GARLIC — A Generic Atmospheric Radiation Line-by-line Infrared Code for Earth and Planetary Science

Franz Schreier, Sebastián Gimeno García, Pascal Hedelt, and Mayte Vasquez

DLR — Remote Sensing Technology Institute, Oberpfaffenhofen, GERMANY

Introduction

Why radiative transfer?

- Sensitivity studies: detectibility of molecules, etc.
- Forward model for atmospheric inverse problems
- Radiation as a key component of atmospheric physics-chemistry

Why line-by-line (lbl)?

- Modeling and analysis of high resolution instruments
- LbL as"training set" and benchmark for parameterized models
- *Exoplanets:* no assumptions like band models, k-distribution, . . .

InfraRed Radiative Transfer

Schwarzschild equation: $I(\nu)$ radiance/intensity at wavenumber ν

$$I(\nu) \;=\; I_b(\nu)\,\mathrm{e}^{-\tau_b(\nu)} \;+\; \int_0^{\tau_b(\nu)} B(\nu, T(\tau'))\,\mathrm{e}^{-\tau'}\,\mathrm{d}\tau'$$

Beer's law: transmission $\mathcal{T}$ and optical depth τ

$$\mathcal{T}(\nu, s) \;=\; \mathrm{e}^{-\tau} \;=\; \exp\left(-\int_0^s \mathrm{d}s' \sum_m k_m\left(\nu, p(s'), T(s')\right)\; n_m(s')\right)$$

Absorption cross section k: line-by-line

$$k(\nu, p, T) \;=\; \sum_l S_l(T)\; g(\nu;\, \hat{\nu}_l, \gamma_l(p, T))$$

Challenges

- Thousands . . . millions of ν grid points, dozens of altitude levels
- Molecular spectroscopy data:
  HITRAN, GEISA, . . . : hundreds to (ten)thousands of lines
  HiTemp, ExoMol, . . . : millions to billions of lines
- LbL–IR–RT for (Earth) Remote Sensing:
  IASI@MetOp: $\approx$ 20GB/day, 10^6 spectra/day
  PREMIER–EarthExplorer: 12 000 limb images, $15{\cdot}10^6$ spectra/day

GARLIC — Features

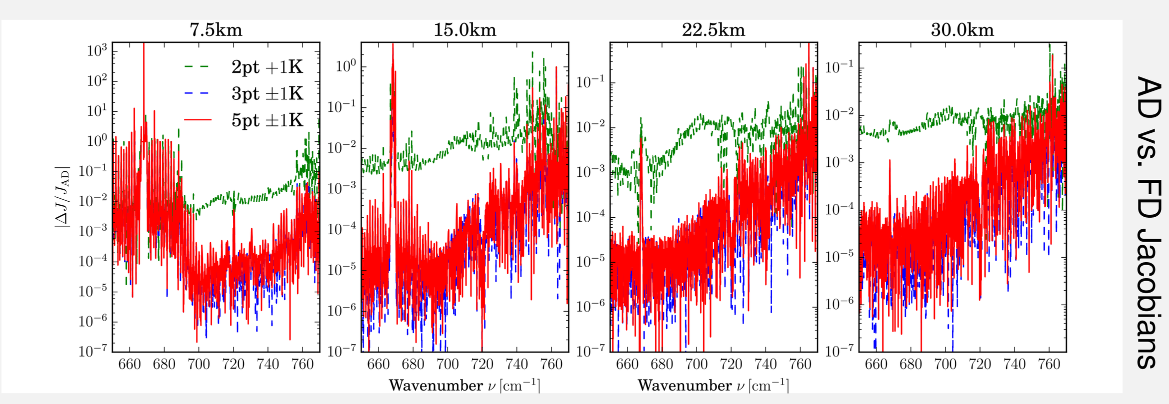
- Voigt etc. lineshapes, continua (H_2O, . . .), CIA
- Limb, uplooking and downlooking geometries (refraction optional)
- Spectral response (FTS, Heterodyne, . . .) and Field-of-View
- "Multigrid" Voigt / complex error function algorithm
- Implementation: Fortran 2008, OpenMP
- Some dozen input variables (about 10 "mandatory", others set to defaults); All data read from external files

Temperature and Density Jacobians

- Jacobians needed for sensitivity studies and iterative solution of nonlinear inverse problems
- Finite differences: computational expensive and risk of cancellation/truncation errors
- Analytic derivatives: implementation laborious, boring, error prone
- *Automatic/Algorithmic Differentiation*: kind of "precompiler"

Code is essentially a sequence of elementary operations, simple differentiation rules for sums, products, . . . , sin, exp, . . . , and chain rule

$\Longrightarrow$ 22 column T Jacobian — execution factor 1.8 slower than radiance alone (but factor $\geq$22 for FD Jacobians!)

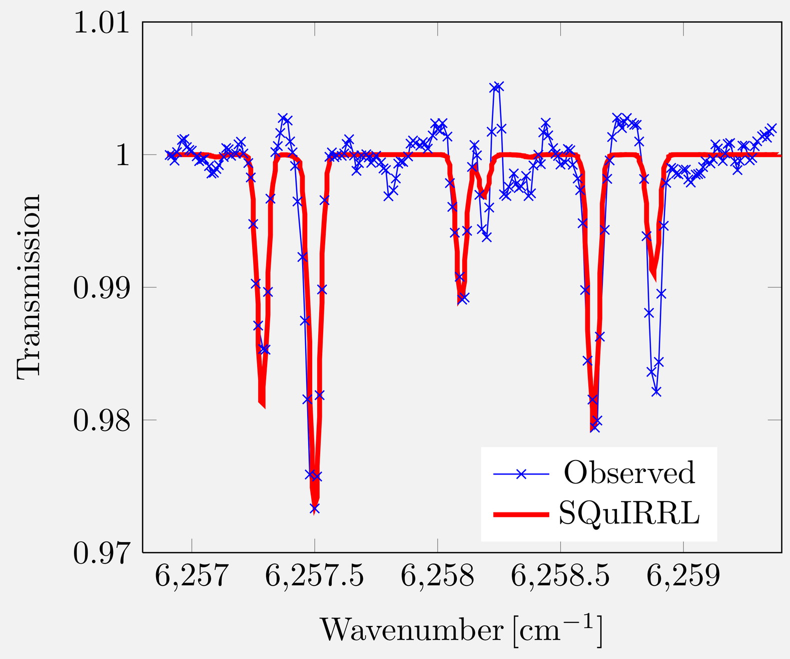


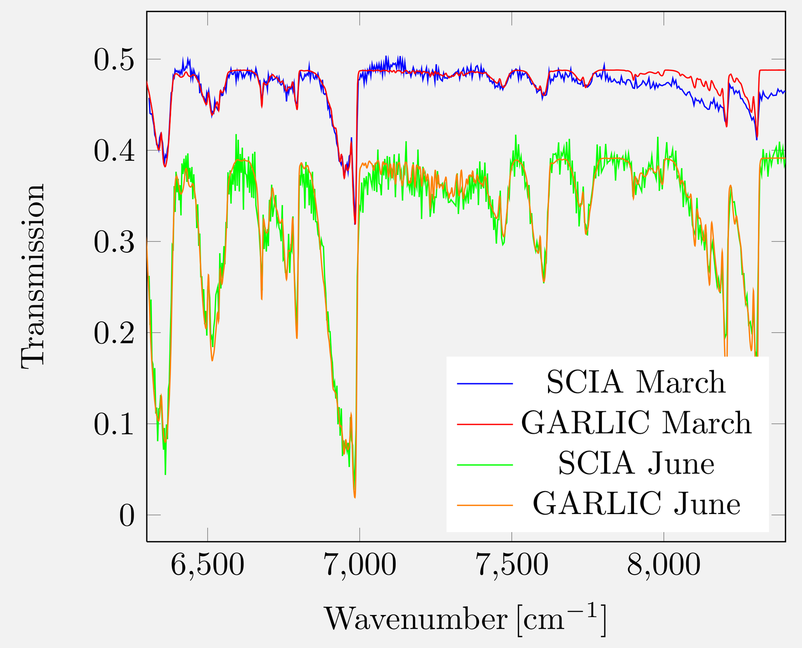
Verification: Code intercomparisons

- AMIL2DA (thermal IR limb emission): GARLIC vs. KOPRA vs. . . .
- IRTMW01 (μWave, up-, down-, limb): GARLIC vs. ARTS vs. . . .
- ARTS–GARLIC–KOPRA: 19 channels (HIRS), 42 atmospheres

Validation

- Cloud covered MIPAS spectra (thermal IR limb sounding)
- Venus transit 2004 (left) and Venus seen by SCIAMACHY (right)



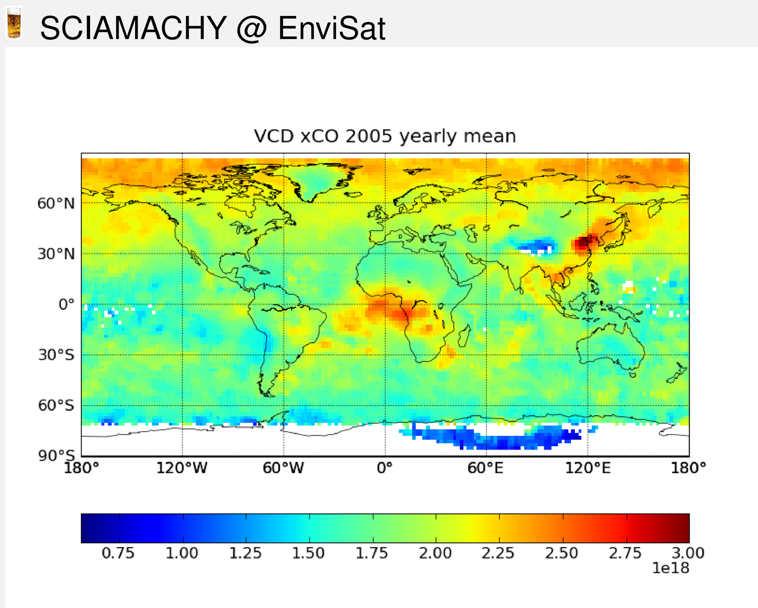


Inversion

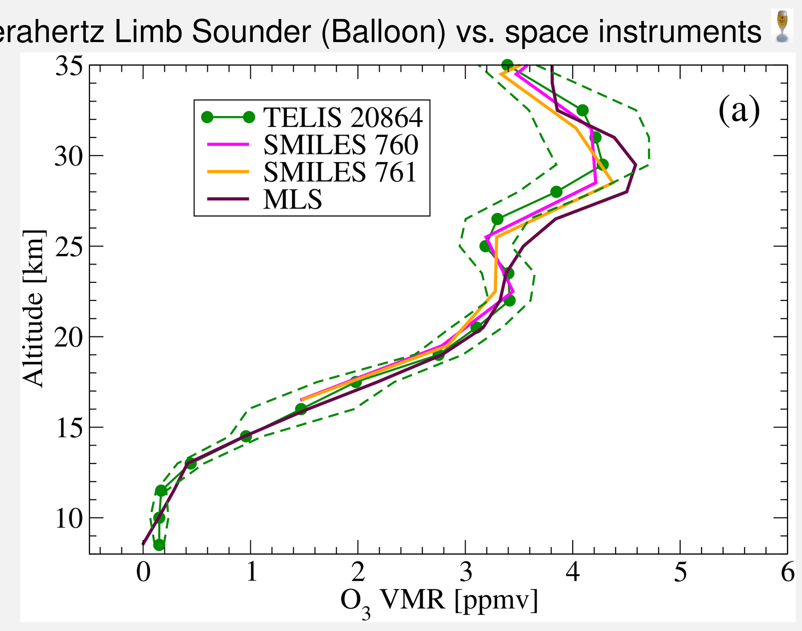
GARLIC routines as core of several inversion codes

- BIRRA (Beer InfraRed Retrieval Algorithm)
  Column density nonlinear least squares fit for NIR nadir
- PILS (Profile Inversion for Limb Sounding): (F)IR and μWave

SCIAMACHY @ EnviSat



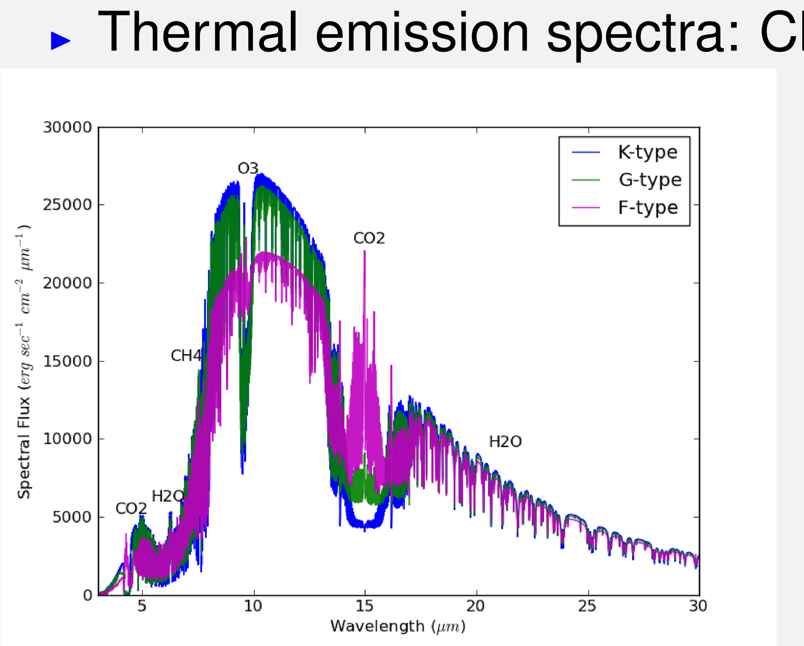
TELIS Terahertz Limb Sounder (Balloon) vs. space instruments

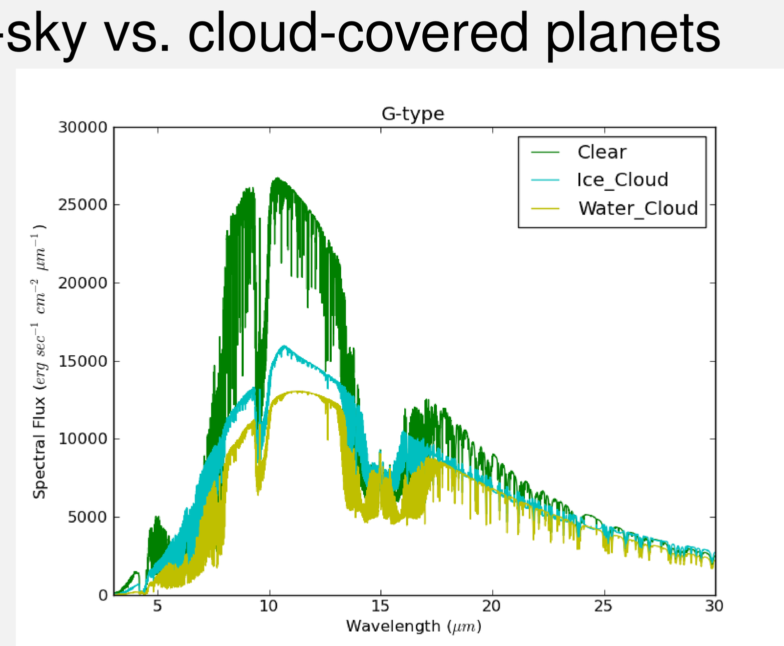


(Exo-)Planet Studies

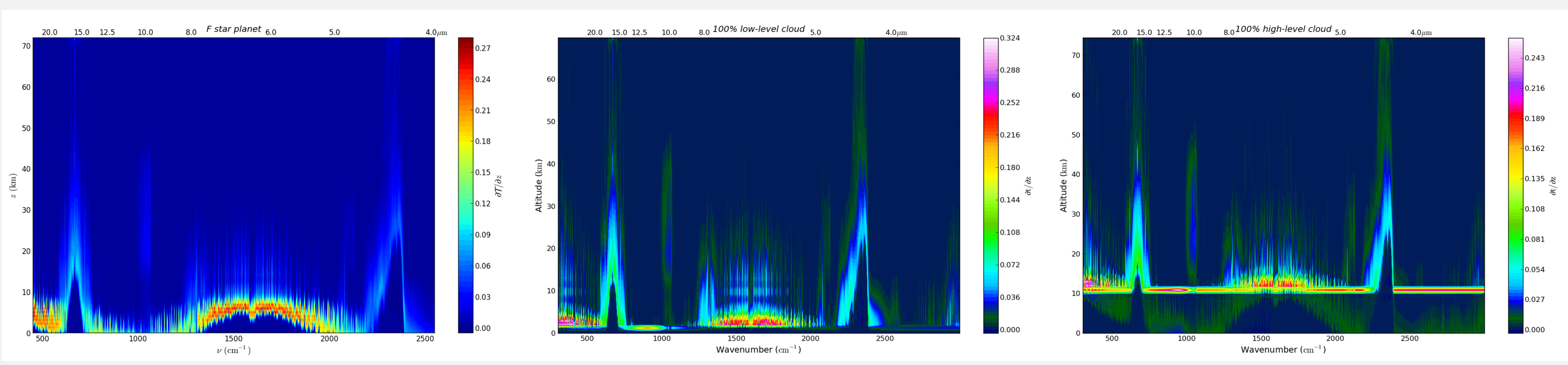
IR radiative transfer in Earth-like planet atmospheres (Vasquez 2014)

- Thermal emission spectra: Clear-sky vs. cloud-covered planets





- Weighting functions: impact of clouds



Further applications:

- Warming the early Earth — CO_2 reconsidered (von Paris et al. 2008)
- Spectroscopy of potentially habitable planets: GL 581 d (von Paris et al. 2011)
- Spectral appearance of super-Earths around M dwarfs (Rauer et al. 2011)
- Detectability of spectral features of F, G, K Earth-like planets (Hedelt et al. 2013)