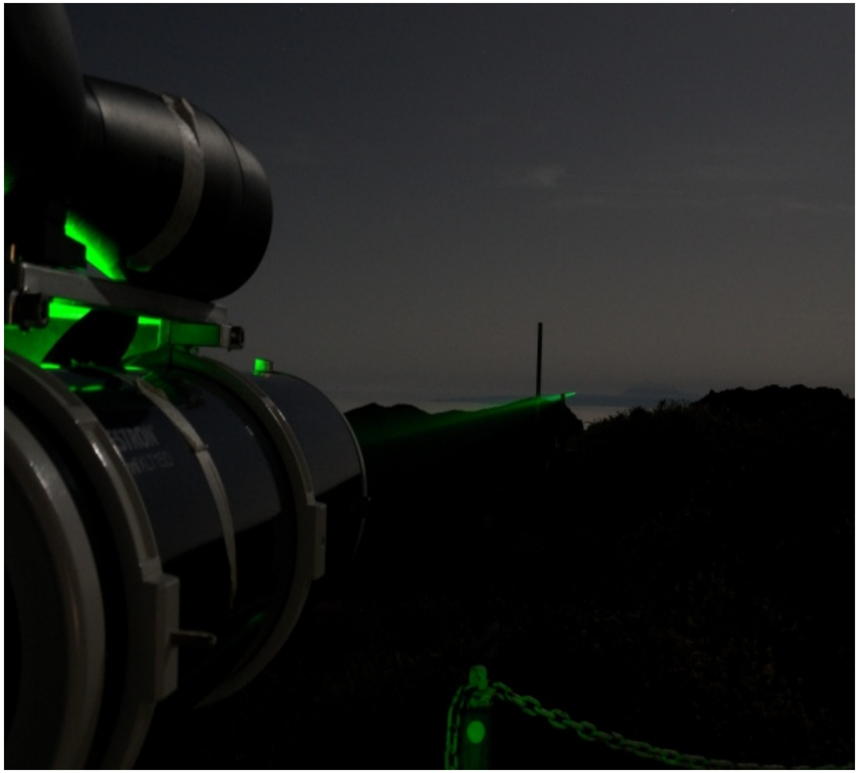
Synthetic spectra with the Reference Forward Model (RFM)



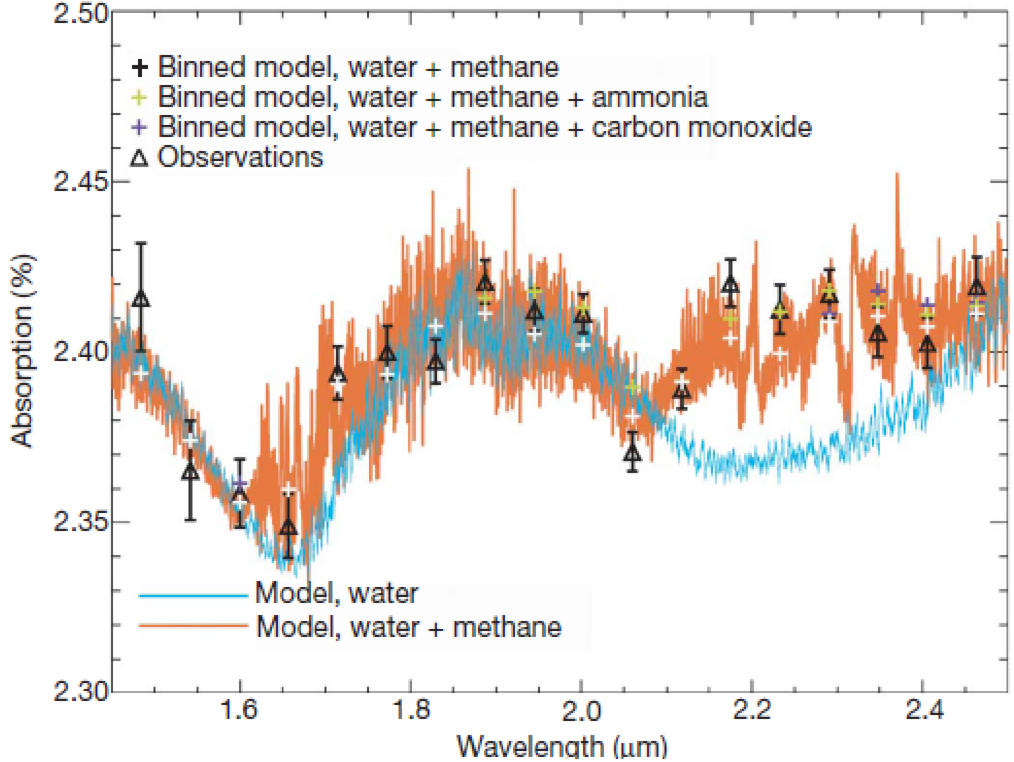
IRDAS-EXP

Vol 452|20 March 2008|doi:10.1038/nature06823 nature

LETTERS

The presence of methane in the atmosphere of an extrasolar planet

Mark R. Swain[1]*, Gautam Vasisht[1]* & Giovanna Tinetti[2]*



Transiting Planets
Proceedings IAU Symposium No. 253, 2008
Frédéric Pont, Dimitar Sasselov & Matthews Holman, eds.

doi:10.1017/S1743921308026446

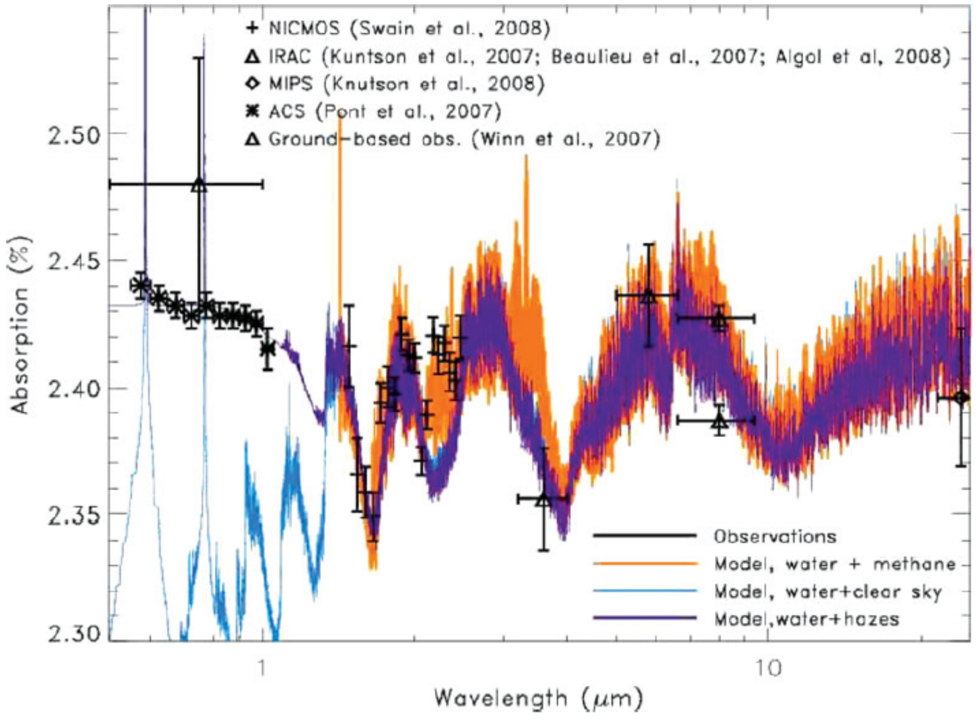
The extrasolar planet atmosphere and exosphere: Emission and transmission spectroscopy

Giovanna Tinetti[1,2] and Jean-Philippe Beaulieu[2,3]

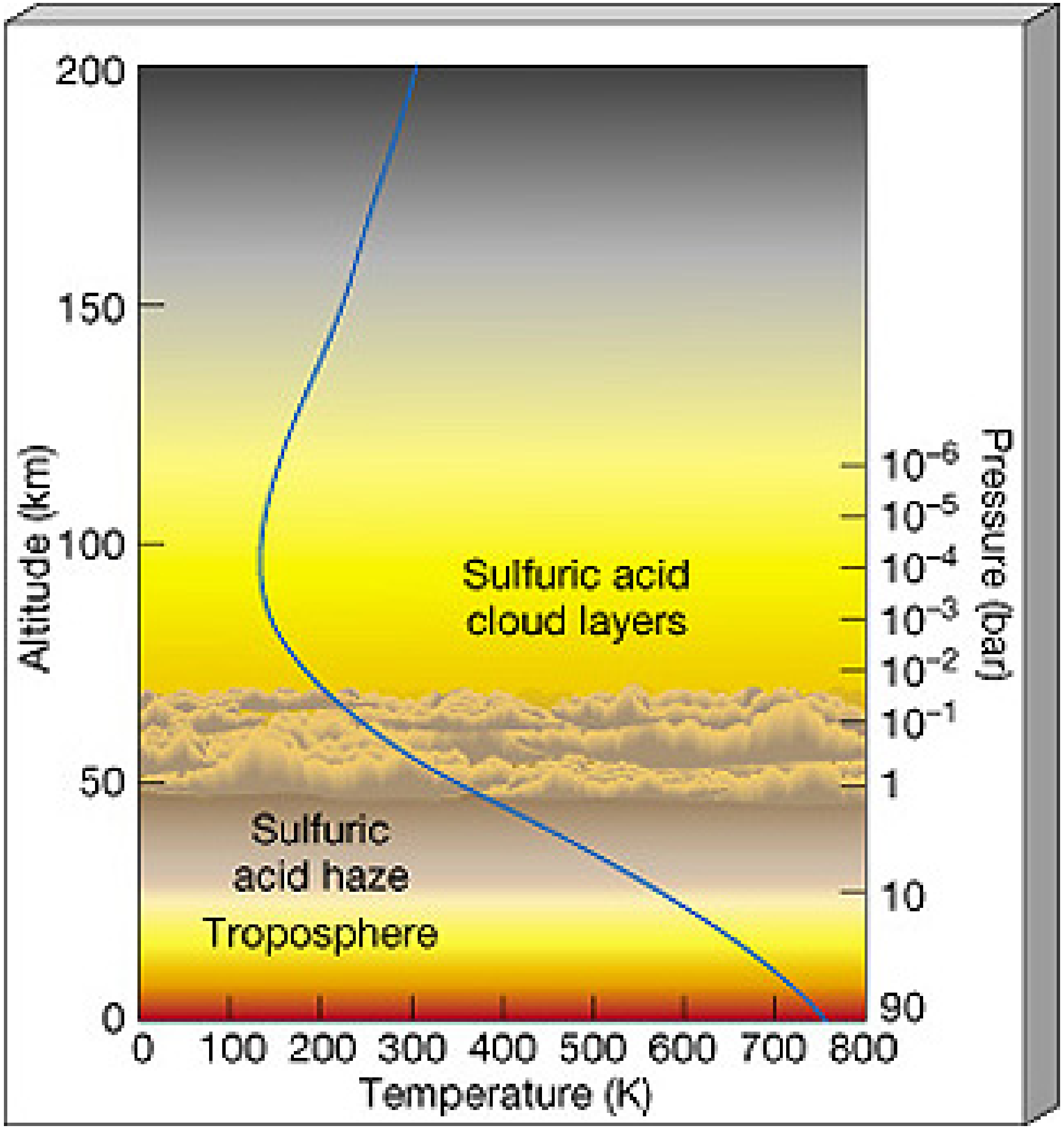
[1]University College London, Gower street, London WC1E 6BT, UK
email: g.tinetti@ucl.ac.uk

[2] HOLMES collaboration

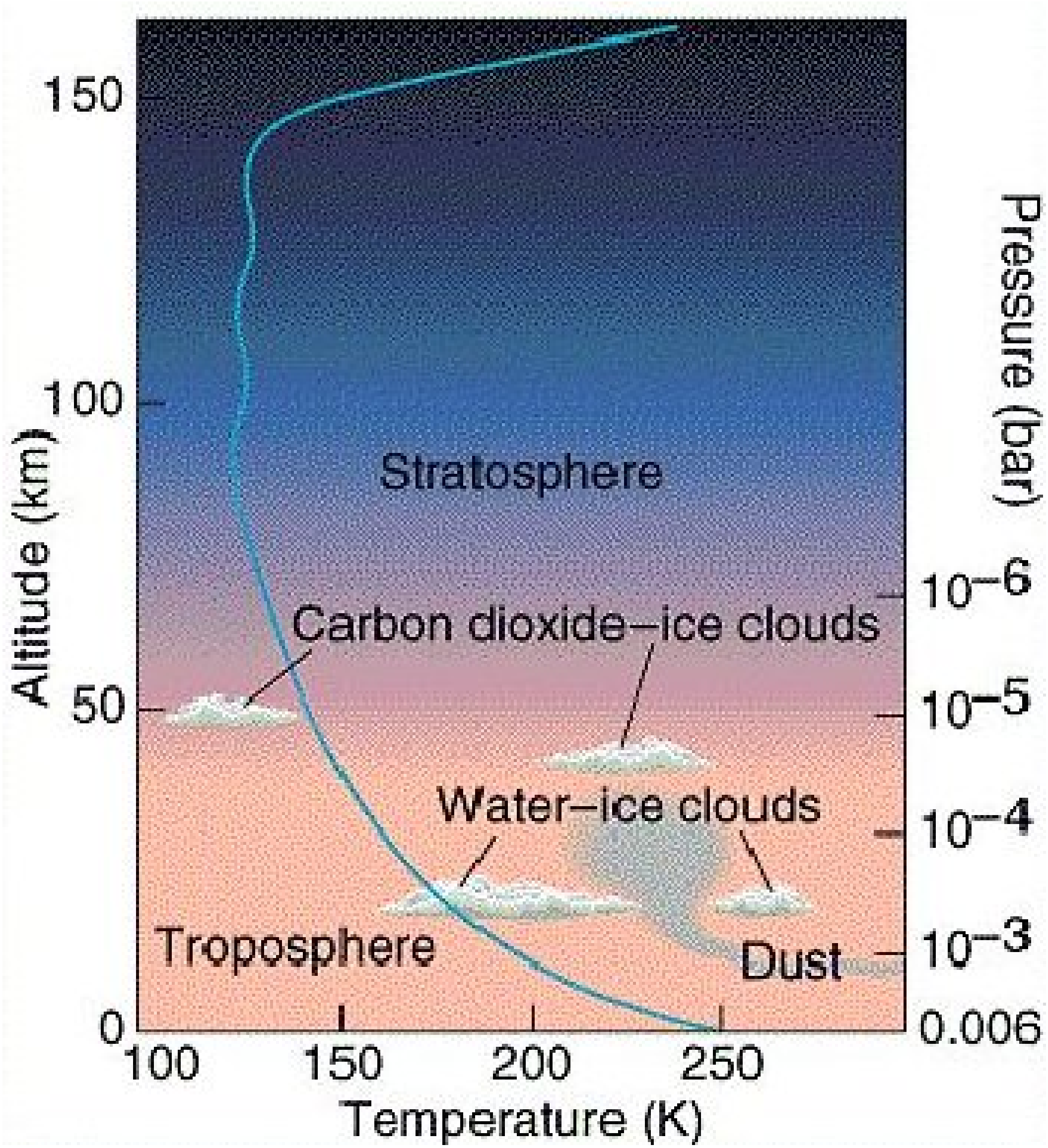
[3]Institut d'Astrophysique de Paris, 98bis Boulevard Arago, 75014 PARIS, France.
email: beaulieu@iap.fr



VENUS

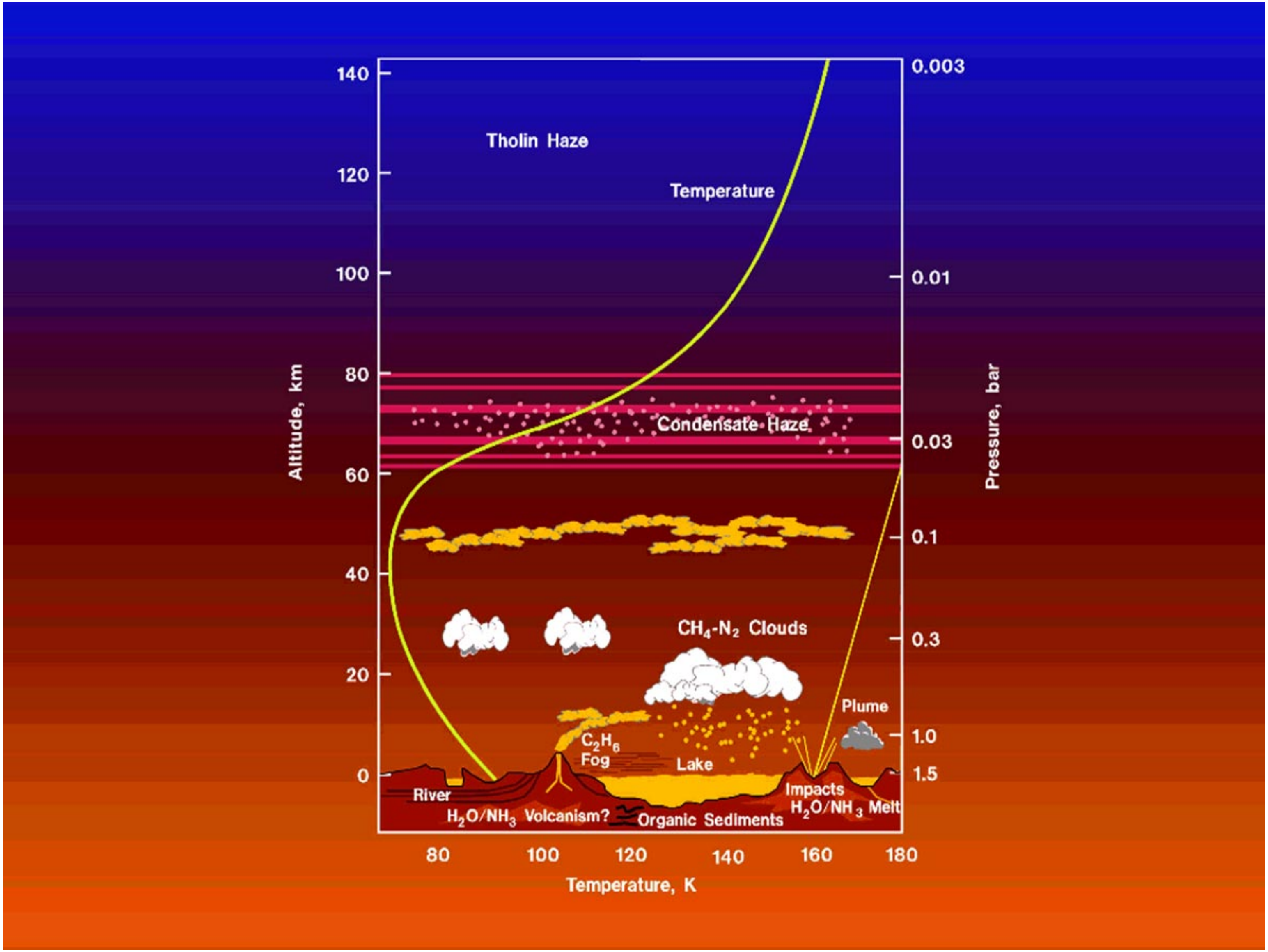

200
150
100
50
0
Altitude (km)
0 100 200 300 400 500 600 700 800
Temperature (K)
Pressure (bar)
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
90
Sulfuric acid cloud layers
Sulfuric acid haze
Troposphere

MARS



150
100
50
0
Altitude (km)
Stratosphere
Carbon dioxide–ice clouds
Water–ice clouds
Troposphere
Dust
100
150
200
250
Temperature (K)
Pressure (bar)
10^{-6}
10^{-5}
10^{-4}
10^{-3}
0.006

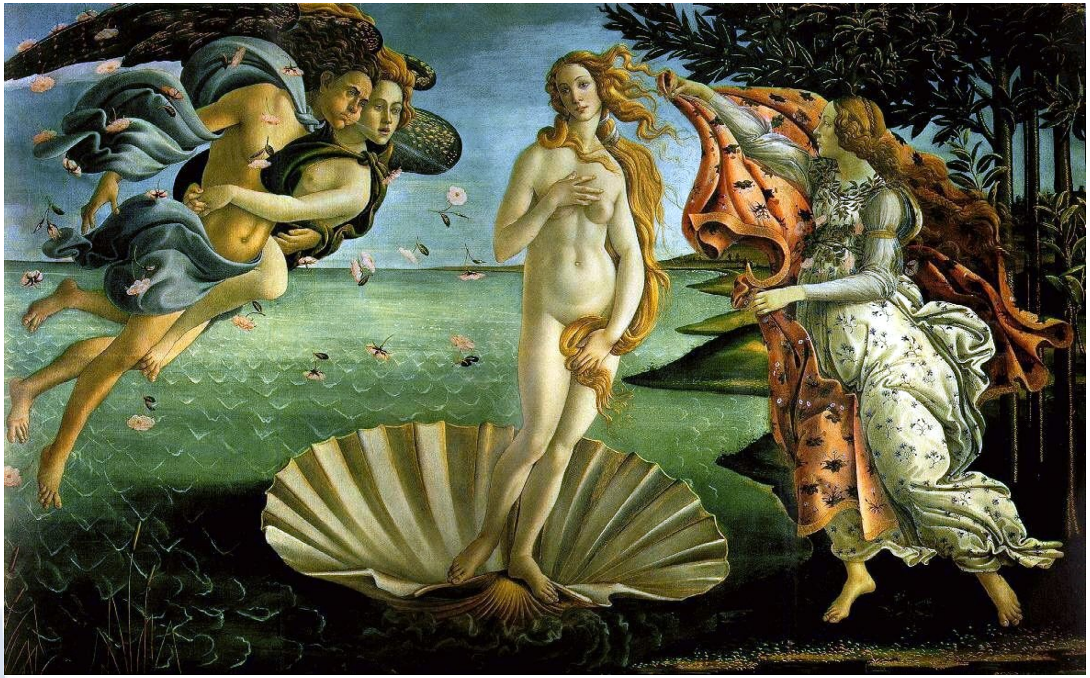
TITAN



140
120
100
80
60
40
20
0
Altitude, km
0.003
0.01
0.03
0.1
0.3
1.0
1.5
Pressure, bar
Tholin Haze
Temperature
Condensate Haze
CH4-N2 Clouds
Plume
C2H6 Fog
Lake
River
H2O/NH3 Volcanism?
Organic Sediments
Impacts
H2O/NH3 Melt
80
100
120
140
160
180
Temperature, K

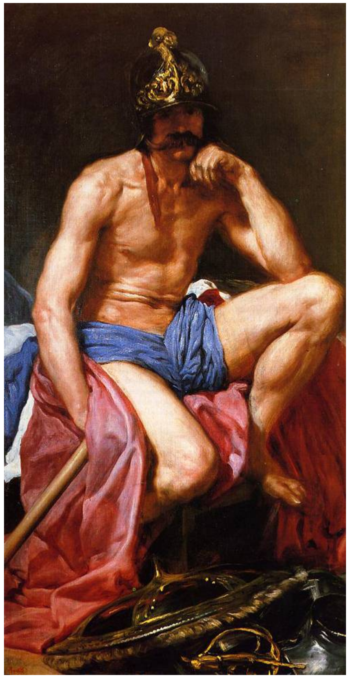
Since I have failed with Exoplanets, and with the Solar system, why not to look at the Mythology

The Birth of Venus



Botticelli

Mars



Velázquez

Cronus

Goya

One slide about PHOENIX

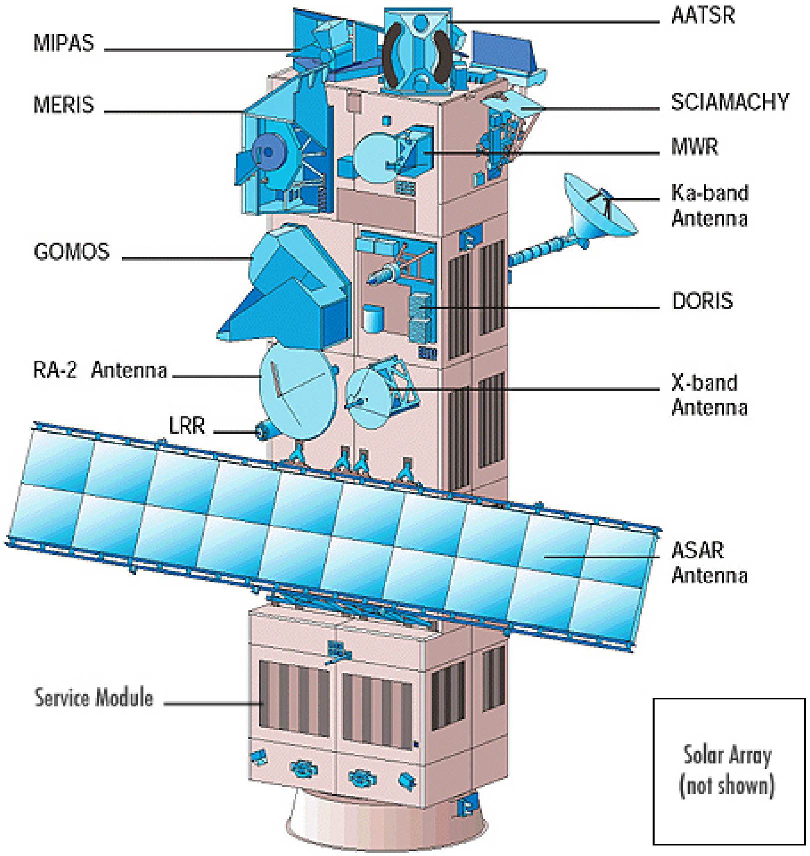
- http://www.hs.uni-hamburg.de/EN/For/ThA/phoenix/index.html
- General purpose radiative transfer code for HR-diagram starts, Ttauri stars, novae, supernovae, brown dwarfs and extrasolar giant planets
- Thesis disertation by Mariana Wagner:

"Reflectance Spectra of Earth-Like Exoplanets" June 2011

The Reference Forward Model(RFM)

- Many thanks to Anu Dudhia (AOPP University of Oxford)
- web page: www.atm.ox.ac.uk/RFM/
- Line-by-line transfer model based on GENLN2 model by D. P. Edwards (1992)
- Started as a limb line-by-line model link to MIPAS studies but now it is a quite general line-by-line model

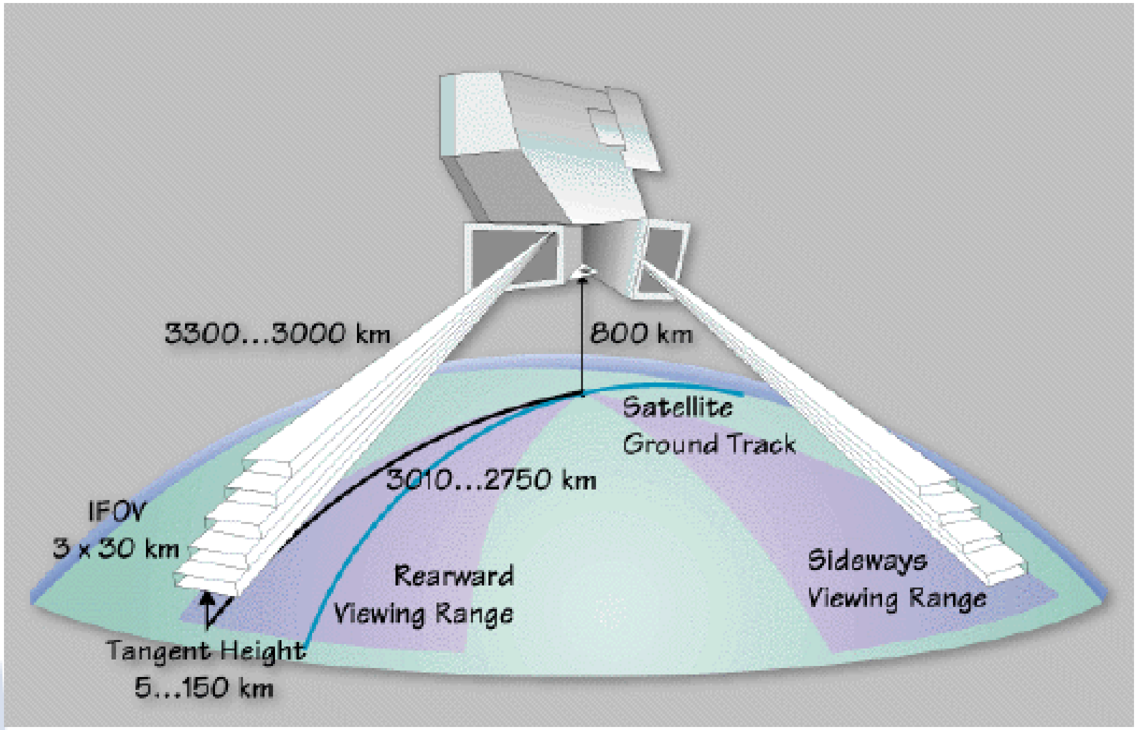
ENVISAT



- ESA
- Sun Synchronous Polar Orbit (800 km)
- 98.55° inclination
- Period 101 minutes, 14.25 Orbits per day
- Launched in 2002

MIPAS

Michelson Interferometer for Passive Atmospheric Sounding



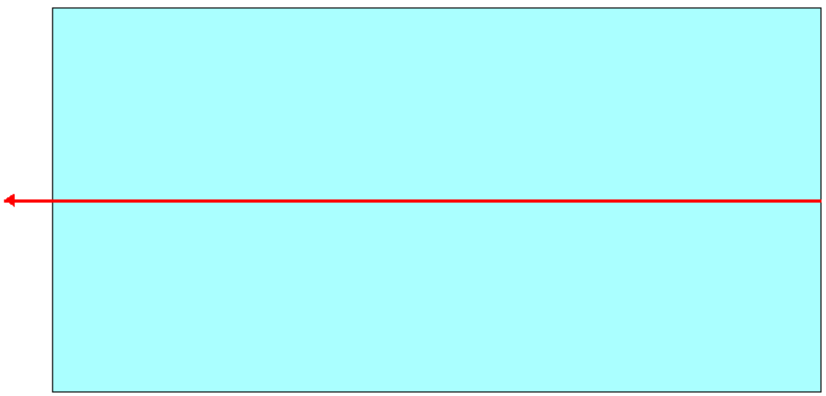
- Fourier Transform Spectrometer
- Spectrum 685-2410cm^{-1} (14.6-4.15µm) at 0.035cm^{-1} resolution in 4.5s
- Limb scan in 17 steps from 150-6km in 85s (~500km)
- 72 profiles per orbit
- ~1000 profiles per day

RFM applications

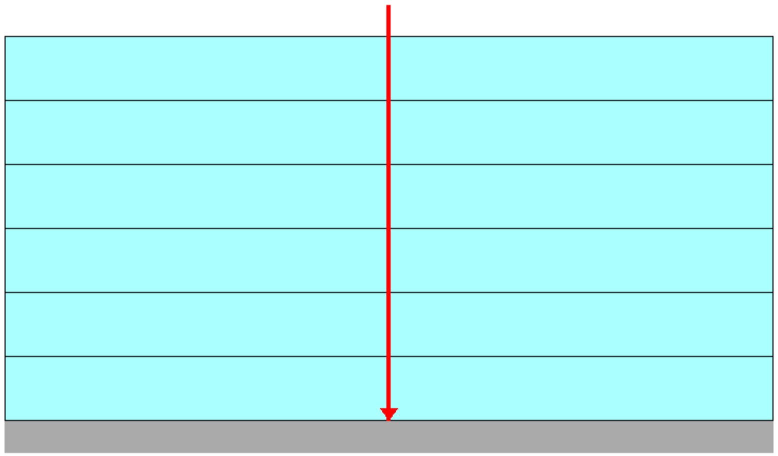
- Simulating atmospheric emission/transmission spectra
- Modelling cell transmittances for spectroscopy
- Flux calculations for radiative forcing
- Generating look-up tables of absorption cross-section
- Atmospheric path ray-tracing and integrations

RFM Geometries

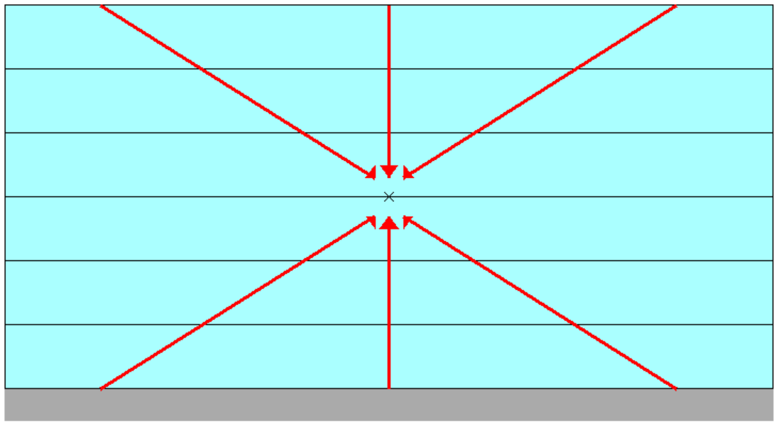
Cell Transmittance



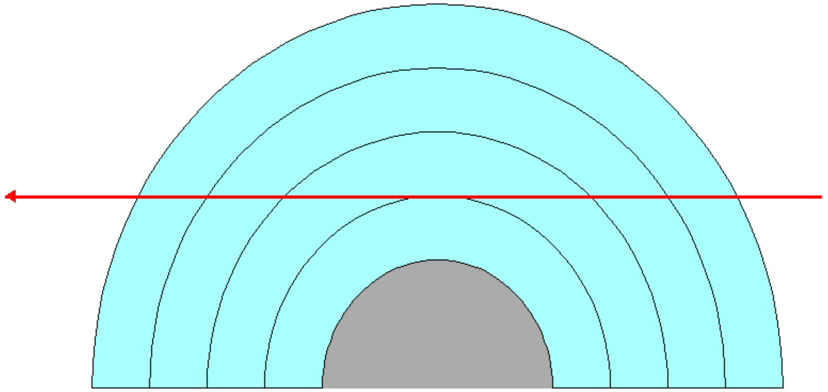
Atmospheric Transmittance



Flux Calculations



Limb Radiance



What RFM can do part I

- Spherical or plane-parallel atmospheres, homogeneous paths
- Field-of-View & Instrument Line Shape convolutions
- CO_2 line mixing
- Curtis-Godson approximation
- Continua for H_2O, O_2, N_2 and CO_2
- Non-LTE

What RFM can do part II

- Jacobians for p, T, VMR, line-of-sight pointing and surface temperature and emissivity
- Satellite/Balloon & Aircraft/Ground-based viewing geometries
- Surface reflections
- Output spectra of radiance, transmittance, absorption, cooling rates, optical depth and brightness temperature

What RFM can do part III

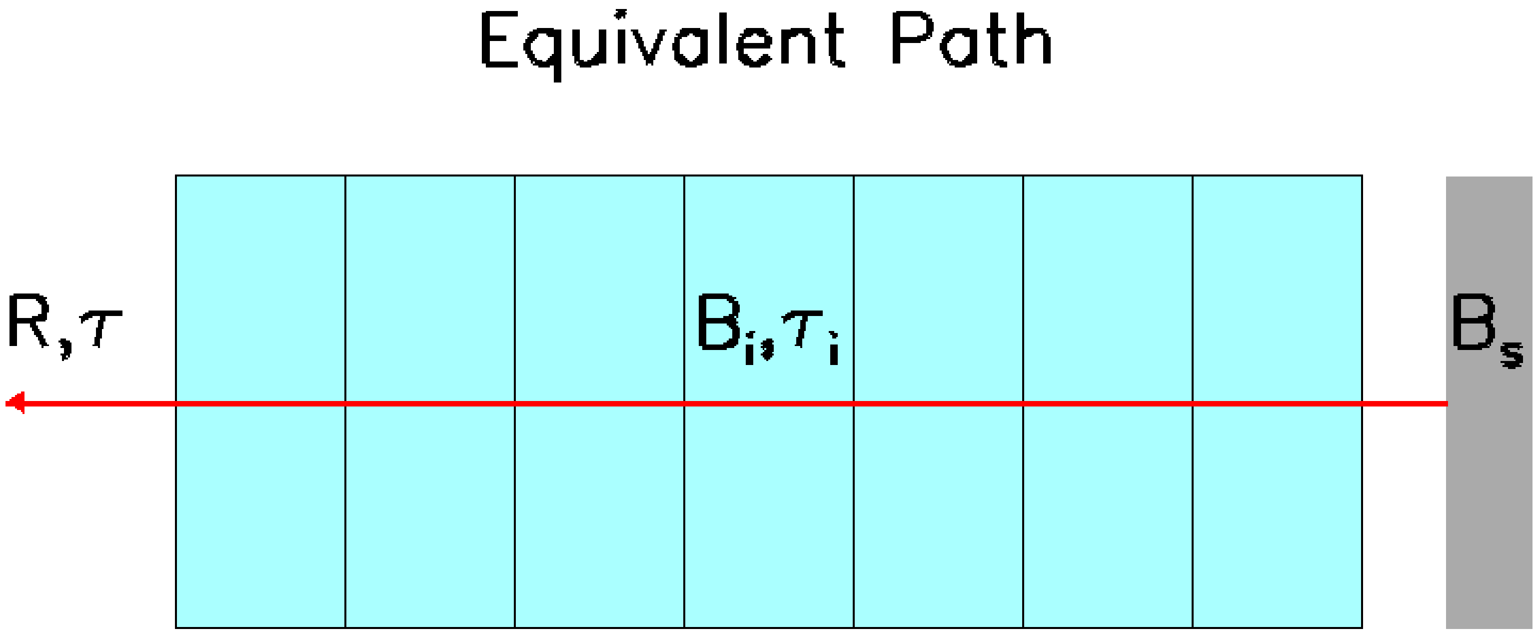
- Output diagnostics from ray-tracing
- Can do horizontal structure of the atmosphere
- Flux calculations
- Different isotopic mixing ratio profiles
- Compatible with HITRAN 2008 and HITRAN cross-sections for heavier molecules such as CFCs and N_2O_5

What RFM can not handle

- Scattering
- Instrument line shape wider than around $1cm^{-1}$

But I like it quite a lot because it is really easy to install and to use

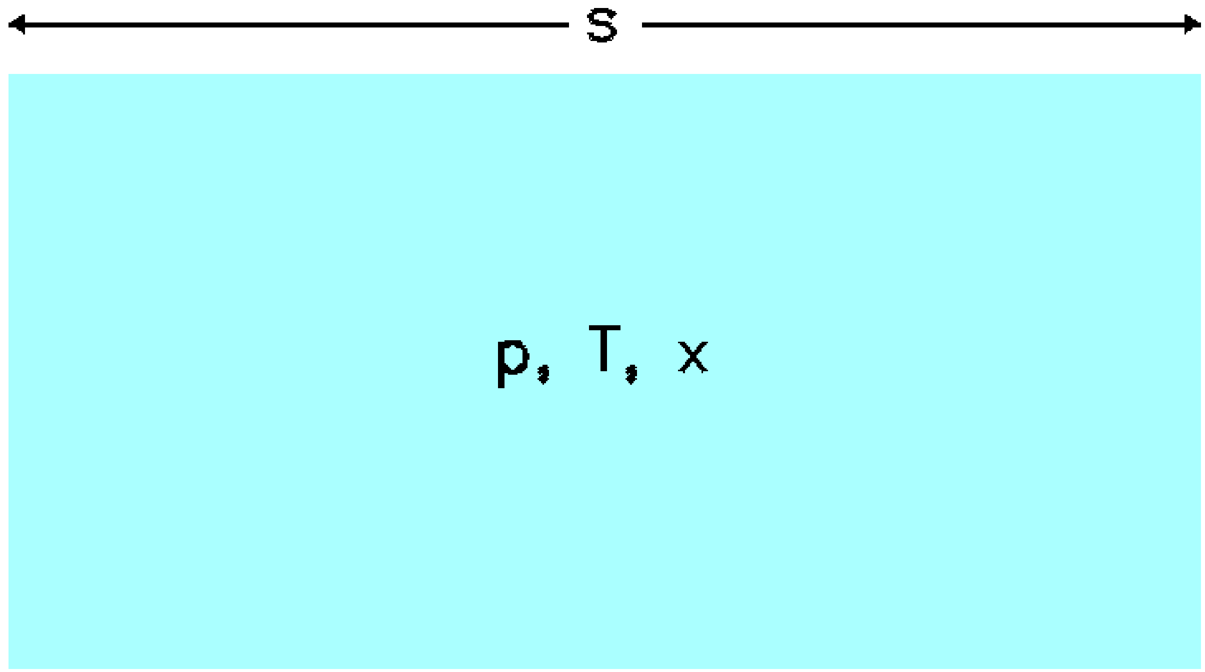
Radiance



Path Transmittance: $\tau = \prod_j \tau_j$

Radiance: $R = \int B \, d\tau = \sum B_i \, \Delta \tau_I \quad (+ B_s \tau)$

Transmittance

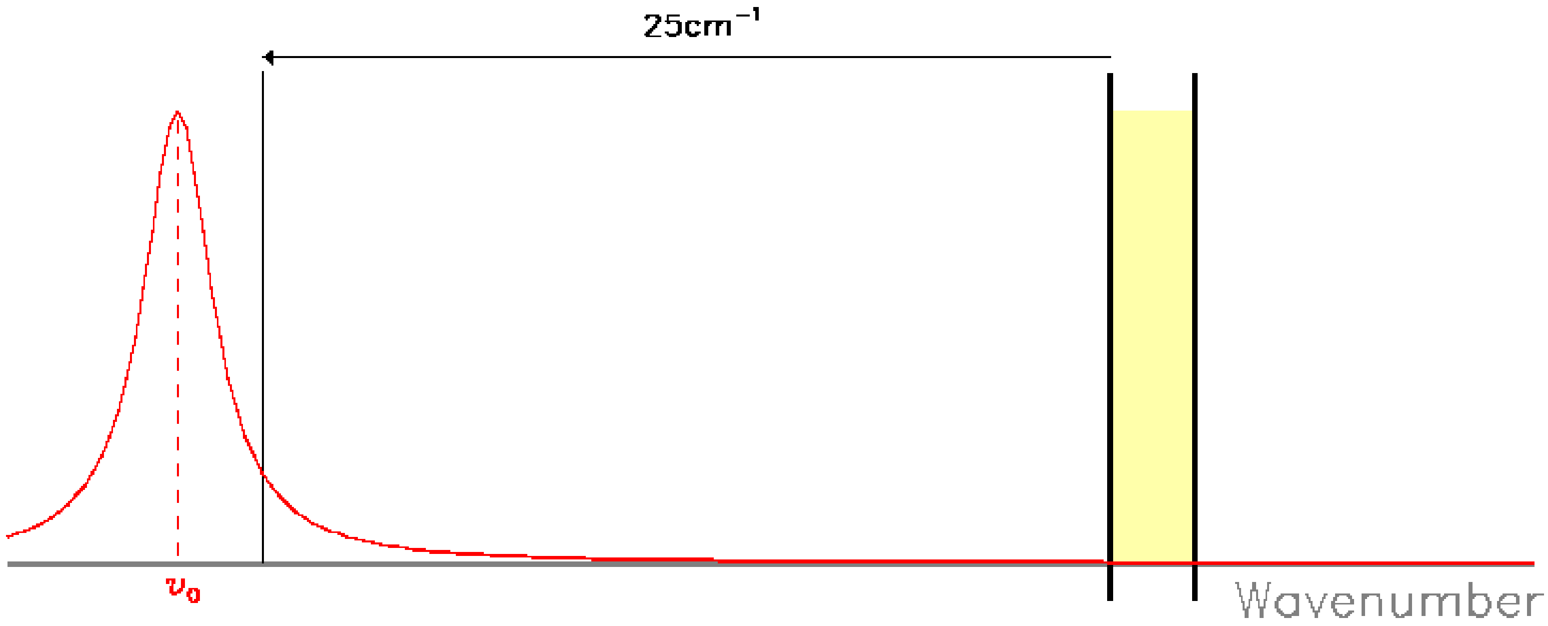


Absorption Coefficient: $k(v) = \sum_l S_l(T)\, F(v-v_{0l}, p, T)$

Transmittance: $\tau_i(v) = \exp(-k\, \rho\, s)$

Multiple absorbers j: $\tau_i(v) = \prod_j \tau_{ij}$

The continua



For more on continuum refer to University of Reading, CAVIAR project
http://www.met.reading.ac.uk/caviar/background.html

Curtis-Godson approximation

- For Lorentzian absorption the effective pressure and temperature for an heterogeneous path:

$$\bar{p} = \frac{1}{m} \int p \, \rho \, dz$$

$$\bar{T} = \frac{1}{m} \int T \, \rho \, dz$$

$$m = \int \rho \, dz$$

Curtis-Godson approximation in the "strong" limit is exact as it is in the "weak" limit

$$\tau = e^{-\int \frac{S}{\pi} \frac{\alpha_L}{(\nu-\nu_0)^2} \rho\, dz}$$

$$\alpha_L \sim \alpha .\, p / p_0$$

$$\tau = e^{\frac{-S}{\pi} \frac{\alpha_0}{(\nu-\nu_0)^2} \frac{\bar{p}\, m}{p_0}}$$

The molecules included

ID	Molecule	ID	Molecule	ID	Molecule	ID	Molecule	ID	Molecule
1	**H2O**	2	**CO2**	3	**O3**	4	**N2O**	5	**CO**
6	**CH4**	7	**O2**	8	**NO**	9	**SO2**	10	**NO2**
11	**NH3**	12	**HNO3**	13	**OH**	14	**HF**	15	**HCl**
16	**HBr**	17	**HI**	18	**ClO**	19	**OCS**	20	**H2CO**
21	**HOCl**	22	**N2**	23	**HCN**	24	**CH3Cl**	25	**H2O2**
26	**C2H2**	27	**C2H6**	28	**PH3**	29	**COF2**	30	**SF6q**
31	**H2S**	32	**HCOOH**	33	**HO2**	34	**O**	35	**ClONO2q**
36	**NO+**	37	**HOBr**	38	**C2H4**	39	**CH3OH**	40	**CH3Br**
41	**CH3CN**	42	**CF4**	43	**BrO**	44	**C3H8**	45	**C2N2**
46	**C4H2**	47	**HC3N**	48	**C3H4**	49	**GeH4**		
50	**Aerosol**								
51	**F11 (CFCl3)**	52	**F12 (CF2CL2)**	53	**F13 (CClF3)**	54	**F14 (CF4)**	55	**F21 (CHCl2F)**
56	**F22 (CHClF2)**	57	**F113 (C2Cl3F3)**	58	**F114 (C2Cl2F4)**	59	**F115 (C2ClF5)**	60	**CCl4**
61	**ClONO2**	62	**N2O5**	63	**HNO4**	64	**SF6**	65	**X65**
66	**X66**	67	**X67**	68	**X68**	69	**X69**	70	**F123** (CHCl2CF3)
71	**F124** (CHClFCF3)	72	**F141b** (CH3CCl2F)	73	**F142b** (CH3CClF2)	74	**F225ca** (CHCl2CF2CF3)	75	**F225cb** (CClF2CF2CHClF)
76	**F32 (CH2F2)**	77	**F125 (CHF2CF3)**	78	**F134** (CHF2CHF2)	79	**F134a (CFH2CF3)**	80	**F143a (CF3CH3)**
81	**F152a (CH3CHF2)**	82	**F116 (C2F6)**	83	**SF5CF3**	84	**PAN**	85	**CH3CN** (AcetoNitrile)
86	**C6H6**	88	**C2H6**	89	**C3H8**	84	**Acetone** (CH3COCH3)		

Key Standard HITRAN line molecules

- HITRAN line Molecules also represented as cross-sections
- Additional GEISA line molecules (RFM-specific IDs)
- Extinction cross-section [km^{-1}] (RFM-specific IDs)
- Molecular cross-section [cm^2/molec] (RFM-specific IDs)
- Dummy names for extra cross-section molecules (RFM-specific IDs)

Installation

- In Linux/Unix with a Fortran77 compiler
- Source code is distributed as a tar file:
  - rfm_v4.28.tar.gz
  - Unpack tar -xzf rfm_v4.28.tar.gz
- With ifort: ifort -O3 -o rfm *.for

Input files: Driver table

```
*HDR
RFM run for IRDAS studies
*FLG
TRA
*SPC
4029.104610 4029.114610 0.00001
*GAS
3
*ATM
/home/gga500/atmfascodes/tro.atm ! Atmospheric conditions, TROPICAL
*TAN
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58
59 60
*HIT
/home/gga500/HITRAN08.bin
*TRA
../out/tro.atm/Target_Species_Transmission/I01/rfm_*.tra
*GRD
!/export/home/ndca500/rfm-source/fov.rfm !mipas.fov
*END
```

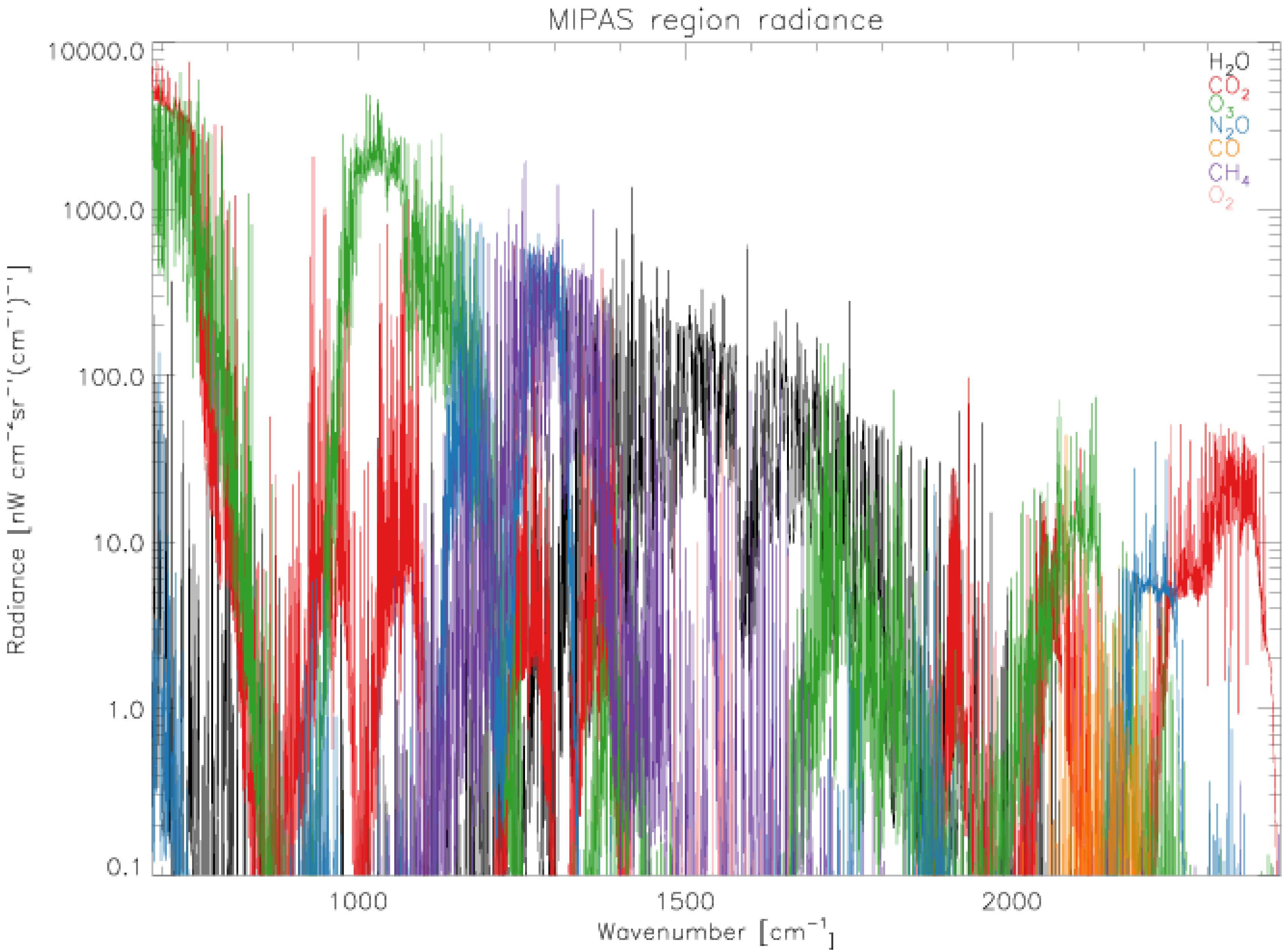
Input files: Atmospheric profile

```
! FASCOD Model 6 U.S. Standard Atmosphere
! Transformed to RFM .atm file format by program USARFM v.23-AUG-96
 1      ! No.Levels in profiles
*HGT        [km]
        2.0
*PRE        [mb]
        7.950E+02
*TEM        [K]
        275.20
*H2O        [ppmv]
        4.631E+03
*CO2        [ppmv]
        3.300E+02
*O3         [ppmv]
        3.237E-02
*N2O[ppmv]
        3.200E-01
*CO         [ppmv]
        1.399E-01
*CH4[ppmv]
        1.700E+00
*O2         [ppmv]
        2.090E+05
*END
```

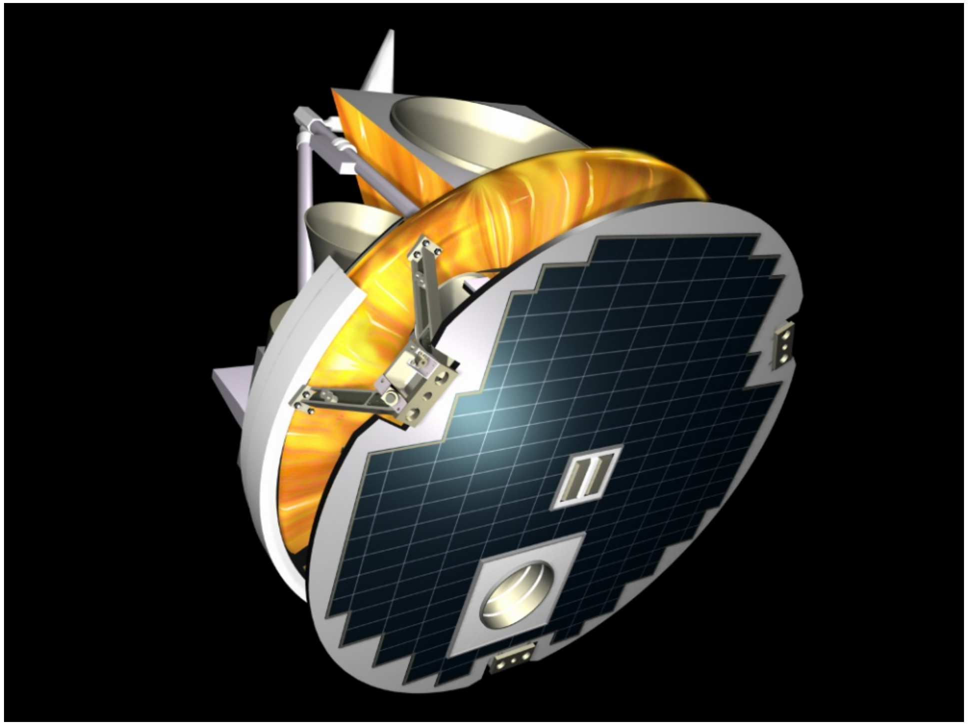
HITRAN08.bin

- It is a binary version of the HITRAN database compatible with the GENLN2 input format
- It can be created starting with the HITRAN ASCII *.par file using hitbin.f program

MIPAS spectral range radiance 15 km

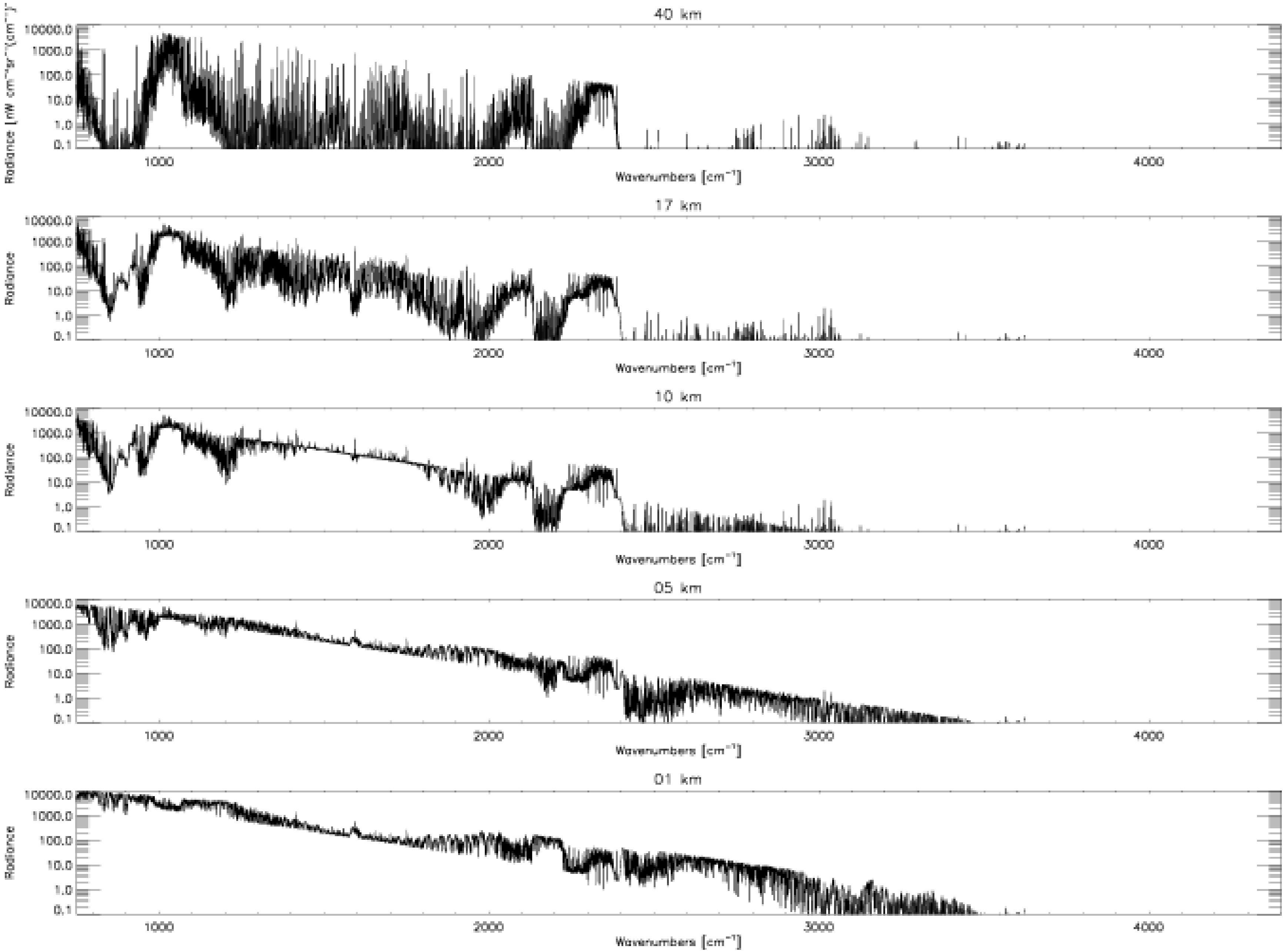


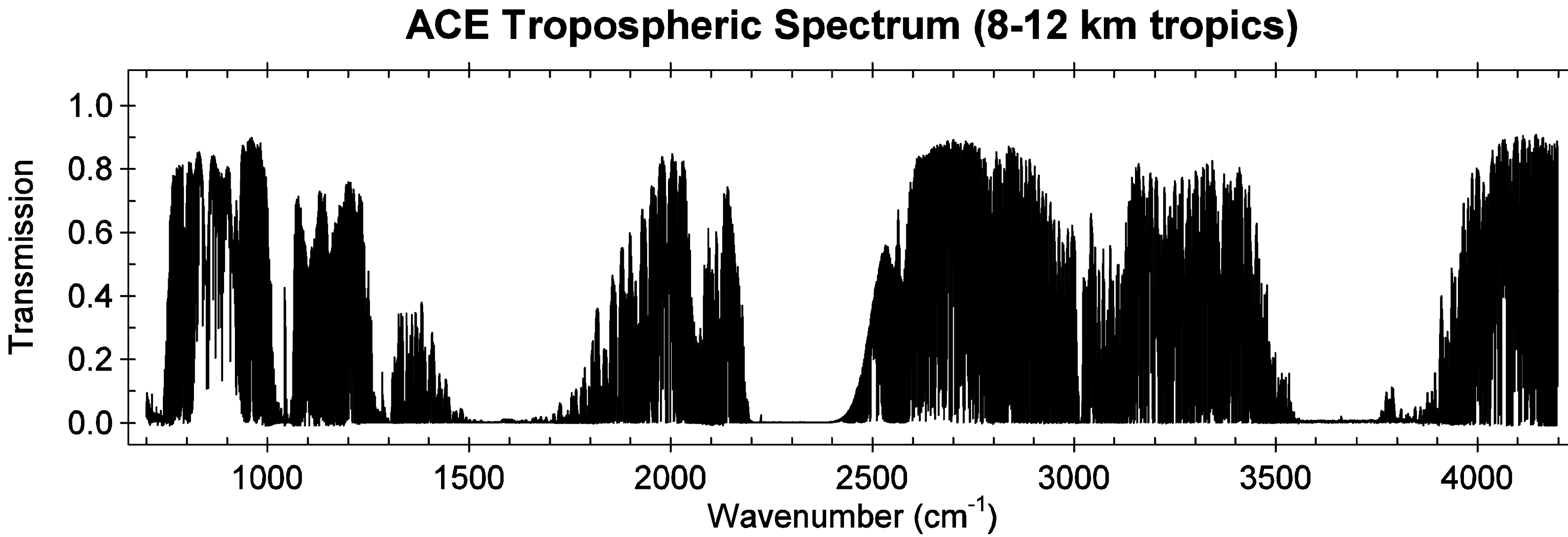
Something about ACE-FTS

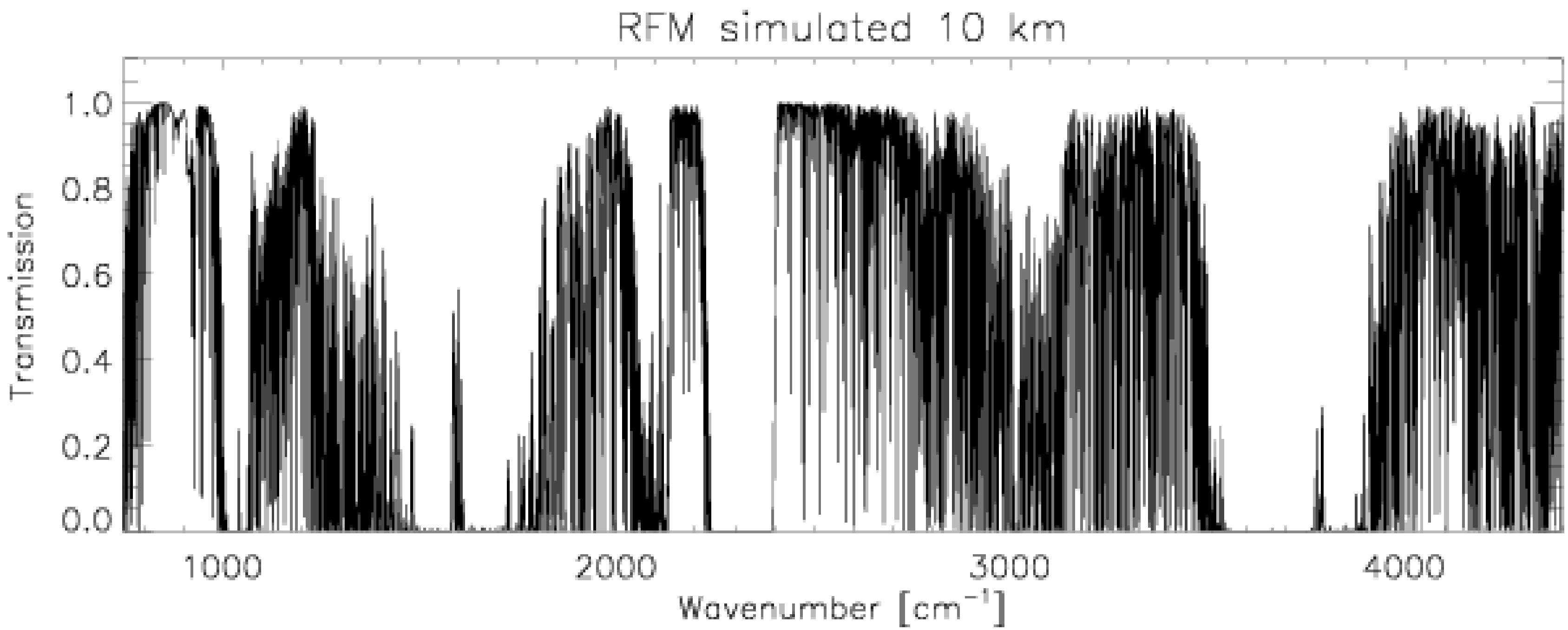


- Solar occultation FTS
- 0.02 cm^{-1}
- Spectral range 750-4400 cm^{-1}
- “High” signal to noise ratio, usually above 300

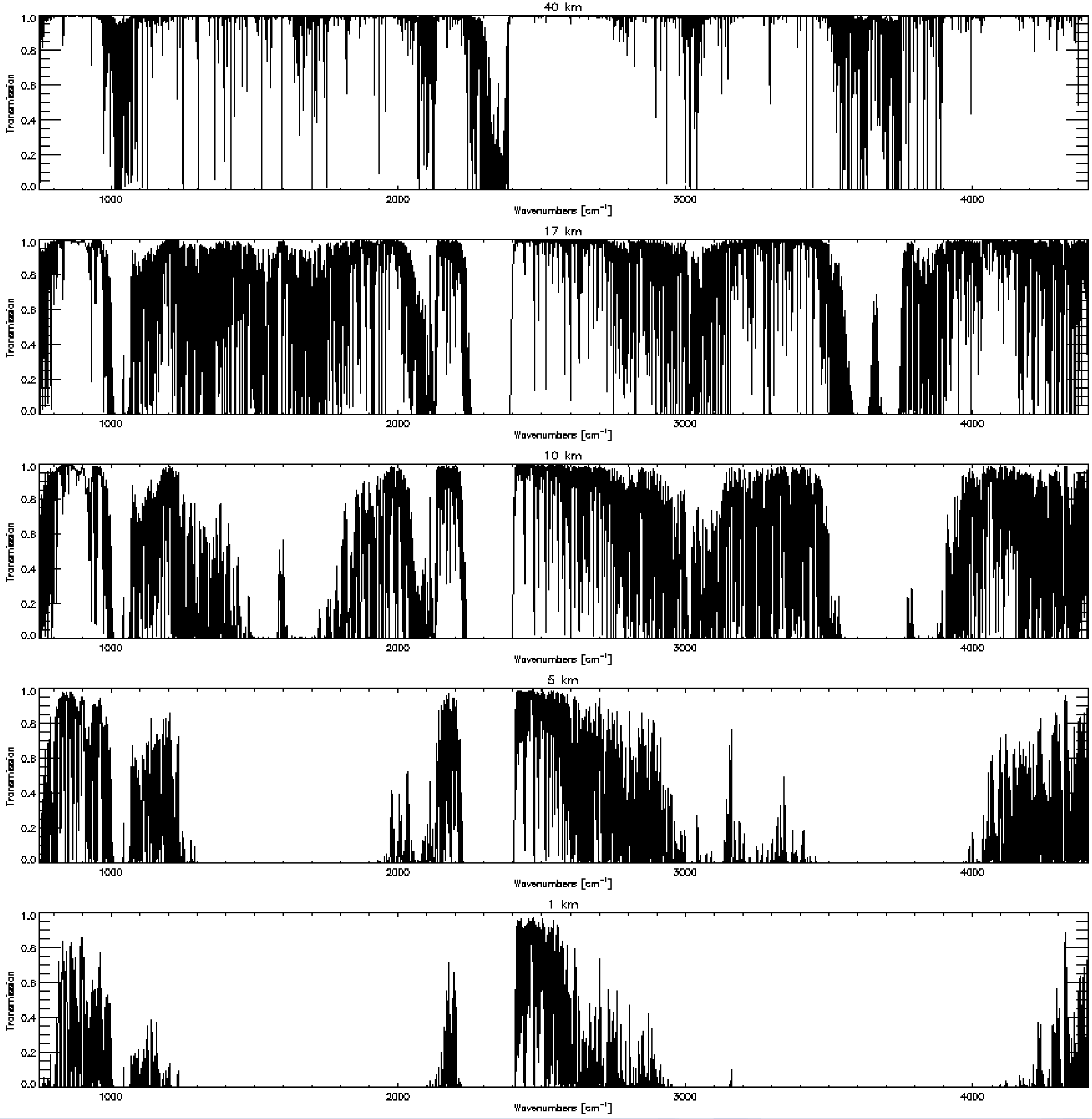
ACE-FTS region RFM radiance spectra




ACE Tropospheric Spectrum (8-12 km tropics)
Transmission
0.0
0.2
0.4
0.6
0.8
1.0
1000
1500
2000
2500
3000
3500
4000
Wavenumber (cm-1)


RFM simulated 10 km
Transmission
0.0
0.2
0.4
0.6
0.8
1.0
1000
2000
3000
4000
Wavenumber [cm-1]

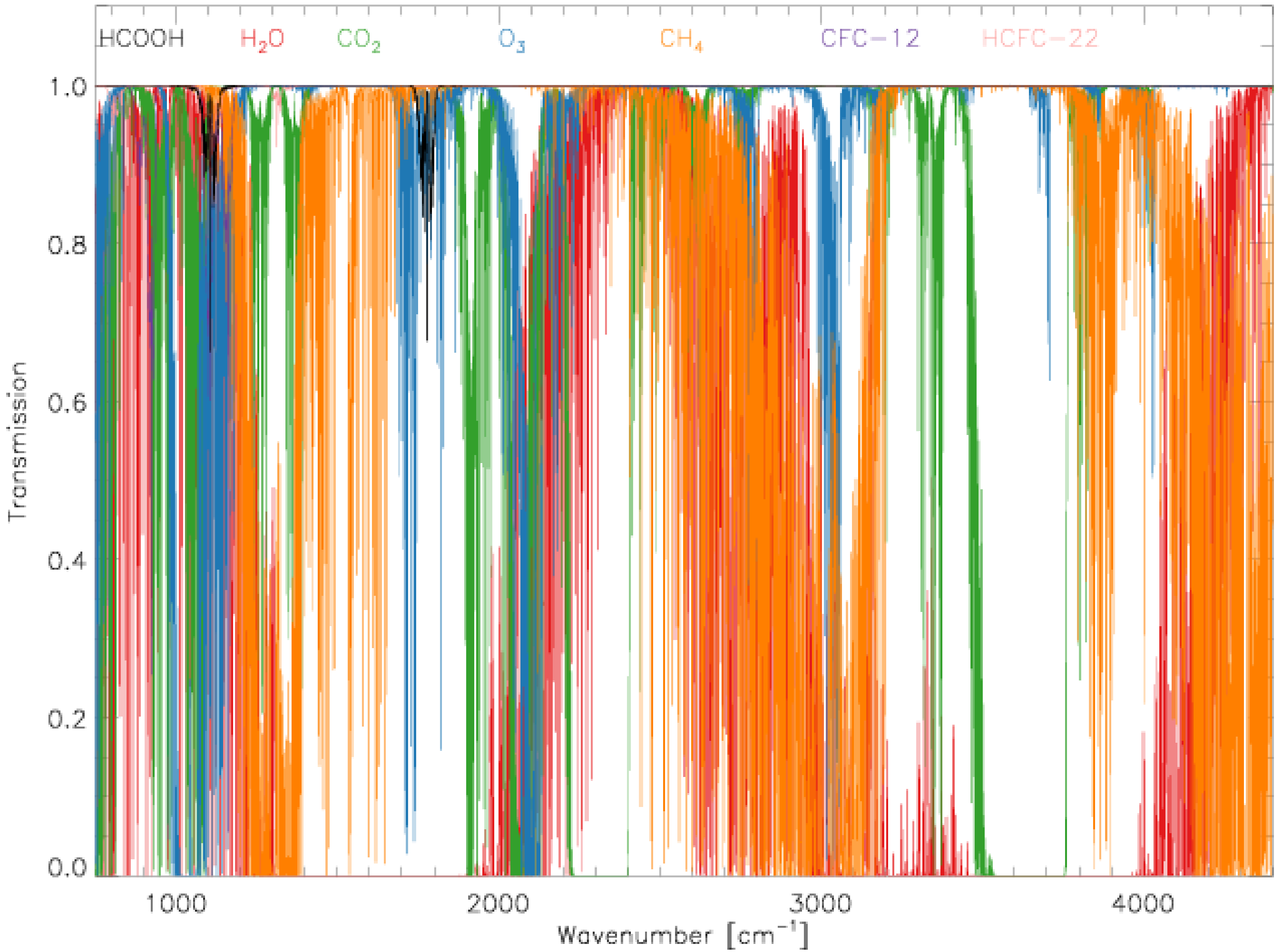
ACE-FTS region transmission spectra



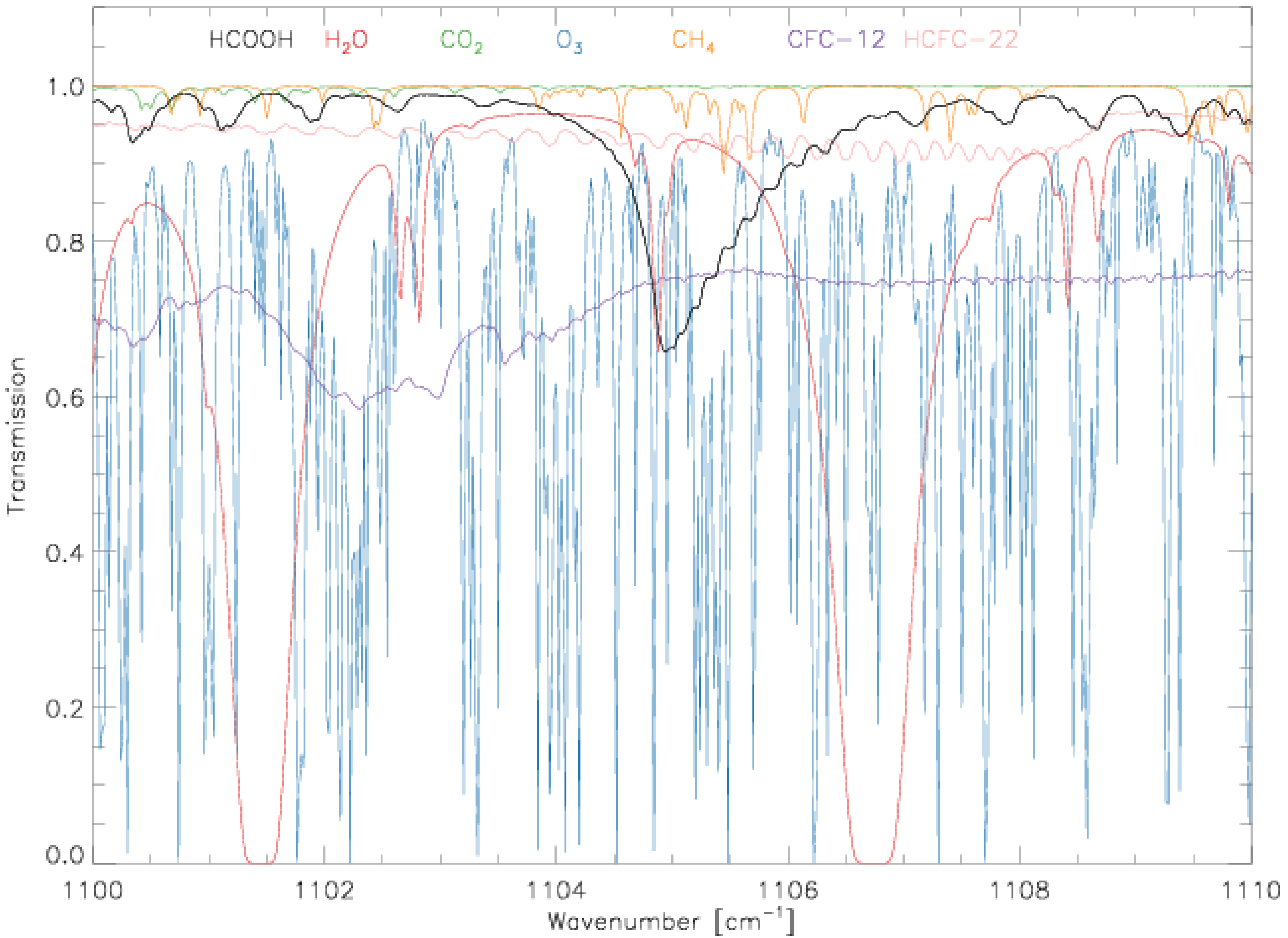
Formic acid

```
!Driver table for lecture HCOOH
*HDR
RFM run using Driver Table SAO 1 (19/03/2012)
*FLG
TRA ABS RAD !Transmission, absorption and radiance
*SPC
FullACE 750.0 4400 2.0 !To have a full picture
RetrACE 1100 1110 0.02 !Where it was actually done
*GAS
32
*ATM
/home/ggonzale/TOOLS/RFM/atmospheres/hgt_std.atm
/home/ggonzale/TOOLS/RFM/atmospheres/std.atm
/home/ggonzale/TOOLS/RFM/atmospheres/minor.atm
/home/ggonzale/TOOLS/RFM/atmospheres/HCOOH.atm
*TAN
1 5 10 17 40
*HIT
/home/ggonzale/TOOLS/RFM/HITRAN08/HITRAN08.bin
*ABS
/home/ggonzale/TOOLS/RFM/HCOOH_1/rfm_*.abs
*TRA
/home/ggonzale/TOOLS/RFM/HCOOH_1/rfm_*.tra
*RAD
/home/ggonzale/TOOLS/RFM/HCOOH_1/rfm_*.rad
*END
```

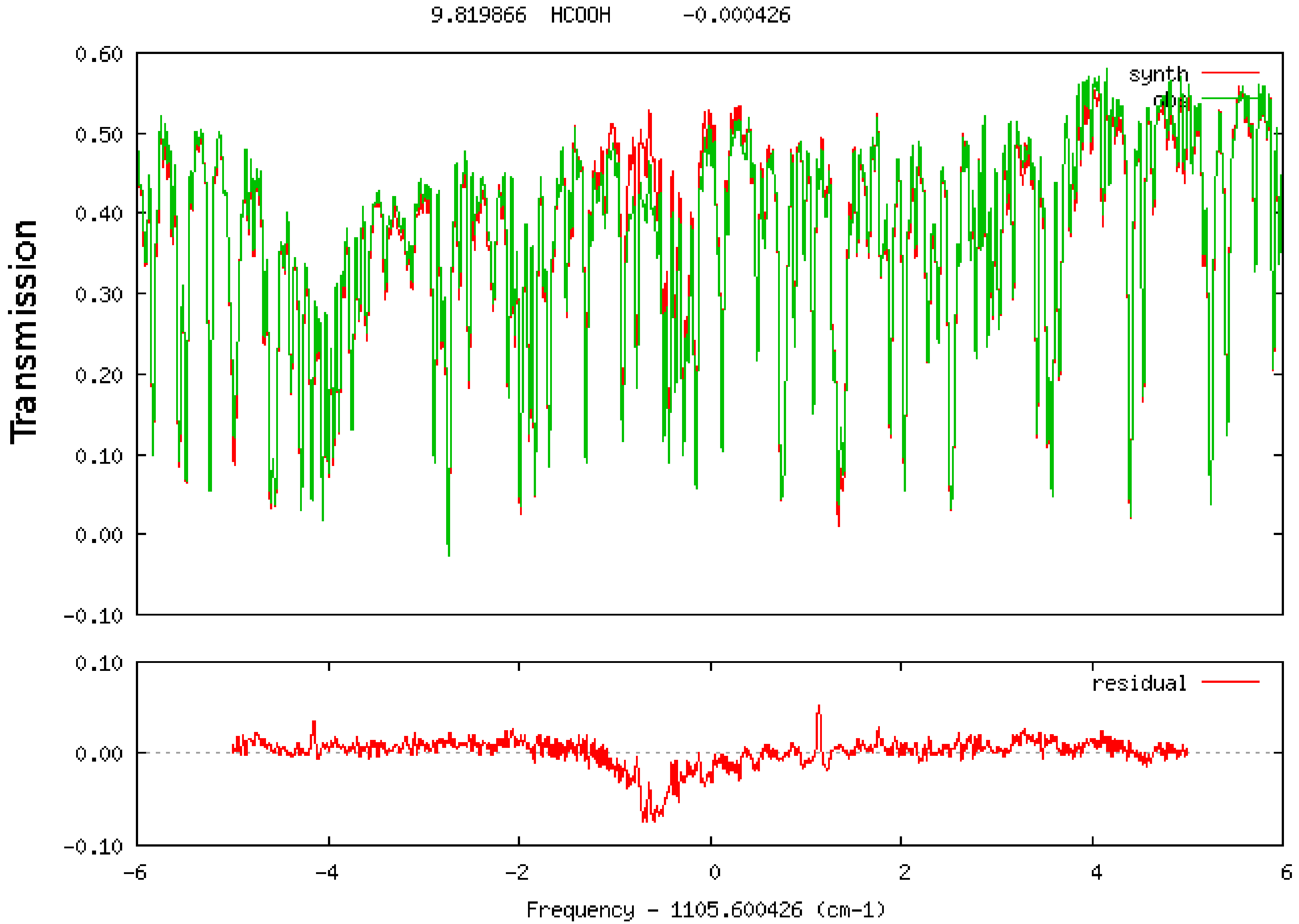
An example: HCOOH



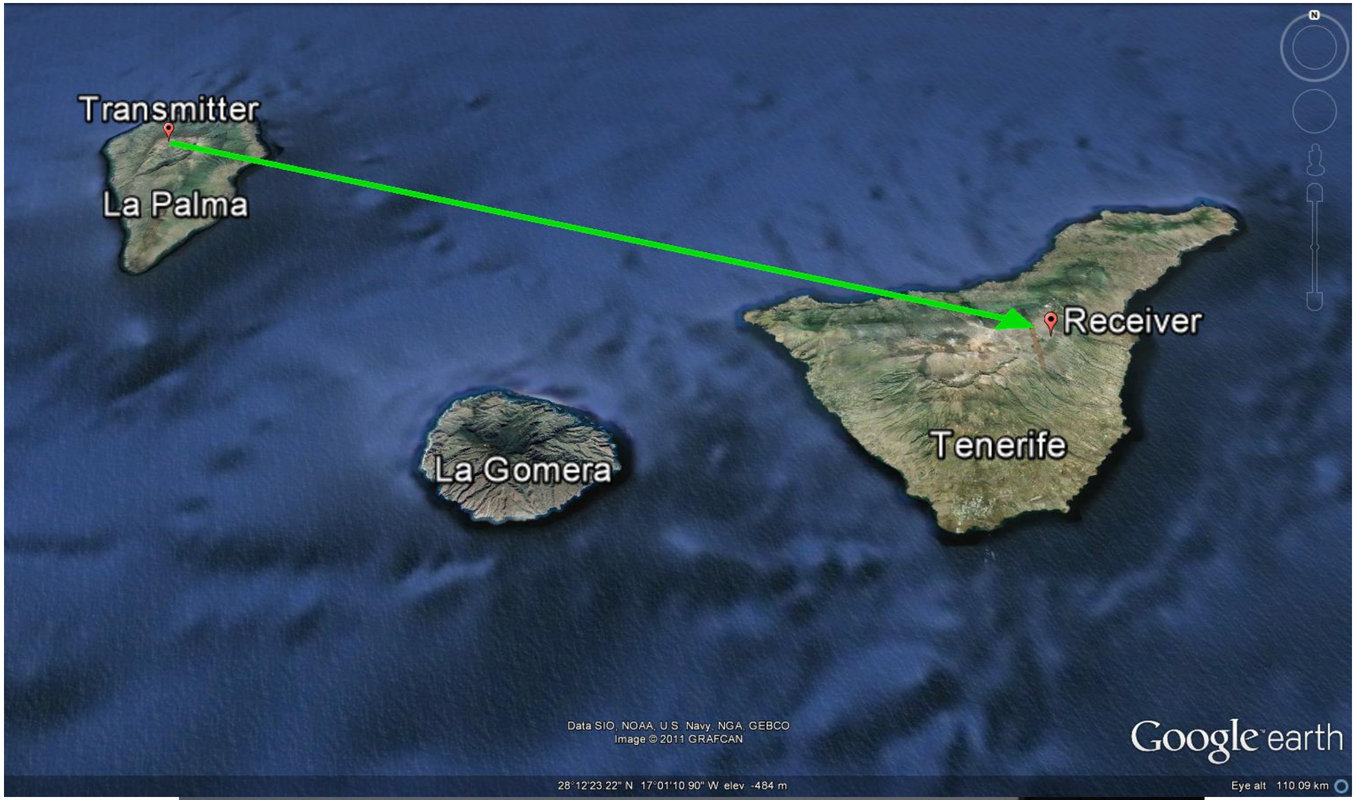
Formic acid, used microwindow



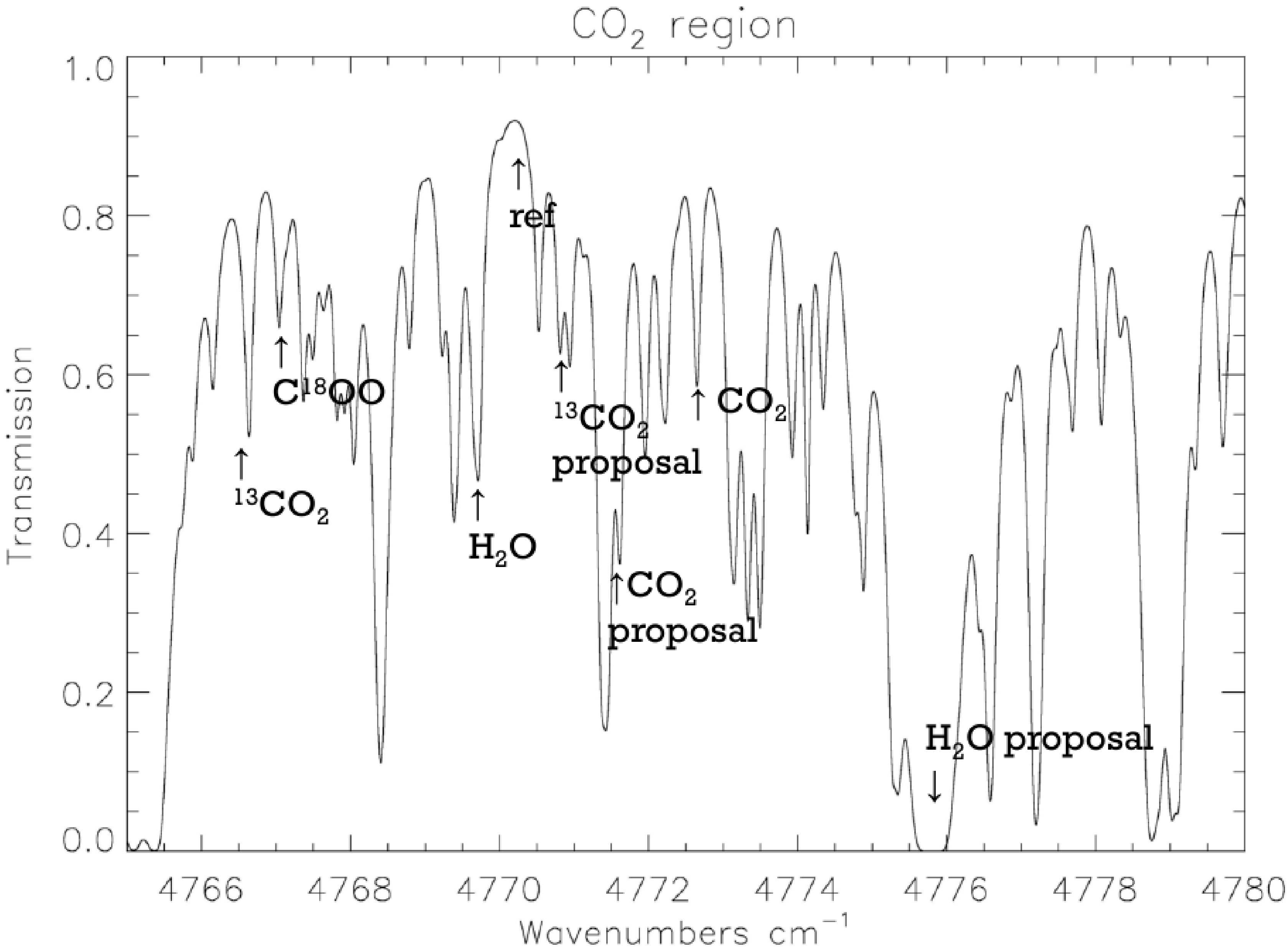
ACE-FTS spectra with HCOOH residual



IRDAS-EXP


Transmitter
La Palma
La Gomera
Receiver
Tenerife
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2011 GRAFCAN
Google earth
28°12'23.22" N 17°01'10.90" W elev -484 m
Eye alt 110.09 km

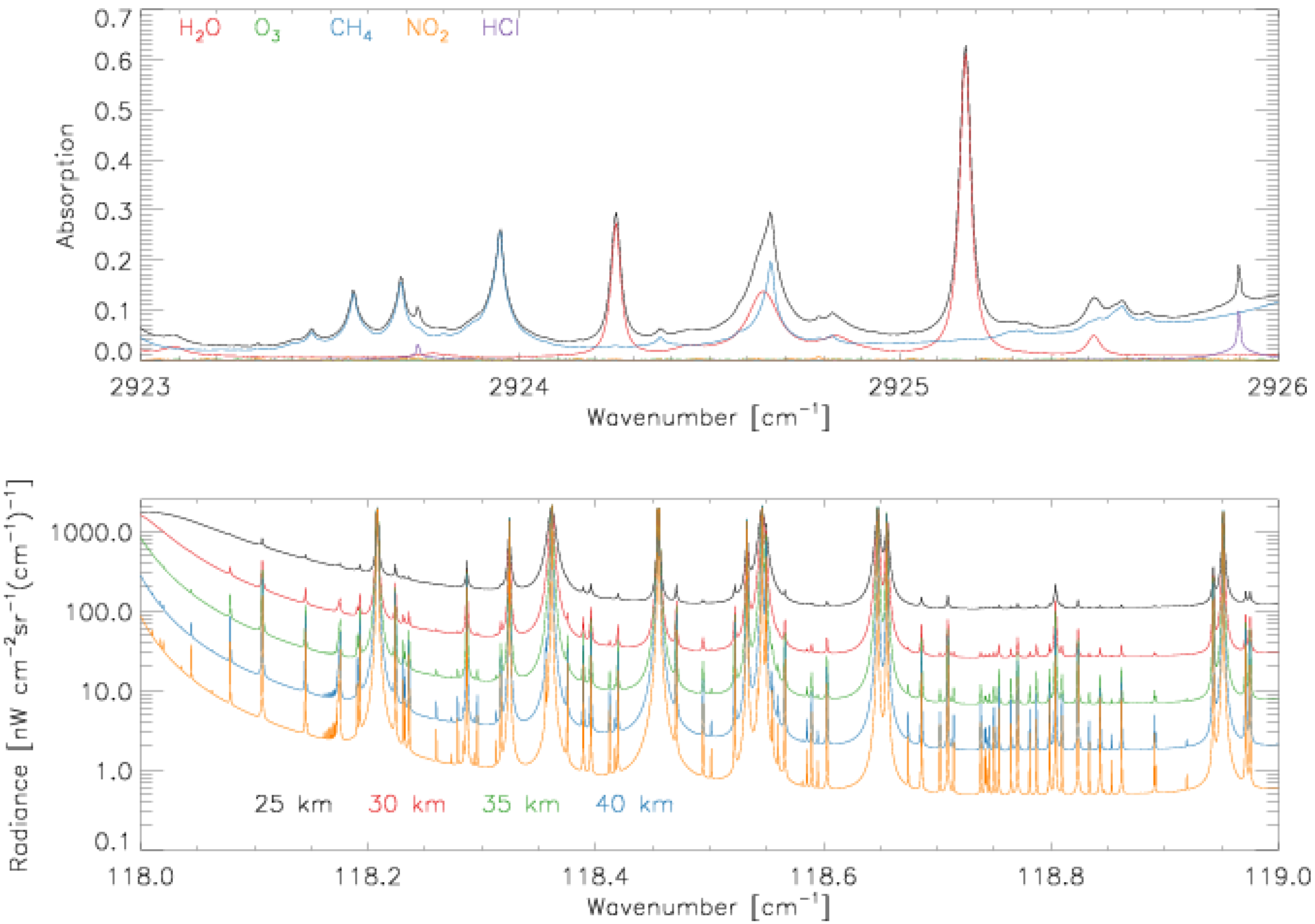
Line selection



Project 2

```
!Driver table for lecture project_2
*HDR
RFM run using Driver Table SAO 2 (16/04/2012)
*FLG
TRA ABS RAD OBS!Transmission, absorption and radiance
*SPC
!OH 118 119 0.0002 !Project second
HCl 2923.00 2926.00 0.0005 ! Project first
!MIPAS 685 2410 2.0 !To have a full picture
!RetrACE 1100 1110 0.02 !Where it was actually done
*GAS
15
!1 3 13 !H2O O3 OH
!1 3 6 10 15 !H2O O3 CH4 NO2 HCl
*ATM
/home/ggonzale/TOOLS/RFM/atmospheres/hgt_std.atm
/home/ggonzale/TOOLS/RFM/atmospheres/std.atm
/home/ggonzale/TOOLS/RFM/atmospheres/minor.atm
!/home/ggonzale/TOOLS/RFM/atmospheres/HCOOH.atm
!*TAN
!25 30 35 40 45
*ELE
45
*OBS
0.0 !Observer in ground
*HIT
/home/ggonzale/TOOLS/RFM/HITRAN08/HITRAN08_22.bin
*XSC
/home/ggonzale/TOOLS/RFM/CX/f12.xsc_h2k !52 CFC-12 cross section
/home/ggonzale/TOOLS/RFM/CX/f22.xsc_h2k !56 HCFC-22 cross section
!/home/ggonzale/TOOLS/RFM/CX/f134.xsc_h2k !79 HFC-143a cross section
*ABS
/home/ggonzale/TOOLS/RFM/PROJECT_2/rfm_*.abs
*TRA
/home/ggonzale/TOOLS/RFM/PROJECT_2/rfm_*.tra
*RAD
/home/ggonzale/TOOLS/RFM/PROJECT_2/rfm_*.rad
*END
```

Project 2



H_2O O_3 CH_4 NO_2 HCl
Absorption
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
2923
2924
2925
2926
Wavenumber [cm^{-1}]
Radiance [nW $cm^{-2}sr^{-1}(cm^{-1})^{-1}$]
0.1
1.0
10.0
100.0
1000.0
25 km
30 km
35 km
40 km
118.0
118.2
118.4
118.6
118.8
119.0
Wavenumber [cm^{-1}]