Spectral Flux Calculation with FORUM-like Measurements Acquired from a Stratospheric Balloon

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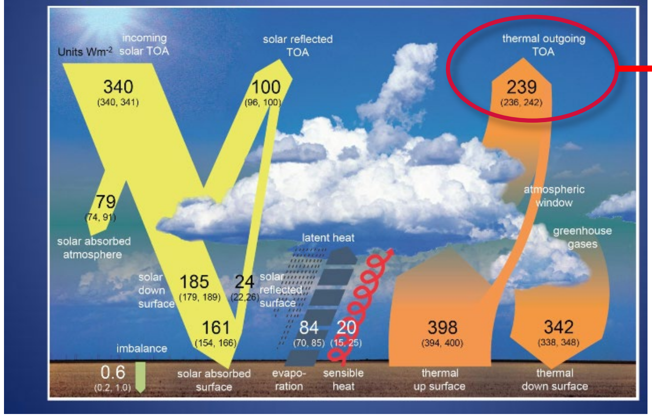
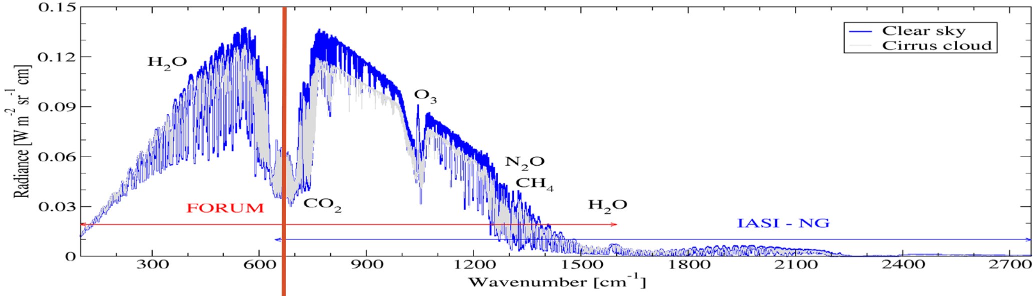
FORUM and the Earth Radiation Budget

Far-infrared-Outgoing-Radiation Understanding and Monitoring ESA EE-9 Mission

New global energy balance [*Wild et al.*, 2013].





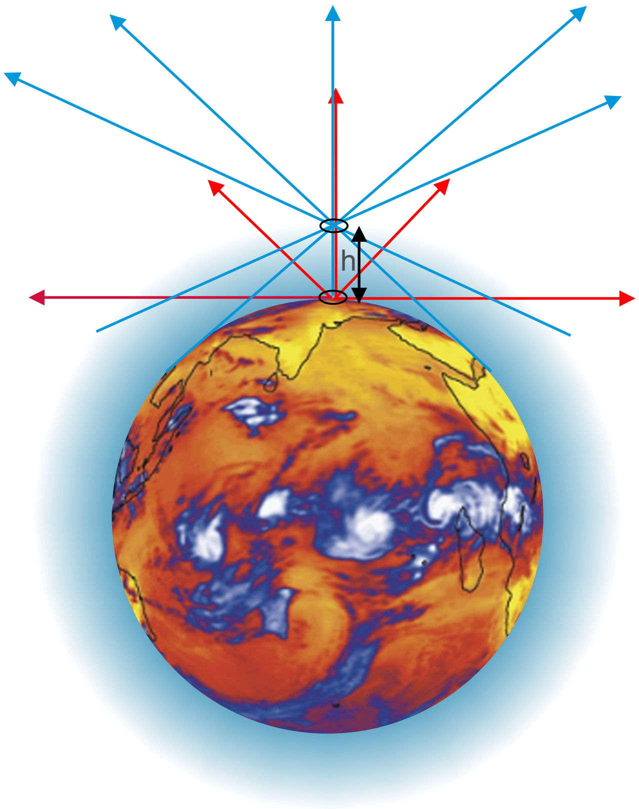
FIR ⟷

Range = 100-1600 cm^{-1}
Resolution = 0.5 cm^{-1}
Accuracy = 0.1 K (3σ confidence)

<u>Objectives</u>

- Reducing FIR uncertainty in models
- Identifying climate signatures in the spectrum to better link observed variations to key underlying physical processes driving climate change

Flux calculation – spherical geometry



Spectral flux

$$F_\nu = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\frac{\pi}{2}} I_\nu(\phi,\theta) cos(\theta) sin(\theta)\ d\theta d\phi$$

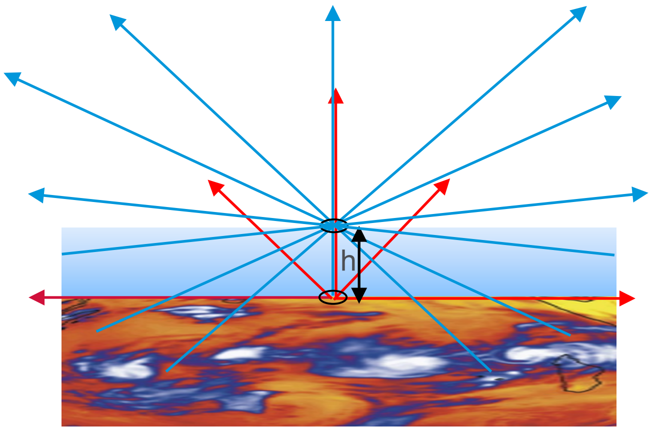
Total flux

$$F = \int_0^\infty F_\nu d\nu$$

Reference level dependence

$$\frac{F_{h1}}{F_{h2}} = \left(\frac{r_e + h_1}{r_e + h_2}\right)^2$$

Flux calculation – plane-parallel geometry



Spectral flux

$$F_\nu = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\frac{\pi}{2}} R_\nu(\phi, \theta) cos(\theta) sin(\theta) \; d\theta d\phi$$

Total flux

$$F = \int_0^\infty F_\nu d\nu$$

Reference level dependence

$$\frac{F_{h1}}{F_{h2}} = \left(\frac{r_e + h_1}{r_e + h_2}\right)^2$$

$$F_{h1} = F_{h2}$$

From radiance measurements to flux

1. Radiance measurements are band-limited and typically not spectrally-resolved so ADM are required to obtain the total flux through the anisotropy factor *R(θ)*.

$$F = \frac{\pi I(\theta)}{R(\theta)}$$

2. Radiance spectral measurements allows to calculate also the spectral flux or using spectral ADM or through a retrieval approach

$$F_{\upsilon} = \frac{\pi I_{\upsilon}(\theta)}{R_{\upsilon}(\theta)}$$

Retrieval approach to calculate spectral flux

Spectral measurement at 1 zenith angle θ ⟹ Retrieval ⟹ Atmospheric state

Atmospheric state ⟹ Radiative transfer ⟹ $I_\nu(\theta)$

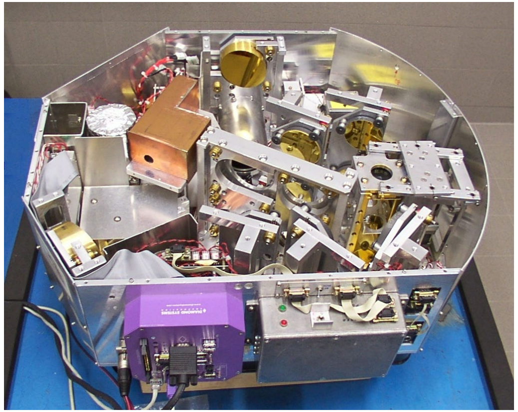
Horizontal and azimuth homogenous approximation

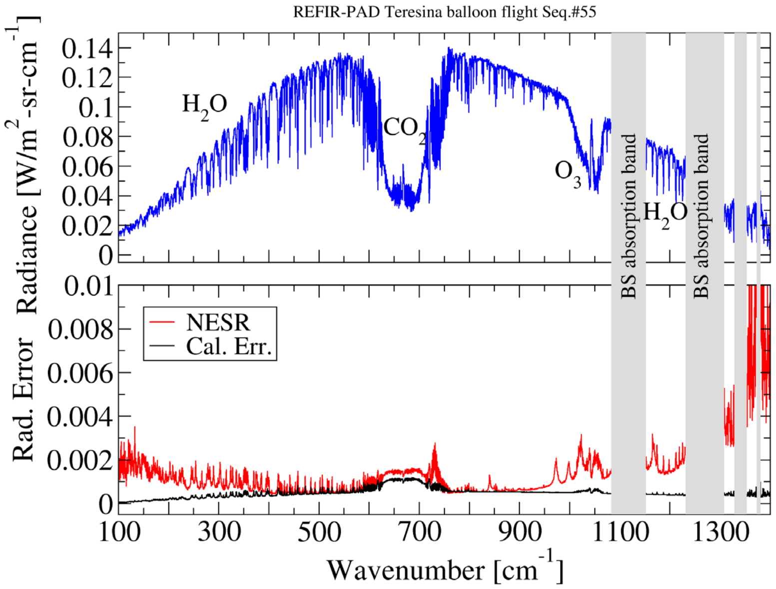
$$F_\nu = 2\pi \int_{\theta=0}^{\frac{\pi}{2}} I_\nu(\theta) cos(\theta) sin(\theta) d\theta$$

$$F = \int_0^\infty F_\nu d\nu$$

Application to stratospheric balloon-borne FIR FTS

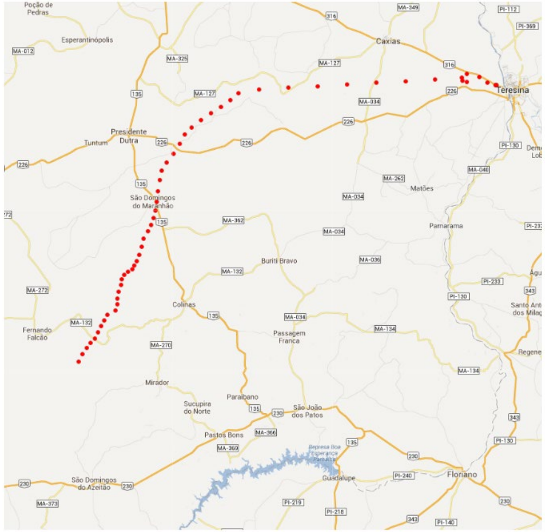
REFIR-PAD (Radiation Explorer in the Far-InfraRed – Prototype for Applications and Development) 2003-04

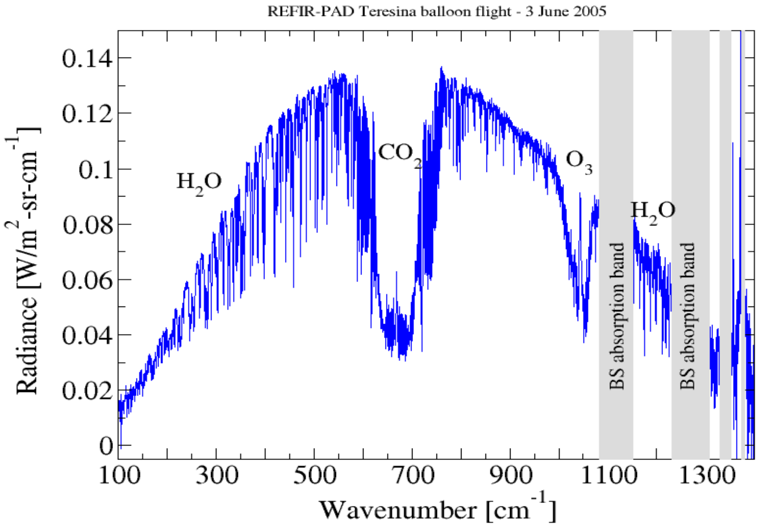




FIR – Fourier Transform Spectrometer
Spectral coverage = 100-1400 cm^{-1},
Resolution 0.475 cm^{-1} max. double-sided
NESR in the range 0.8-2.5 mW/(m^2 sr cm^{-1})
Absolute calibration error < 0.5 K
Small Payload: 62 cm dia., 55 kg weight, 50 W avg power

Teresina campaign – 30 June 2005





North-East of Brazil (5° 5’ S, 42° 52’ W)
Launch at night at 03:36 local time
Floating altitude at 34 km for about 8 h
Landing 10 h later, 270 km south-west

54 nadir measurements (10 during the ascending leg and 44 at floating altitude) + calibrations and deep space views
1 meas. = average of 10 nadir acquis.
1 meas. lasts 6 min

Retrieval of the atmospheric state

Different approaches have been used

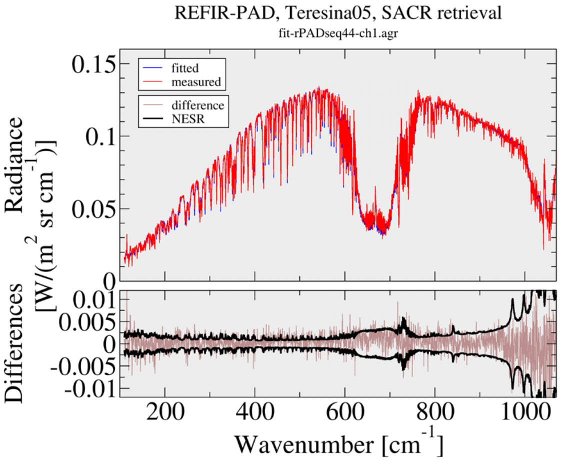
- Best fit with χ^2 minimization based on LBLRTM FM https://doi.org/10.1029/2010JD014530
- Optimal estimation approach based on SACR FM (LBLRTM) https://doi.org/10.1016/j.jqsrt.2020.106927
- Optimal estimation approach https://doi.org/10.4401/ag-6331 based on KLIMA FM (HITRAN / AER)

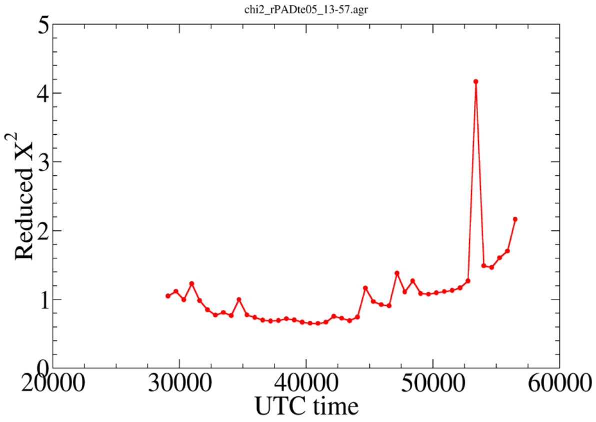
Instrument lineshape fitting

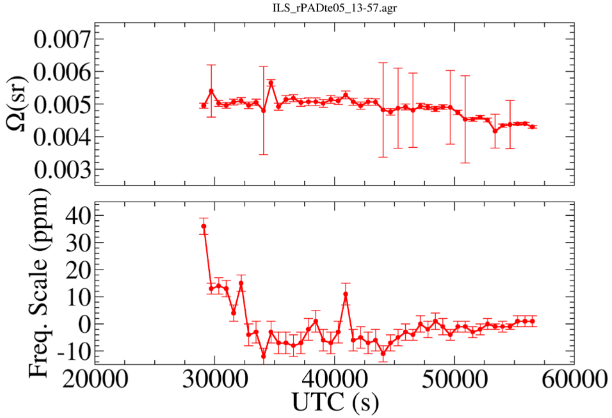
$$ILS(\sigma) = \alpha(\sigma) \cdot sinc\left(\frac{\sigma}{\Delta\sigma}\right) + (1-\alpha(\sigma)) \cdot sinc^2\left(\frac{\sigma}{2\Delta\sigma}\right)$$

$$\alpha(\sigma) = sinc\left(\frac{\sigma\Omega}{4\Delta\sigma}\right)$$

$$\sigma = (1+FS)\,\sigma_{meas}$$

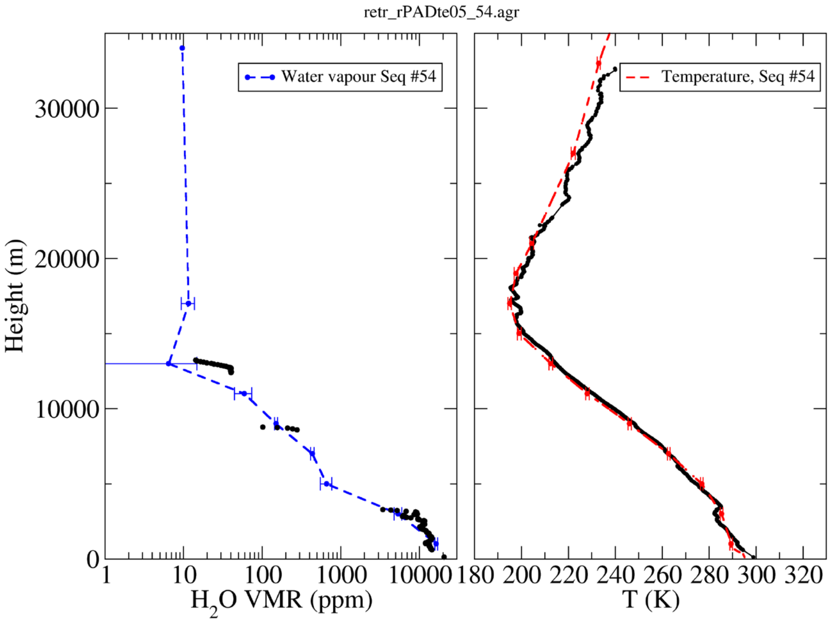


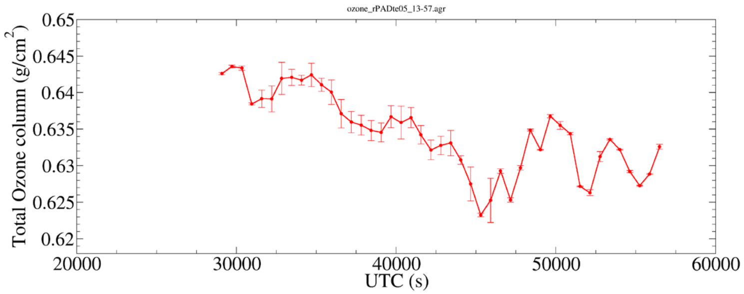


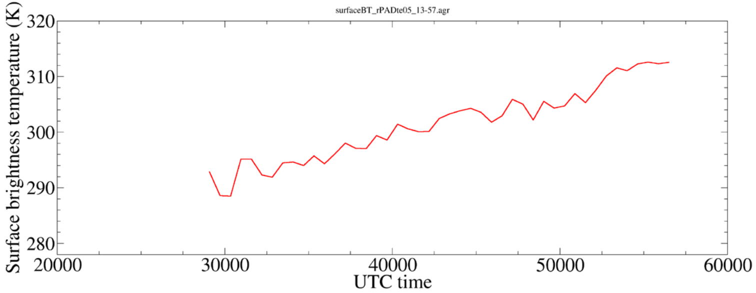


Retrieval water vapour / temperature prof. and Tsurf

SACR retrievals







Spectral flux calculation

From the retrieved atmospheric state using FMs, the flux can be calculate by solving the integral
- Numerical integration for many zenith angles
- Gaussian quadrature with x=cos(θ)

$$F_V = 2\pi \int_0^1 I_\upsilon(x)dx = 2\pi \sum_{k=1}^{3} w_k\, I_\upsilon(x_k)$$

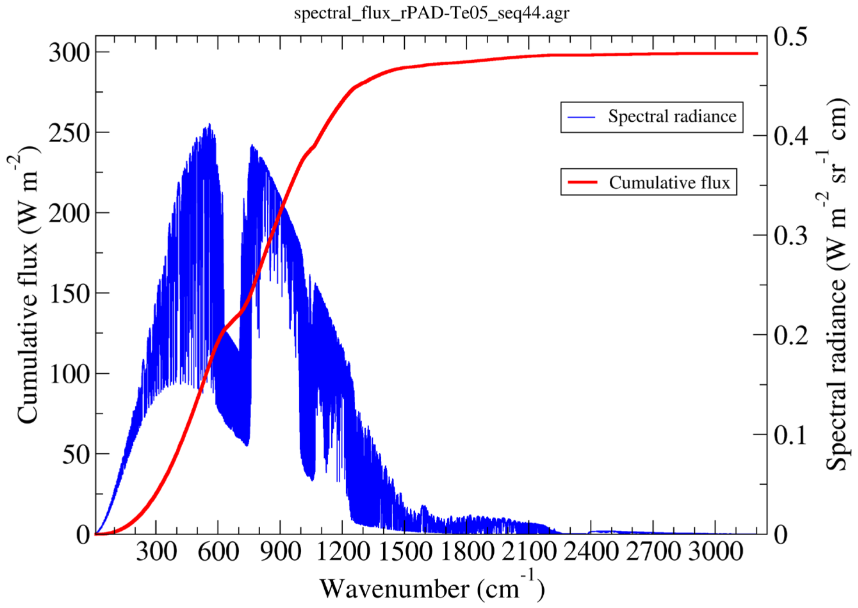
θ_1= 77.740 deg
θ_2= 53.803 deg
θ_3= 24.299 deg

Radiance *I*(θ_1) calculated with FMs: LBLRTM, SACR, KLIMA

LBLRTM and SACR use plane-parallel atmosphere
KLIMA uses spherical geometry => for the comparison flux must be scaled to ground according to

$$F_{ground} = F_h \left(\frac{r_e + h}{r_e}\right)^2$$

Spectral integration



$$F = \int_0^\infty F_\nu d\nu$$

$Ftot_{10\text{-}3250cm\text{-}1}$ = 299.03 W m^{-2}

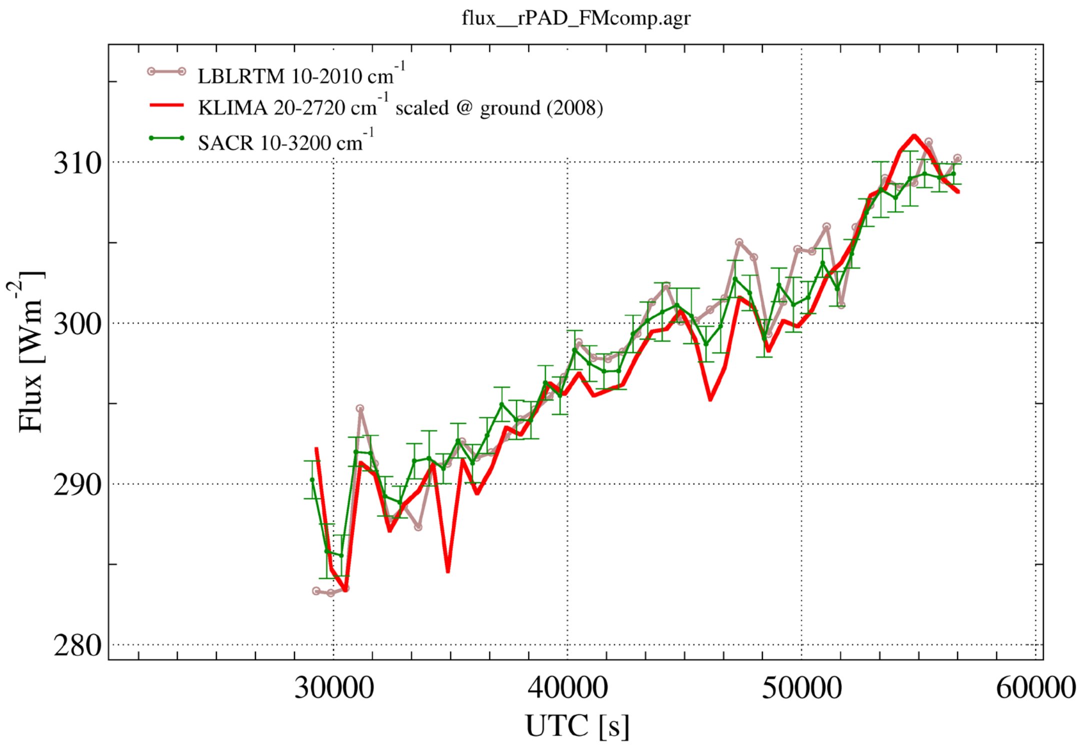
$F_{10\text{-}3200cm\text{-}1}$ = Ftot – 7.10^{-6} W m^{-2}

$F_{10\text{-}2750cm\text{-}1}$ = Ftot – 0.21 W m^{-2}

$F_{20\text{-}2720cm\text{-}1}$ = Ftot – 0.26 W m^{-2}

$F_{10\text{-}2010cm\text{-}1}$ = Ftot – 2.6 W m^{-2}

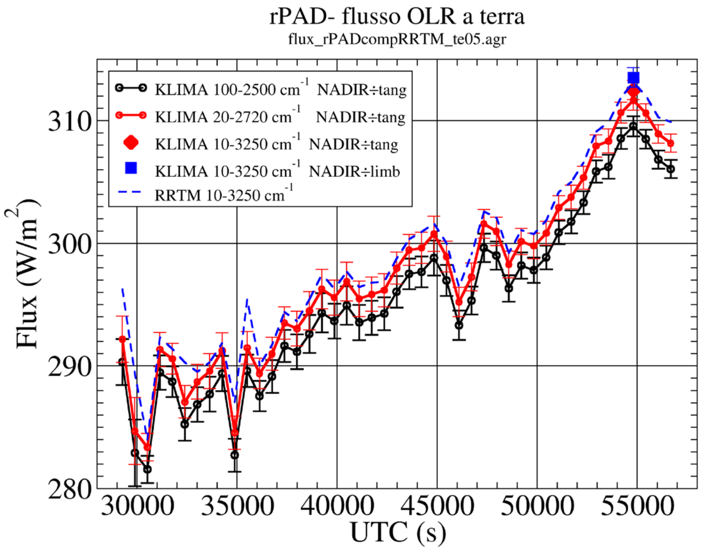
Flux comparison



Flux calculation – fast model: AER – RRTM

RRTM is a rapid radiative transfer model which utilizes the correlated-k approach to calculate fluxes and heating rates
http://rtweb.aer.com/rrtm_frame.html

- 16 bands in 10-3250 cm^{-1}
- flux differences with LBLRTM are within 1.5 W/m^2 at all levels

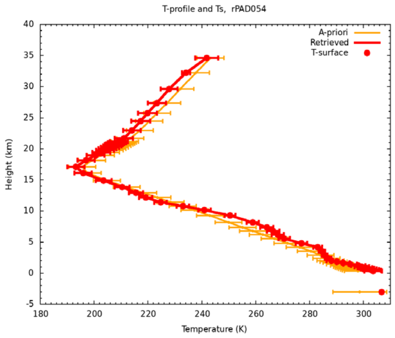


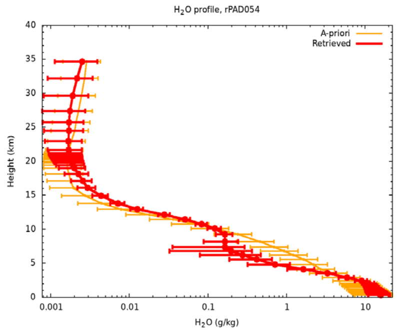
Flux calculation – fast model: σ-FORUM

σ-FORUM is a monochromatic fast radiative transfer model based on an extension of σ-IASI developed at Univ. of Basilicata

https://doi.org/10.1016/S1364-8152(02)00027-0

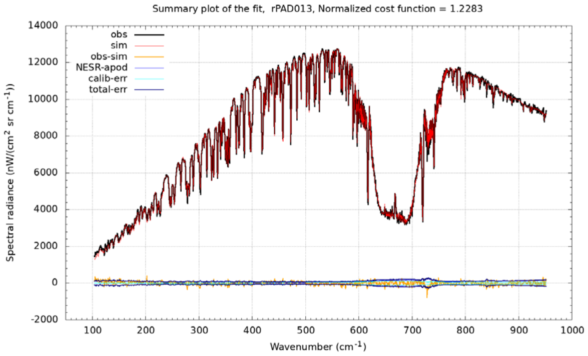
- Spectral range: 5-3000 cm^{-1}
- High res. = 0.01 cm^{-1}
- LBLRTM12.2 / KLIMA
- Geophysical par.: Atm. profiles (T,q); cloud/aerosols profiles; Surface par.

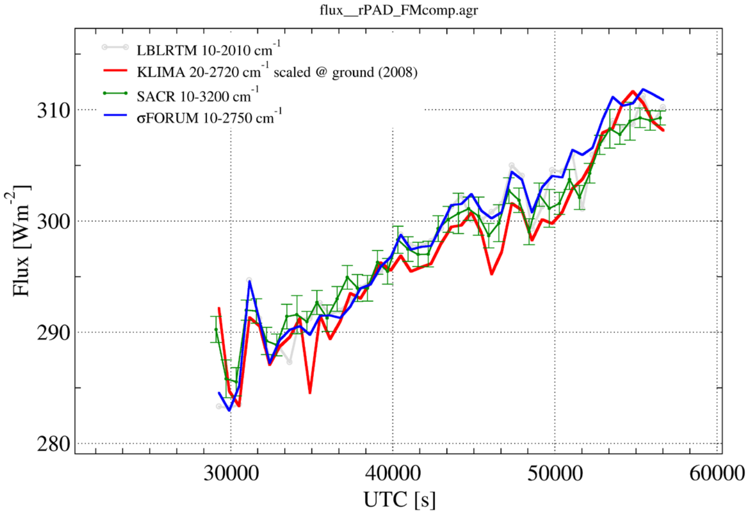




Retrieval with Opt. Estimation in 100-950 cm^{-1}

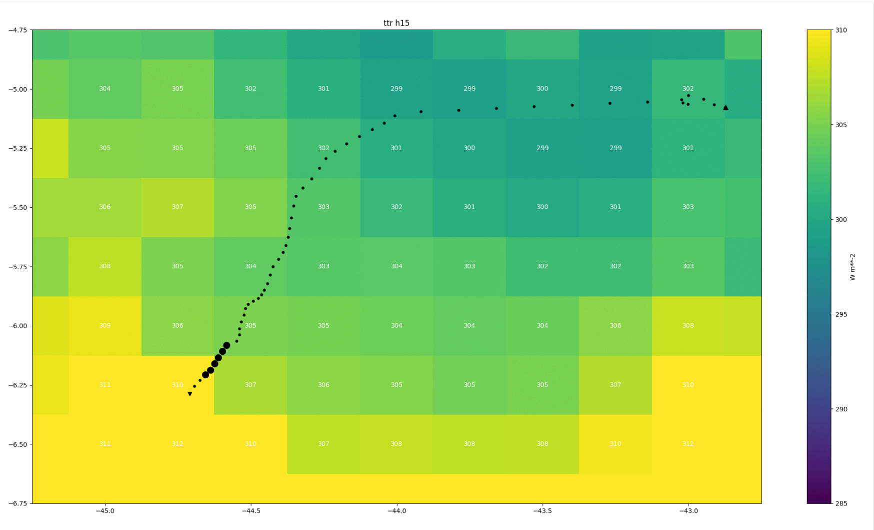
Flux calculation in 10-2750 cm^{-1}

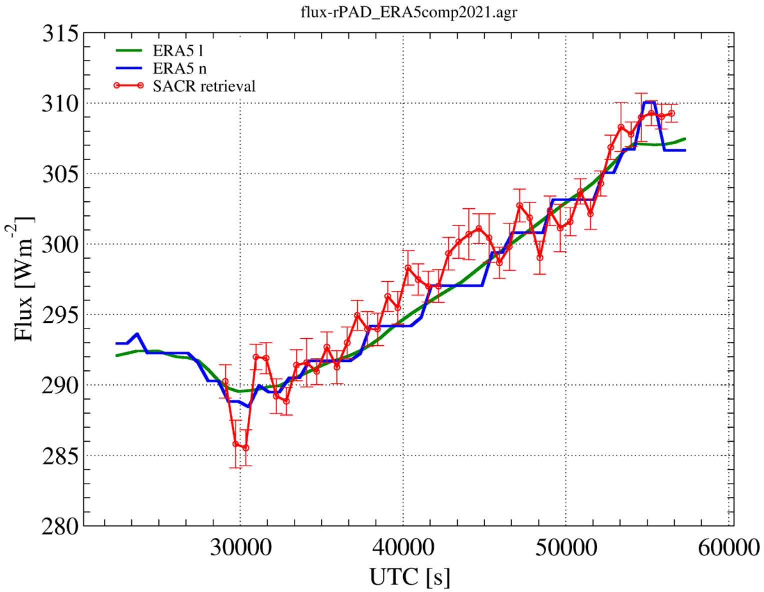




Comparison with ERA-5 and SACR fluxes

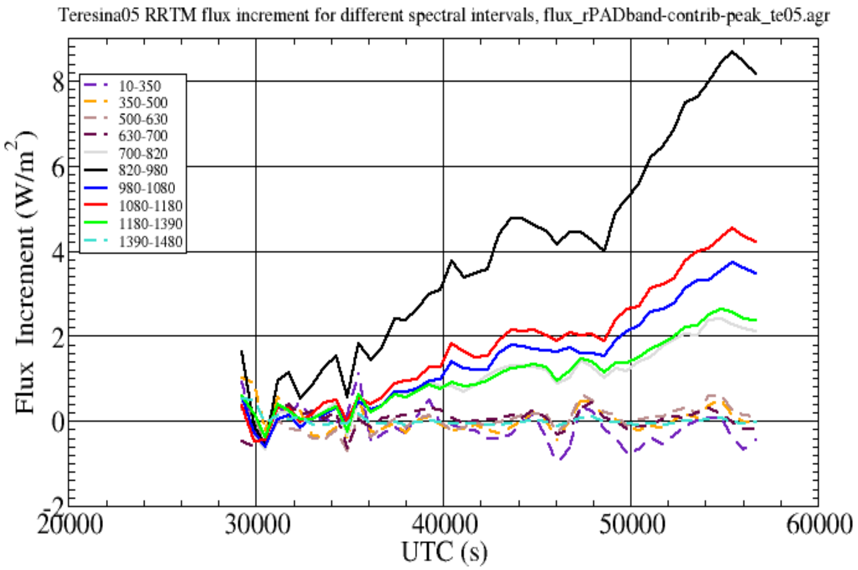
ERA5 hourly data on single levels
Mean top net long-wave radiation flux

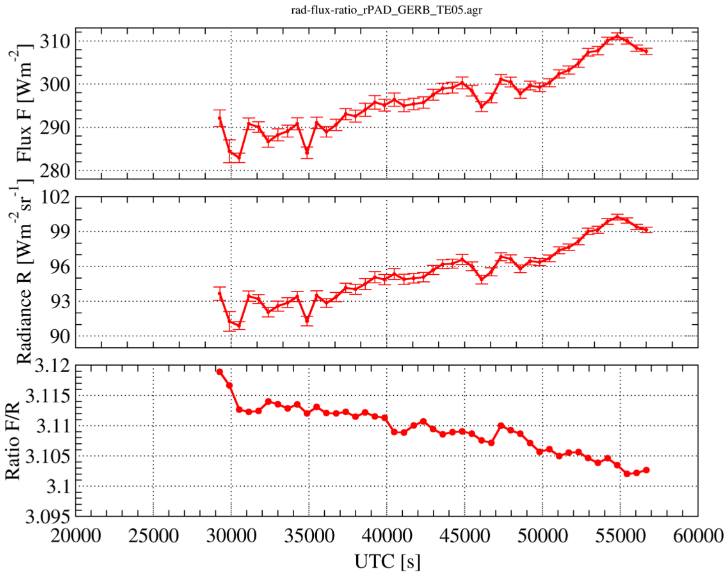




Disadvantages/Advantages of spectral observations

Disadvantages: single direction observation; more data => more time for data analysis
Advantages: attribution of changes; better accuracy in the rad. to flux conversion





Thank you for your attention

Far-infrared-Outgoing-Radiation Understanding and Monitoring
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