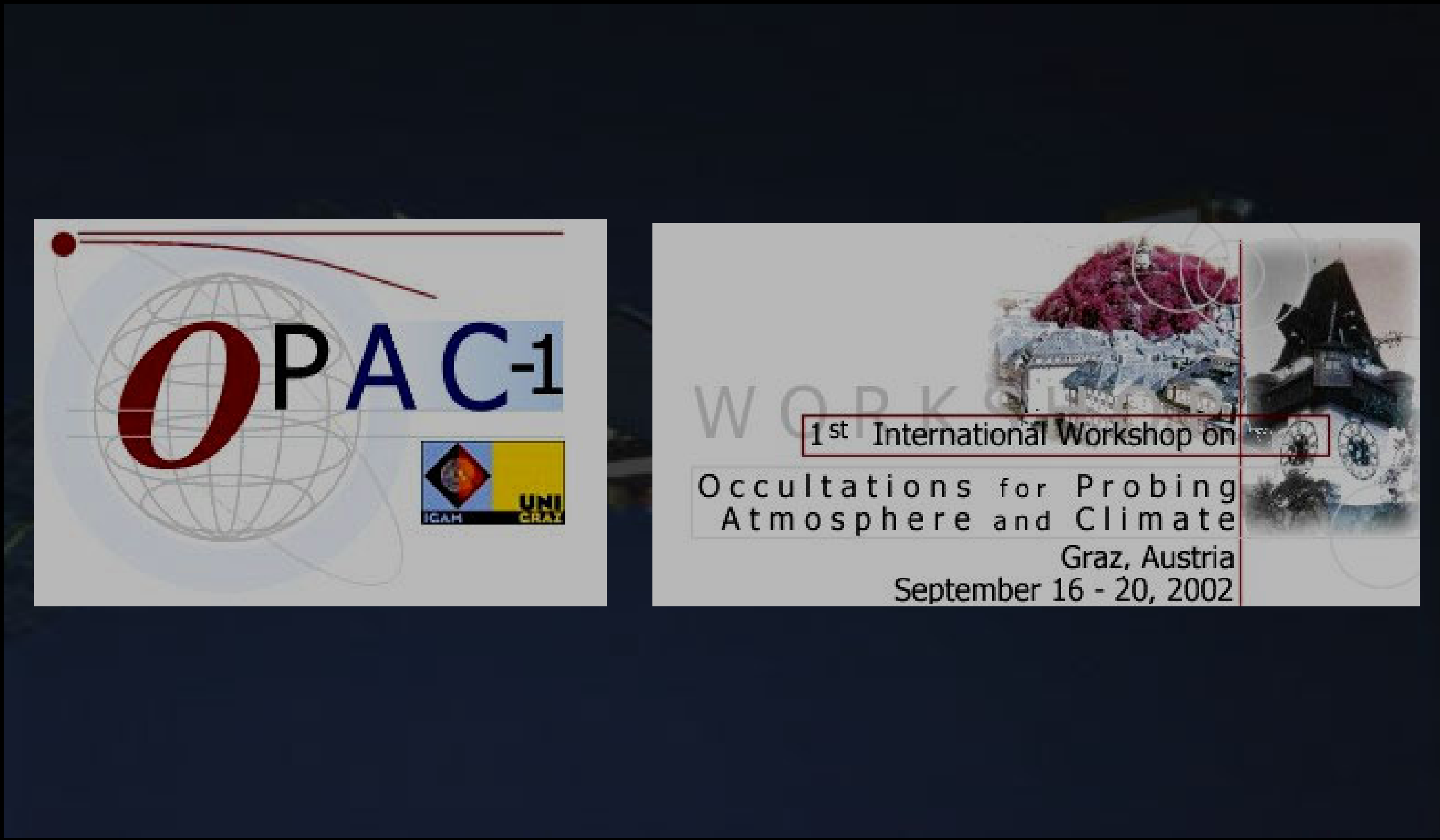

OPAC-1
1st International Workshop on
Occultations for Probing Atmosphere and Climate
Graz, Austria
September 16 - 20, 2002

Stratospheric Temperature and Ozone Sounding with ENVISAT/GOMOS Stellar Occultation

C. Retscher[1], G. Kirchengast[1], A. Gobiet[1], and A. Hauchecorne[2]

(1) ARSCliSys@IGAM, University of Graz, Austria
(2) Service d'Aéronomie du CNRS, Verrières-le-Buisson, France

(christian.retscher@uni-graz.at, gottfried.kirchengast@uni-graz.at, andreas.gobiet@uni-graz.at, alain.hauchecorne@aerov.jussieu.fr)

OPAC-1 Workshop, IGAM/UG, Graz, Austria, September 16-20, 2002.

Outline

- **ENVISAT/GOMOS Stellar Occultation Sensor**
- **Forward Modeling and Retrieval**
- **First Results**
- **Summary and Conclusions**

Source: http://envisat.esa.int

Middle Atmospheric Ozone Sounding by the ENVISAT/GOMOS Stellar Occultation Sensor

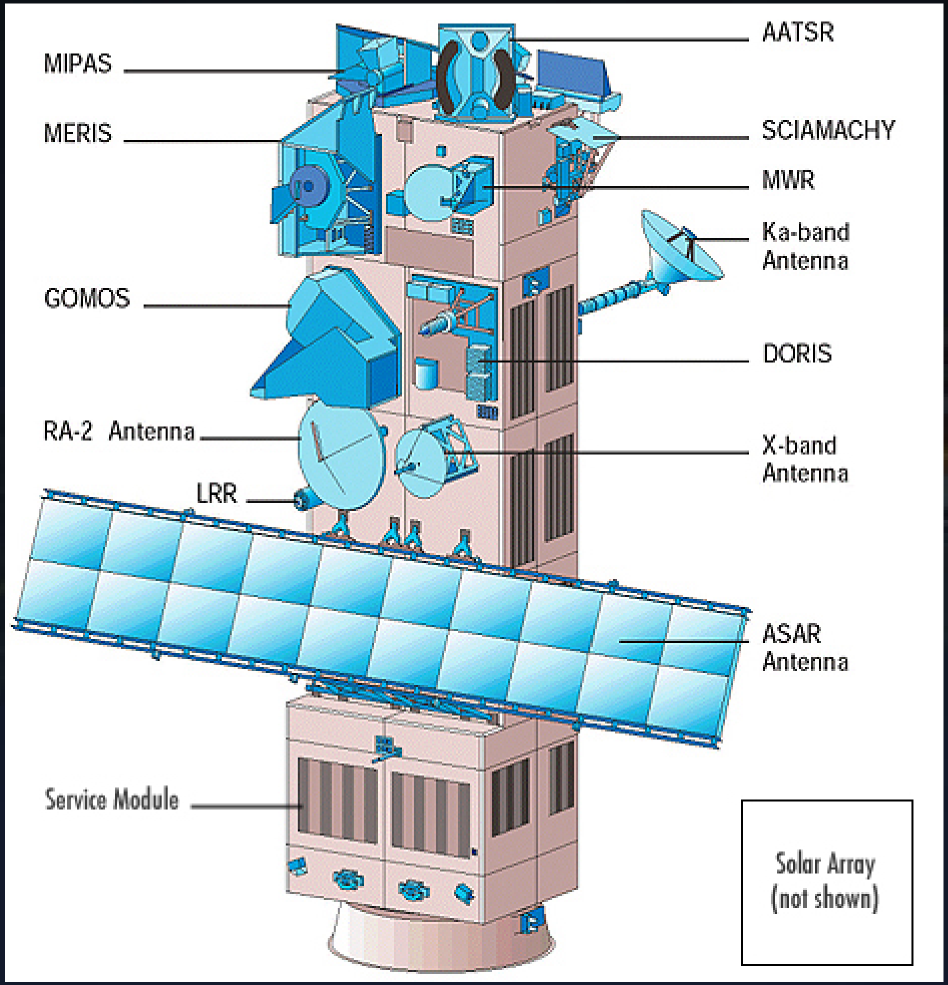
ENVISAT/GOMOS
Stellar Occultation Sensor

ENVISAT/GOMOS Stellar Occultation Sensor

the ENVISAT mission

- Launch with Ariane 5 on 1st March 2002, 1:07:59 UT
- Mission duration > 5 years
- Sun-synchronous orbit: inclination 98 deg, ~800 km altitude
- Ten instruments on-board: ASAR, GOMOS, LRR, MIPAS, MERIS, MWR, RA-2, AATSR, DORIS, SCIAMACHY
- Simultaneous monitoring of land, oceans, ice fields and the atmosphere

ENVISAT/GOMOS Stellar Occultation Sensor



the ENVISAT satellite

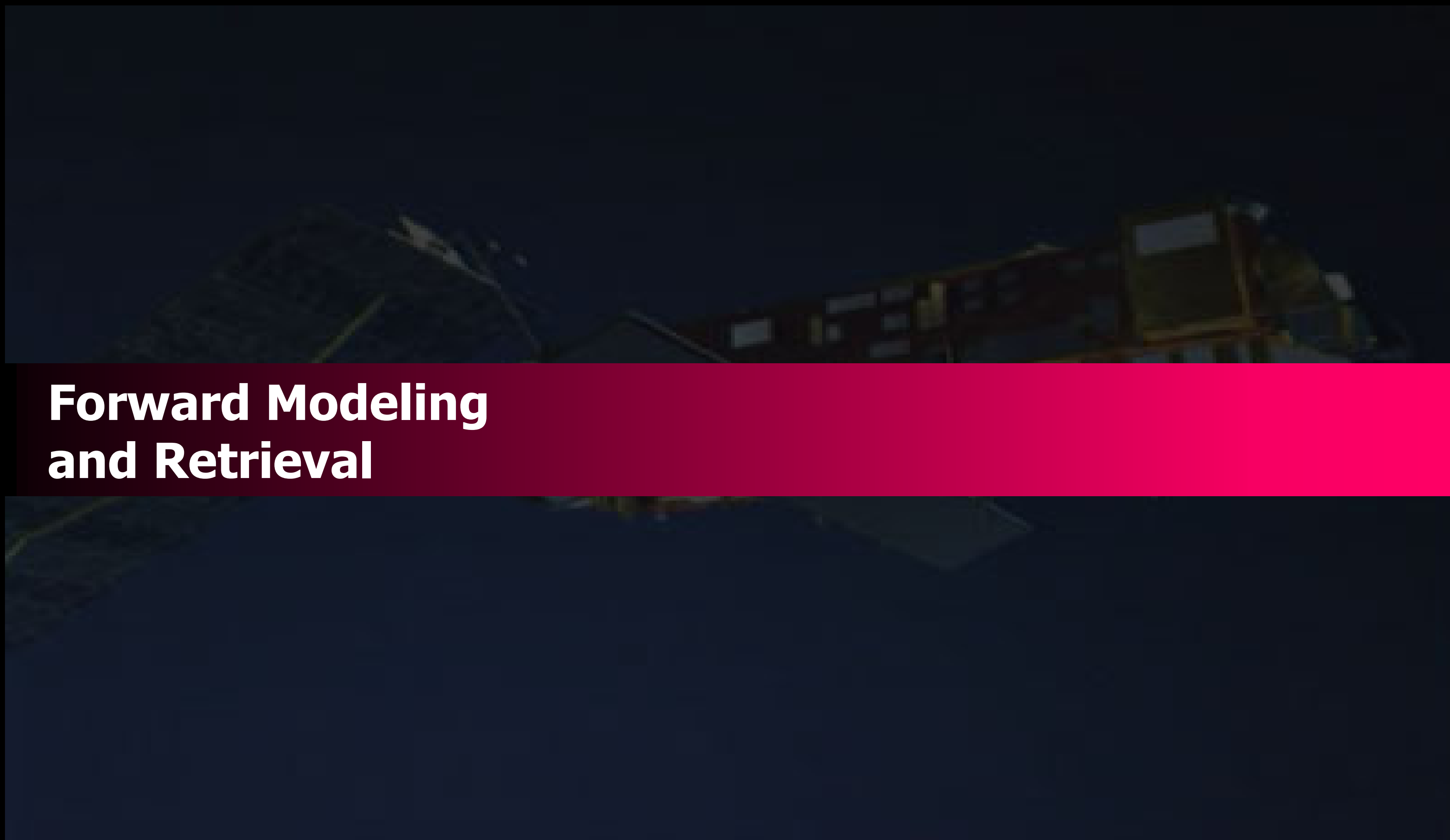
the GOMOS sensor concept

- Atmospheric profiles by stellar occultation method (~15 - 90 km)
- Two Spectrometers
  - A: 248 - 371 nm (UV), 387 - 693 nm (VIS)
  - B: 750 - 776 nm (IR1), 915 - 956 nm (IR2)
- Two broad-band Photometers with 1 kHz sampling rate
  - 466 - 528 nm, 644 - 705 nm
- Self-calibrated transmission data (normalized intensities)
- Profiles of O_3, NO_2, NO_3, BrO, OClO, O_2, water vapor, air density, temperature and turbulence

ENVISAT/GOMOS Stellar Occultation Sensor

the star tracking unit

- SFM (steering front mechanism) acquires the star image
  - angular range: ±26°
  - maintains the position and rotates the mirror
- SFA (steering front assembly) with 5 Hz sampling
  - azimuth angle: -11° to 91°
  - elevation angle: 61.7° To 69°
- SATU (star acquisition and tracking unit) with 100Hz sampling
  - nominal and redundant star tracker
  - image of the observed star at focal length of 630 nm
  - SATU errors are between ~ ±10μrad in both directions



Forward Modeling and Retrieval

Forward Modeling and Retrieval

the forward model

- Observed-Transmission model basic formula (no defocusing):

$$T_{obs} = \int_{\Delta t}\int_{\Delta\vartheta}\int_{\Delta\lambda} T_\nu(\lambda,\vartheta,t)\,W(\lambda,\vartheta,t)\,d\lambda\, d\vartheta\, dt$$

- Modeled atmospheric transmission given by Beer-Bouguer-Lambert law

$$T_\nu(t) = \frac{I_\nu(t)}{I_\nu(0)} = \exp\left[-\int_{x_S(t)}^{x_G(t)} \sum_i n_i(s')\sigma_{i\nu}(s')ds'\right]$$

- no finite field of view integration needed, no aerosol extinction used

- CIRA-86 or MSIS-90 models used for bulk atmosphere and standard profiles for trace species O_3, NO_2, and NO_3

Forward Modeling and Retrieval

the forward model

- Absorption cross sections for O_3, NO_2, and NO_3
- Scattering cross section (Rayleigh scattering)
- realistic refractive path by fast 3D raytracing
- realistic geometry used and Earth's shape approximated by WGS-84
- channel selection (260, 280, 290, 295, 305, 310, 320, 328, 330, 600, 610 nm)
  - O_3 Hartley band (~200 - 300 nm)
  - slight temperature dependencies and NO_2 sensitivity
- standard GOMOS 2Hz sampling of transmission data → 1.5 km spacing

Forward Modeling and Retrieval

connecting the forward and the retrieval model

- the forward model reads

$$\mathbf{y} = \mathbf{K}(\mathbf{x}) + \boldsymbol{\varepsilon}$$

  - **y**, **x**... measurement and state vector
  - **K**... forward model operator, Jacobian matrix (m×n)
  - ε... measurement error vector
  - rows of Jacobian **K** can be interpreted as “weighting functions”

- the direct inversion reads

$$\mathbf{x}_r = \mathbf{K}^{-g}\mathbf{y}$$

  - ill-conditioned problem at high altitudes
  - over-determined for m>n

Forward Modeling and Retrieval

the retrieval model

- Optimal estimation
  - incorporates sensibly *a priori* knowledge
  - statistically optimal combination of unbiased measurements and prior data
- fast converging iterative optimal estimation scheme

$$\mathbf{x}_{i+1} = \mathbf{x}_{ap} + \mathbf{S}_i \mathbf{K}_i^T \mathbf{S}_\varepsilon^{-1} \left[(\mathbf{y} - \mathbf{y}_i) + \mathbf{K}_i \left(\mathbf{x}_i - \mathbf{x}_{ap} \right) \right]$$

$$\mathbf{S}_i = \left(\mathbf{K}_i^T \mathbf{S}_\varepsilon^{-1} \mathbf{K}_i + \mathbf{S}_{ap}^{-1} \right)^{-1}$$

  - $\mathbf{S}_\varepsilon$... observation and forward modeling error covariance matrix
  - $\mathbf{S}_i$... retrieval error covariance matrix
  - $\mathbf{S}_{ap}$... *a priori* error covariance matrix
  - $\mathbf{x}_{ap}$... *a priori* profile
  - $\mathbf{x}_{i+1}$ ... *retrieved* profile (iteration *i*)

Forward Modeling and Retrieval

bending angles and refractive index

- exploitation of bending angles (α) data (SFA/SATU)
- direct inversion of the refractive index (Abel Transform)

$$\alpha(a) = 2a \int_{r=r_0}^{r=\infty} \frac{1}{\sqrt{n^2 r^2 - a_0{}^2}} \frac{d\ln(n)}{dr} dr$$

$$n(r_0) = \exp\left[\frac{1}{\pi} \int_{\alpha=\alpha(a_0)}^{\alpha_0} \ln\left(\frac{a(\alpha)}{a_0} + \sqrt{\left(\frac{a(\alpha)}{a_0}\right) - 1} \right) d\alpha \right]$$

- r... radius at tangent point
- a... impact parameter

Forward Modeling and Retrieval

optimized bending angles

- statistical optimization to find the most probable bending angle profile

$$\alpha_{opt} = \alpha_b + (\mathbf{B}^{-1} + \mathbf{O}^{-1})^{-1}\mathbf{O}^{-1}(\alpha_o - \alpha_b)$$

  - α_{opt} ... most probable bending angle profile
  - α_o ... observed bending angle profile (ionosphere-corrected)
  - α_b ... background (*a priori*) bending angle profile (from climatology)
  - **O** observation error covariance matrix
  - **B** background error covariance matrix

- high altitudes: α_{opt} determined by climatology
- low altitudes: α_{opt} determined by observed data

Forward Modeling and Retrieval

refractivity, pressure and temperature

- refractivity (*N*) converted to pressure (*p*) by integration of the hydrostatic equation

$$N(r) = (n(r) - 1) \times 10^6$$

$$p(r) = -b_1 \int_z^\infty N(r')g(r')dr'$$ with $$b_1 = 4.489 \times 10^{-5}\ \mathrm{hPa\,s^2/m^2}$$

- temperature obtained from *p* and *N* by equation of state

$$T(r) = c_1 \frac{p(r)}{N(r)}$$ with $$c_1 = 82.86\ \mathrm{K/hPa}$$

at 300 nm slightly λ-dependent

First Results

First Results

error modeling, first ten O_3 *a priori* error patterns

- error patterns from $\mathbf{S}_{ap}$ (20% uncertainty, 6 km vertical correlation length)

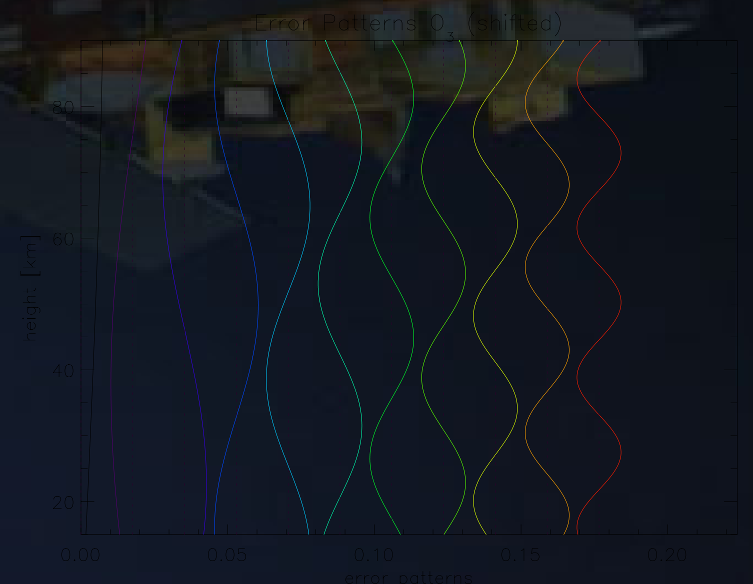
$$\mathbf{S}_{ap} = \sum_i \mathbf{e}_i \mathbf{e}_i^T \quad \text{with} \quad \mathbf{e}_i = \sqrt{\lambda_i}\,\mathbf{l}_i$$

- consistent $\mathbf{x}_{ap}$ based on "true" profile

$$\mathbf{x}_{ap} = \mathbf{x}_{true} + \Delta\mathbf{x}$$

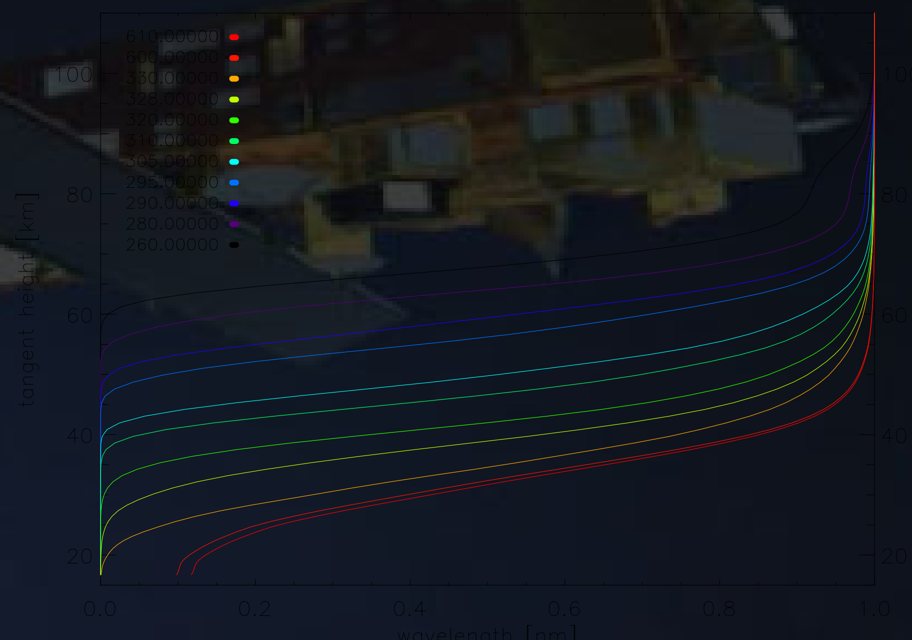
$$\Delta\mathbf{x} = \sum_i a_i \mathbf{e}_i$$

  - a_i random deviates drawn from a normalized Gaussian distribution



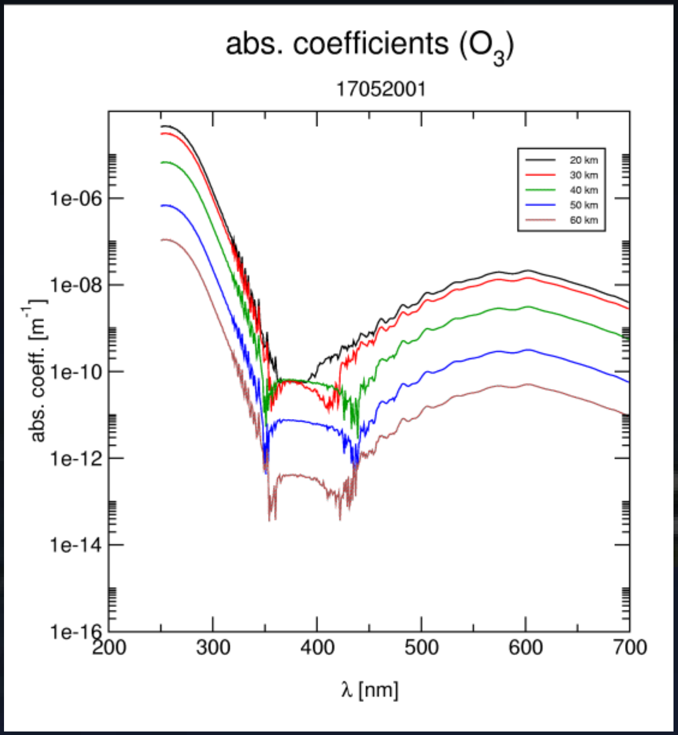
First Results

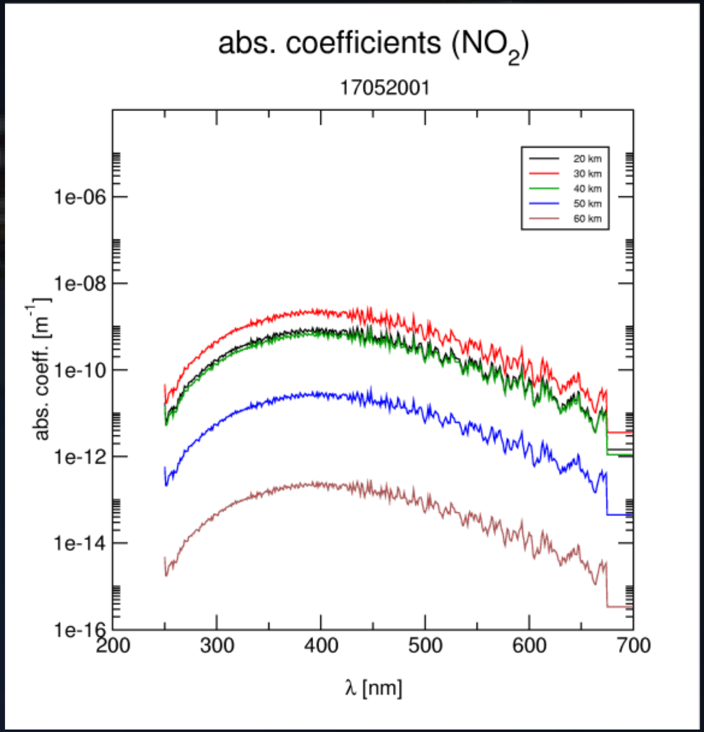
location of simulated example event and transmissions



First Results

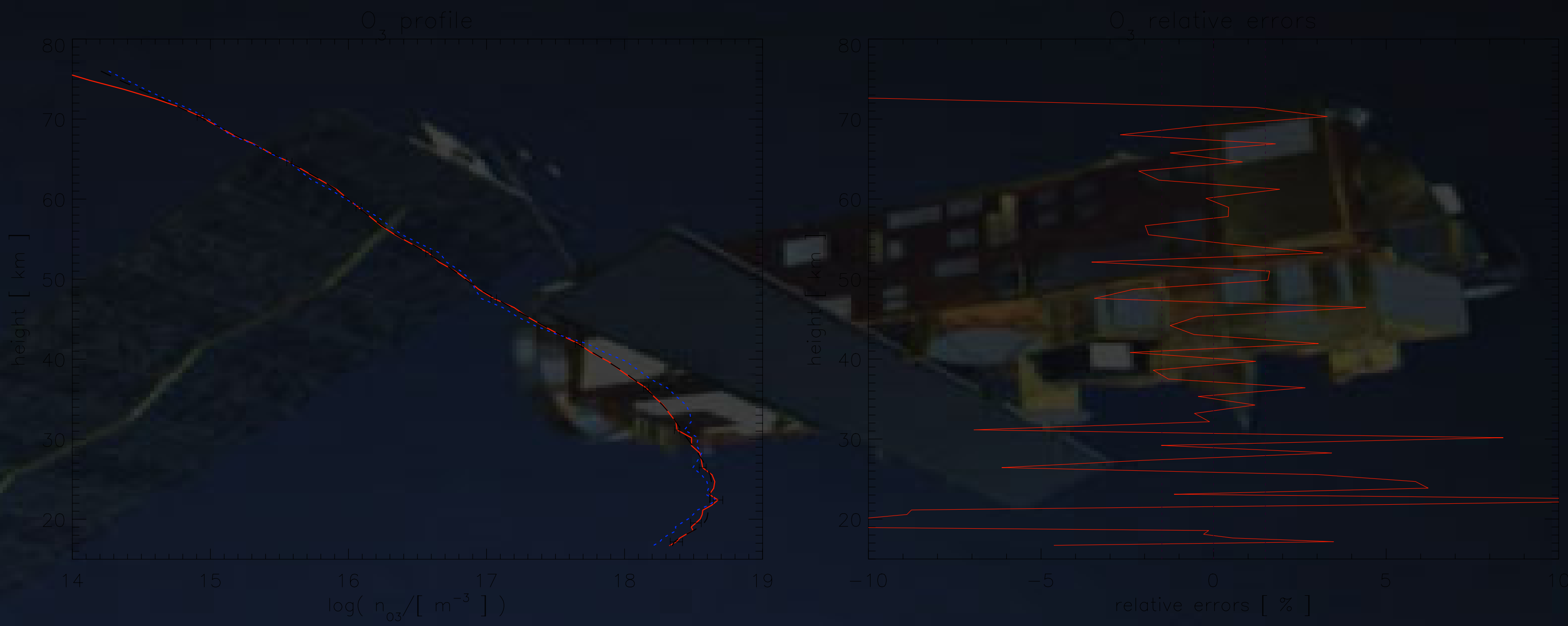
absorption coefficients of O_3 and NO_2





First Results

retrieved O_3 profile and errors for example event



- transmission errors: GOMOS-type values of $0.01\times(T)^{-1/2}$
- no correlation between channels assumed

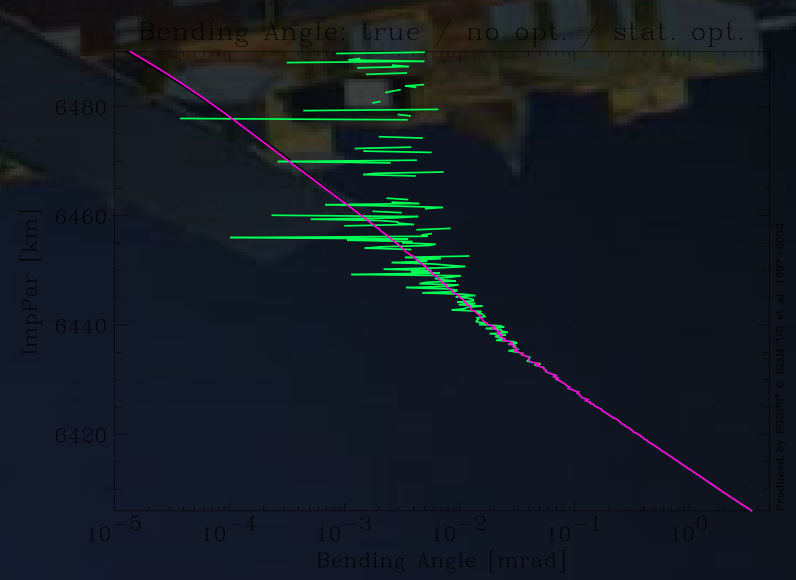
First Results

statistically optimized bending angles

- analytical background (*a priori*) covariance matrix

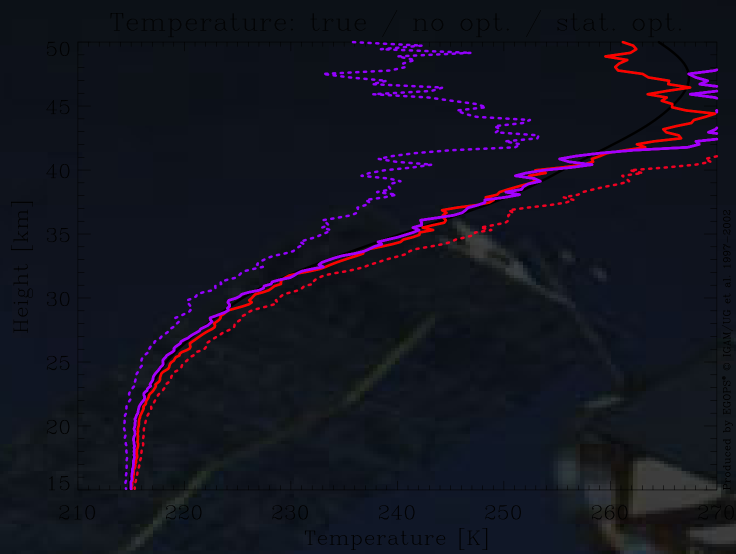
$$B_{ij} = \sigma_i \sigma_j e^{-\left[\left|a_i - a_j\right| / L\right]}$$

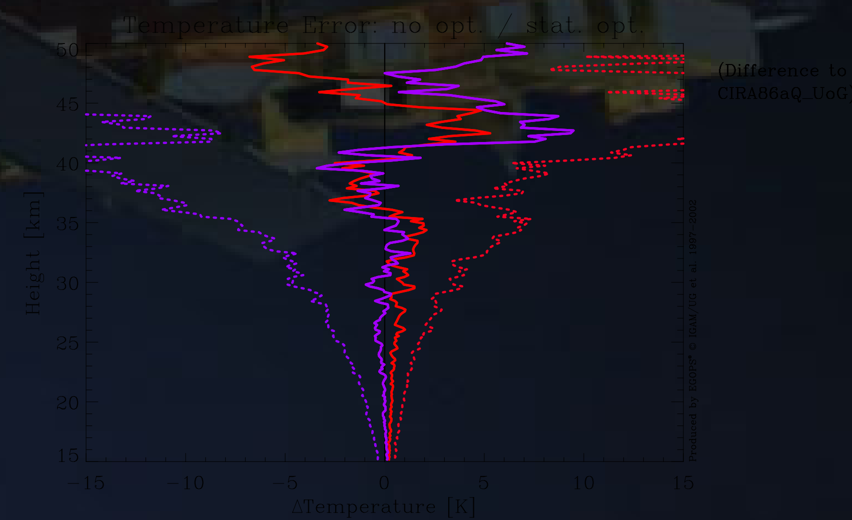
- a_i, a_j... *i* th and *j* th impact parameter values
- L... error correlation length = 6 km
- $\sigma_{i,j}$... 20% uncertainty



First Results

temperature profiles





- errors of 3μrad superimposed (10 Hz SATU sampling rate)

Summary and Conclusions

Summary and Conclusions

the forward model

- realistic observed transmissions from 0 - 120 km
- channel selection within 260 - 340 nm (channels outside possible)

- raytracing to be enhanced by GOMOS-measured bending angles

- along-ray integration to be updated by including aerosol extinction

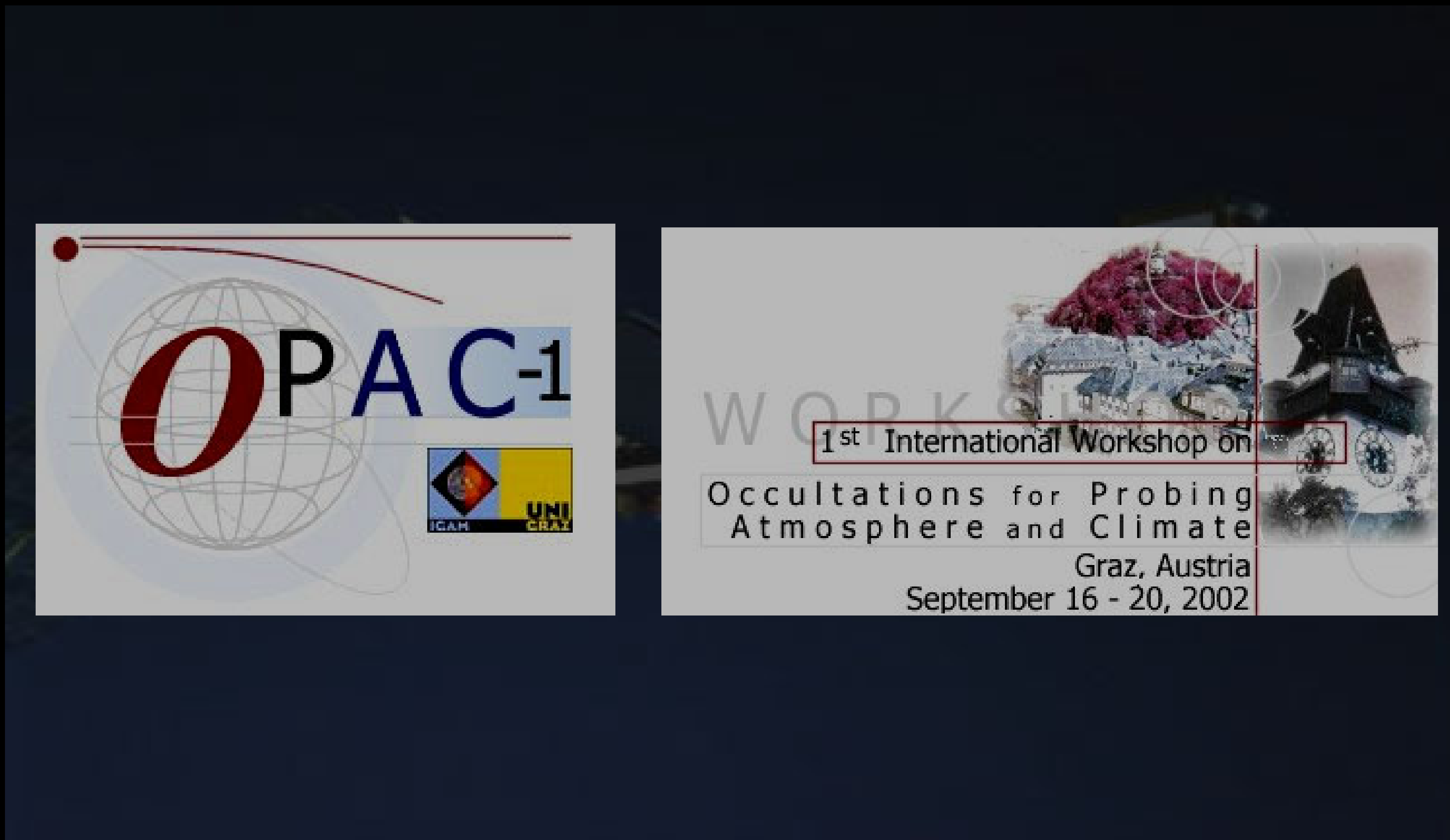
Summary and Conclusions

the retrieval model

- simultaneous O_3 and NO_2 retrieval

- errors of retrieved O_3 profiles within expected ranges (<2%)

- performance to be further improved by
    - channel clustering
    - simultaneous estimation of O_3, NO_2, refractivity, and temperature
- best performance between 15 and 35 km (<1 K below 25 km, < 2 K
- below 35 km) with statistical optimization
- temperature retrieval between 15 and 50 km
- errors > 3 K above 30 km without statistical optimization
- further algorithm enhancements for use with
    - real level1b SFA/SATU data


OPAC-1
1st International Workshop on
Occultations for Probing Atmosphere and Climate
Graz, Austria
September 16 - 20, 2002