Does a priori information improve occultation measurements?

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OPAC-1

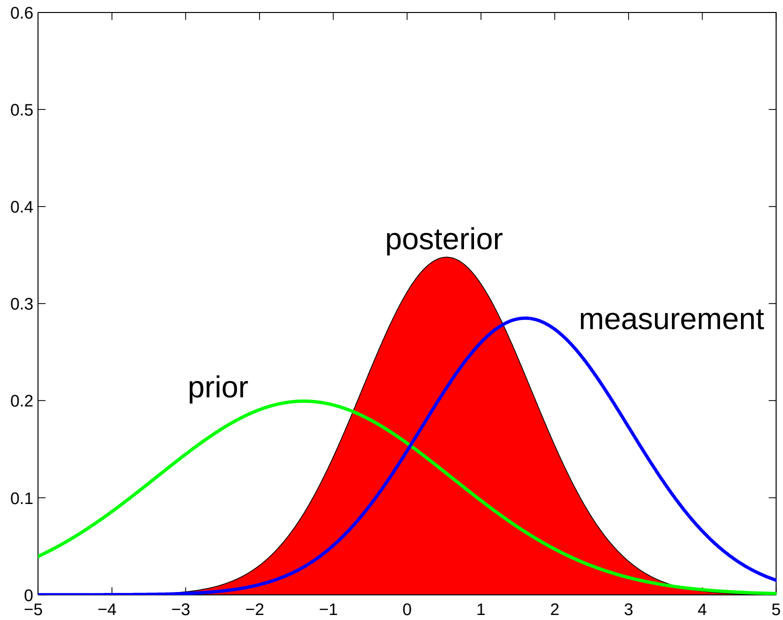
16-20.9. 2002 Graz, Austria

Contents

Role of prior information

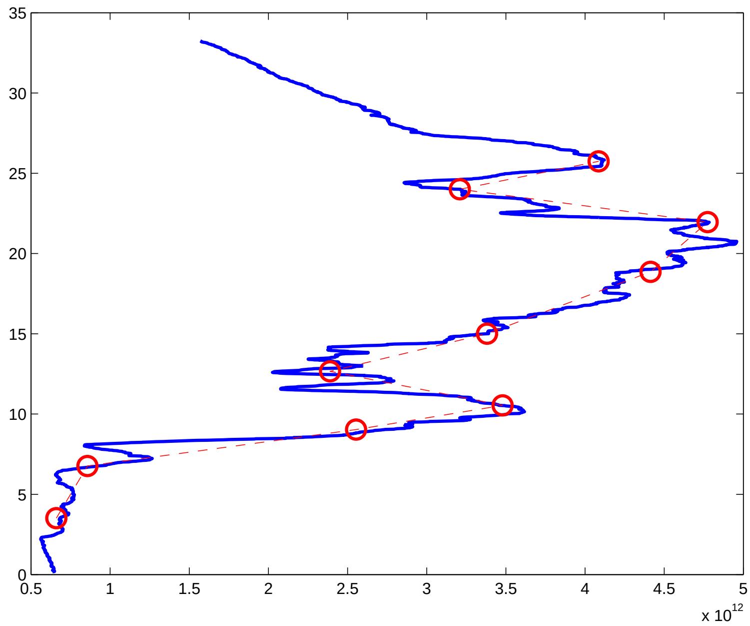
- Bayesian approach: use all available information

$$\boxed{\text{posterior} \propto \text{prior} \times \text{likelihood}}$$



- Ill-posed problems $\longrightarrow$ regularization

Atmospheric remote sensing problems are typically underdetermined: continuous profile is wanted from a discrete set of measurements.



GOMOS inversion problem

The inversion

$$T_{ext} = e^{-\mathcal{T}} = \exp\left\{ -\sum_j \int \rho_j(s)\sigma_j(\lambda)ds \right\}$$

is solved in two steps:

1. Spectral Inversion: at each altitude separately:

$$T_{ext} = e^{-\mathcal{T}} = \exp\left\{ -\sum_j \sigma_j(\lambda)N_j \right\}$$

where N_j is the line density of the species j

and

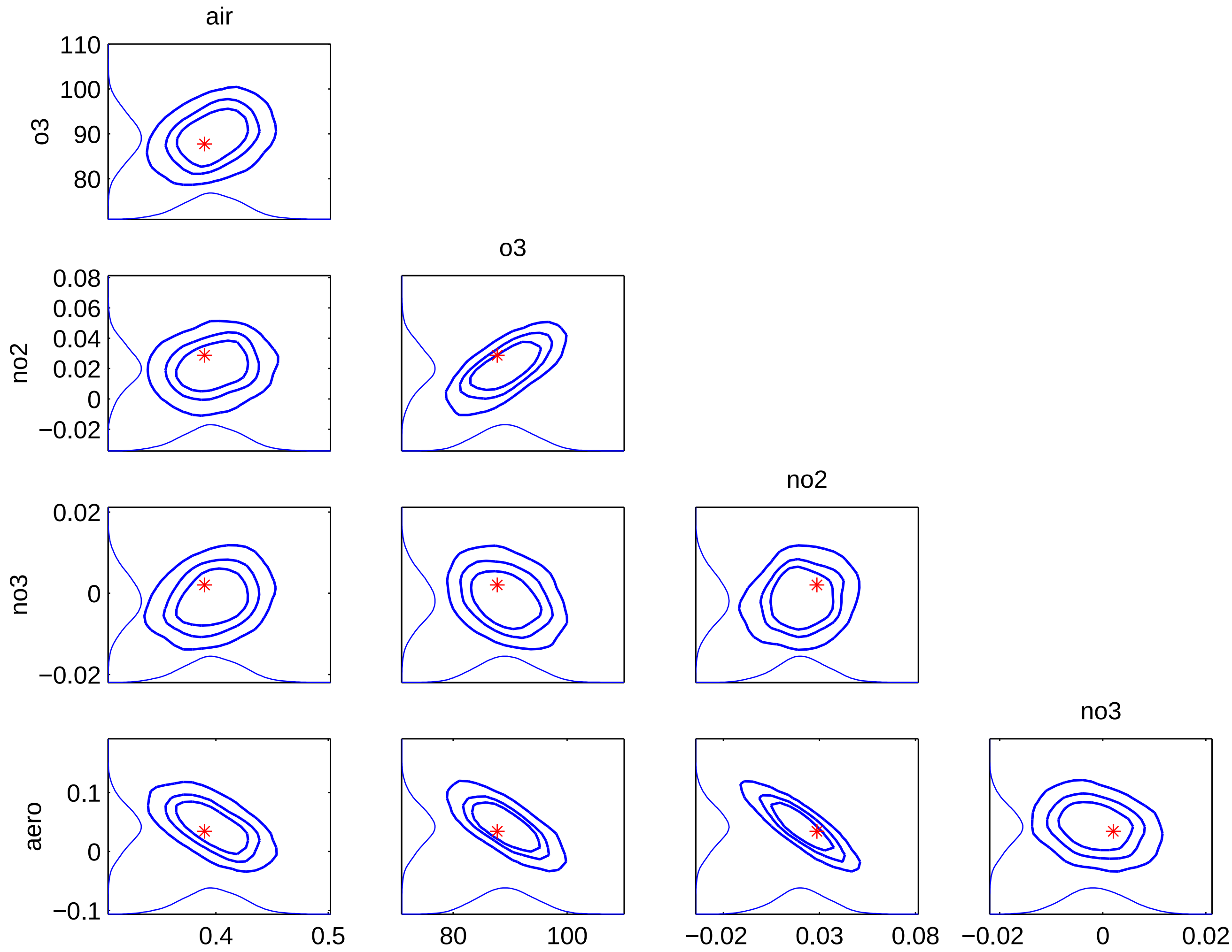
2. Vertical inversion for each gas separately:

$$N_{j,\ell} = \int_\ell \rho_j(z(s))\,ds \qquad (\ell = \ell_1, \ldots, \ell_M)$$

with local densities $\rho_j(z)$ as the unknowns.

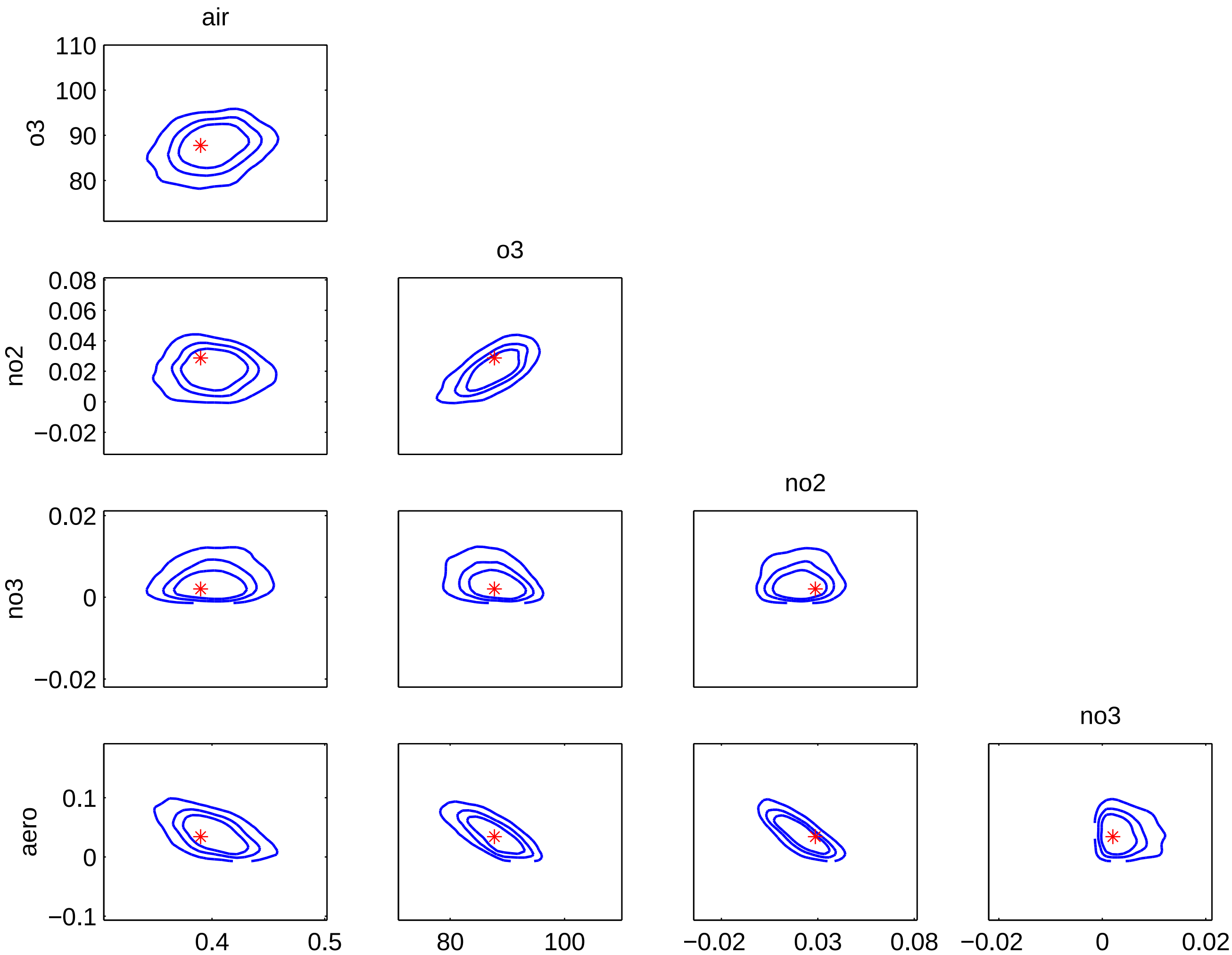
Spectral inversion

- Cross sections of different constituents are correlated $\longrightarrow$ a posteriori errors of constituent line densities are correlated
- Measurements can be noisy (dim star, bright limb)
- At low altitudes iterative Levenberg-Marquardt algorithm may suffer.



Contour curves: marginal posterior distribution (50, 70 and 90% probability regions), true value denoted with red dot. Dim star (Mv=4). (Scaled line density values).

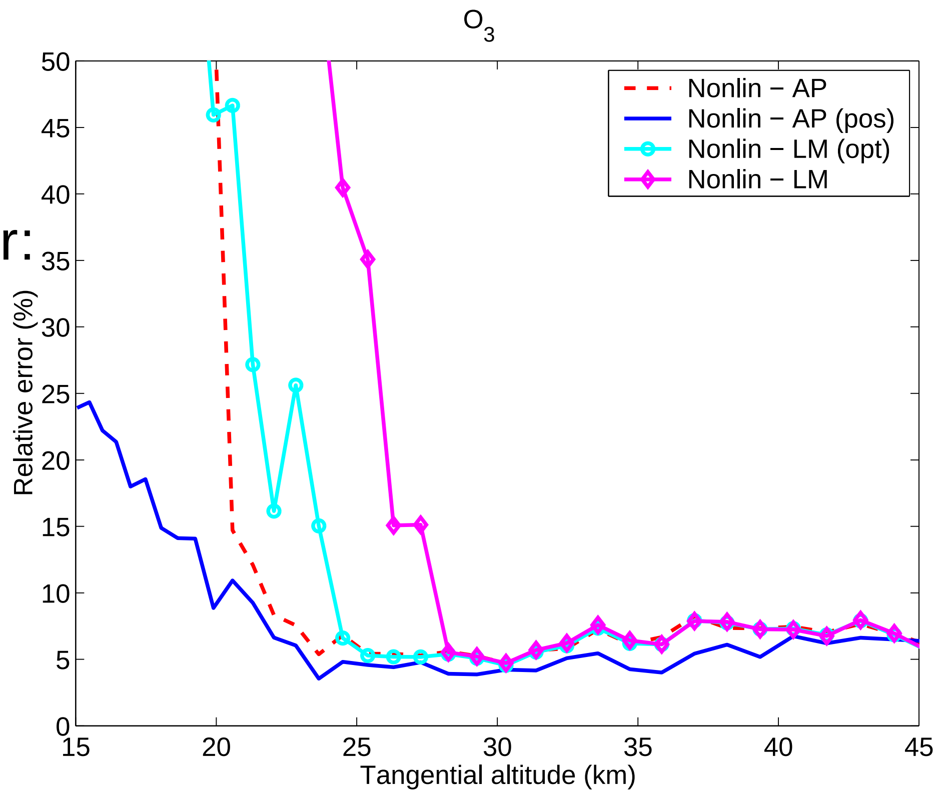
Positivity prior in GOMOS spectral inversion



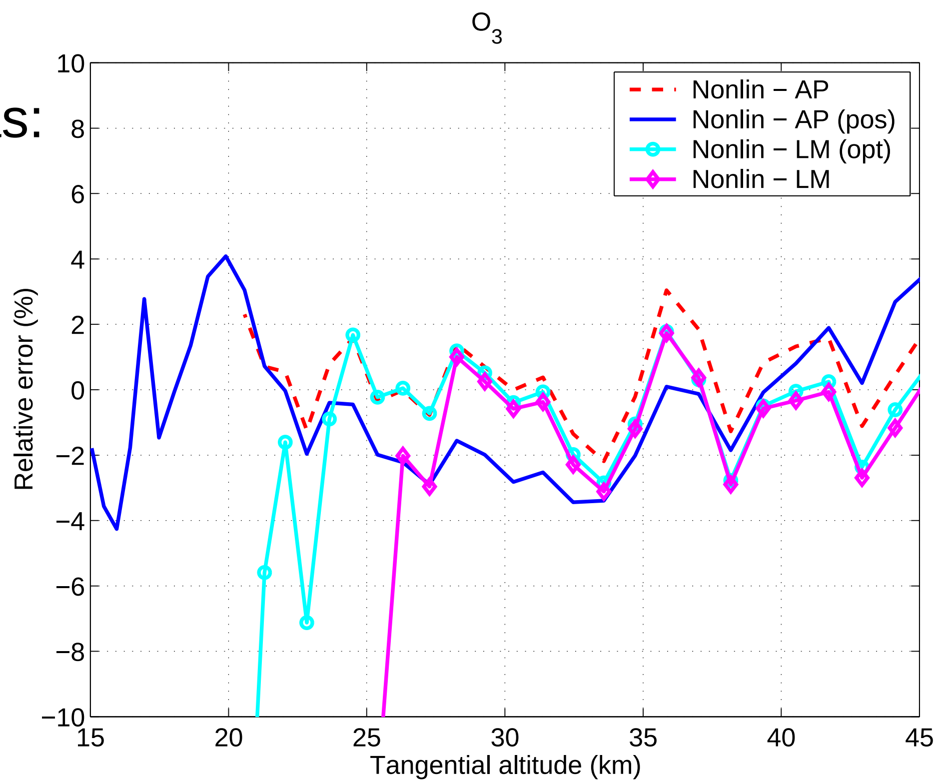
Contour curves: marginal posterior distribution (50, 70 and 90% probability regions), true value denoted with red dot. Dim star, mv=4. (Scaled line density values).

Positivity prior in GOMOS spectral inversion (cont.)

RMS error:



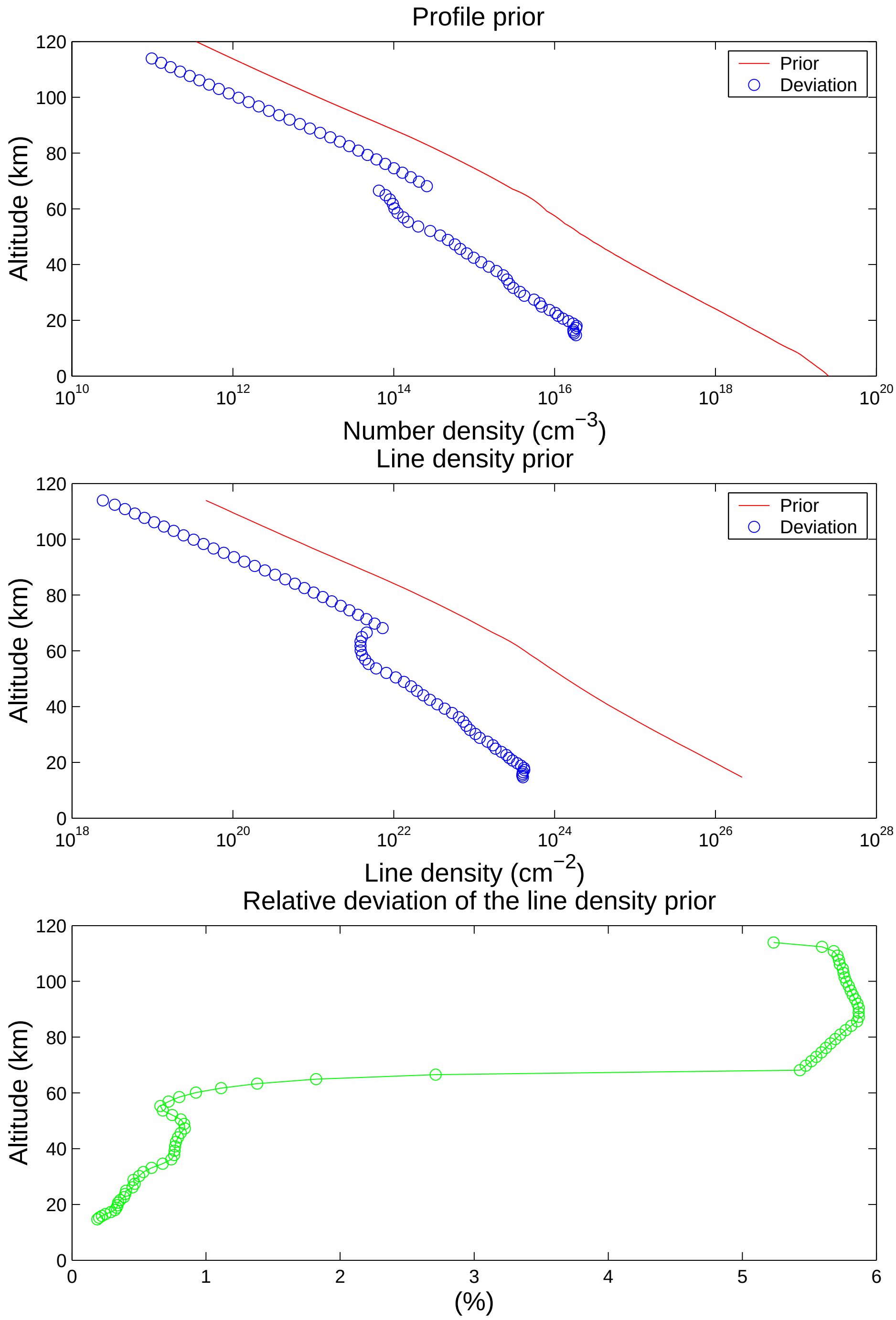
Bias:



Neutral density prior

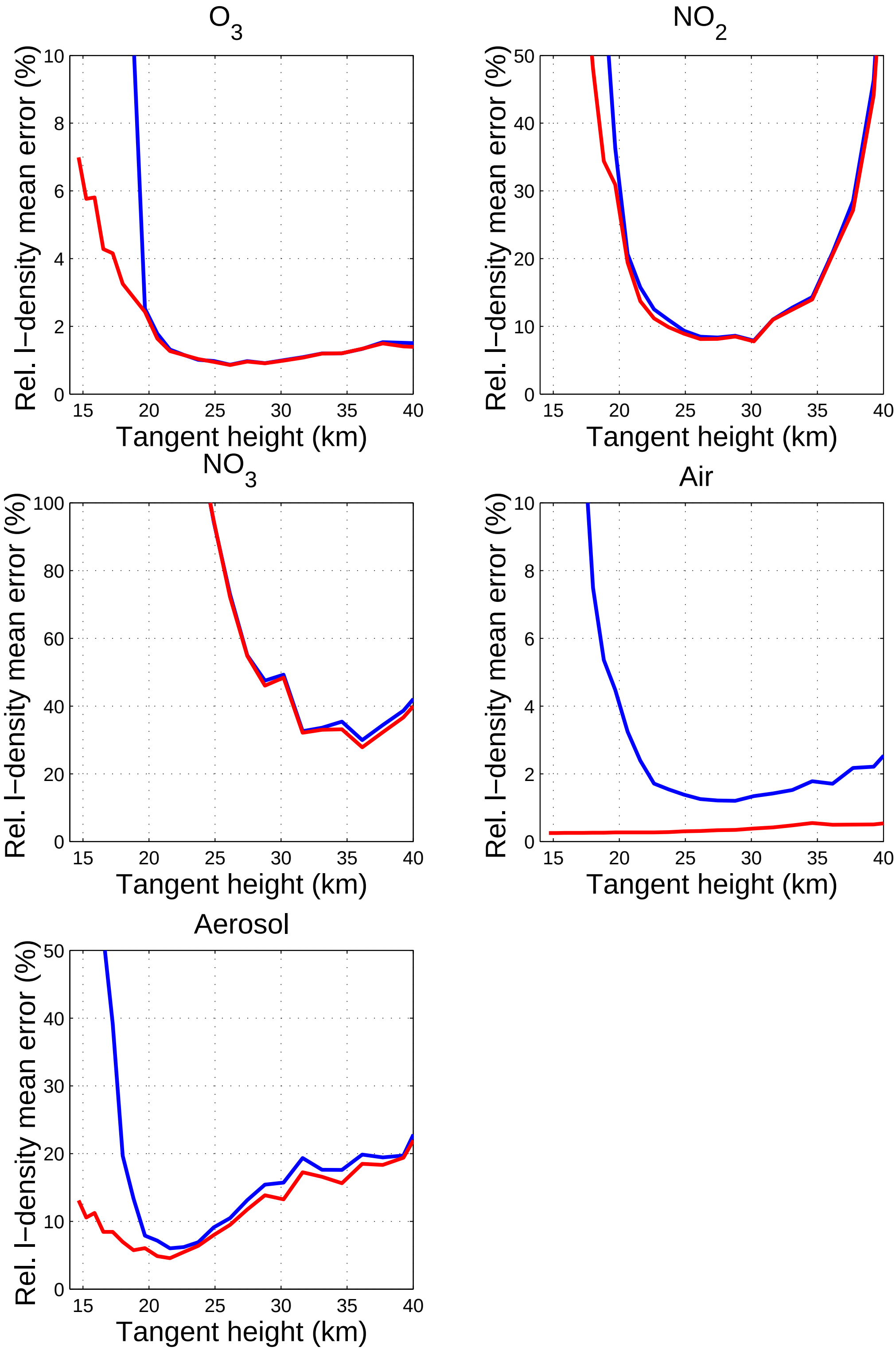
- ECMWF analysis for air density available and already used in GOMOS ray tracing
- ECMWF analysis error estimates $\approx$ 1% below 30 km.
- GOMOS air density retrieval in dim star case and at low altitudes (below 20 km) worse than ECMWF error estimates.
- Could we improve GOMOS retrieval below 20 km by using prior for air density?

Neutral density prior



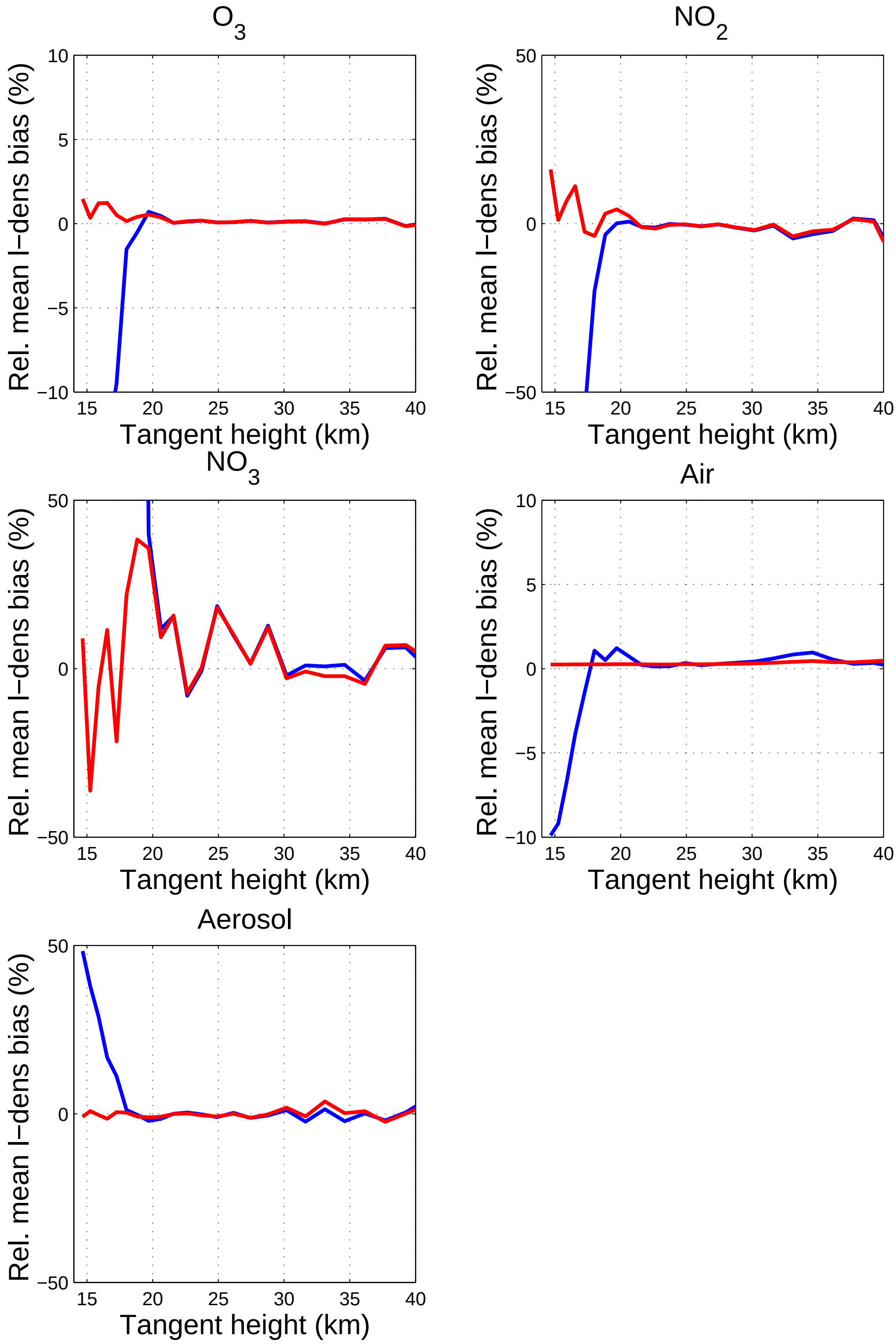
Neutral density prior. Upper figure: profile prior and deviation. Middle figure: line density prior and deviation. Lower figure: relative line density prior.

Air density prior



RMS error. Blue curve - no prior, red curve with prior for neutral density. Typical star (magnitude 2 and temperature 10 000 K).

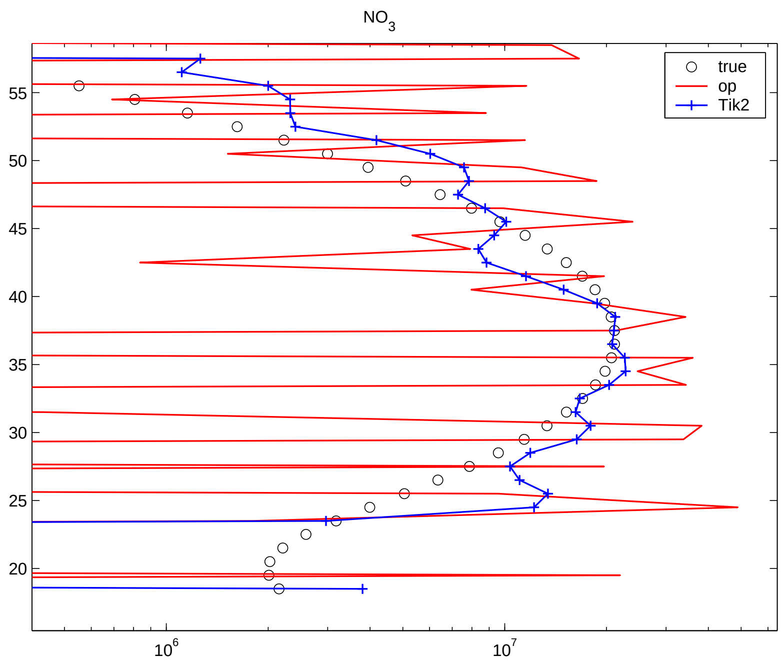
Air density prior



Bias. Blue curve - no prior, red curve with prior for neutral density.
Typical star (magnitude 2 and temperature 10 000 K).

GOMOS vertical inversion: capabilities of the instrument, resolution and smoothing

- Occultation measurement: good vertical sampling resolution $\longrightarrow$ good profile resolution.
- Noisy measurements: Possible small scale structures in NO_2 and NO_3 profiles are difficult to detect because of the noise.
- Ozone retrieval at high altitudes also noisy
- Could we improve the quality of the results by assuming smoothness?



Example of retrieved NO_3 profile.

Tikhonov regularization

Discretized vertical inversion:

$$N = K\rho.$$

Tikhonov regularization solution is $\widehat{\rho}$ which minimizes the functional

$$F_\lambda = \|K\rho - N\|^2 + \lambda G(\rho), \quad (1)$$

λ – regularization parameter

$G(\rho)$ – penalty function

Typical penalty function uses second differences $G(\rho) = \|L\rho\|$:

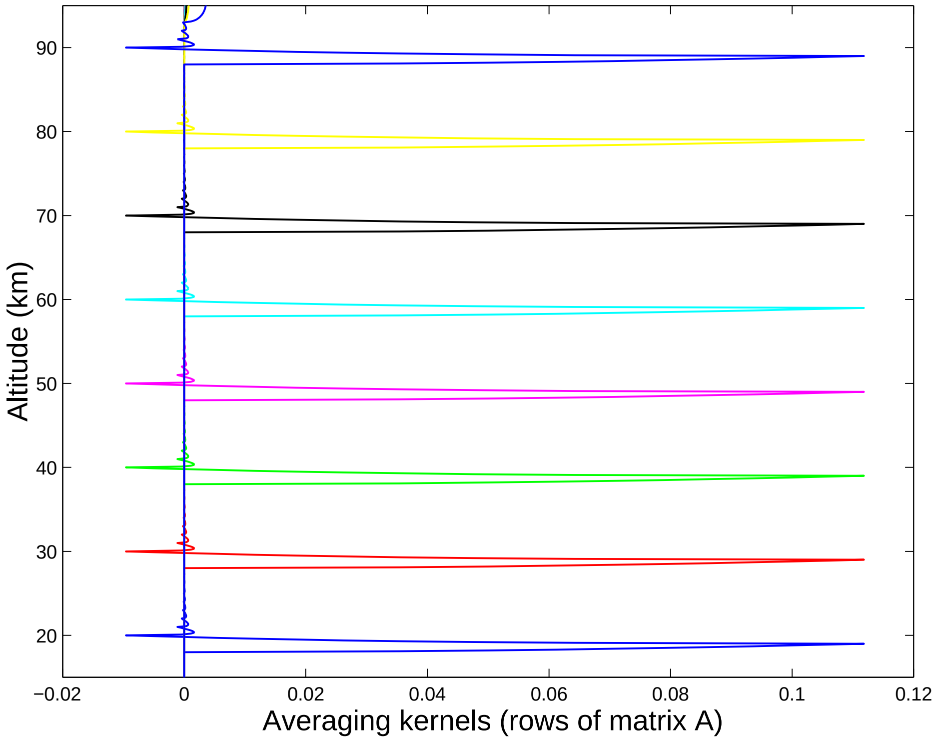
$$L = \frac{1}{h^2}\begin{bmatrix} -1 & 1 & 0 & \dots & 0 \\ 1 & -2 & 1 & \dots & 0 \\ \dots & .. & \dots & \dots & \dots \\ 0 & \dots & 1 & -2 & 1 \\ 0 & 0 & \dots & 1 & -1 \end{bmatrix}$$

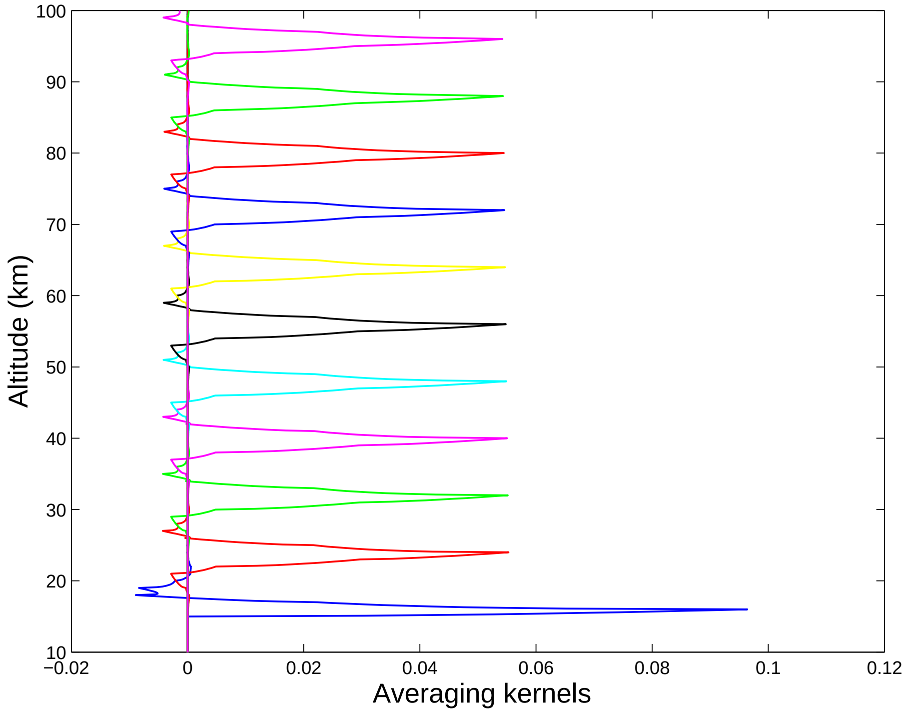
Choosing the amount of smoothing (λ)

- Smoothing improves accuracy but diminishes resolution: Defining the amount of smoothing is a tradeoff between resolution and accuracy.
- Theoretical approach (Morozov's discrepancy principle):
  - Residual should be of the same size as the measurement noise
- Practical approach: Requirements on resolution

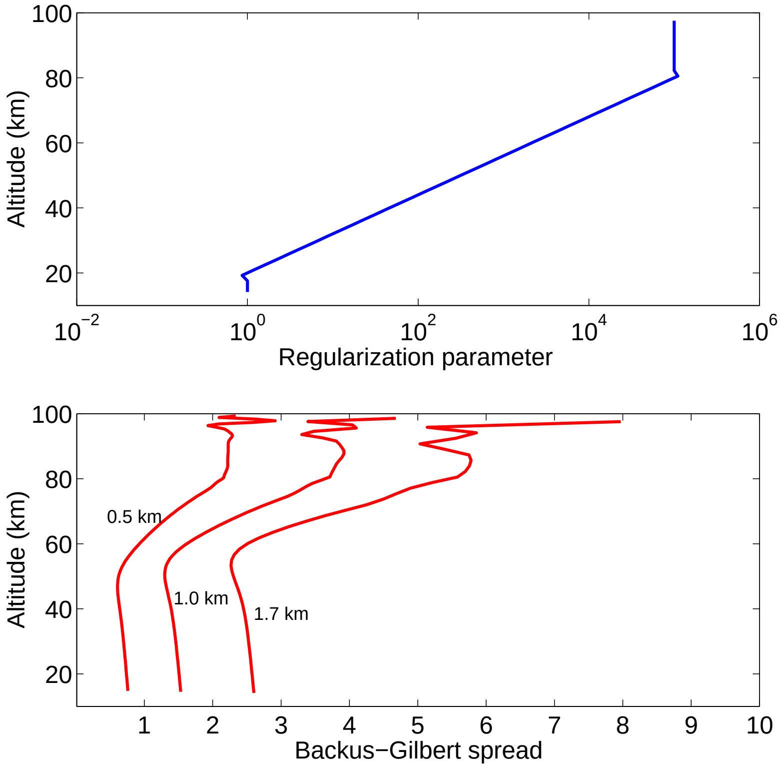
Gas	15-50 km	50-80 km	80-100 km
Ozone	Best possible	2–3 km	5 km
Air	Best possible	2–3 km	5 km
NO_2	3 km	–	–
NO_3	3 km	–	–
Aerosols	3 km	–	–

Averaging kernels

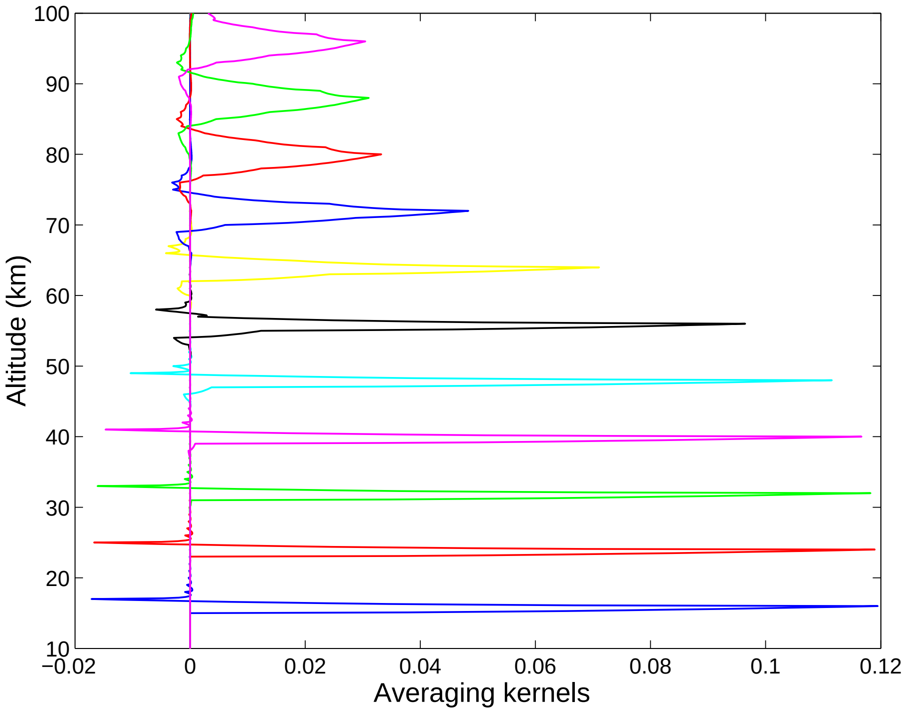




Top: onion peeling averaging kernel (sampling resolution 1 km) Bottom: averaging kernels for NO_2, NO_3 and aerosol with $\lambda = 10^4$.

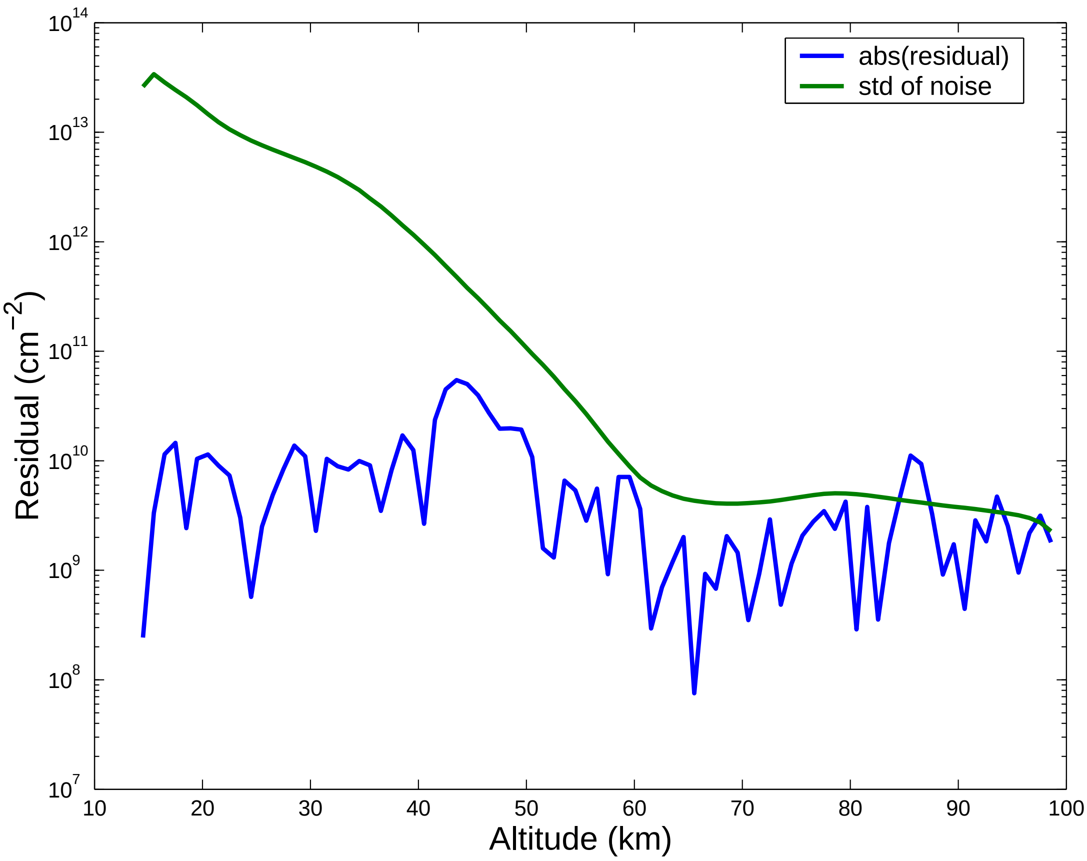


Upper figure: altitude dependent regularization parameter.
Lower figure: Backus-Gilbert spread for different sampling resolutions: 0.5 km, 1.0 km and 1.7 km.



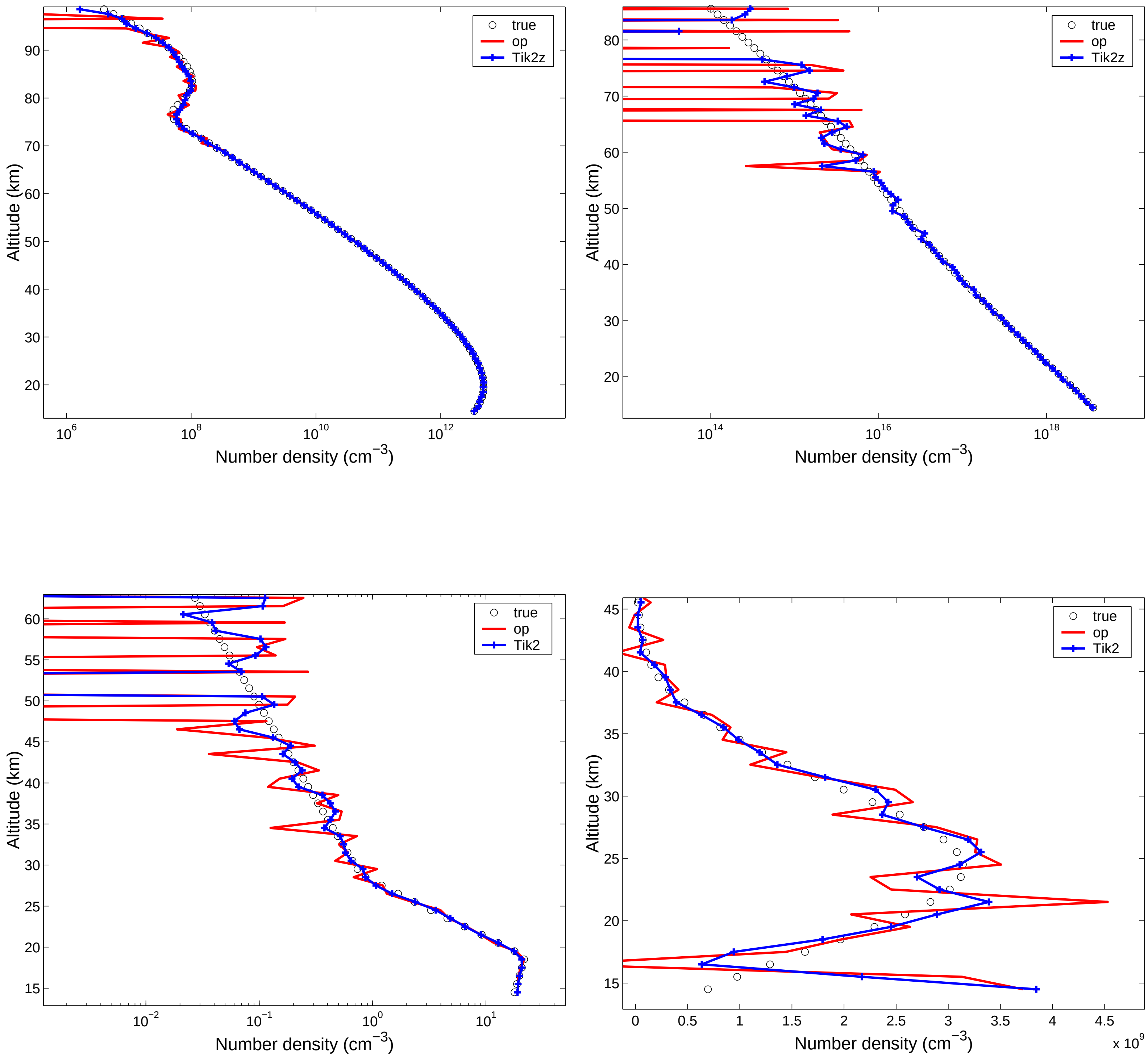
Averaging kernels with altitude dependent regularization parameter $\lambda \in [1, 10^5]$.

Residual



Residual and noise deviation in ozone retrieval with altitude dependent regularization parameter.

Examples of profiles

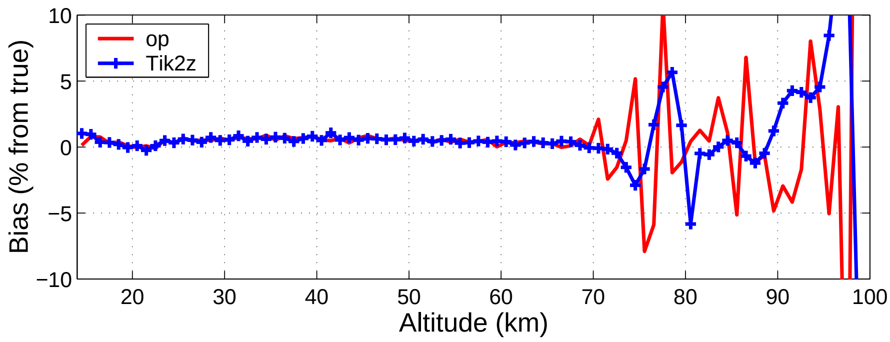


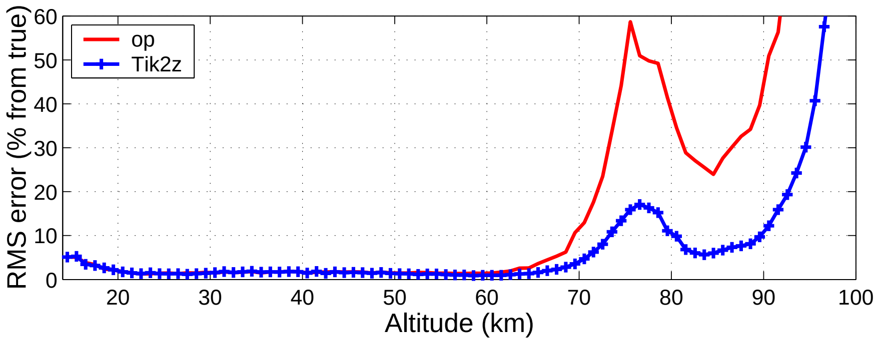
Retrieved profiles of Ozone, Air, aerosols and NO_2.

Red curve - classical onion peeling. Blue curve - Tikhonov regularisation.

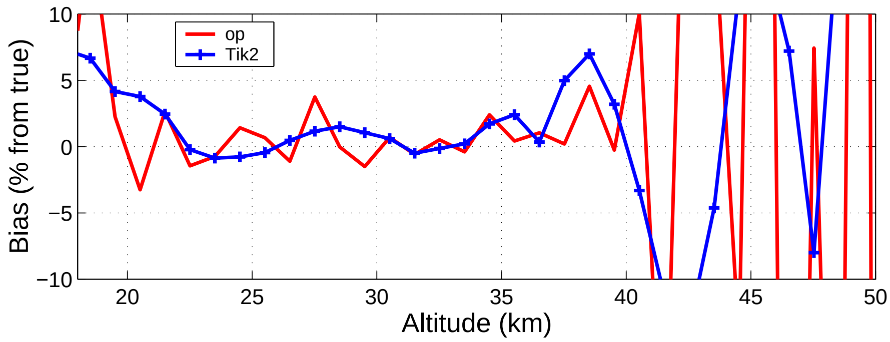
Statistical results - typical star (100 repetitions)

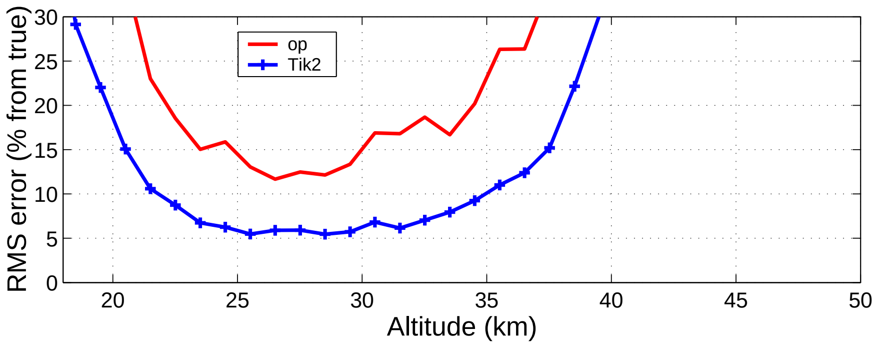
Ozone





NO2





Summary

- Retrieval of ozone profiles below 20 km can be improved by using air prior.
- Positivity requirement reduces correlation between constituent errors and also stabilizes retrieval results
- The retrieval of NO3, NO2 and aerosols can be improved by using smoothness requirement.
- Ozone profiles at high altitudes above 70 km can be improved by using altitude dependent smoothness requirement.

Atmospheric research

Stellar occultation measurements

- Measurement geometry varies $\longrightarrow$ vertical resolution varies
- Different stars $\longrightarrow$ accuracy of profiles varies

Critical points

- Can these characteristics be correctly taken into account in analysis and assimilation?
- How to characterize resolution? (Backus-Gilbert spread is not intuitively correct in all cases)
- How good is ECMWF air density data?
- How to compare measurements with different priors?