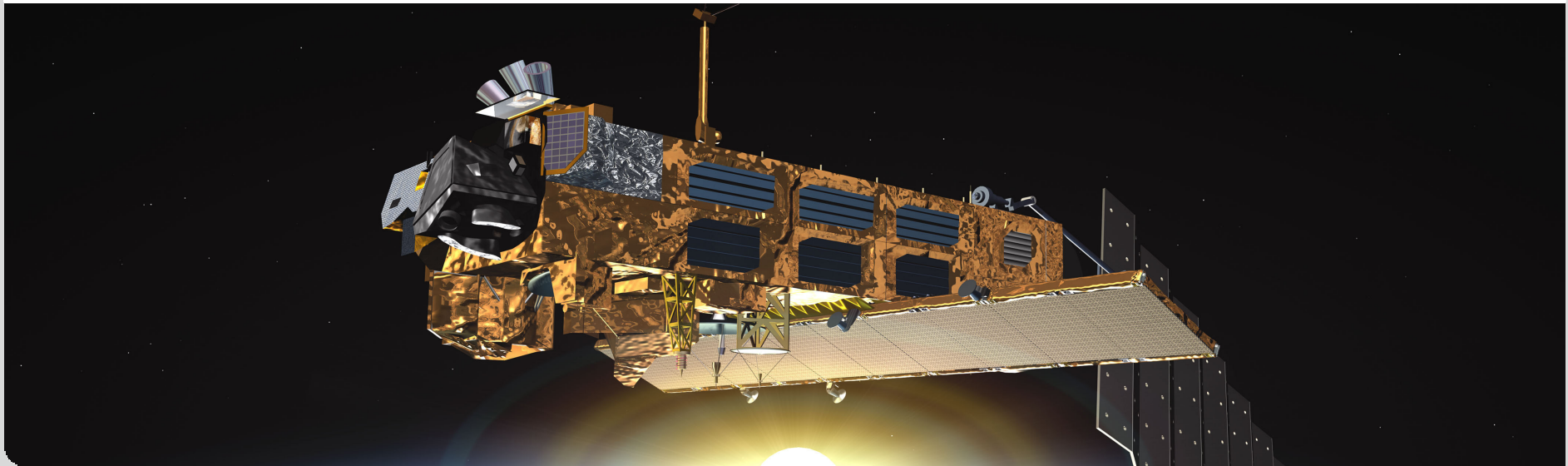


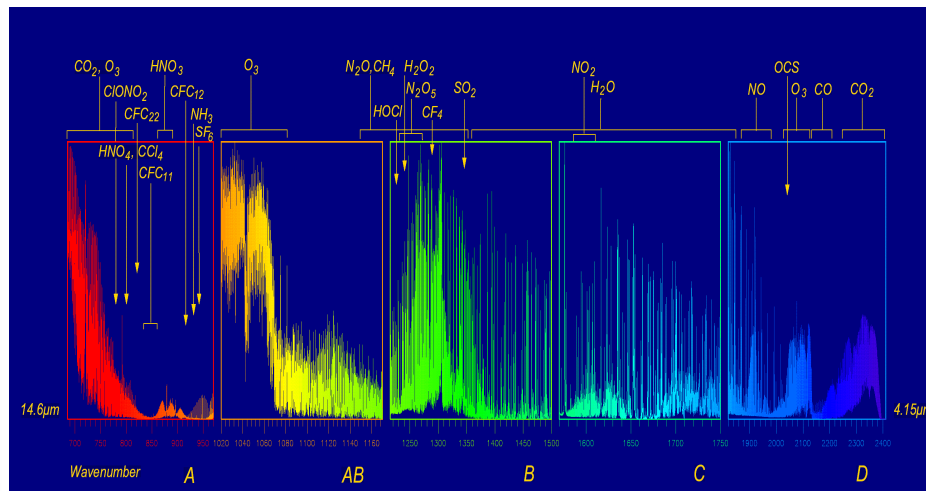
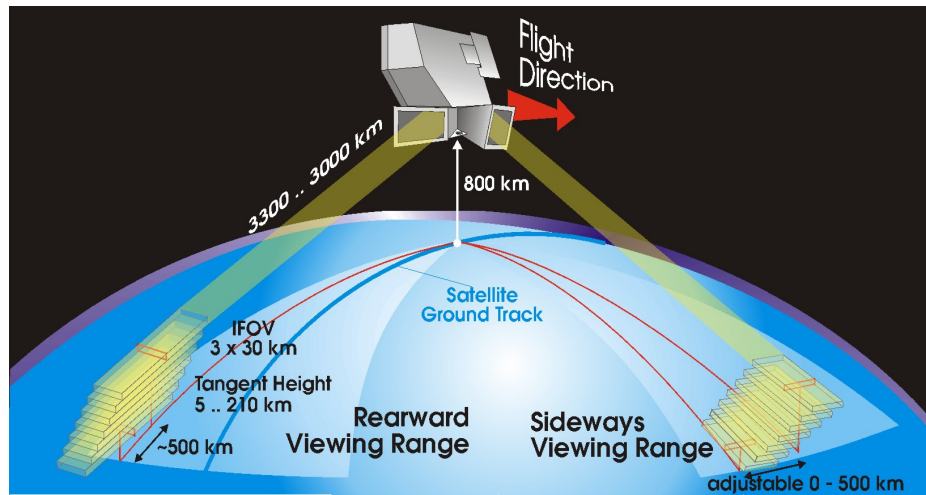
The MIPAS ozone record since 2002

Thomas von Clarmann
and the MIPAS-Envisat teams at IMK, KIT Karlsruhe and IAA, CSIC, Granada, Spain

Institute for Meteorology and Climate Research – Atmospheric Trace Gases and
Remote Sensing



MIPAS measurement principle

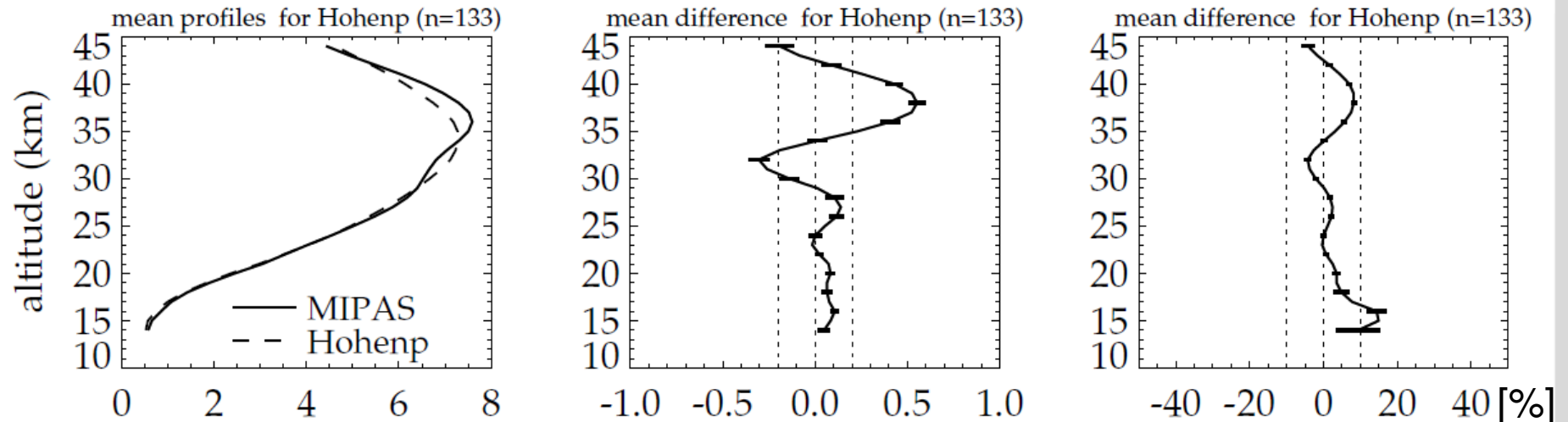


- IR limb emission spectrometer
- Measures day and night
- Altitude range 6 to 70 km (170 km)
- Pole-to-pole, > 1000 profiles/day
- So far 30 trace species, temperature and cloud composition
- **2002 – 2004:** full spectral res., vertical resolution 3.5 - 6 km
- **Since 2005:** reduced spectral resolution, vertical resolution improved (2 - ... km)
- Non-operational scientific analysis of MIPAS data at IMK/IAA

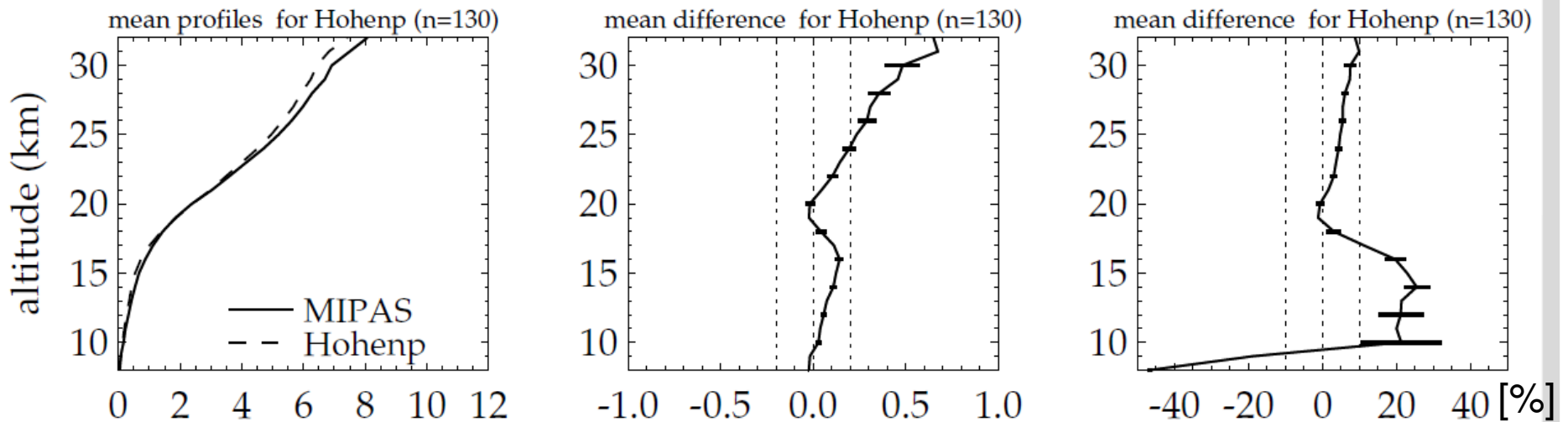
Validation of full-resolution MIPAS ozone profiles (examples)



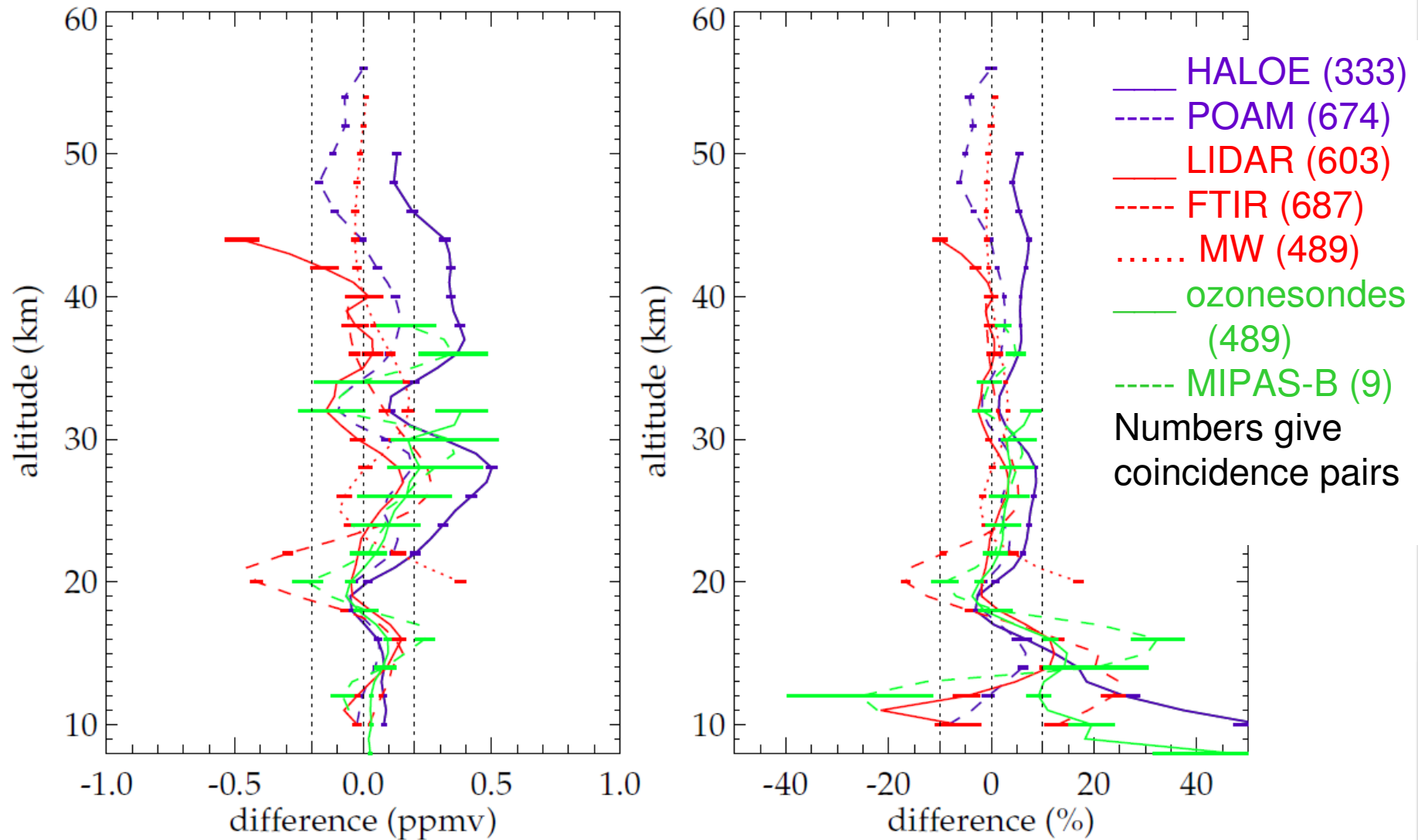
Hohenpeissenberg LIDAR measurements



Hohenpeissenberg ozone sondes



Validation of full-resolution MIPAS ozone profiles cntd.



MIPAS optimized-resolution retrievals (2005 – ...)

Spectral resolution: 0.0625 cm⁻¹ unapodized



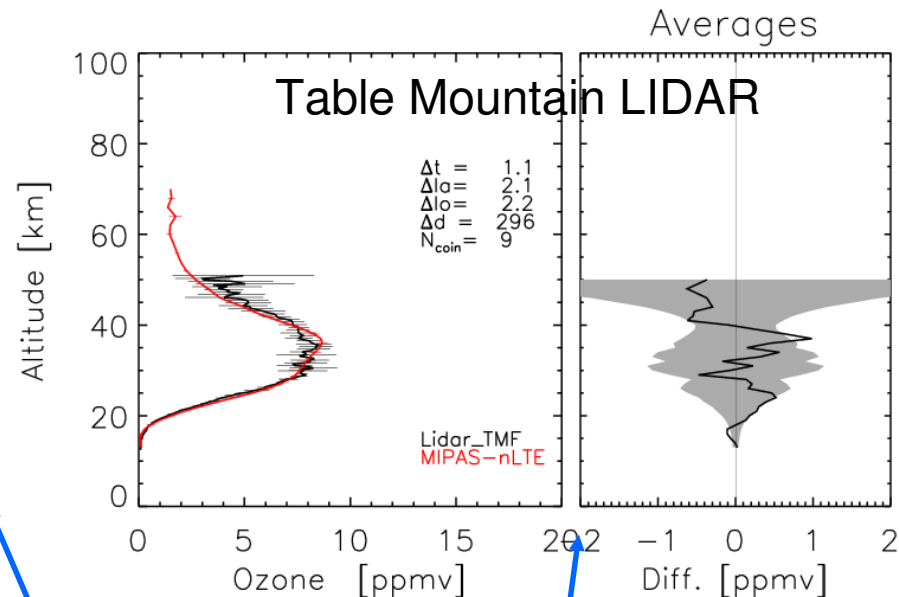
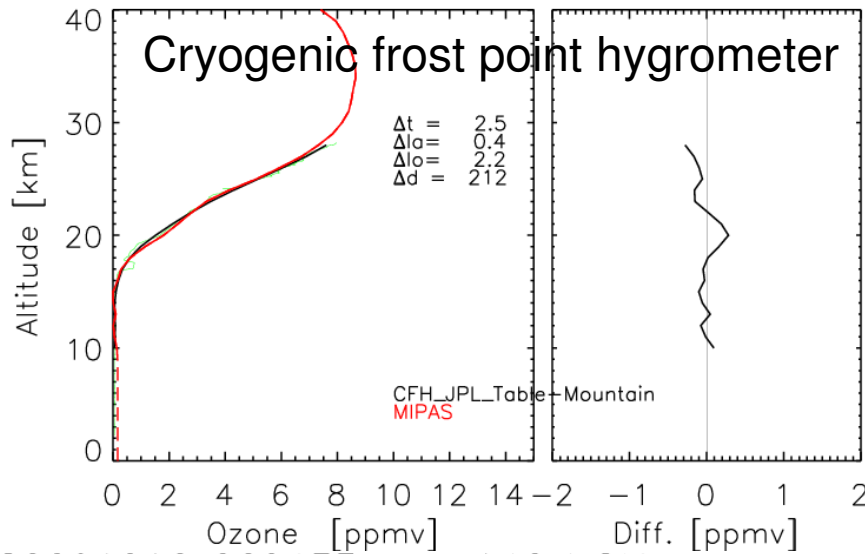
Table 7. O₃ retrieval error budget.

Height km	Noise ppbv (%)	Pointing ppbv (%)	Gain ppbv (%)	T ppbv (%)	Precision ppbv (%)	ILS ppbv (%)	Spectroscopy ppbv (%)	Total error ppbv (%)
50	75.0 (2.1)	180.0 (5.1)	25.0 (0.7)	76.0 (2.1)	210.8 (5.9)	2.5 (0.1)	230.0 (6.5)	312.0 (8.8)
40	50.0 (0.9)	210.0 (3.6)	120.0 (2.1)	130.0 (2.2)	279.1 (4.8)	0.3 (0.0)	650.0 (11.1)	707.4 (12.1)
35	73.0 (1.3)	170.0 (3.1)	95.0 (1.7)	78.0 (1.4)	222.1 (4.0)	85.0 (1.5)	620.0 (11.2)	664.1 (12.0)
30	67.0 (1.1)	200.0 (3.3)	130.0 (2.2)	67.0 (1.1)	256.7 (4.3)	170.0 (2.8)	720.0 (12.1)	783.1 (13.1)
25	60.0 (1.0)	220.0 (3.7)	130.0 (2.2)	85.0 (1.4)	275.9 (4.7)	130.0 (2.2)	700.0 (11.9)	763.6 (12.9)
20	46.0 (1.3)	51.0 (1.4)	120.0 (3.3)	22.0 (0.6)	140.0 (3.8)	89.0 (2.4)	410.0 (11.2)	442.3 (12.1)
15	33.0 (1.9)	1.7 (0.1)	62.0 (3.6)	9.8 (0.6)	70.9 (4.1)	28.0 (1.6)	150.0 (8.6)	168.3 (9.6)
10	28.0 (7.0)	38.0 (9.5)	13.0 (3.2)	13.0 (3.2)	50.7 (12.6)	22.0 (5.5)	40.0 (10.0)	68.2 (17.0)

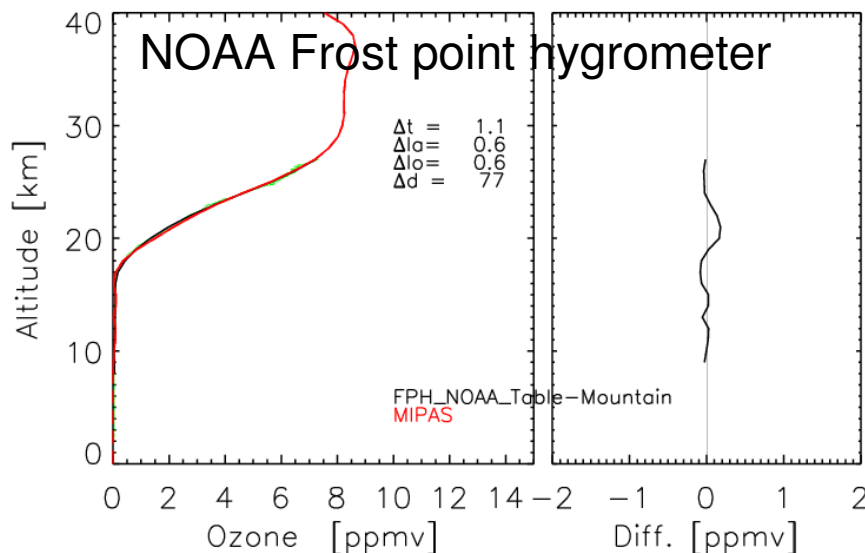
Vertical resolution: 2.4km @ 20km to
3.5km @ 50km
Horizontal resolution: 250km @ 10km to
400km @ 40 km

Validation of optimized-resolution MIPAS ozone data: MOHAVE campaign

20091022 061601 sza=148 NOM



20091016 060433 sza=146 NOM



Averages of TMF and MIPAS: within combined error (precision)
 Max. Time Diff. = 4h
 Max. Distance Diff. = 500km

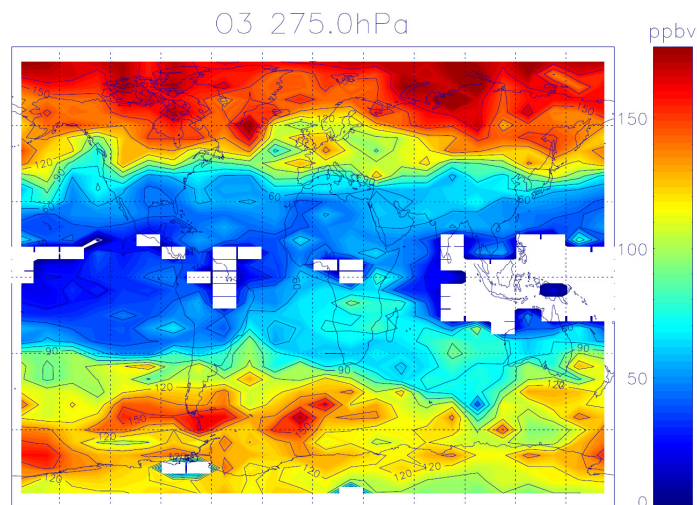
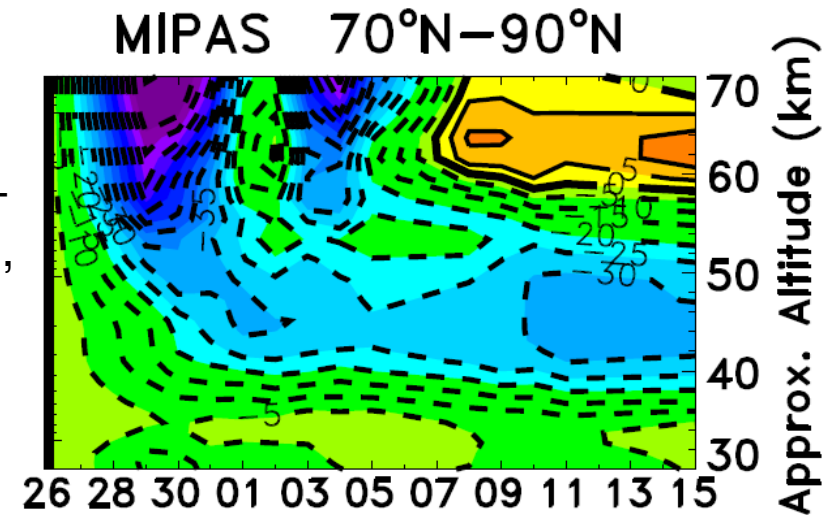
Individual profiles (best coincidences)

Δt (mean) time lag (h)

Δd (average) distance (km)

We see episodes:

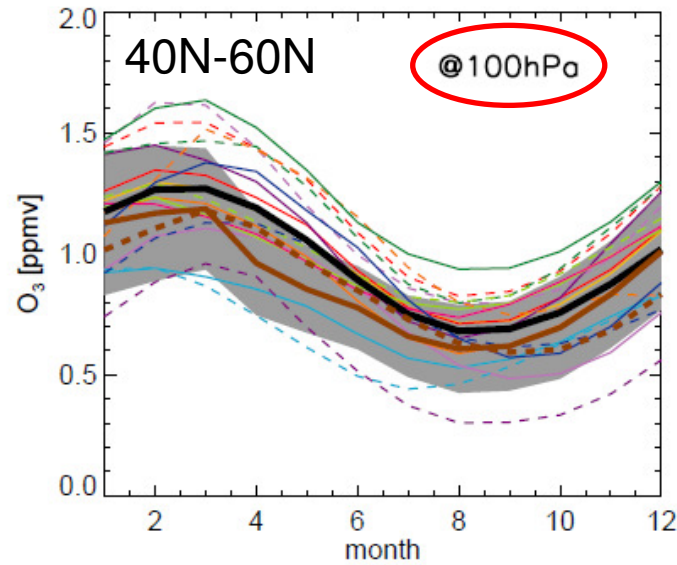
Ozone reduction after SPE (Lopez-Puertas et al, 2005; Jackman et al., 2008)



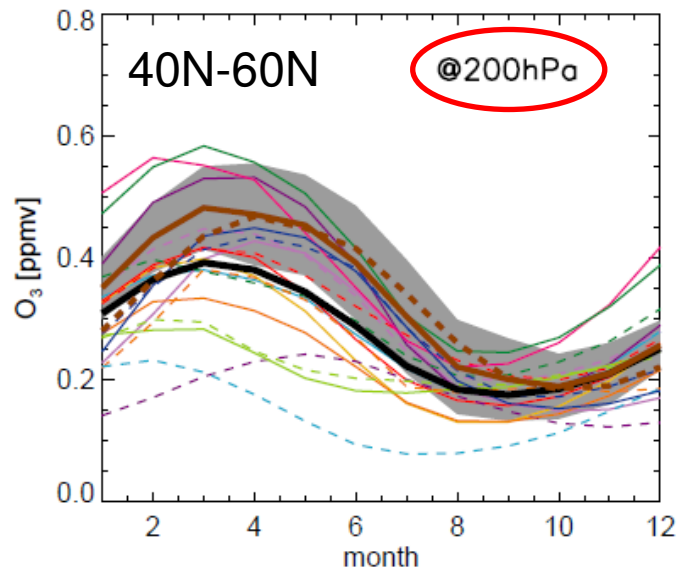
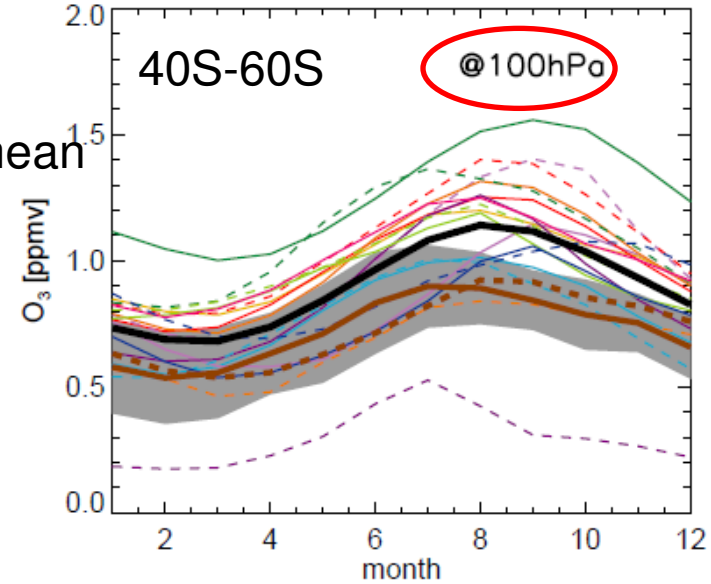
Biomass burning, v. Clarmann et al. 2007,

Use of MIPAS O3 in SPARC-CCMVal activities

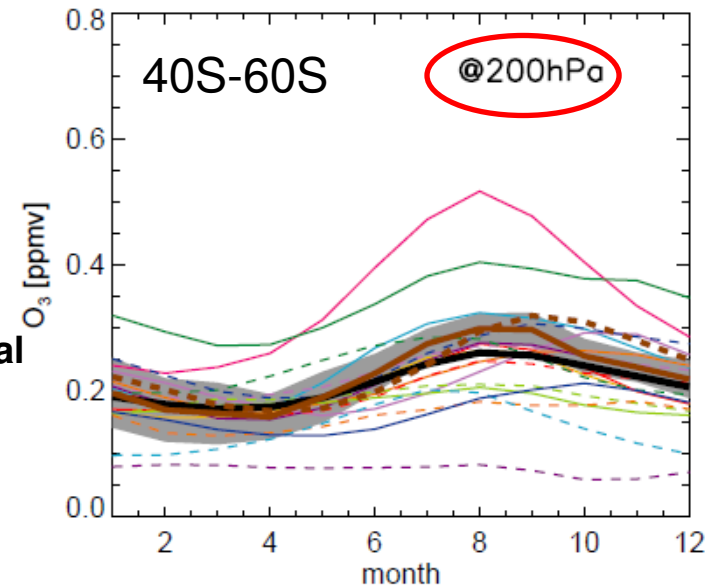
Validation of phase and amplitude of the seasonal cycle of ozone in the extra-tropical UTLS



— MIPAS
- - - MLS
— model mean
Other colors: models



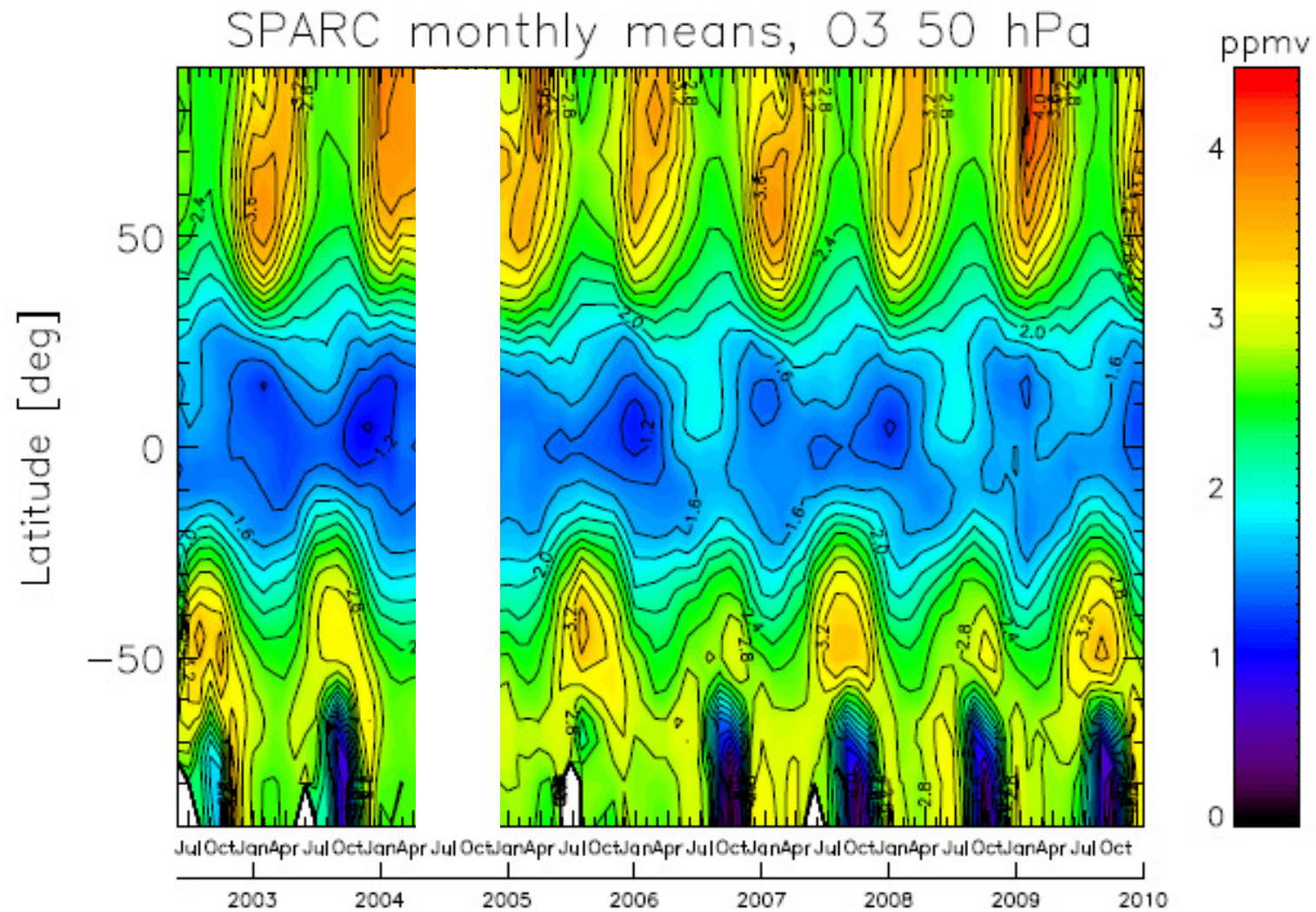
Hegglin et al.,
JGR, 2010 /
SPARC CCMVal
report



al. MIPAS ozone recor

ny

The MIPAS data record since 2002



How to cope with different characteristics?

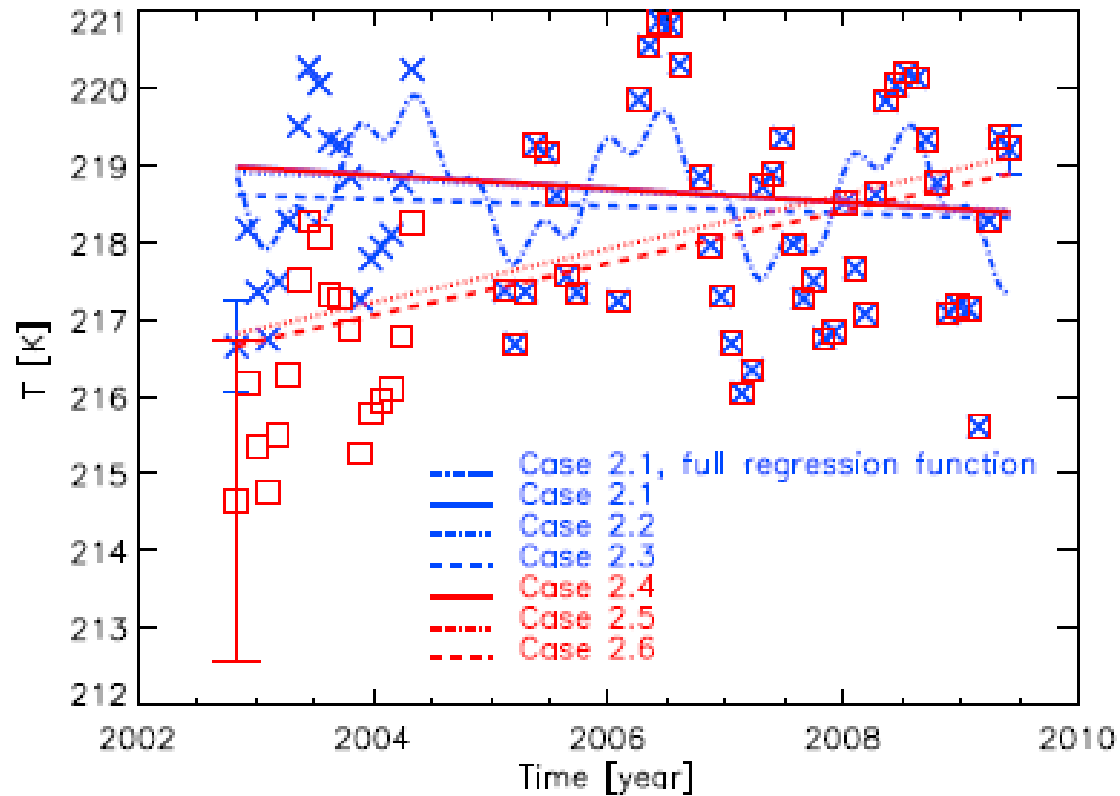
- Rough estimate of the bias (not even the sign must be known, only the order of size of the bias)
- Build covariance matrix of data errors, where a fully correlated error block is added to one subset of the data to describe the bias uncertainty.
- Calculate linear regression under consideration of the full covariance matrix

$$\begin{aligned}
 b &= \frac{\mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{y} - \frac{\mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{e} \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{y}}{\mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{e}}}{\mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{x} - \frac{\mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{e} \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{x}}{\mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{e}}} \\
 &= \frac{\mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{y} \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{e} - \mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{e} \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{y}}{\mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{x} \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{e} - \mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{e} \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{x}}.
 \end{aligned}$$

$$\begin{aligned}
 a &= \frac{\mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{y} - \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{x} b}{\mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{e}} \\
 &= \frac{\mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{y} - \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{x} \frac{\mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{y} \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{e} - \mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{e} \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{y}}{\mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{x} \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{e} - \mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{e} \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{x}}}{\mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{e}} \\
 &= \frac{\mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{y} \mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{x} - \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{x} \mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{y}}{\mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{e} \mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{x} - \mathbf{e}^T \mathbf{S}_y^{-1} \mathbf{x} \mathbf{x}^T \mathbf{S}_y^{-1} \mathbf{e}}.
 \end{aligned}$$

T. von Clarmann et al., ACP, 2010

It works!



... but treatment of a superimposed periodic function requires additional sophistication

Conclusions:

- MIPAS ozone records (global, altitude resolved) are available since 2002.
- These data sets have been validated against various independent measurements.
- Accurate data characterization (error covariance matrices, horizontal and vertical averaging kernels) are available.
- The measurement mode and thus data characteristics have changed in 2004.
- A method has been developed to cope with such data inconsistencies, data inhomogeneities, clustered data etc...

- This tool may also be useful to infer trends from multiple data sources.



$$\sigma_{\text{mean,inter}}^2 = \left(\frac{1}{M}, \dots, \frac{1}{M}\right) S_{\text{inter}} \begin{pmatrix} \frac{1}{M} \\ \vdots \\ \frac{1}{M} \end{pmatrix}$$

$$S_y = S_{\text{noise}} + \begin{pmatrix} \left(\begin{matrix} \text{bias}_{2,1}^2 & \dots & \text{bias}_{2,1}^2 \\ \vdots & \ddots & \vdots \\ \text{bias}_{2,1}^2 & \dots & \text{bias}_{2,1}^2 \end{matrix} \right) \begin{pmatrix} 0 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 0 \end{pmatrix} \\ \left(\begin{matrix} 0 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 0 \end{matrix} \right) \begin{pmatrix} 0 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 0 \end{pmatrix} \end{pmatrix}, \quad (15)$$

$$\sigma_{\text{mean}} = \sqrt{\sigma^2 \left(\frac{1 + (M-1)\bar{r}_{\text{inter}}}{M} \right)},$$

$$S_{a,b,c,d} = \begin{pmatrix} \frac{\partial a}{\partial y} \\ \frac{\partial b}{\partial y} \\ \frac{\partial c}{\partial y} \\ \frac{\partial d}{\partial y} \end{pmatrix} S_y \begin{pmatrix} \frac{\partial a}{\partial y} \\ \frac{\partial b}{\partial y} \\ \frac{\partial c}{\partial y} \\ \frac{\partial d}{\partial y} \end{pmatrix}^T$$

$$= \left(\Gamma^{-1} \left(\frac{\partial q}{\partial y} \right) \right) S_y \left(\Gamma^{-1} \left(\frac{\partial q}{\partial y} \right) \right)^T$$

$$= \left(\Gamma^{-1} \begin{pmatrix} 2e^T S_y^{-1} \\ 2v_{\text{sin}}^T S_y^{-1} \\ 2v_{\text{cos}}^T S_y^{-1} \end{pmatrix} \right) S_y$$

$$\times \left(\Gamma^{-1} \begin{pmatrix} 2e^T S_y^{-1} \\ 2v_{\text{sin}}^T S_y^{-1} \\ 2v_{\text{cos}}^T S_y^{-1} \end{pmatrix} \right)^T$$

$$\frac{\partial \chi^2}{\partial a} = -2e^T S_y^{-1}(y - ae - bx) = 0;$$

$$e^T S_y^{-1}y = e^T S_y^{-1}ae + e^T S_y^{-1}bx;$$

$$a = \frac{e^T S_y^{-1}y - e^T S_y^{-1}bx}{e^T S_y^{-1}e}$$

and

$$\frac{\partial \chi^2}{\partial b} = -2x^T S_y^{-1}(y - ae - bx) = 0;$$

$$x^T S_y^{-1}y - x^T S_y^{-1}ae - x^T S_y^{-1}bx = 0$$

$$x^T S_y^{-1}y = x^T S_y^{-1}bx + x^T S_y^{-1}ae.$$

Combining Eqs. 5 and 6 gives

$$x^T S_y^{-1}y = x^T S_y^{-1}bx + x^T S_y^{-1}ae$$

$$= x^T S_y^{-1}bx + x^T S_y^{-1}e \frac{e^T S_y^{-1}y - e^T S_y^{-1}bx}{e^T S_y^{-1}e}$$

This can be rearranged as

$$x^T S_y^{-1}bx - \frac{x^T S_y^{-1}e e^T S_y^{-1}bx}{e^T S_y^{-1}e} = \quad (8)$$

$$x^T S_y^{-1}y - \frac{x^T S_y^{-1}e e^T S_y^{-1}y}{e^T S_y^{-1}e}$$

and finally solved to give b:

$$e^{T \left(\frac{1}{M} \dots \frac{1}{M} \right)} \frac{x^T S_y^{-1}e e^T S_y^{-1}y}{e^T S_y^{-1}e} - \frac{x^T S_y^{-1}e e^T S_y^{-1}x}{e^T S_y^{-1}e} \quad (9)$$

$$\frac{-1e - x^T S_y^{-1}e e^T S_y^{-1}y}{-1e - x^T S_y^{-1}e e^T S_y^{-1}x}$$

to Eq. 5 allows to calculate a:

$$\frac{e^T S_y^{-1}xb}{e^T S_y^{-1}e} \quad (10)$$

$$\frac{e^T S_y^{-1}y - e^T S_y^{-1}x \frac{x^T S_y^{-1}e e^T S_y^{-1}y - x^T S_y^{-1}e e^T S_y^{-1}x}{x^T S_y^{-1}e e^T S_y^{-1}e - x^T S_y^{-1}e e^T S_y^{-1}x}}{e^T S_y^{-1}e}$$

$$= \frac{e^T S_y^{-1}yx^T S_y^{-1}x - e^T S_y^{-1}xx^T S_y^{-1}y}{e^T S_y^{-1}ex^T S_y^{-1}x - e^T S_y^{-1}xx^T S_y^{-1}e}$$

Thank you for
your
patience!

$$\bar{a} = \frac{\sum y_n}{N} - \bar{b} \frac{\sum x_n}{N}, \quad (11)$$

where

$$\bar{b} = \frac{N \sum x_n y_n - \sum x_n \sum y_n}{N \sum x_n^2 - (\sum x_n)^2} \quad (12)$$

The uncertainty of the slope b is:

$$\sigma_b^2 = \left(\frac{\partial b}{\partial y} \right) S_y \left(\frac{\partial b}{\partial y} \right)^T \quad (13)$$

$$= \left(\frac{e^T S_y^{-1} x e^T S_y^{-1} - x^T S_y^{-1} e e^T S_y^{-1}}{x^T S_y^{-1} x e^T S_y^{-1} e - x^T S_y^{-1} e e^T S_y^{-1} x} \right)$$

$$S_y \left(\frac{e^T S_y^{-1} x e^T S_y^{-1} - x^T S_y^{-1} e e^T S_y^{-1}}{x^T S_y^{-1} x e^T S_y^{-1} e - x^T S_y^{-1} e e^T S_y^{-1} x} \right)^T$$

where $\left(\frac{\partial b}{\partial y} \right) = \left(\frac{\partial b}{\partial y_1}, \dots, \frac{\partial b}{\partial y_N} \right)$. The uncertainty of a is estimated accordingly:

$$\sigma_a^2 = \left(\frac{\partial a}{\partial y} \right) S_y \left(\frac{\partial a}{\partial y} \right)^T$$

$$= \left(\frac{x^T S_y^{-1} x e^T S_y^{-1} - e^T S_y^{-1} x x^T S_y^{-1}}{e^T S_y^{-1} x e^T S_y^{-1} x - e^T S_y^{-1} x x^T S_y^{-1} e} \right)$$

$$S_y \left(\frac{x^T S_y^{-1} x e^T S_y^{-1} - e^T S_y^{-1} x x^T S_y^{-1}}{e^T S_y^{-1} x e^T S_y^{-1} x - e^T S_y^{-1} x x^T S_y^{-1} e} \right)^T$$

$$\frac{\partial \chi^2}{\partial a} = -2e^T S_y^{-1}(y(x) - ae - bx - cv_{\text{sin}} - dv_{\text{cos}})$$

$$\frac{\partial \chi^2}{\partial b} = -2x^T S_y^{-1}(y(x) - ae - bx - cv_{\text{sin}} - dv_{\text{cos}}) =$$

$$\frac{\partial \chi^2}{\partial c} = -2v_{\text{sin}}^T S_y^{-1}(y(x) - ae - bx - cv_{\text{sin}} - dv_{\text{cos}}) = 0$$

$$\frac{\partial \chi^2}{\partial d} = -2v_{\text{cos}}^T S_y^{-1}(y(x) - ae - bx - cv_{\text{sin}} - dv_{\text{cos}}) = 0,$$

$$0 = -2e^T S_y^{-1} \left(y(x) - a_{i+1}e - b_{i+1}x - \right.$$

$$c_{i+1} \text{diag} \left((a_i e + b_i x) v_{\text{sin}}^T \right) -$$

$$d_{i+1} \text{diag} \left((a_i e + b_i x) v_{\text{cos}}^T \right) \left. \right);$$

$$(22)$$

$$(23)$$

$$bx))^T S_y^{-1}(y - (ae + bx))$$