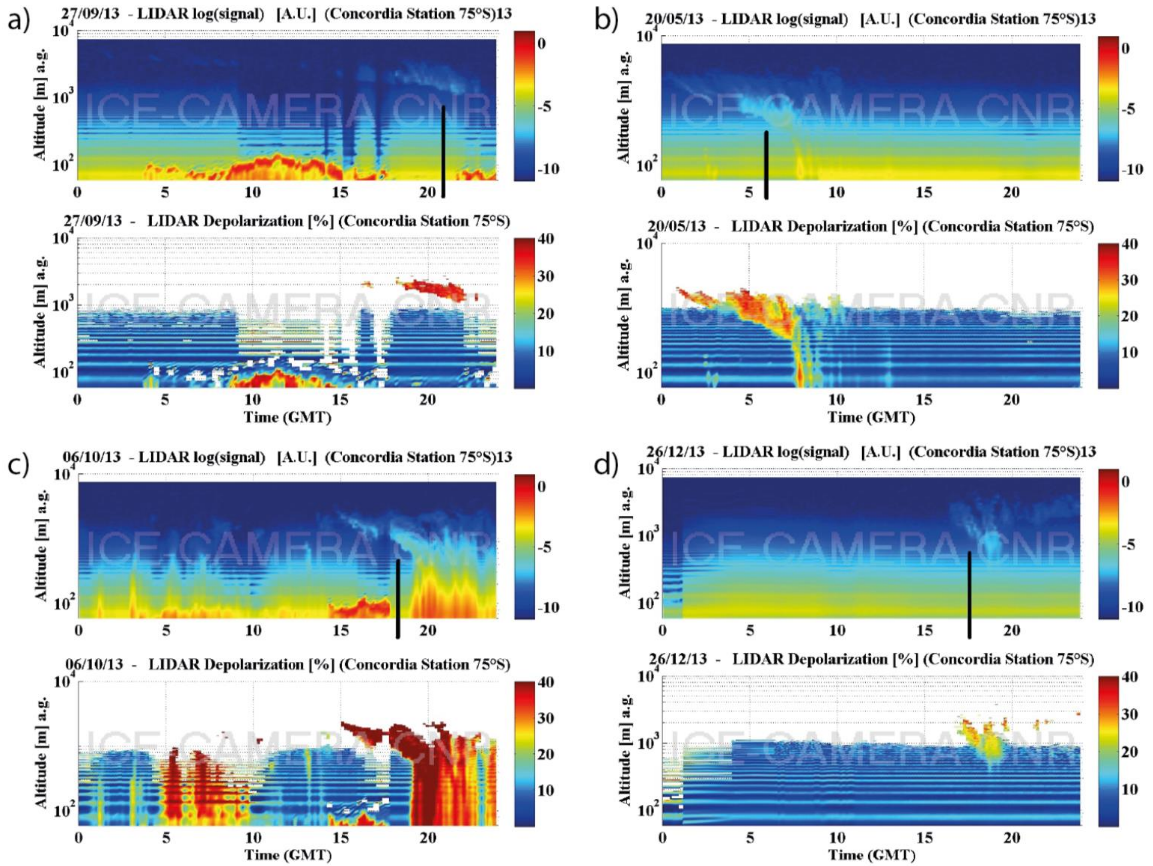
precipitating – not precipitating clouds

Interval at $[cm^{-1}]$	Interval at $[cm^{-1}]$	Occurrences	Type
559.2	573.2	52	FIR-FIR
238.4	381.2	52	FIR-FIR
238.4	390.0	38	FIR-FIR
531.2	573.2	38	FIR-FIR
522.4	573.2	35	FIR-FIR
680.0	900.0	35	CO_2-WIN
573.2	900.0	30	FIR-WIN
573.2	870.0	29	FIR-WIN
238.4	410.4	22	FIR-FIR
680.0	870.0	19	CO_2-WIN

Channels between 380 and 575 cm^{-1} are key channels for the clear/cloud and phase identification due to their sensitivity to cloud properties;

FIR channels down to 380 cm^{-1} are exploited for the selection of precipitating or non precipitating cases because of their sensitivity also to water vapor content [Maestri et al., 2018].

Cloudy sky spectra selected for case study



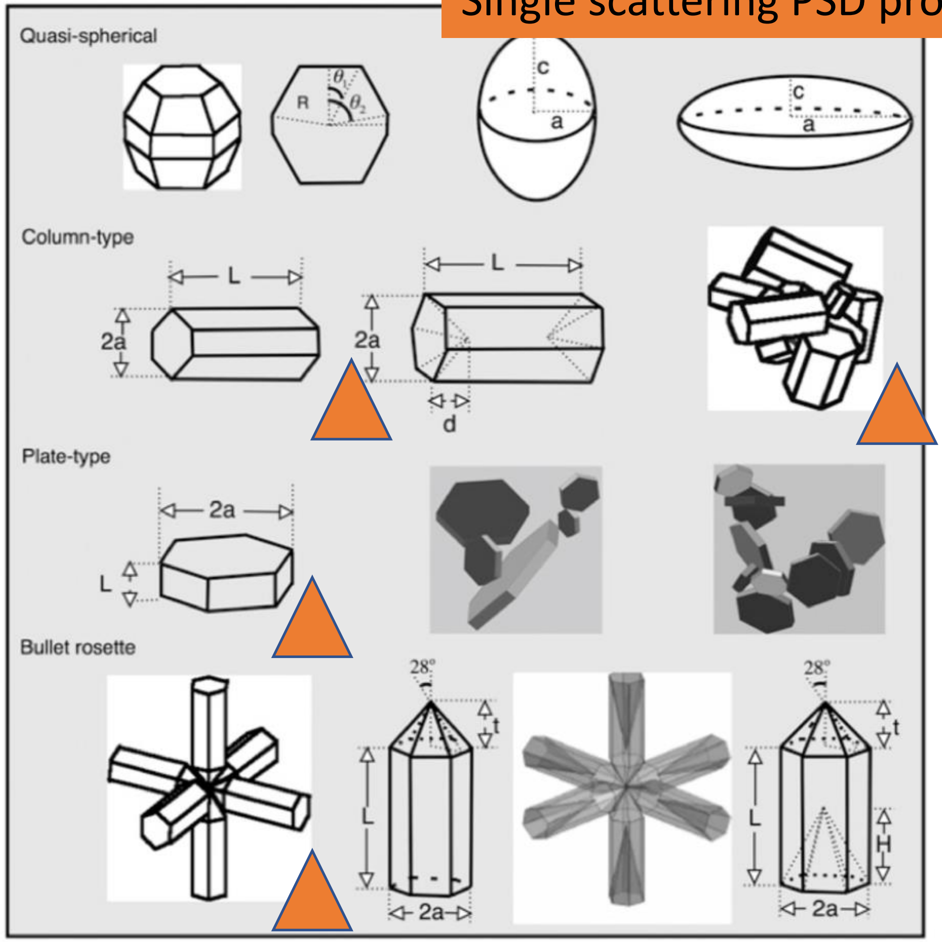
From a combined analysis of the classification algorithm and the lidar quick-looks, 26 non-precipitating ice cloud episodes are selected over the entire year 2013.

For each case one REFIR-PAD spectrum (that is the average of 4 consecutive acquisitions lasting 5.6 min) is used unless the scene is particularly stable (in this case two or three spectra are averaged).

	all	summer	winter
Mean cloud base height [m agl]	1450	1650	1350
Mean cloud base temperature [K]	236	239	230
Mean vertical extent [m]	1050	1000	1100
N cases	26	6	5

Cloudy sky retrieval strategy

Single scattering PSD properties



1. Each selected cloudy scene is analyzed singularly. The atmospheric profiles are built from ancillary data.
2. Cloud geometrical properties are derived from lidar data
3. An assumption on particle habit (Ping Yang properties) and IWC vertical distribution (Veglio and Maestri) is made.
4. A cloud property retrieval algorithm, RT-RET (Maestri and Holz) is used to derive cloud parameters (optical depth and effective dimension) from MIR part of the spectrum
5. Inverted properties are used as inputs to simulate the observed radiances over the whole REFIR-PAD spectrum
6. The residuals are evaluated

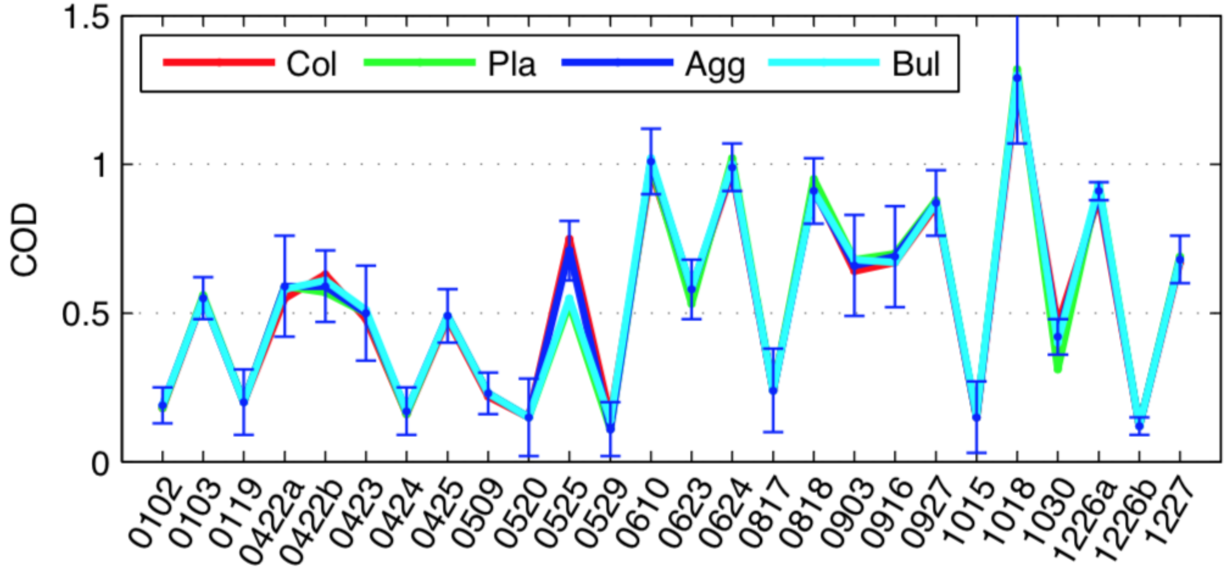
Cloudy sky results/1

Optical depth
No clear seasonal signal in terms of COD and Reff is found. Small changes in the mid level temperature of the observed clouds during the varying season.

For the aggregates assumption it is found that:

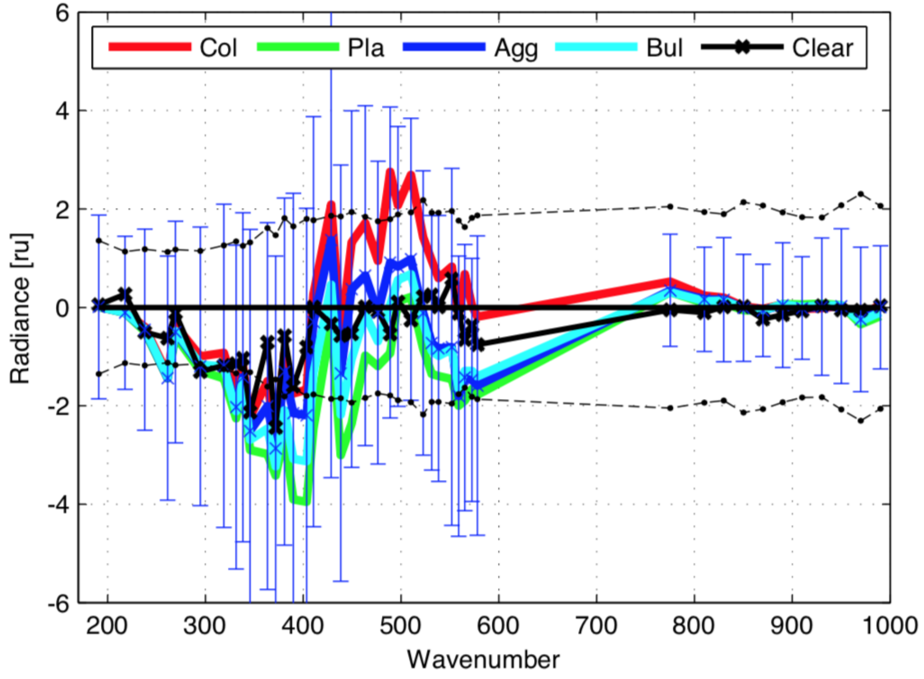
Mean COD of 0.38 for T< 230 *K*
Mean COD of 0.59 for T>230 *K*

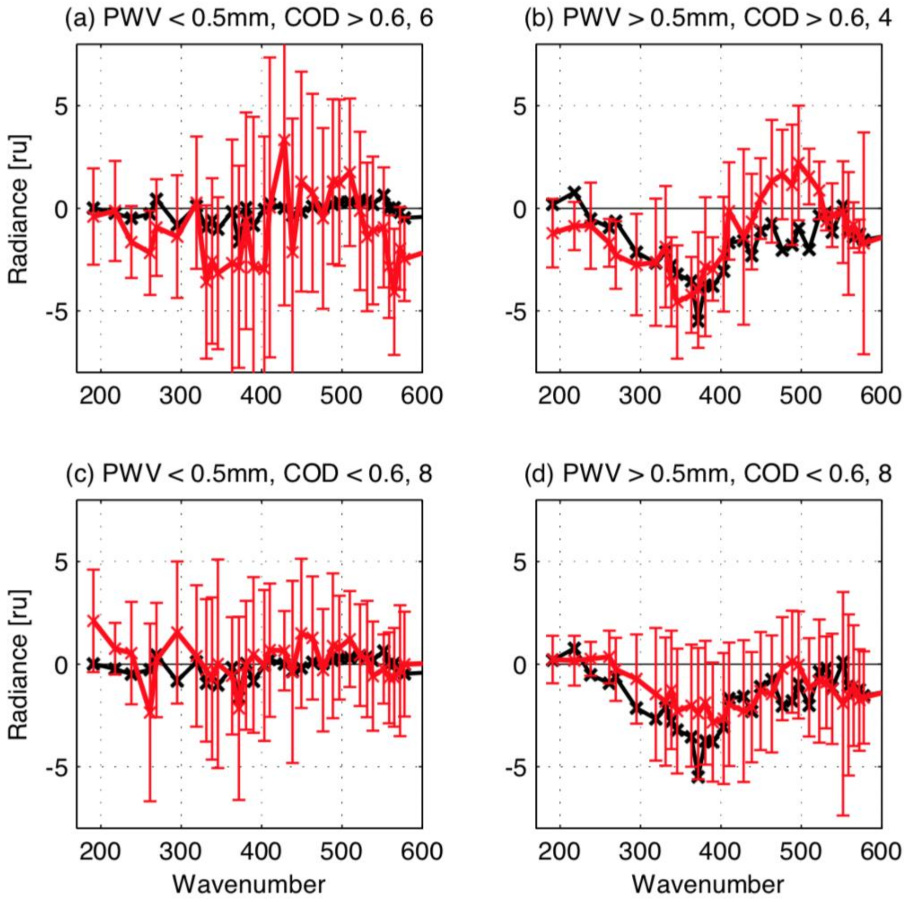
Mean R_{eff} of 19 µ*m* for T< 230 *K*
Mean R_{eff} of 35 µ*m* for T>230 *K*



Cloudy sky results/2

Average spectral structure of the residuals in FIR m-ws and in the main IR window is shown for each crystal habit.





The FORUM perspective

What did we learn from ground-based high spectral resolution measurements in the FIR?

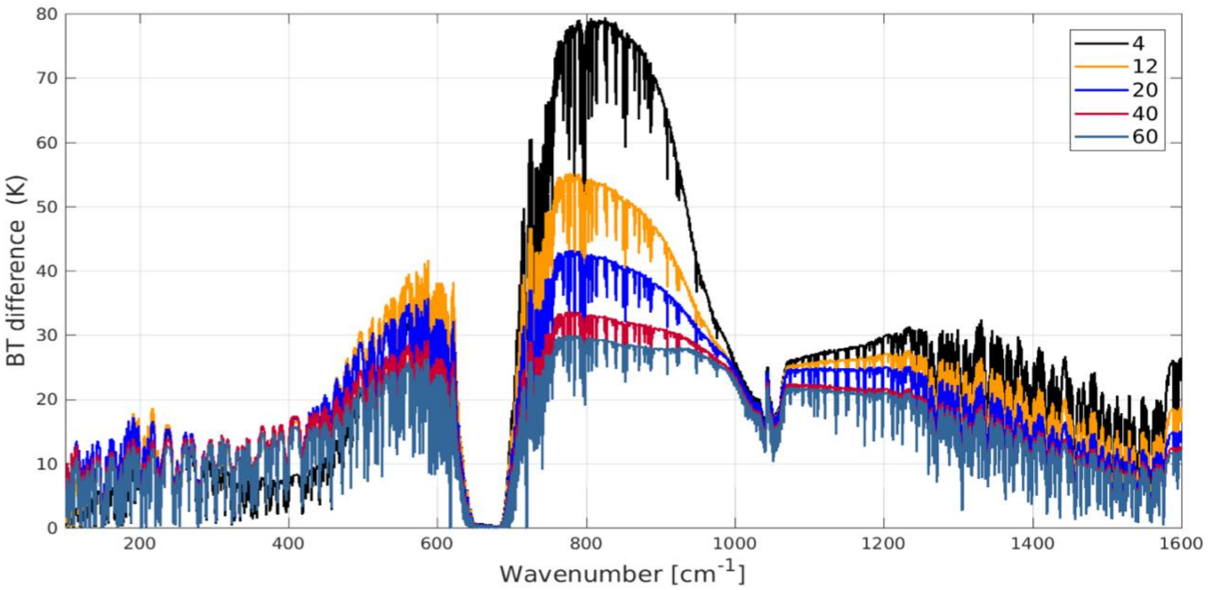
- BT at FIR channels (features) provides key information for cloud identification and classification
- The smallest residuals in presence of cirrus clouds are found for the smallest PWVs.
- For larger PWVs high correlation values are found for the clear and cloudy sky residuals suggesting a not-negligible role of water vapor modelling.

The satellite view offers many advantages and some drawbacks

Main advantages
- global view (i.e. ocean)
- cirrus first

Main drawbacks
- large fov (inhomogeneous scenes)
- lack of ancillary data

FORUM Sensitivity tests
Tropical atmosphere: size and habit

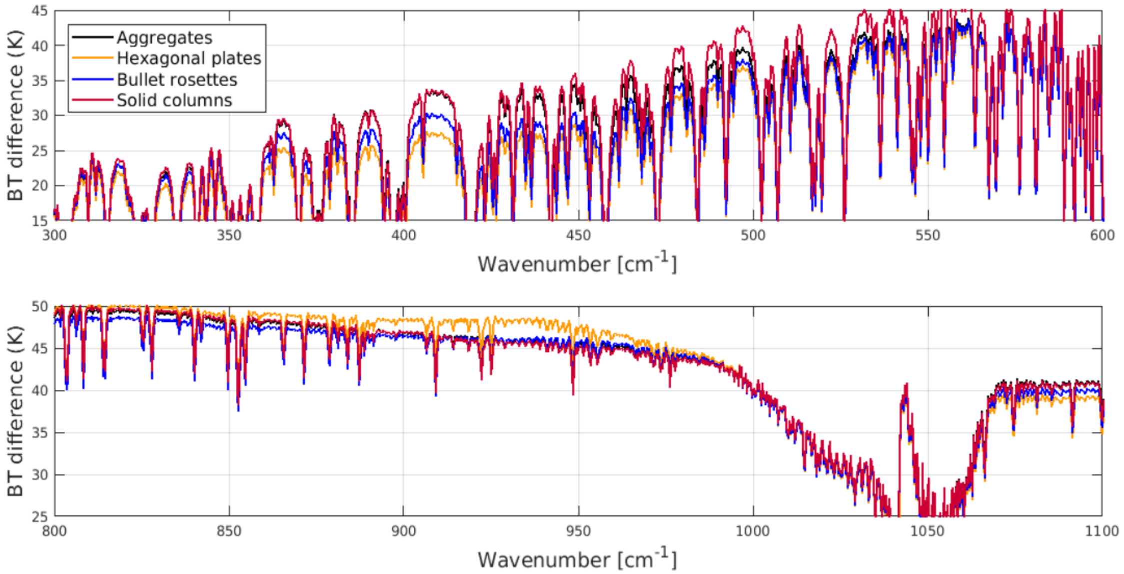


Atmosphere:

- IG2 TRO NO WI NI
- SST= 300.93 K.

Cirrus properties:

- Top Height: 14 km; Bottom Height: 13 km
- **Varying effective dimensions**
- ICE Hexagonal plates
- OD=0.5 at 1000 cm^{-1}



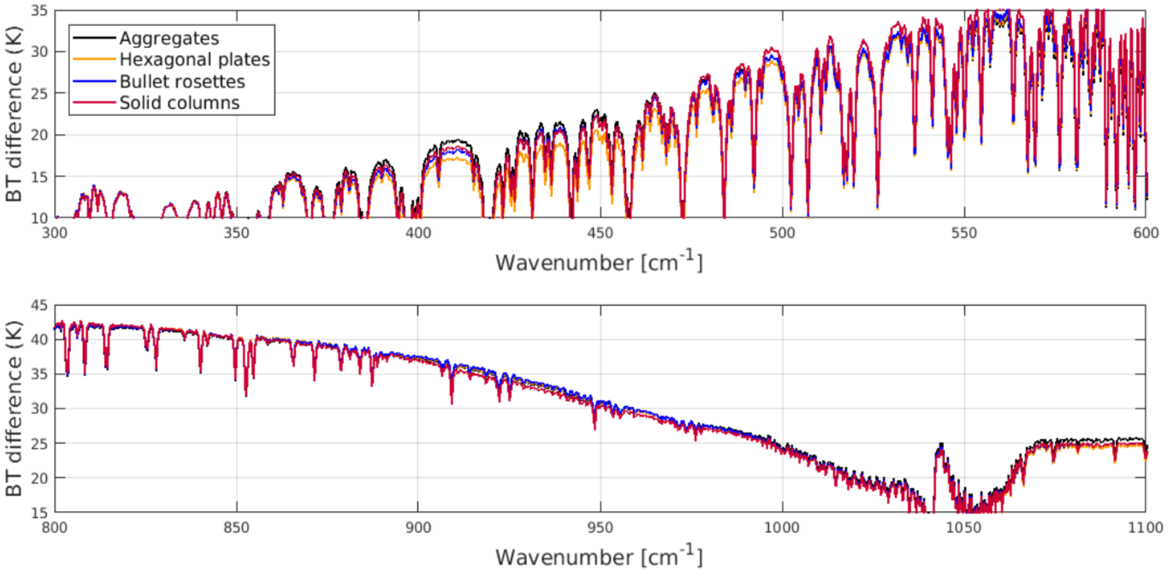
Atmosphere:

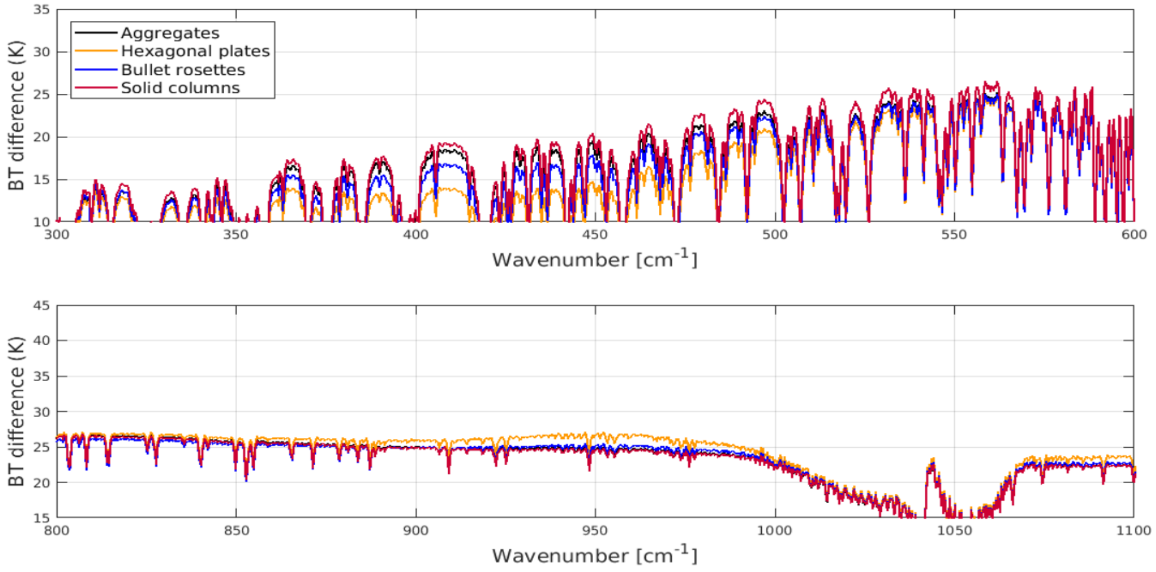
- IG2 TRO NO WI NI
- SST= 300.93 K.

Cirrus properties:

- Top Height: 14 km; Bottom Height: 13 km
- Effective dimensions**= 60 microns**
- **Varying habit**
- OD=0.5 at 1000 cm^{-1}

FORUM Sensitivity tests
Tropical atmosphere: size and habit





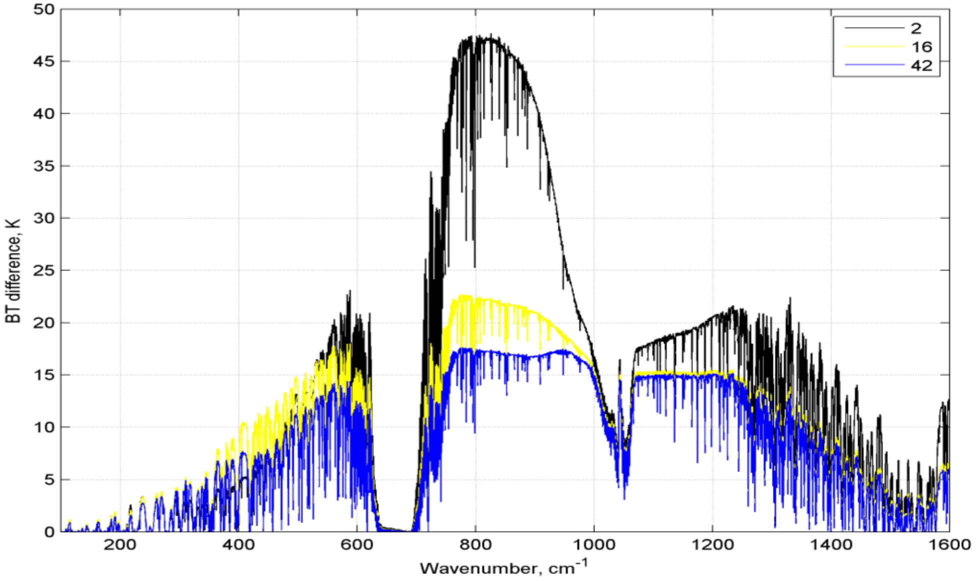
Atmosphere:
- IG2 TRO NO WI NI
- SST= 300.93 K.

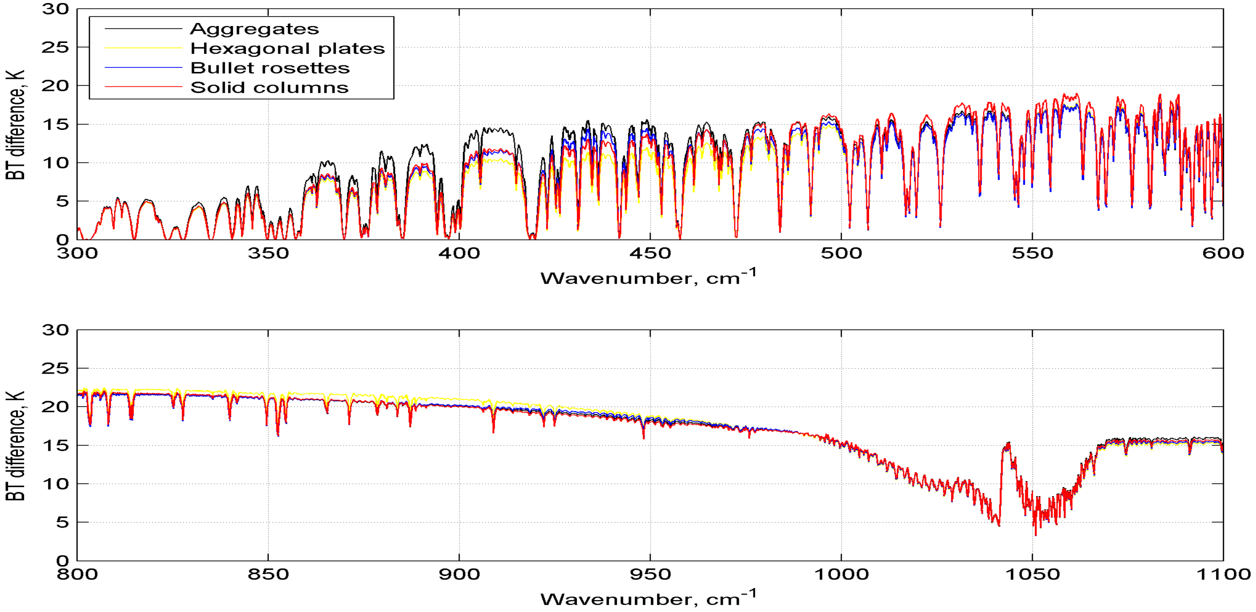
Cirrus properties:
- Top Height: 14 km; Bottom Height: 13 km
- Effective dimensions= **20 microns**
- **Varying habit**
- OD=0.5 at 1000 cm^{-1}

Atmosphere:
- IG2 TRO NO WI NI
- SST= 300.93 K.

Cirrus properties:
- Top Height: 14 km; Bottom Height: 13 km
- Effective dimensions= **100 microns**
- **Varying habit**
- OD=0.5 at 1000 cm^{-1}

FORUM Sensitivity tests
Mid Latitude atmosphere: size and habit





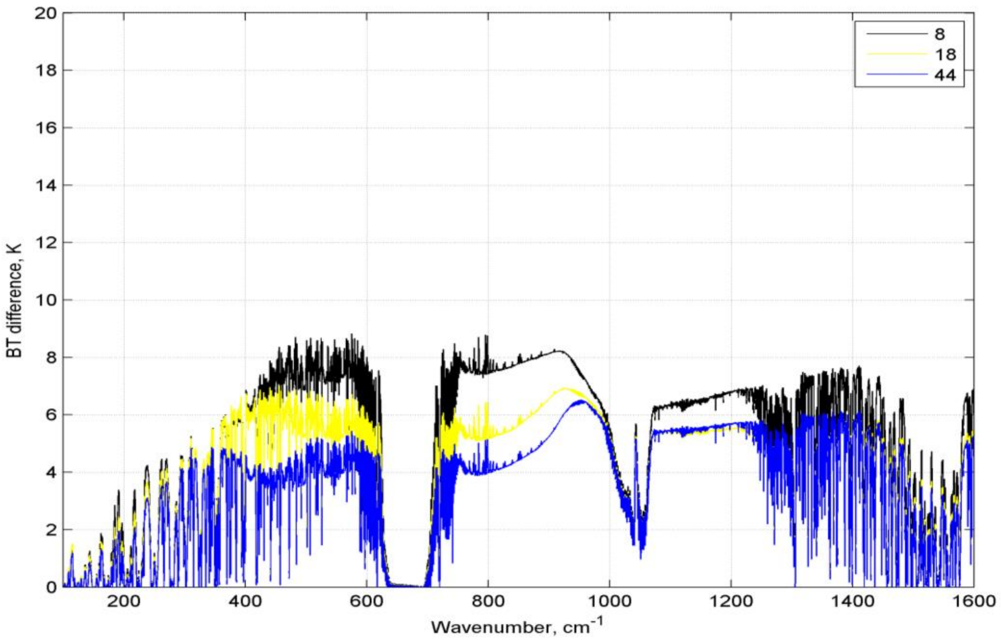
Atmosphere:
- ECMWF Re-analysis – 30/01/2016 - Night
- SST= 284.2 K.

Cirrus properties:
- Top Height: 10 km; Bottom Height: 8 km
- **Varying effective dimensions**
- ICE Hexagonal plates
- OD=0.5 at 1000 cm^{-1}

Atmosphere:
- ECMWF Re-analysis – 30/01/2016 - Night
- SST= 284.2 K.

Cirrus properties:
- Top Height: 10 km; Bottom Height: 8 km
- Effective dimensions= 32 microns
- **Varying habit**
- OD=0.5 at 1000 cm^{-1}

FORUM Sensitivity tests
Antarctic atmosphere: size and habit

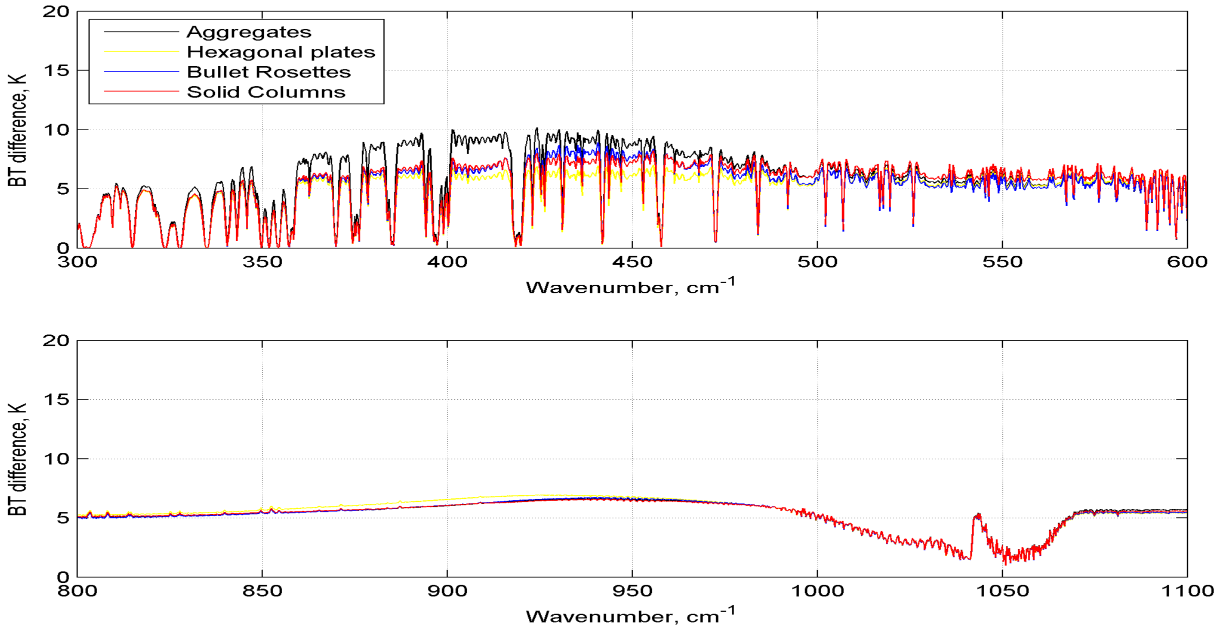


Atmosphere:

- ECMWF Re-analysis – 22/01/2016 - Night
- SST= 244.7 K.

Cirrus properties:

- Top Height: 8 km; Bottom Height: 6 km
- **Varying effective dimensions**
- ICE Hexagonal plates
- OD=0.5 at 1000 cm^{-1}



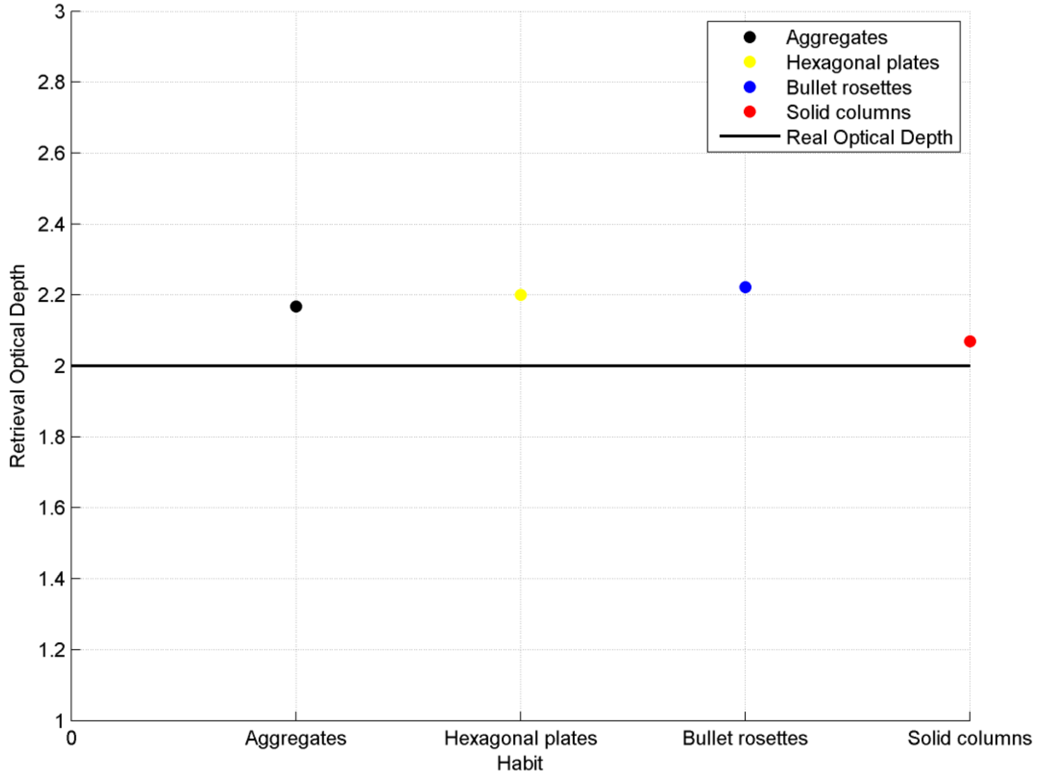
Atmosphere:

- ECMWF Re-analysis – 22/01/2016 - Night
- SST= 244.7 K.

Cirrus properties:

- Top Height: 8 km; Bottom Height: 6 km
- Effective dimensions= 36 microns
- **Varying habit**
- OD=0.5 at 1000 cm^{-1}

FORUM cloud retrieval sensitivity tests: Habit a-priori assumption



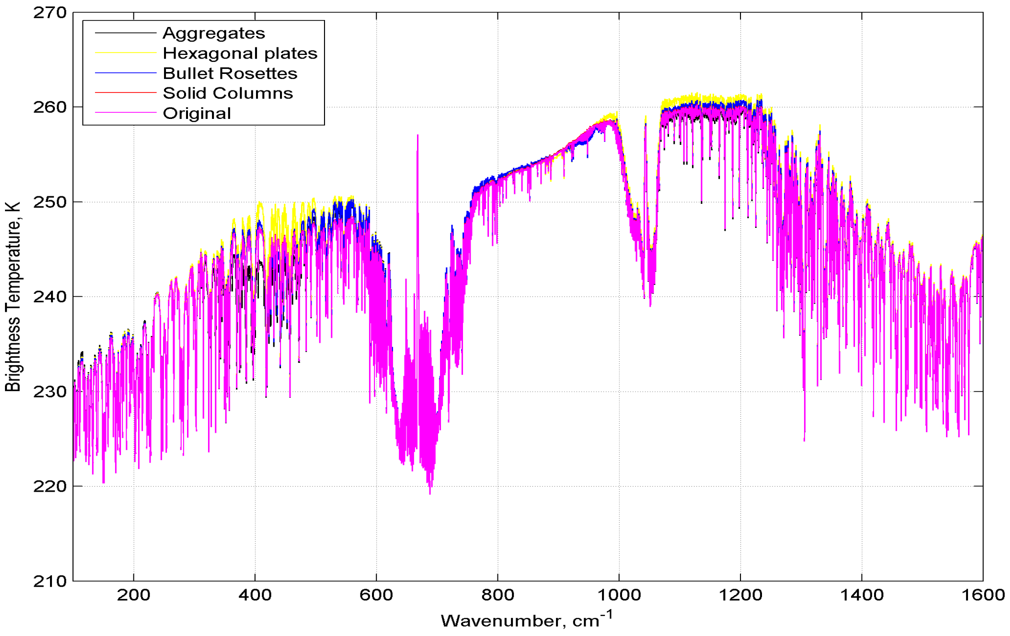
The retrieval sensitivity to the a-priori habit assumption is evaluated.

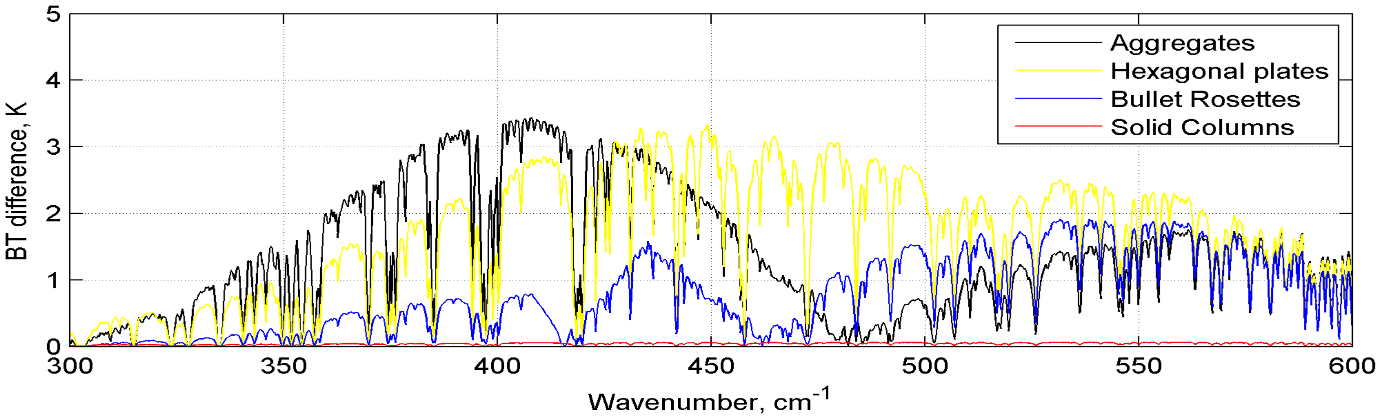
Forward simulation assumption are

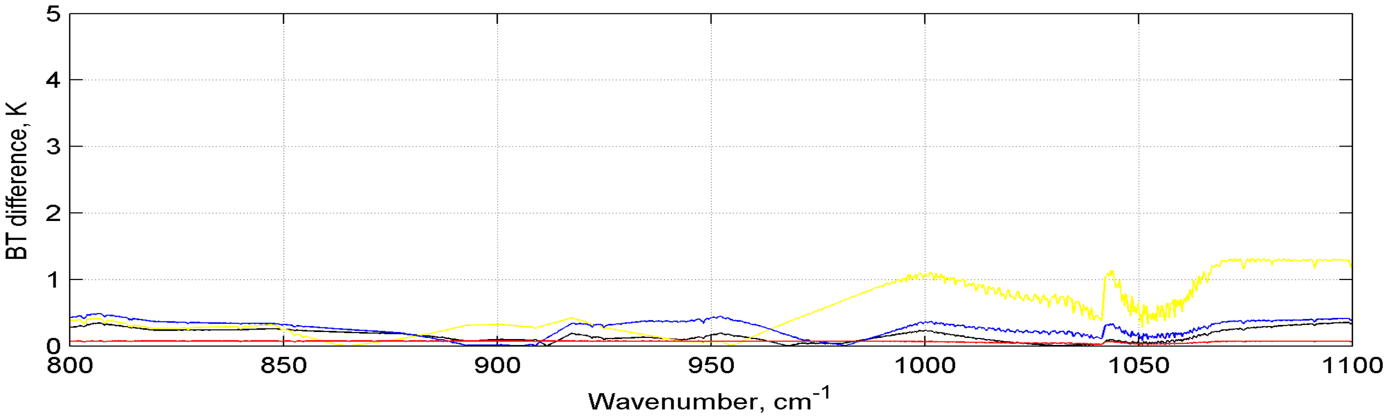
Atmosphere:
- IG2 MID NO SU DA
- SST= 285.14 K.

Cirrus properties:
- Top Height: 10 km; Bottom Height: 8 km
- Reff=16.0 microns
- Habit: solid column
- **OD = 2 at 1000 cm^{-1}**

FORUM cloud retrieval sensitivity tests: Habit a-priori assumption







Atmosphere:

- IG2 MID NO SU DA
- SST= 285.14 K.

Cirrus properties:

- Top Height: 10 km; Bottom Height: 8 km
- Reff=16.0 microns
- Varying Habit
- OD=2 at 1000 cm^{-1}

Conclusions

- The SVM algorithm (and other techniques) is used for cloud identification and classification and to highlight the information content of the FIR part of the spectrum.

- The largest sensitivity to crystal shape is found in the 400-550 cm^{-1} interval and is dependent on particle dimensions, cloud altitude and thickness and water vapor content.

- The smallest residuals (between simulations and observations) are found for the smallest PWVs. For larger PWVs high correlation values are found for the clear and cloudy sky residuals suggesting a not-negligible role of water vapor modelling.

- Observation of global up-welling high spectral radiances in the full IR spectrum will allow
    1. the characterization of the radiative signatures of ice clouds
    2. more accurate cloud identification and classification (**see poster: Cossich, Maestri and Sbrolli**)
    3. derivation of more accurate and larger set of features of high clouds.