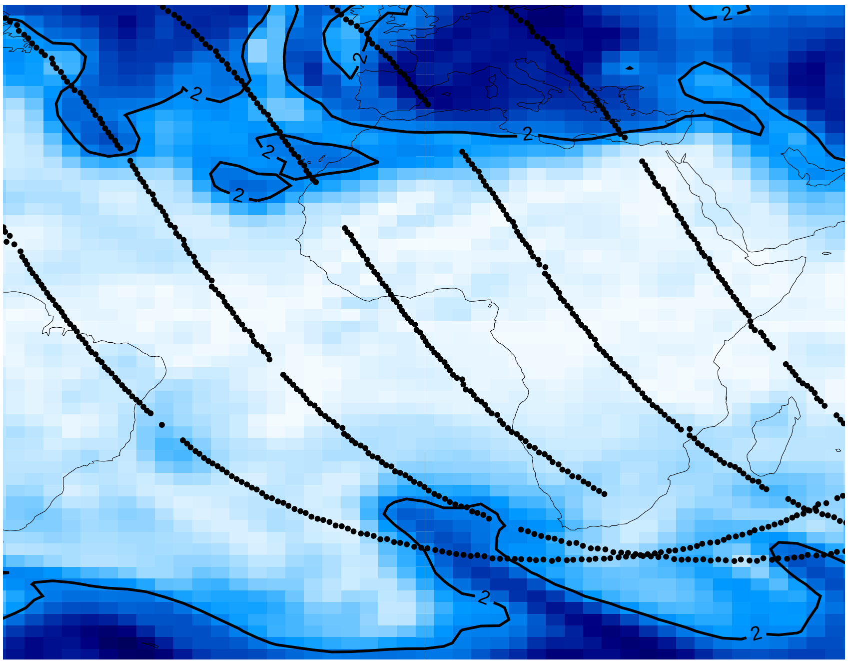
Instrumental Requirements for a Submillimeter-Wave Limb Sounder

Stefan Bühler, Björn-Martin Sinnhuber
Institute of Remote Sensing
University of Bremen

International Workshop on Submillimeter-wave Observation of Earth's Atmosphere from Space
Tokyo, January 27–29, 1999



IFE

Overview

- Motivation
- Retrieval method
- Error analysis: The linear mapping method
- The SOPRANO instrument
- Antenna
  - Antenna efficiency
  - Far wing knowledge
- Pointing
  - Pointing accuracy
  - Pointing stability
- Radiometric errors
  - Baseline ripples
  - Baseline discontinuities
  - Calibration errors
- Error summary for selected species
- Conclusions
- Ongoing work

Motivation

- Which instrument parameters are crucial for the scientific goal?
- Minimize systematic errors
- Optimize performance

Retrieval by optimal estimation

- Described in: Rodgers, C. D., *Journal of Geophysical Research*, *95*, 5587–5595, 1990.

- Minimize:

$$\chi^2_{\mathrm{OEM}} = [\vec{y} - F(\vec{x})]\,\mathbf{S}_{\vec{y}}^{-1}\,[\vec{y} - F(\vec{x})] + [\vec{x} - \vec{x}_a]\,\mathbf{S}_{\vec{x}_a}^{-1}\,[\vec{x} - \vec{x}_a]$$

$\vec{x}$	:	state vector
$\vec{x}_a$	:	a priori
$\mathbf{S}_{\vec{x}_a}$	:	a priori covariance matrix
$\vec{y}$	:	measurement
$F(\vec{x})$	:	forward model
$\mathbf{S}_{\vec{y}}$	:	meas. covariance matrix

- We use the Levenberg-Marquardt method to find the minimum

Method of investigation

- Impact of instrument parameters on the retrieval investigated by **linear mapping**:

$$\mathbf{D} = \partial\hat{\mathbf{x}}/\partial\mathbf{y}$$

$\mathbf{D}$: Contribution function matrix
$\hat{\mathbf{x}}$: Retrieved atmospheric profile
$\mathbf{y}$: Measured spectrum

- Impact on retrieval then given as

$$\Delta\hat{\mathbf{x}} = \mathbf{D}\Delta\mathbf{y}$$

- Generate ensembles of 100 or 1000 cases and calculate RMS error.

The SOPRANO Instrument

Band	f [GHz]	Species
A	497.5 – 504.75	**O_3**, **ClO**, **CH_3Cl**, (**BrO**), N_2O, H_2O, (HNO_3), (COF_2)
B1	624.6 – 626.5	**HCl**, O_3, HOCl, (HNO_3), (BrO), (HO_2)
B2	627.95 – 628.95	**HOCl**, O_3, HNO_3, (COF_2)
C1	635.6 – 637.4	**CH_3Cl**, O_3, HNO_3, HOCl, HO_2
C2	648.0 – 652.0	**ClO**, **O_3**, N_2O, HNO_3, (H_2CO), (HOCl), (HO_2), (NO_2), (BrO)
D	730.8 – 732.25	**T**, O_3, Scan, **HNO_3**, (CH_3Cl), (HO_2)
E	851.5 – 852.5	**NO**, O_3, N_2O, (HNO_3), (NO_2), (H_2O_2)
F	952.0 – 955.0	**NO**, **T**, Scan, O_3, N_2O, (HO_2), (HNO_3), (CH_3Cl), (NO_2)
G1	685.5 – 687.2	**ClO**, O_3, (HNO_3), (HOCl), (H_2O_2), (COF_2), (NO_2)
G2	688.5 – 692.0	**CO**, **CH_3Cl**, ClO, O_3, HNO_3, (HO_2), (HOCl), (HCN), (NO_2), (H_2O)

Antenna

Assumed full width at -3 dB around a typical tangent point: $\approx$ **2.7 km**. (SOPRANO antenna)

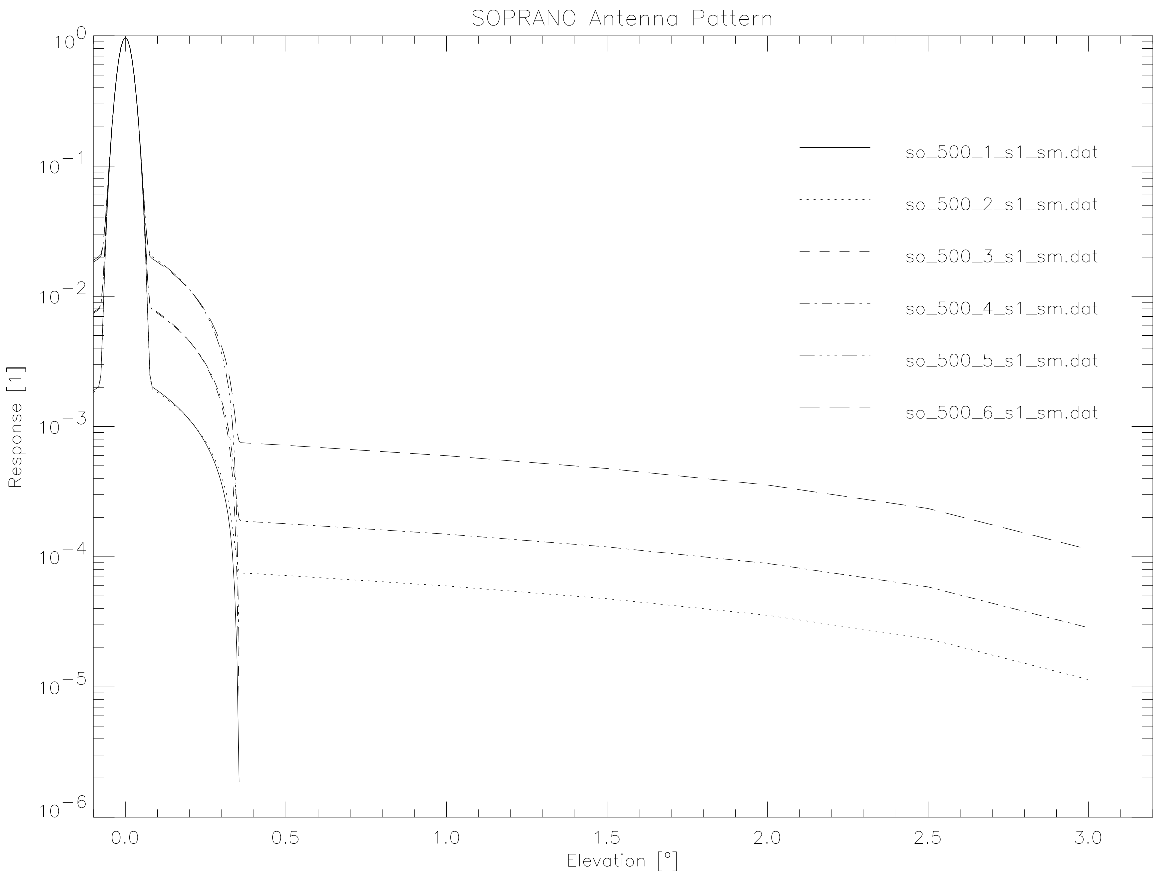
(Should be about 12 % narrower for JEM/SMILES if one takes into account only platform altitude and antenna diameter.)

Investigation of:

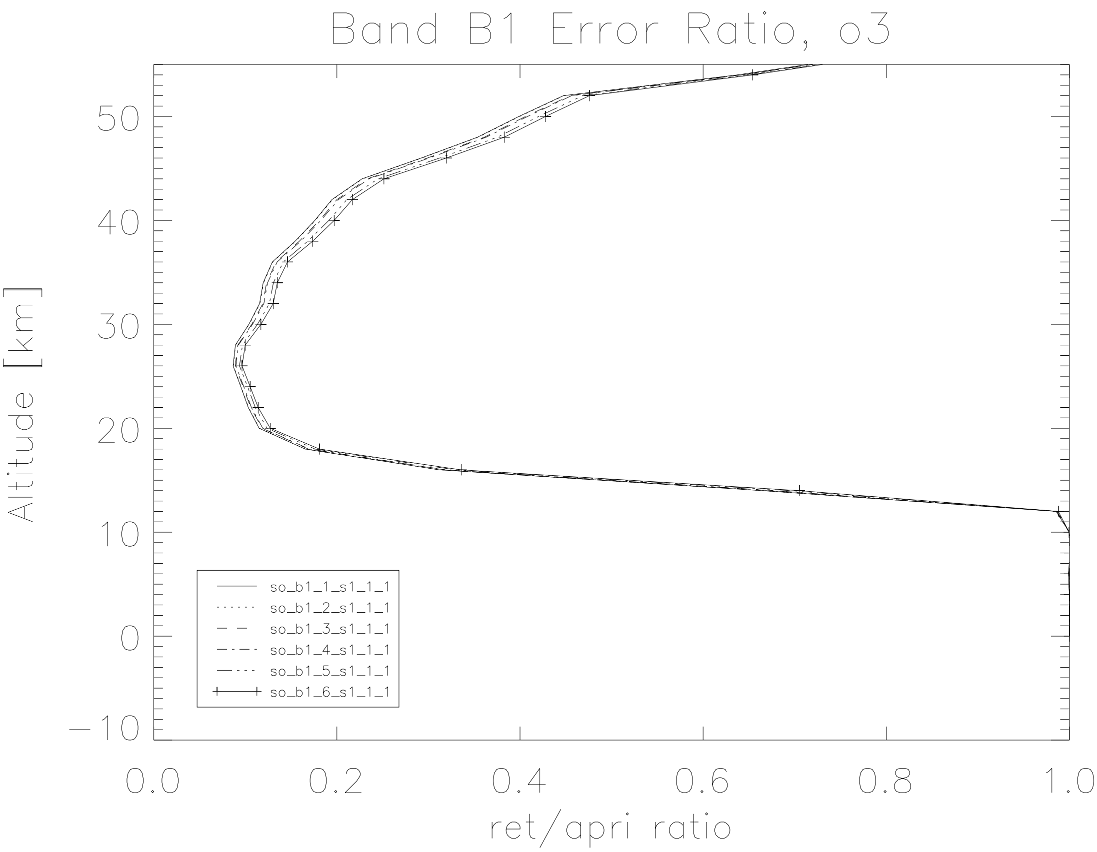
- Perfectly known antenna pattern:
  How important is a good antenna efficiency (small near and far wing)?
- Imperfect antenna knowledge

Near and far wings

Case	Integration [%]	
	Near Wing	Far Wing
1	1.0	0.0
2	1.0	0.4
3	4.0	0.0
4	4.0	1.0
5	10.0	0.0
6	10.0	4.0



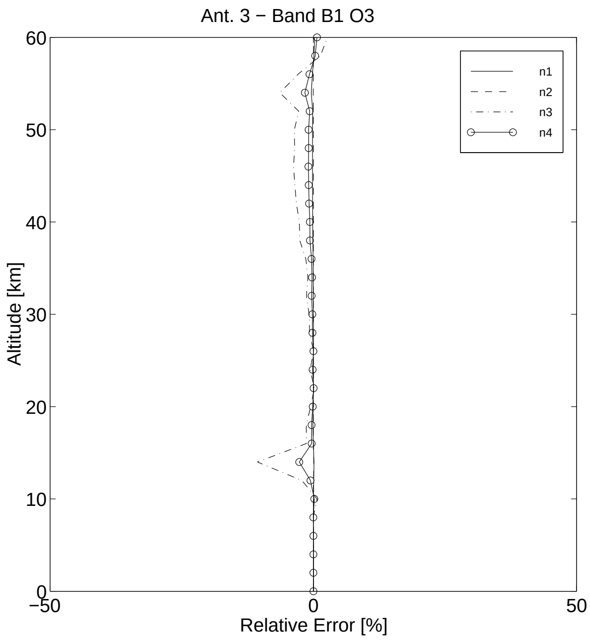
Near and far wings: O_3 near 625 GHz



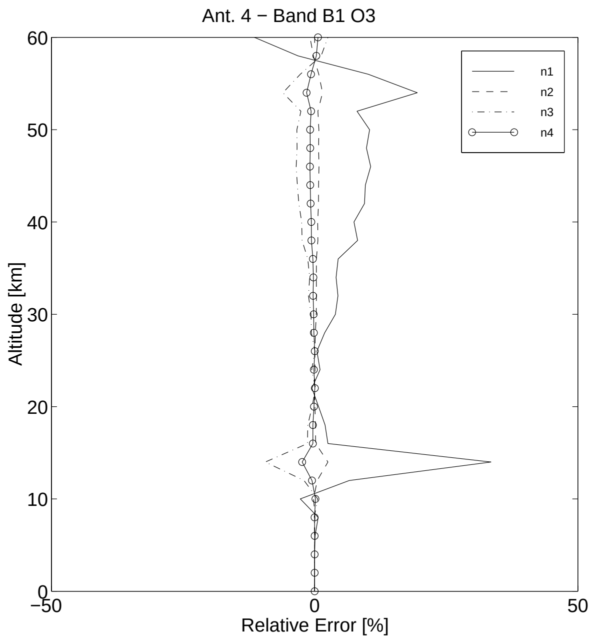
$\Longrightarrow$ Negligible,
but
under the assumption that the antenna response is perfectly known throughout near and far wing.

Imperfect antenna knowledge

4 % near, 0 % far wing



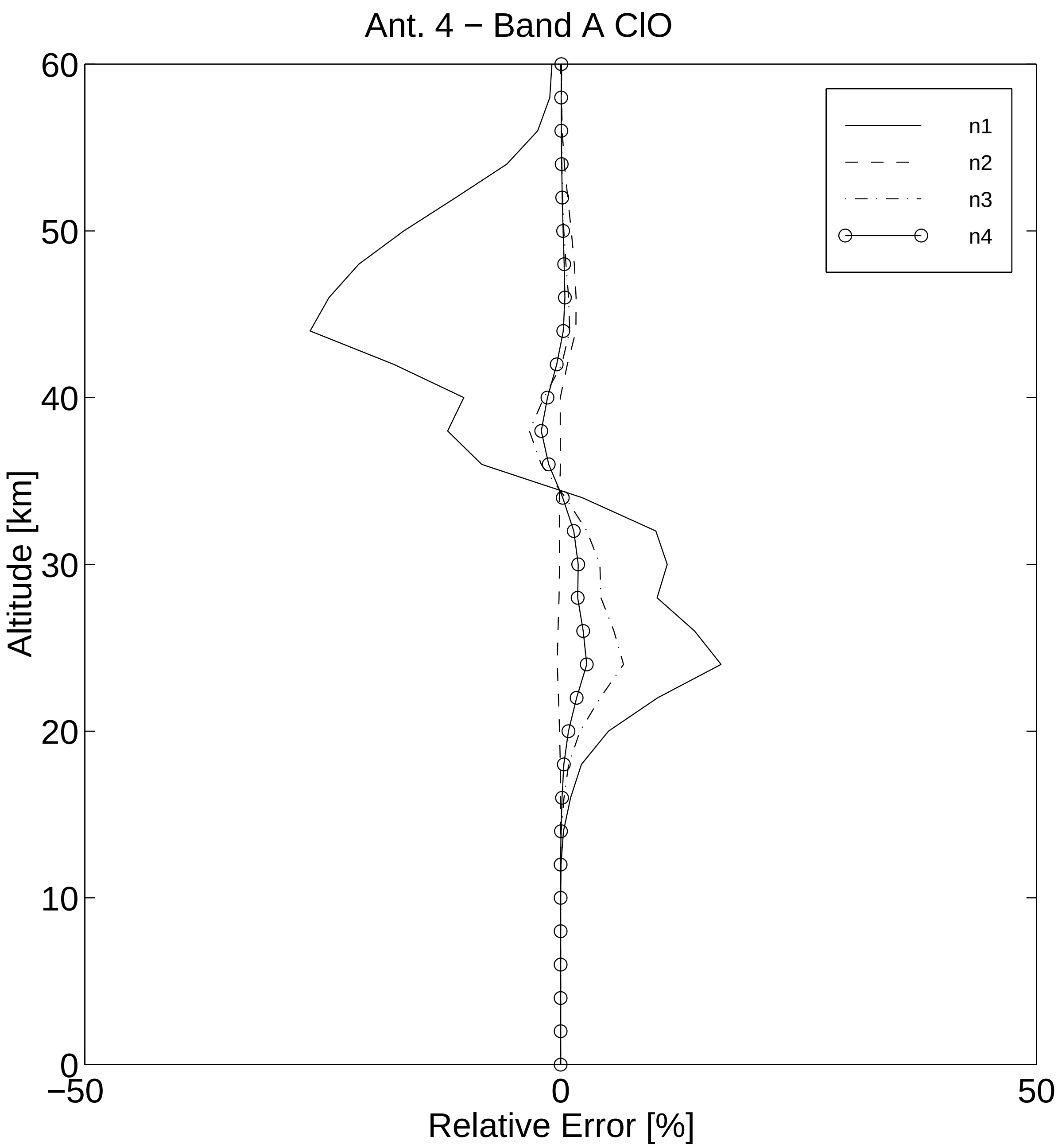
4 % near, 1 % far wing



- **n1**: Antenna pattern measured with 20 dB non-linearity, 35 dB noise
- **n2**: Antenna pattern measured with 30 dB non-linearity, 45 dB noise
- **n3**: 10μm antenna distortion
- **n4**: 0.25 times the effect of n3

Imperfect knowledge: ClO near 500 GHz

- 4 % near wing, 1 % far wing



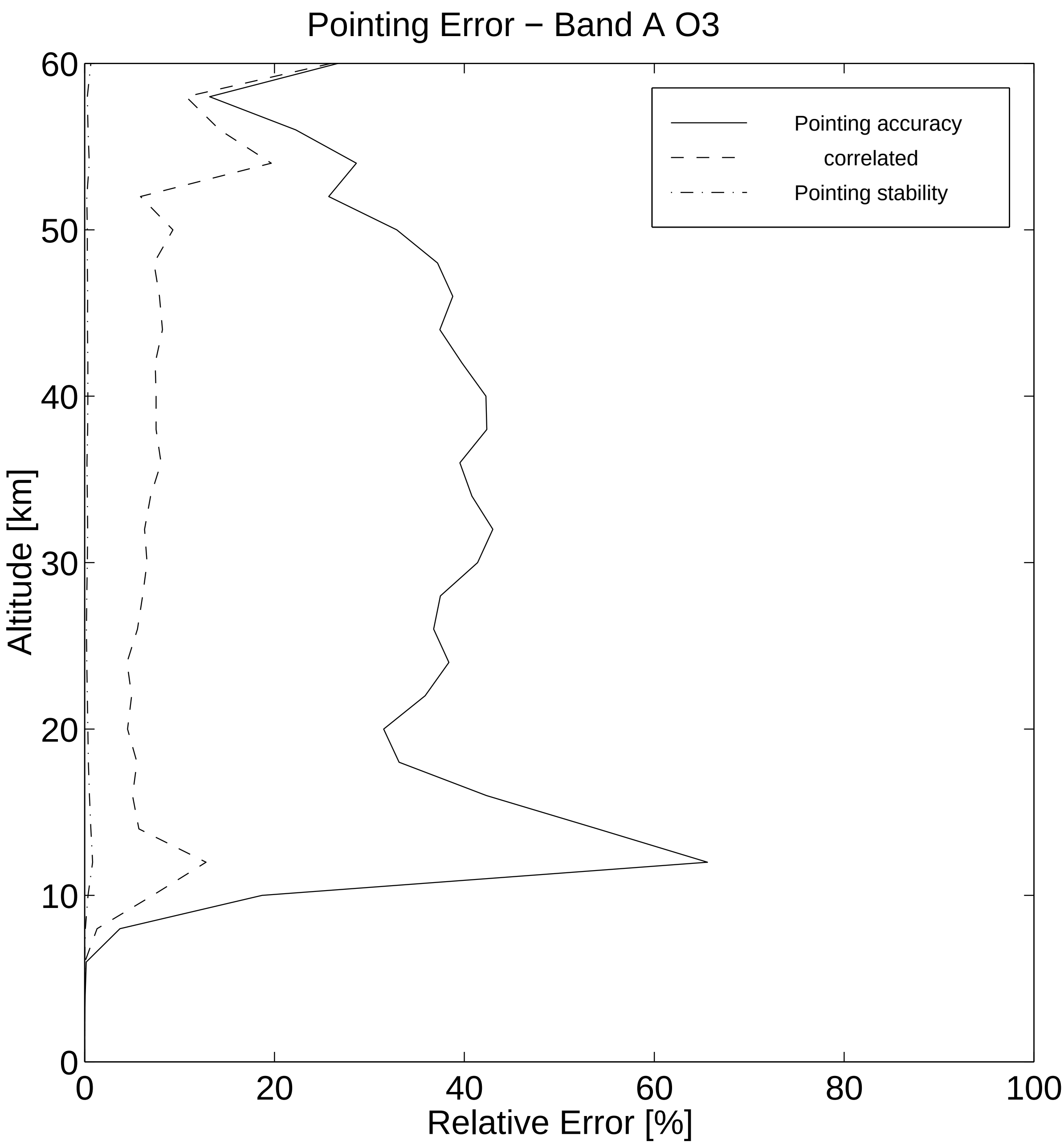
Imperfect knowledge: Conclusions

- If there is a significant far wing it must be covered by the antenna measurement
- An antenna distortion of 10 μm is not critical

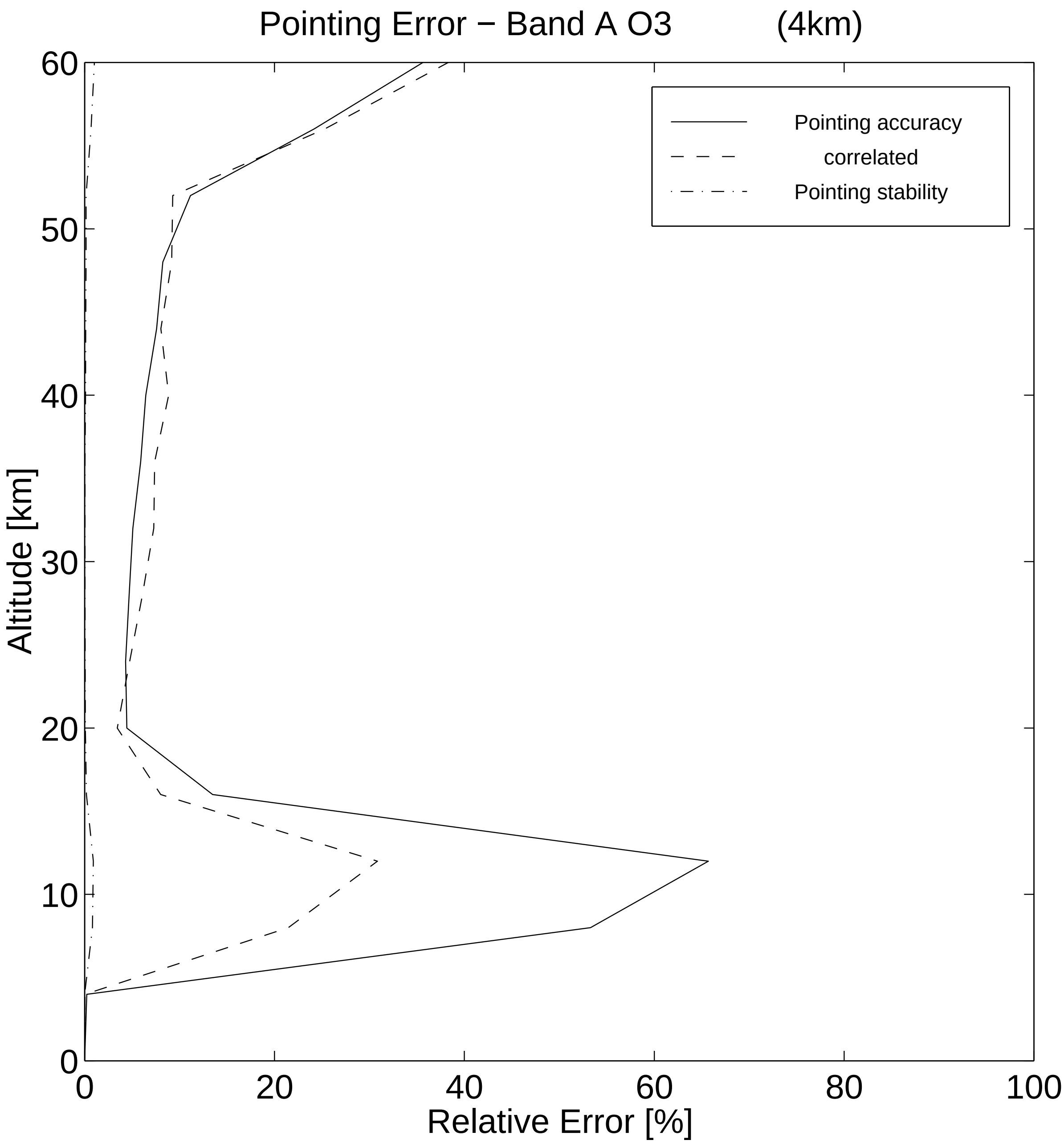
Pointing

- **Pointing accuracy**: Two cases studied:
  - $\pm$ 200 m random pointing offsets
  - Correlated random pointing with 200 m RMS (convolved first case with 6 km FWHM filter and scaled to 200 m RMS)
    Can be achieved technically by increased delay in antenna control loop
- **Pointing stability** (small scale pointing variations):
  - Simulated with different effective antenna patterns ($\pm$ 200 m)
- **Coregistration error**: Scan offset of 200 m between different bands assumed
  - With and without scan offset fit

Pointing: Ozone Band A (near 500 GHz)

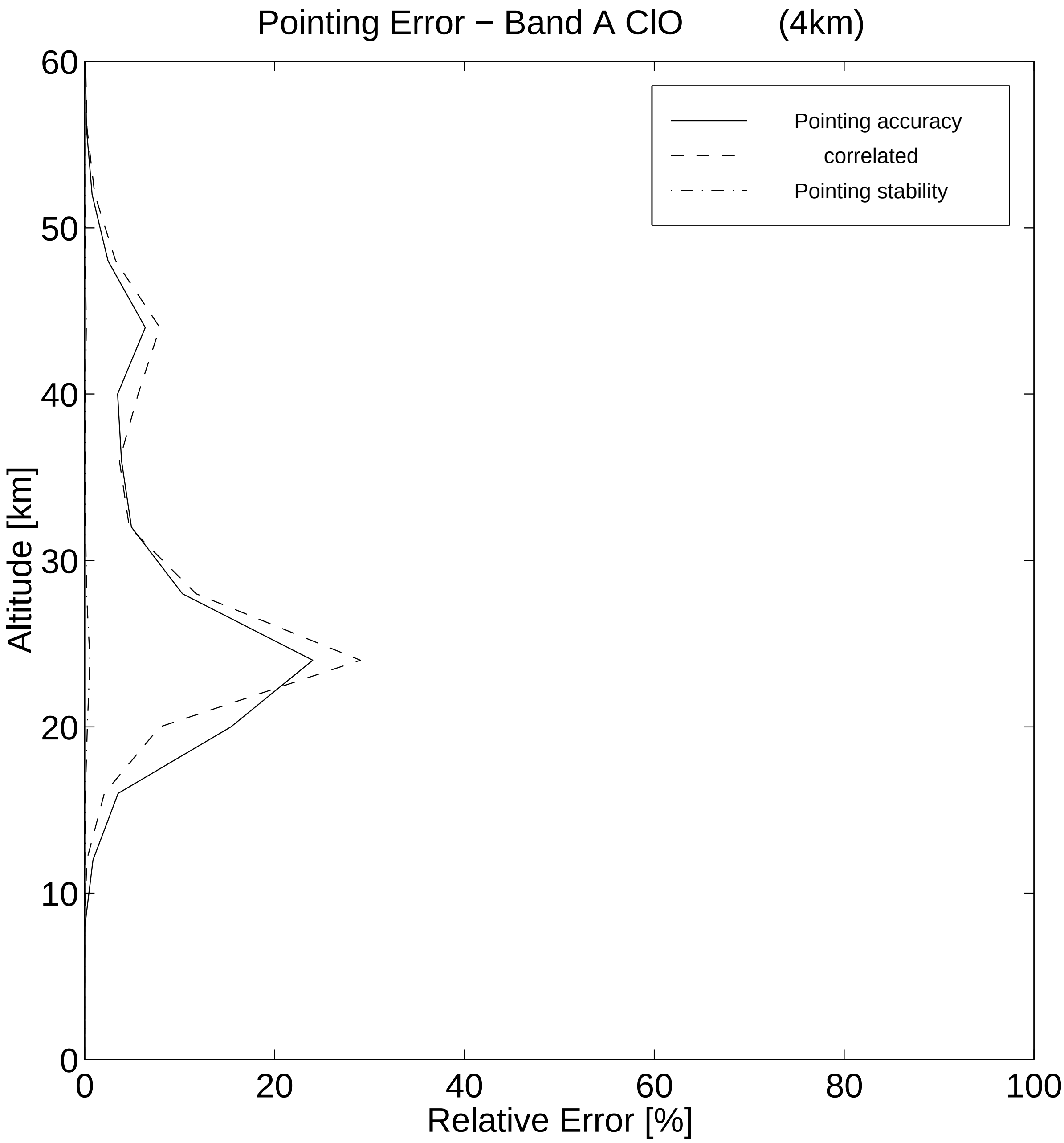


Pointing: Ozone on 4 km retrieval grid

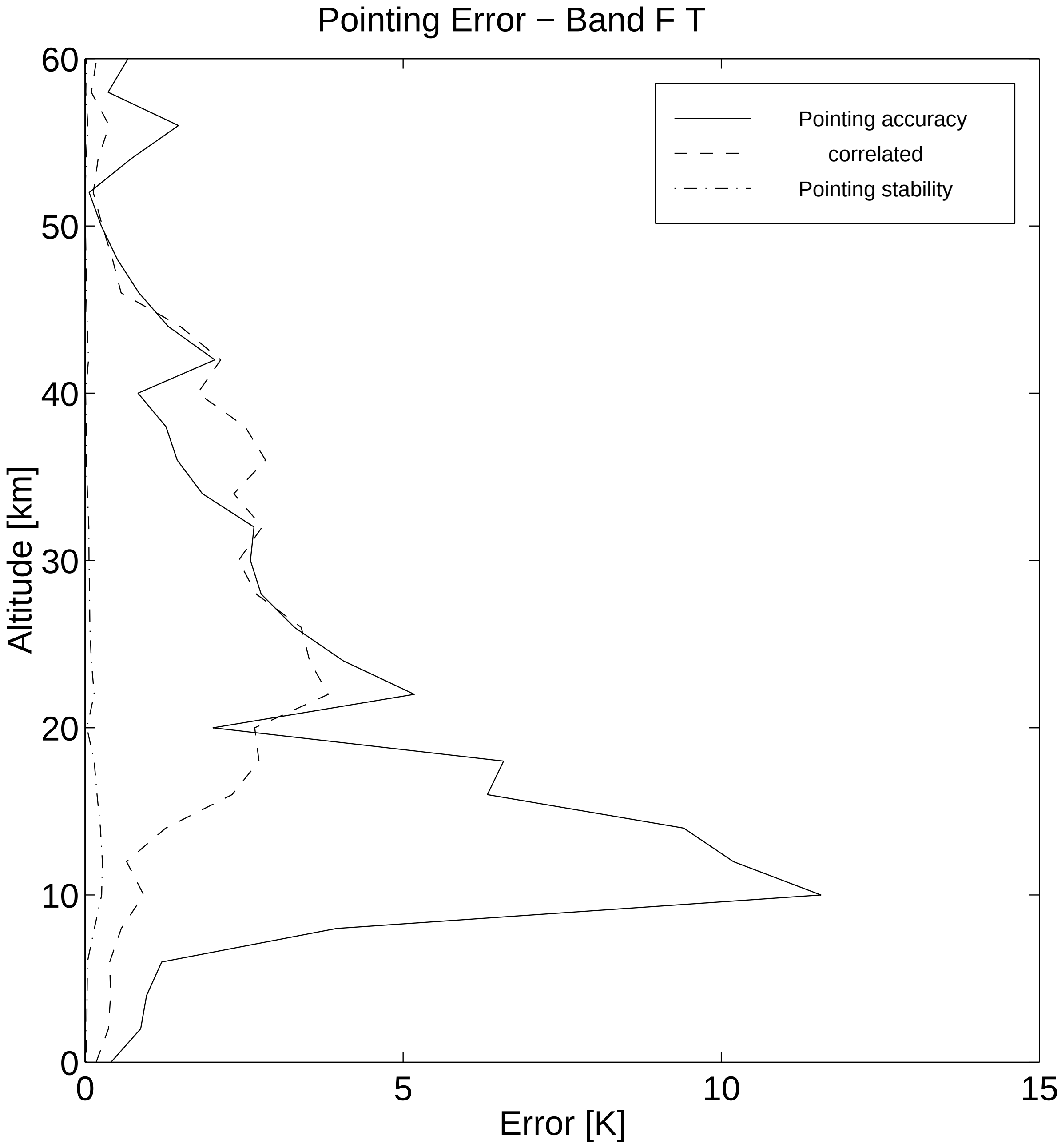


- 4 km retrieval grid reduces impact

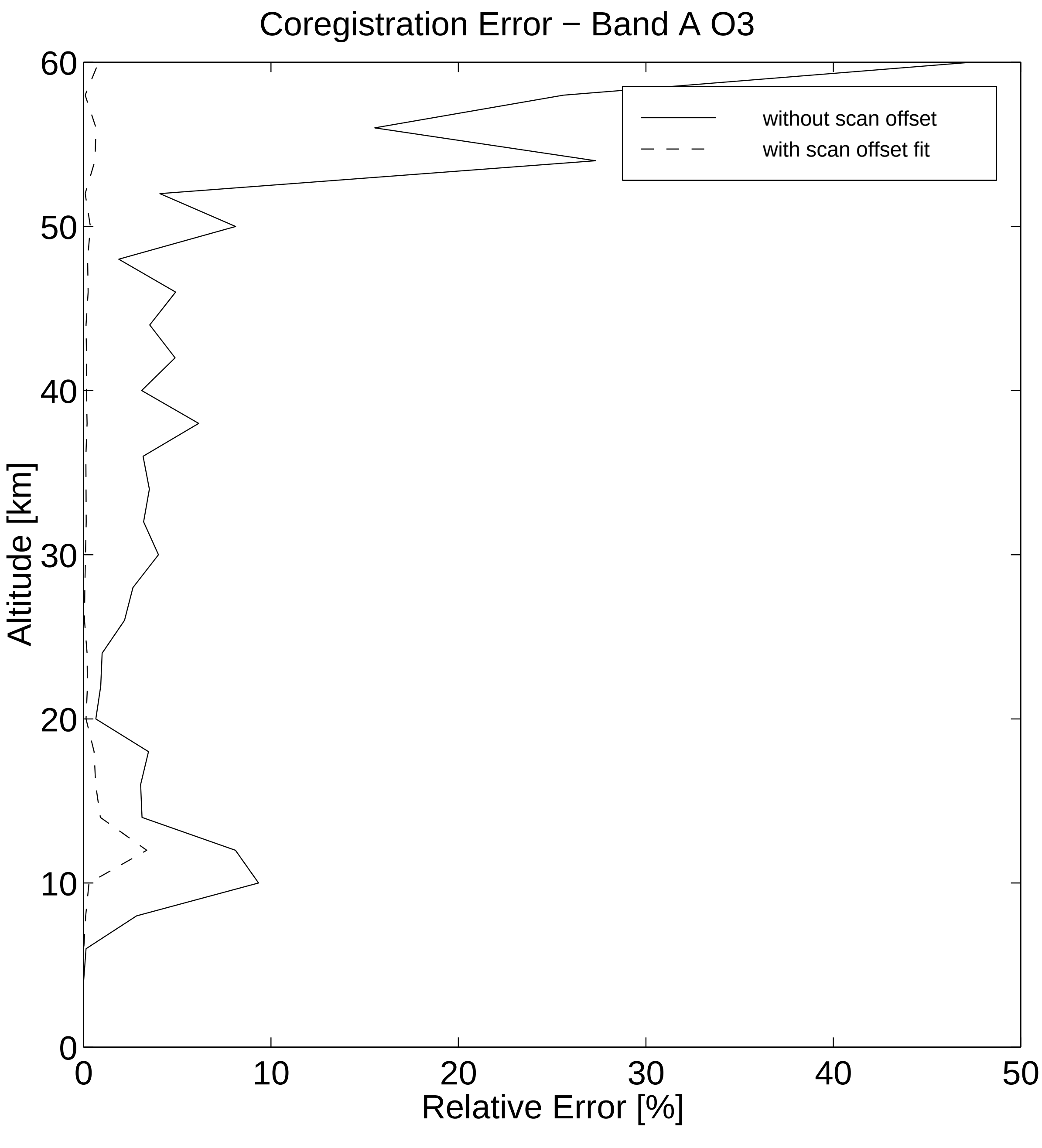
Pointing: ClO Band A (near 500 GHz)



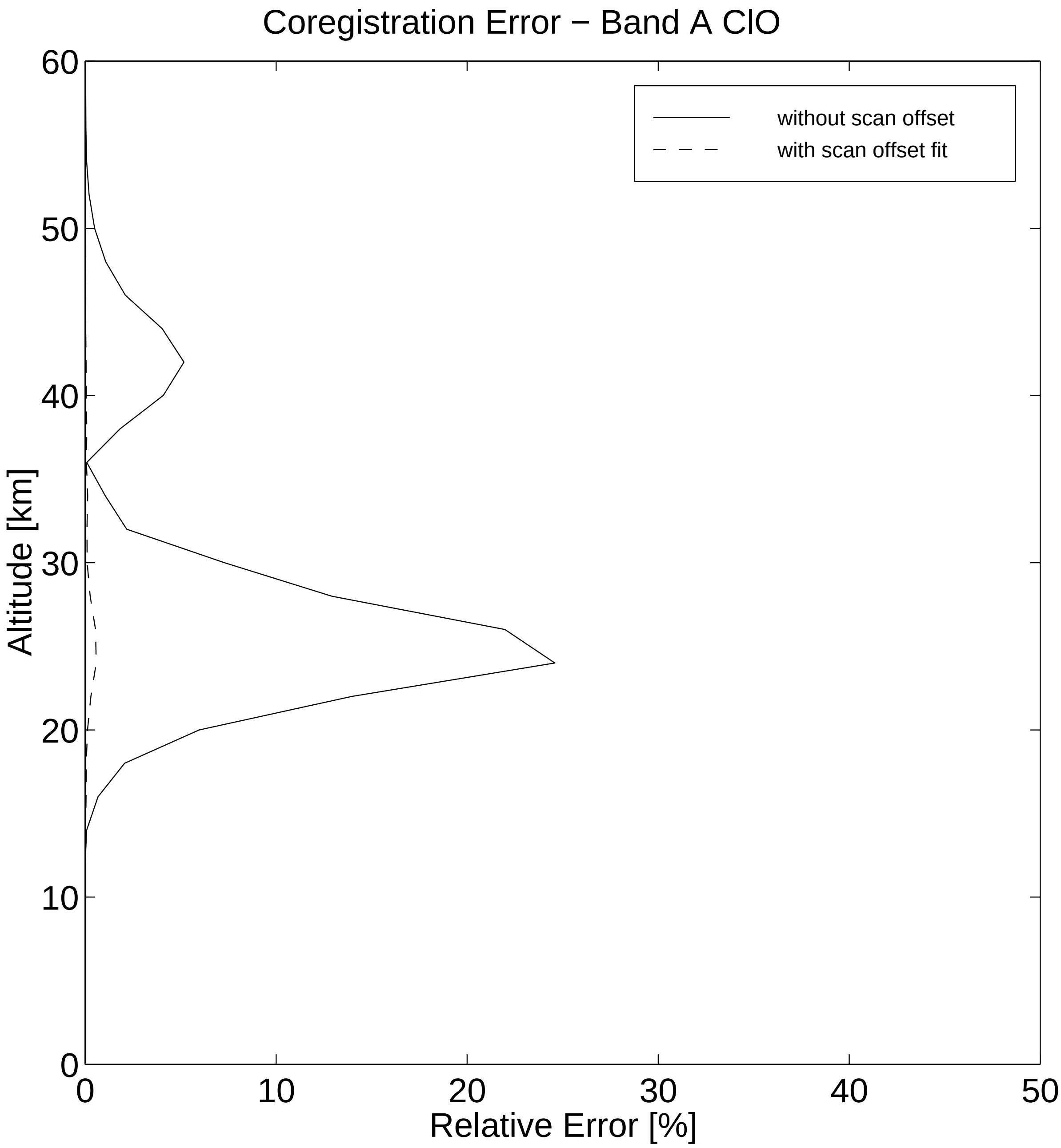
Pointing: Temperature Band F (near 954 GHz)



Coregistration error: Ozone Band A (near 500 GHz)



Coregistration error: ClO Band A



Pointing: Conclusions

Pointing accuracy:

- $\pm$ 200 m has very critical impact on retrieval
- Impact can be reduced by:
  either
  - Correlated pointing error (corresponding to increased delay in antenna control loop)

  or
  - 4 km retrieval grid

  but
  - Doing both gives no additional improvement (actually 4 km grid retrievals are often even slightly better with uncorrelated pointing errors)

Pointing: Conclusions continued

Pointing stability:

- $\pm$ 200 m not critical

Coregistration error:

- $\pm$ 200 m coregistration error has large impact
- . . . but can be minimized with scan offset fit
- $\longrightarrow$ Not critical

Radiometric errors

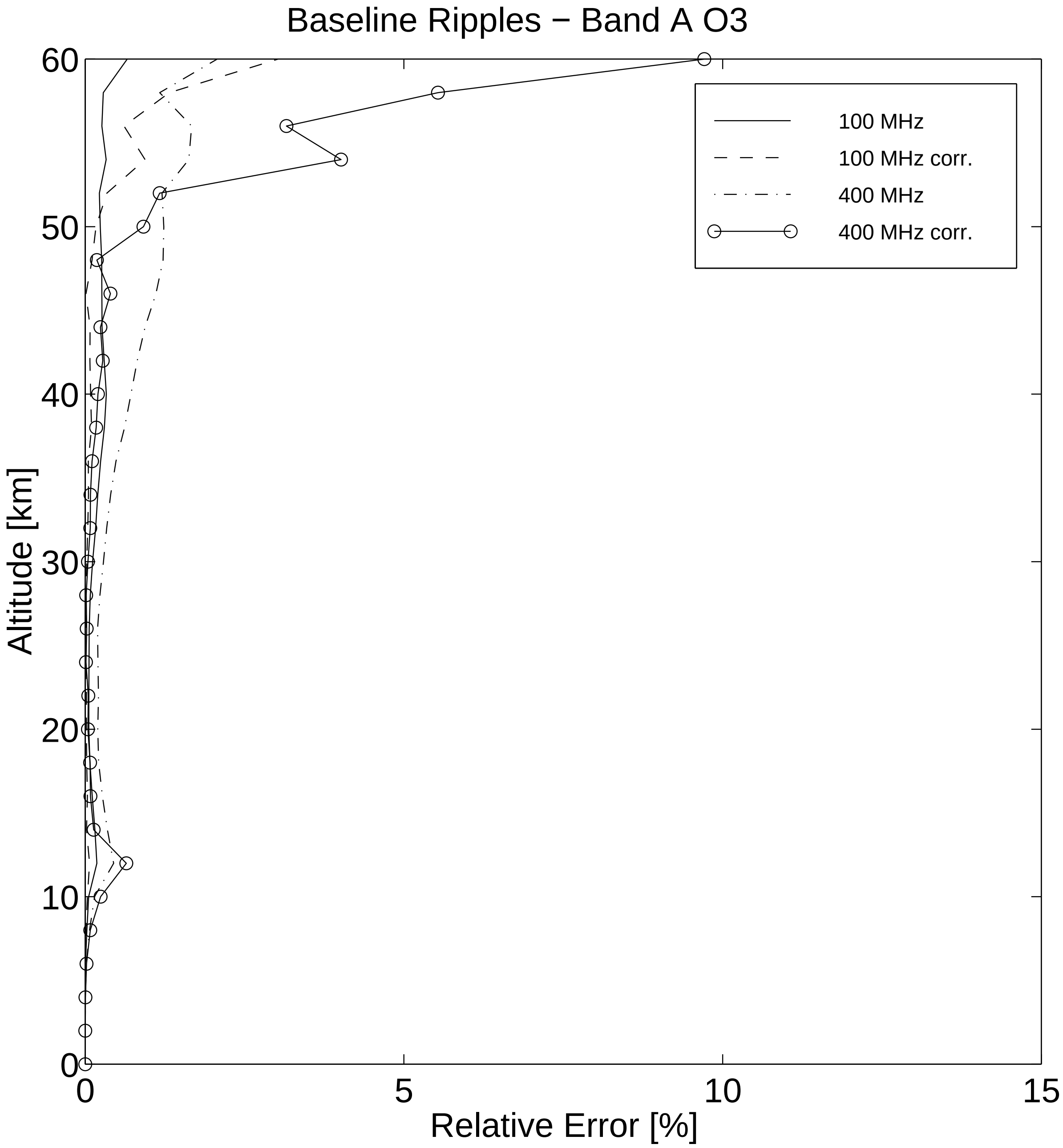
- **Baseline ripples**
- **Baseline discontinuities**
- **Unwanted sideband**
- **Calibration errors**
- **Correlated noise**

Baseline ripples

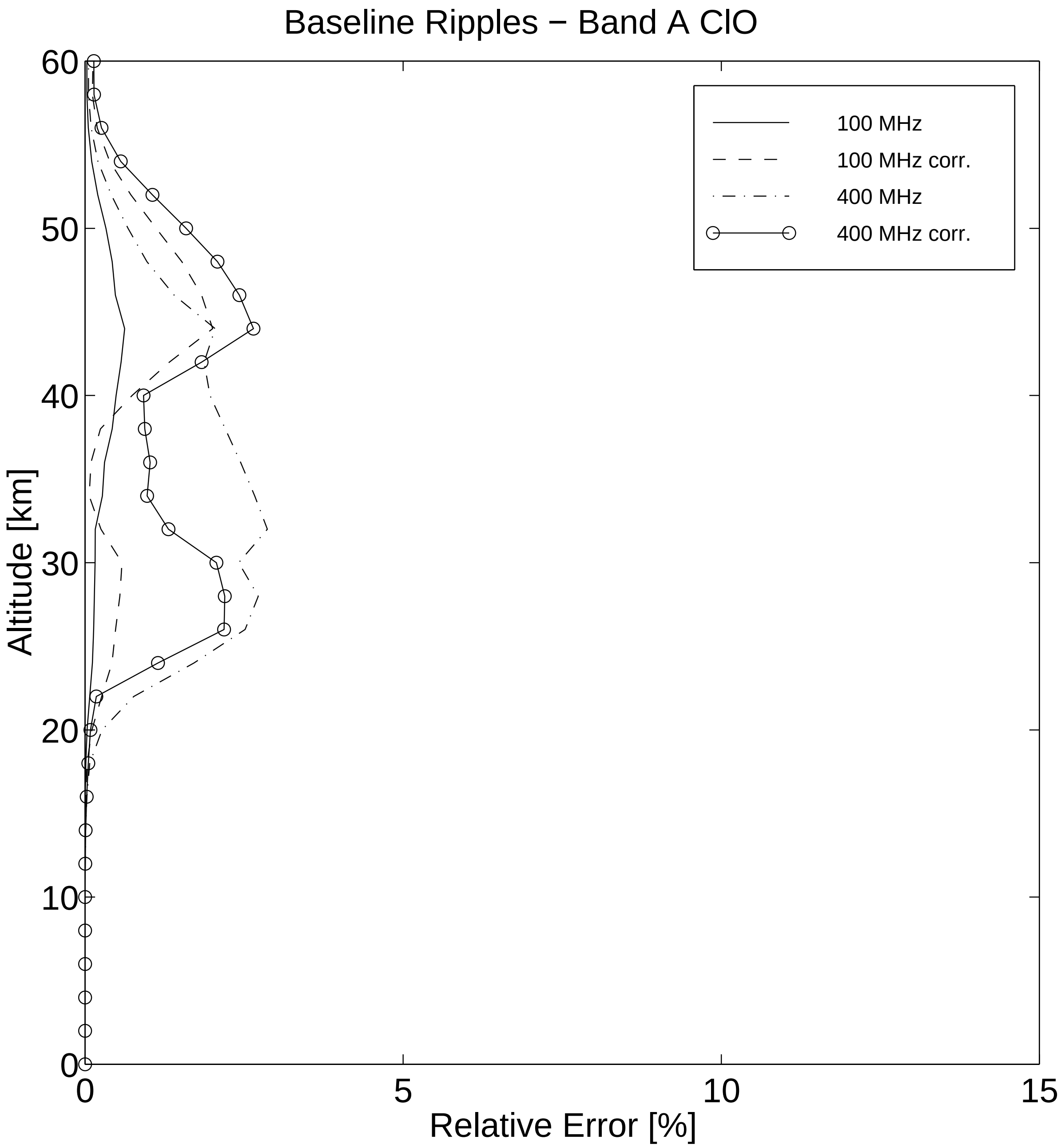
Assumptions:

- Sinusoidal baseline structure
- 0.1 K amplitude
- 100 and 400 MHz periods
- Phase randomly distributed
- Two cases:
  - Phase constant during scan
  - Phase randomly distributed during scan

Baseline ripples: Ozone Band A (near 500 GHz)



Baseline ripples: ClO Band A



Baseline ripples: Conclusions

- Impact of 400 MHz periods larger than 100 MHz periods
- Not critical
- However: 0.1 K seems optimistic

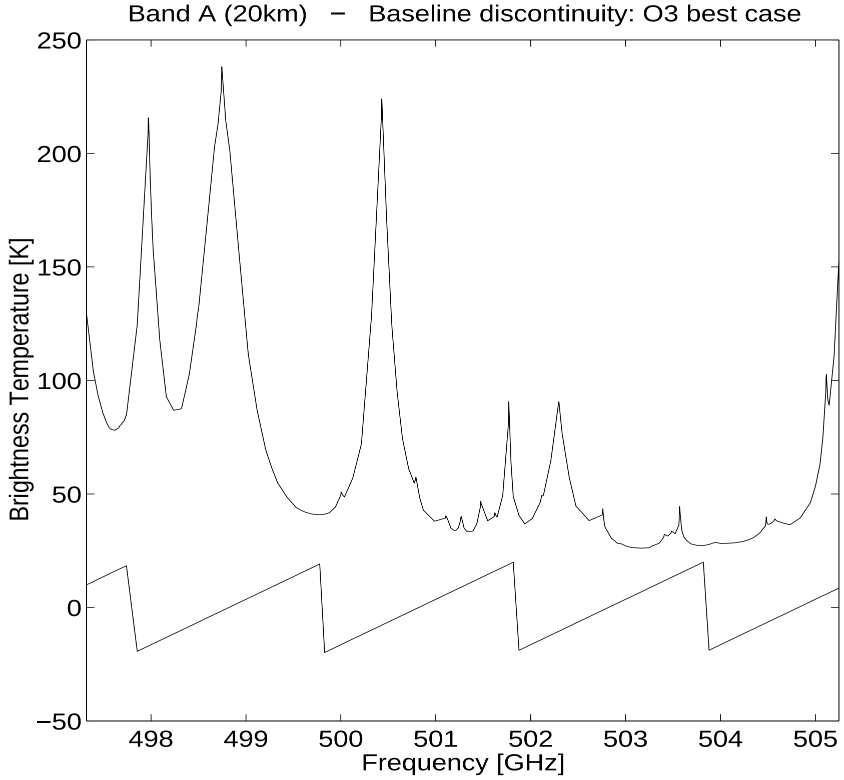
Baseline discontinuities

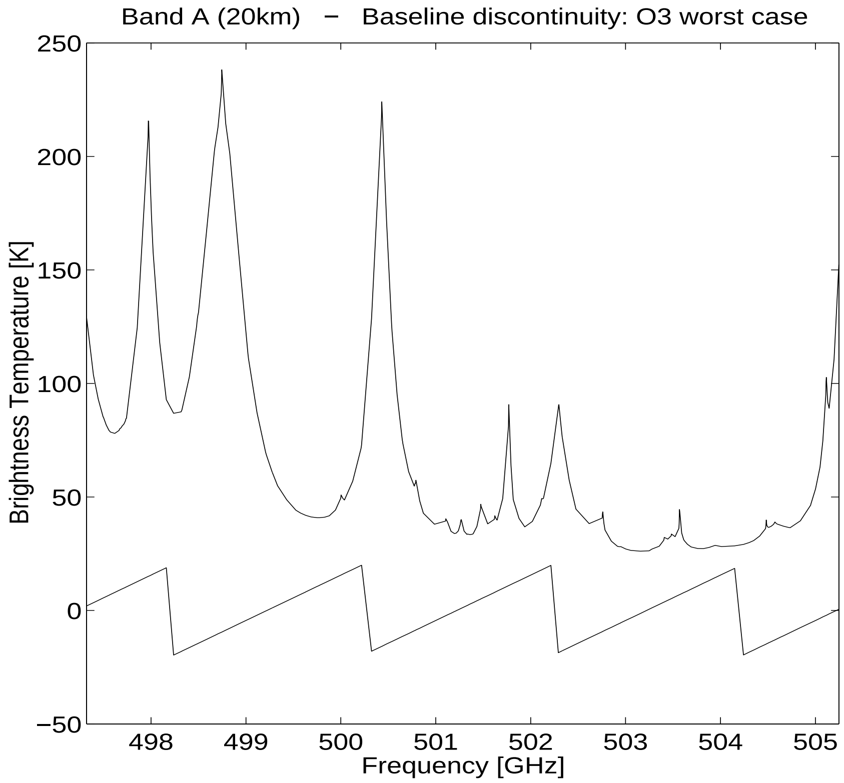
... may be caused by AOS modules

Assumptions:

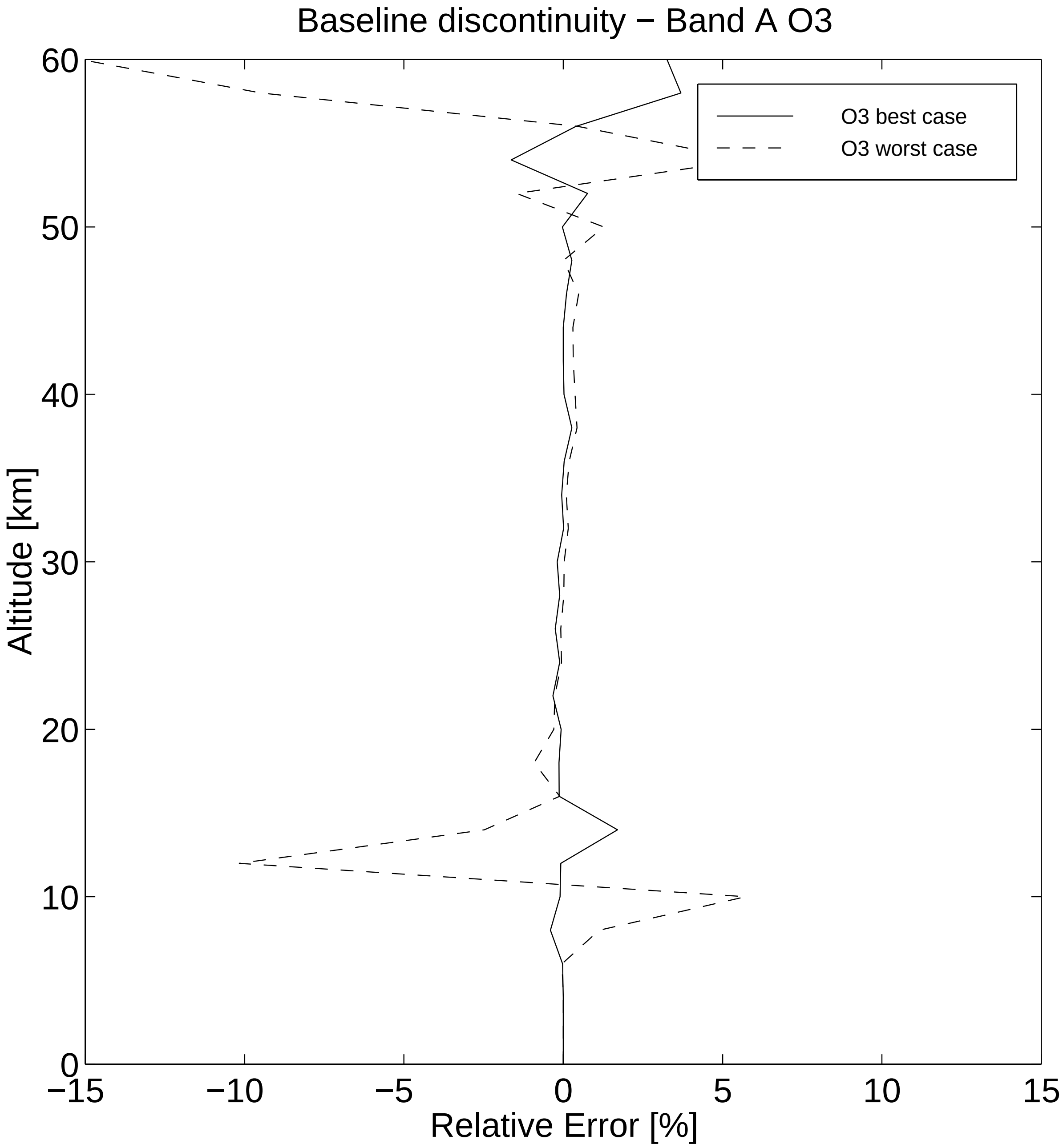
- Simulated by sawtooth function from -0.2 K to +0.2 K every 2 GHz
- Phase shifted by 100 MHz $\longrightarrow$ 20 cases

Baseline discontinuity: O_3 Band A

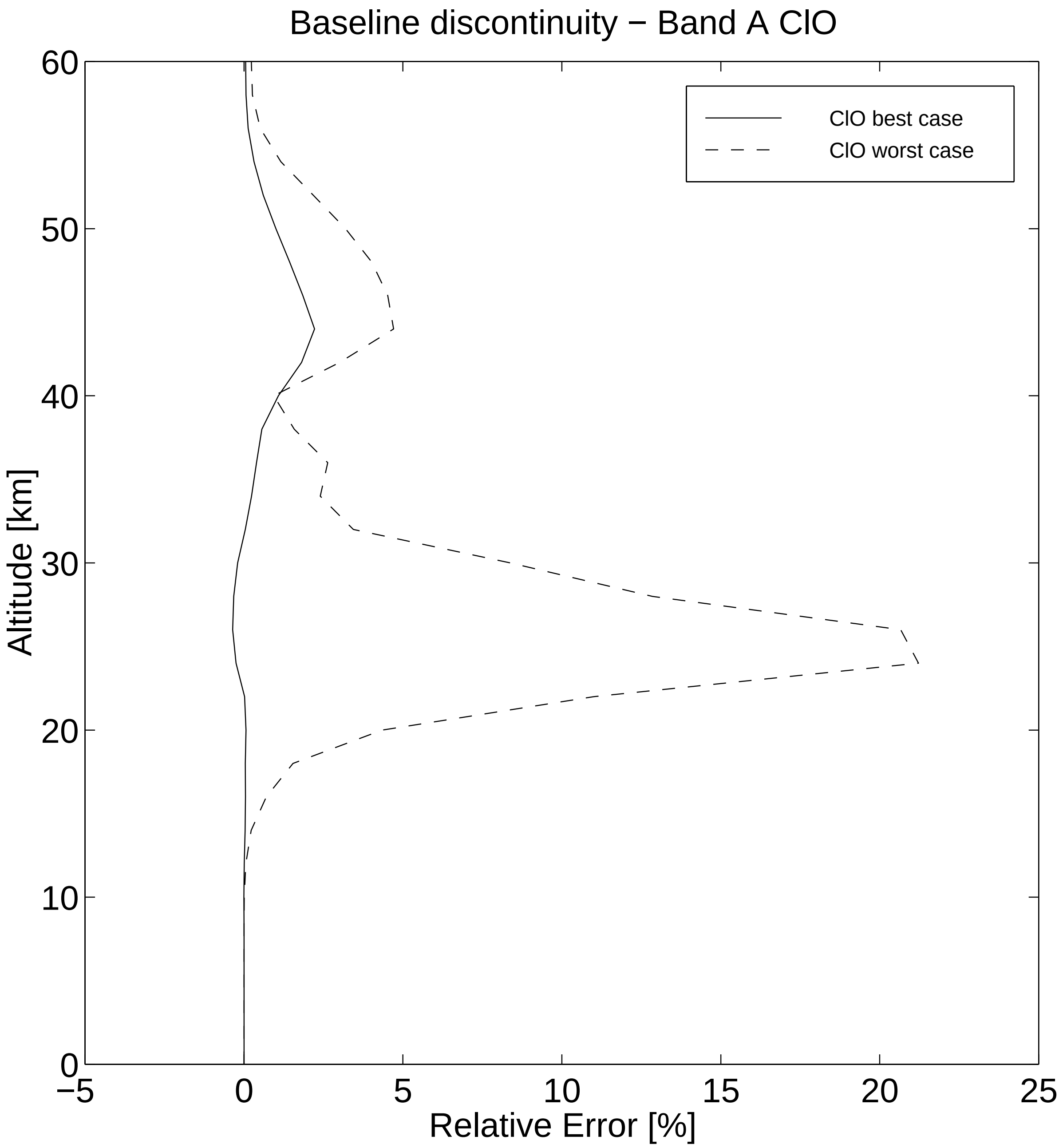




Baseline discontinuity: O_3 Band A



Baseline discontinuity: ClO Band A



Baseline discontinuity: Conclusions

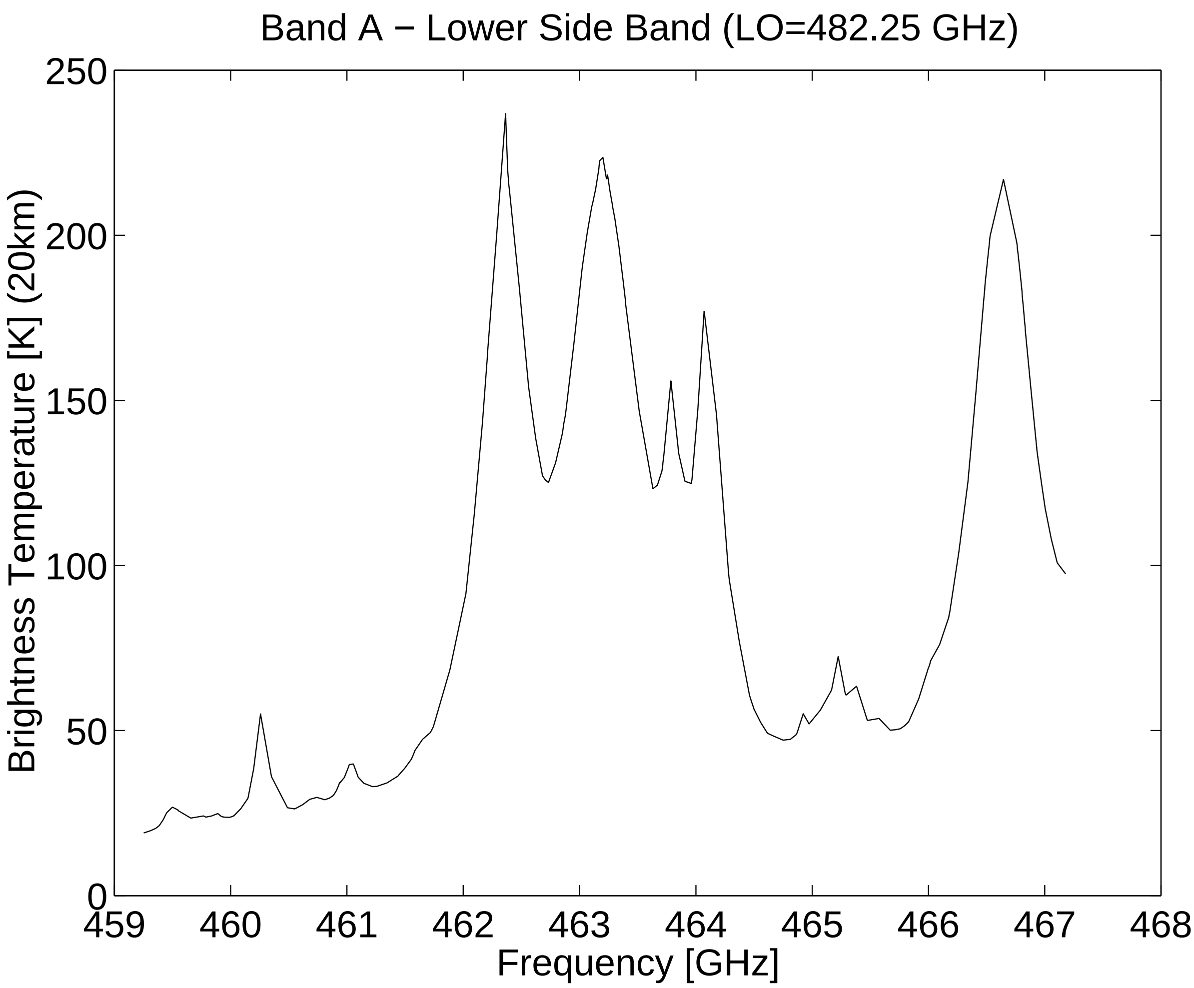
- Worst case for discontinuity near center of line of interest
- Impact stronger for weak lines
- Impact can be minimized by appropriate placement of AOS modules

Unwanted sideband

- Nominal 20 dB suppression
- $\longrightarrow$ 200 K line in sideband will appear with 2 K in measured spectrum!
- Impact depends on LO frequencies
- For SOPRANO study Dornier setup:

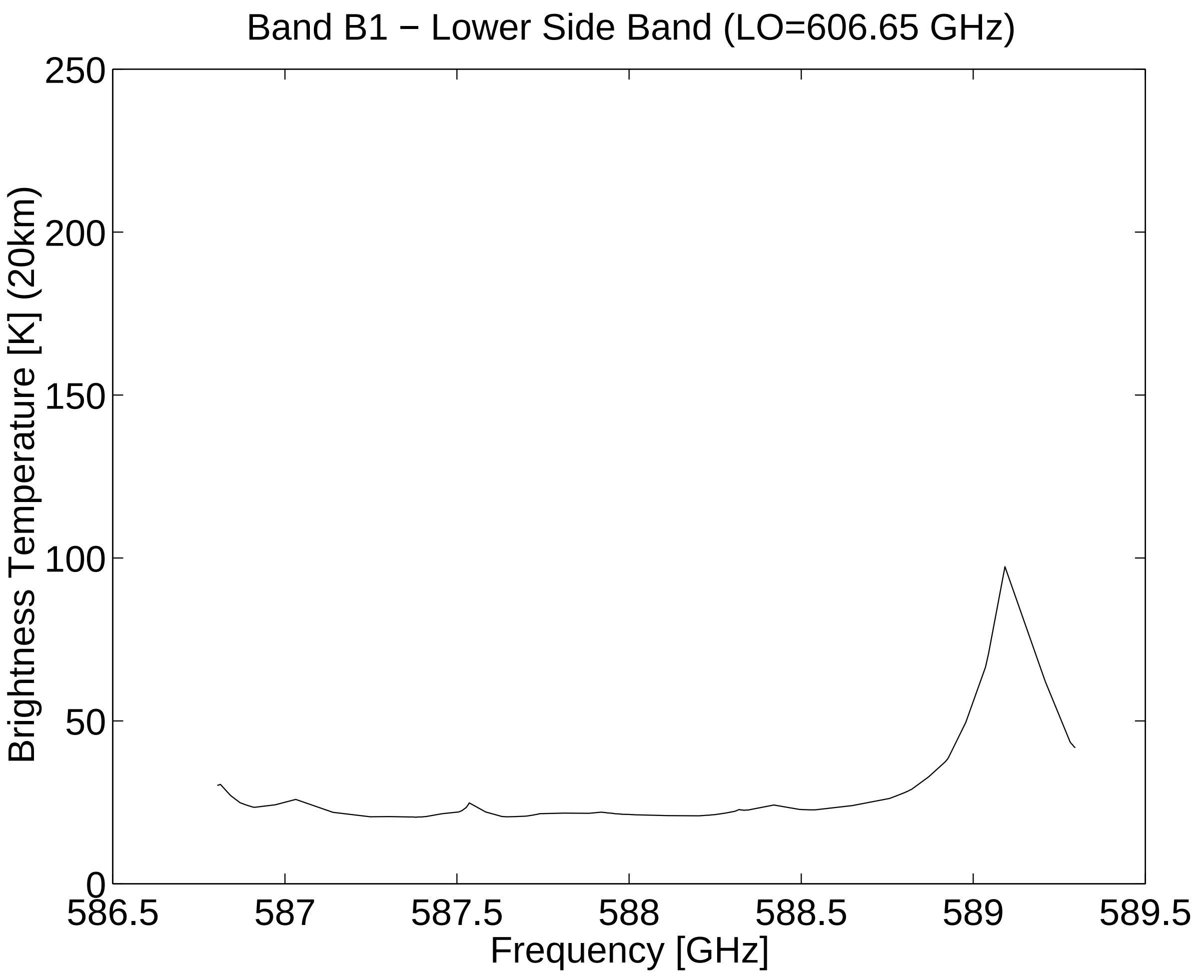
Band	LO frequency [GHz]
A	482.25
B1	606.65
B2	606.65
F	933.50

Lower Sideband: Band A (near 500 GHz)



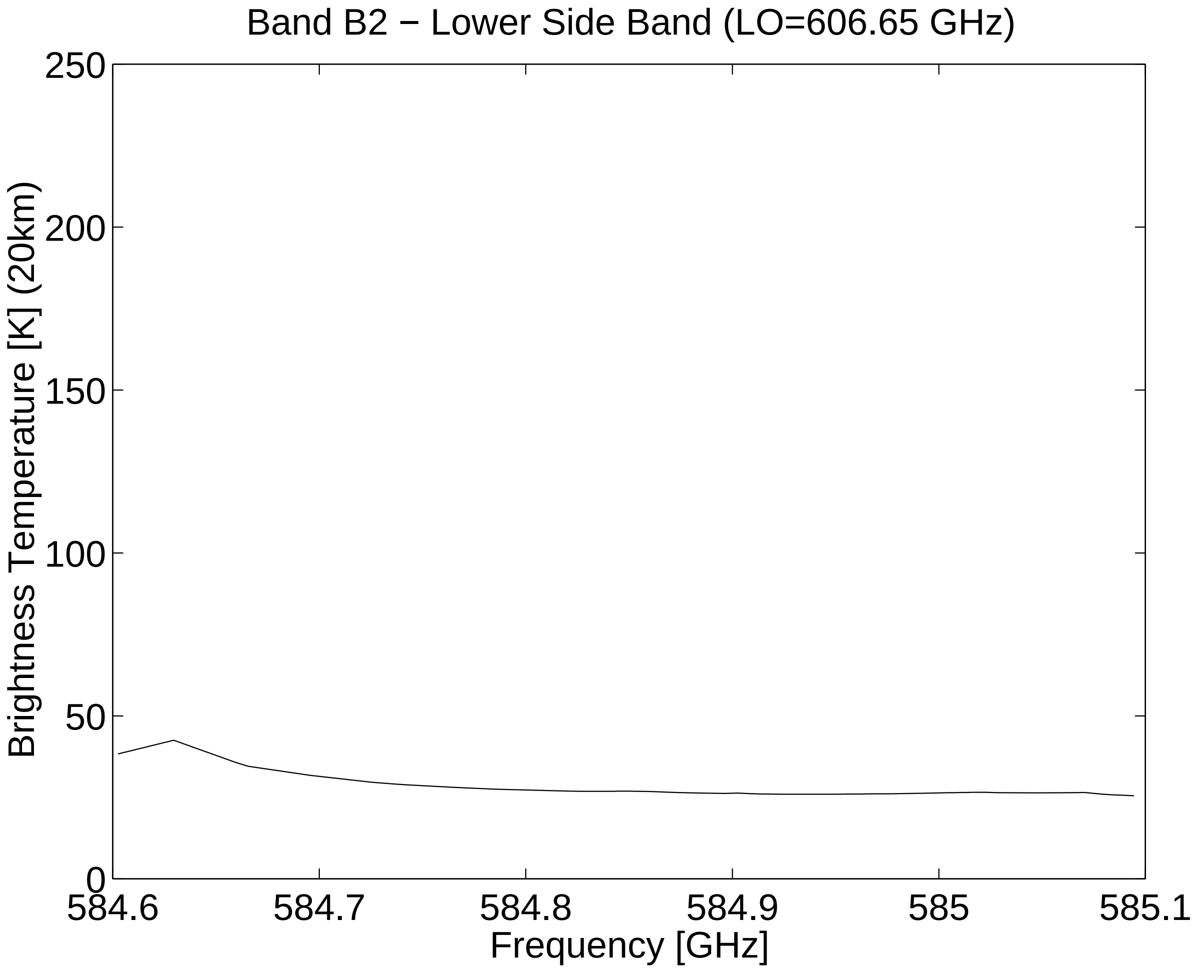
- Many strong lines !

Lower Sideband: Band B1 (near 625 GHz)

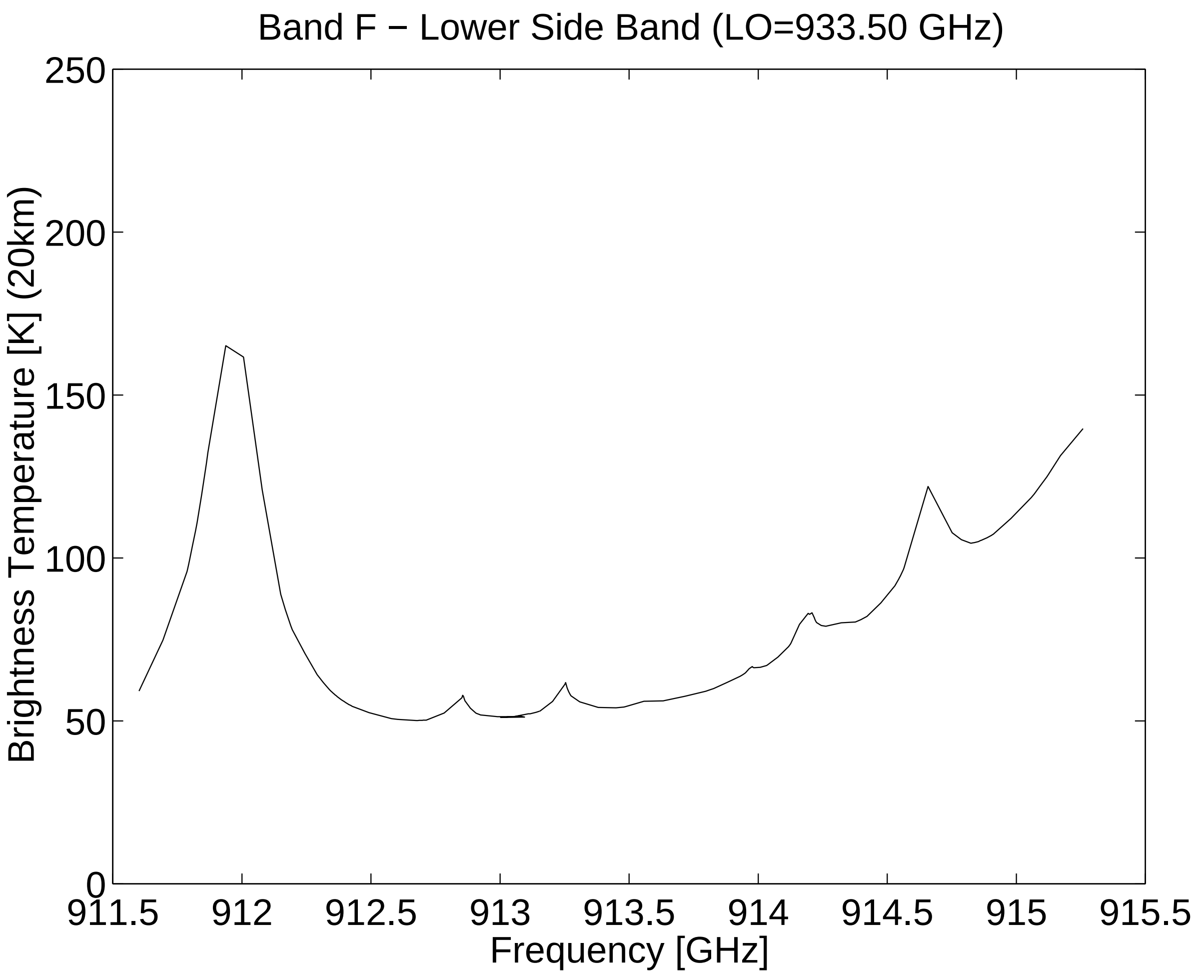


- Little structure

Lower Sideband: Band B2 (near 628 GHz)

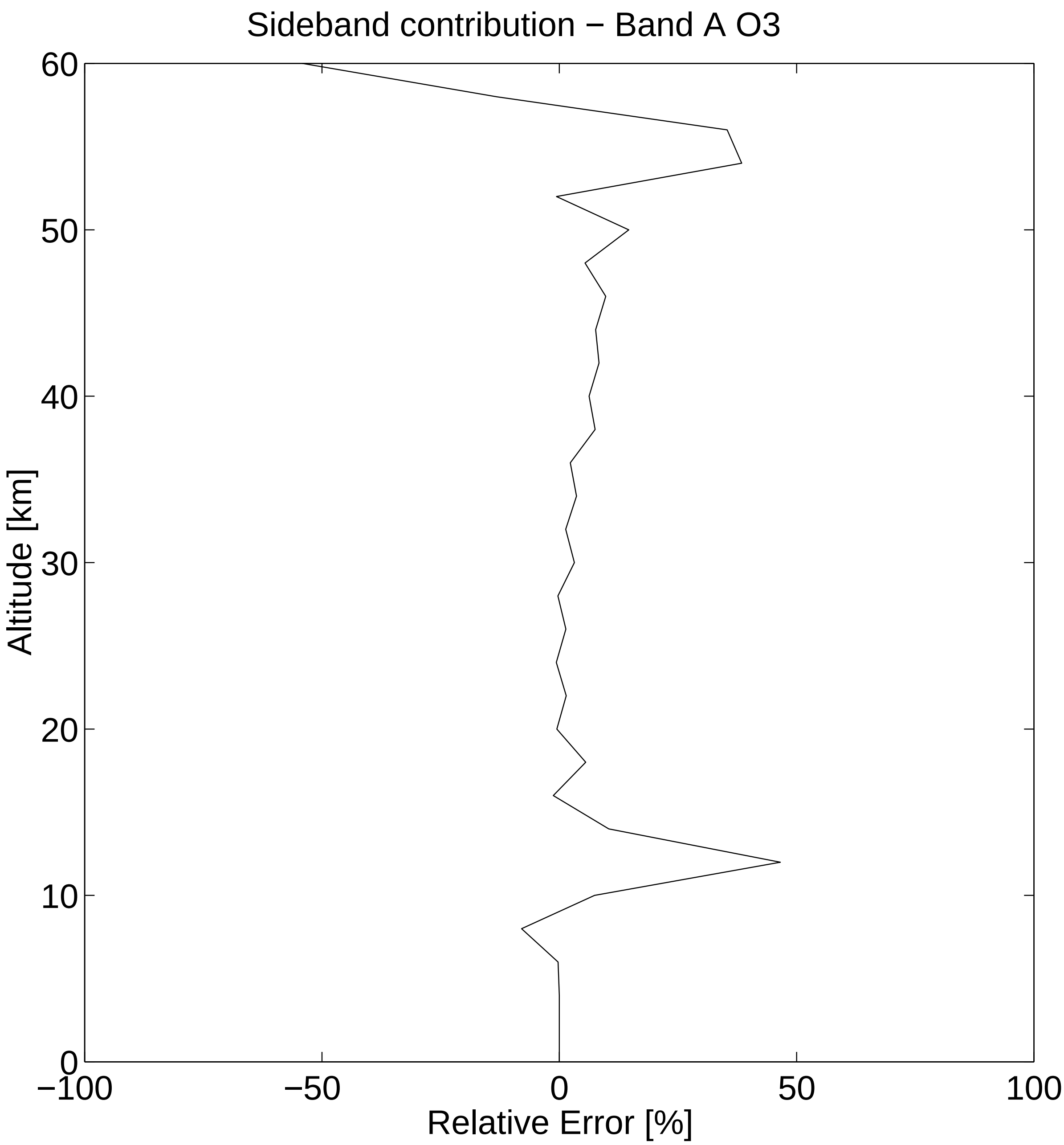


Lower Sideband: Band F (near 954 GHz)

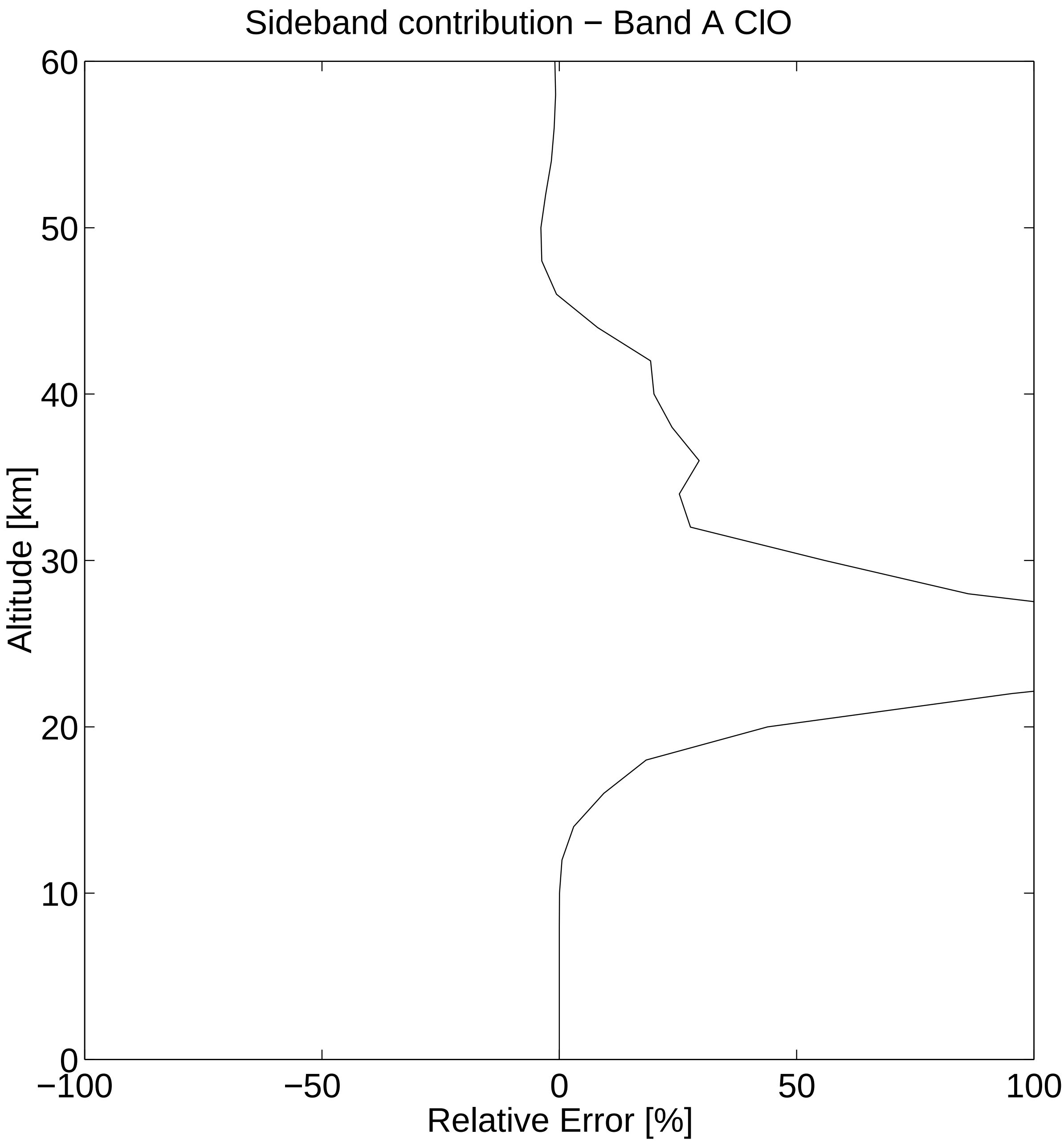


- Moderate structure

Unwanted Sideband: Ozone Band A (near 500 GHz)



Unwanted Sideband: ClO Band A



Unwanted Sideband: Conclusions

- Severe impact if uncorrected
- Dornier setup LO frequencies not optimal
  - Especially Band A should be optimized
- Impact can be corrected to first order if sideband ratio is known
- Present results can also be interpreted as error due to 20 dB knowledge of sideband ratio

Calibration

Calibration process:

$$T_a = G(T_h - T_c) + T_c$$

with

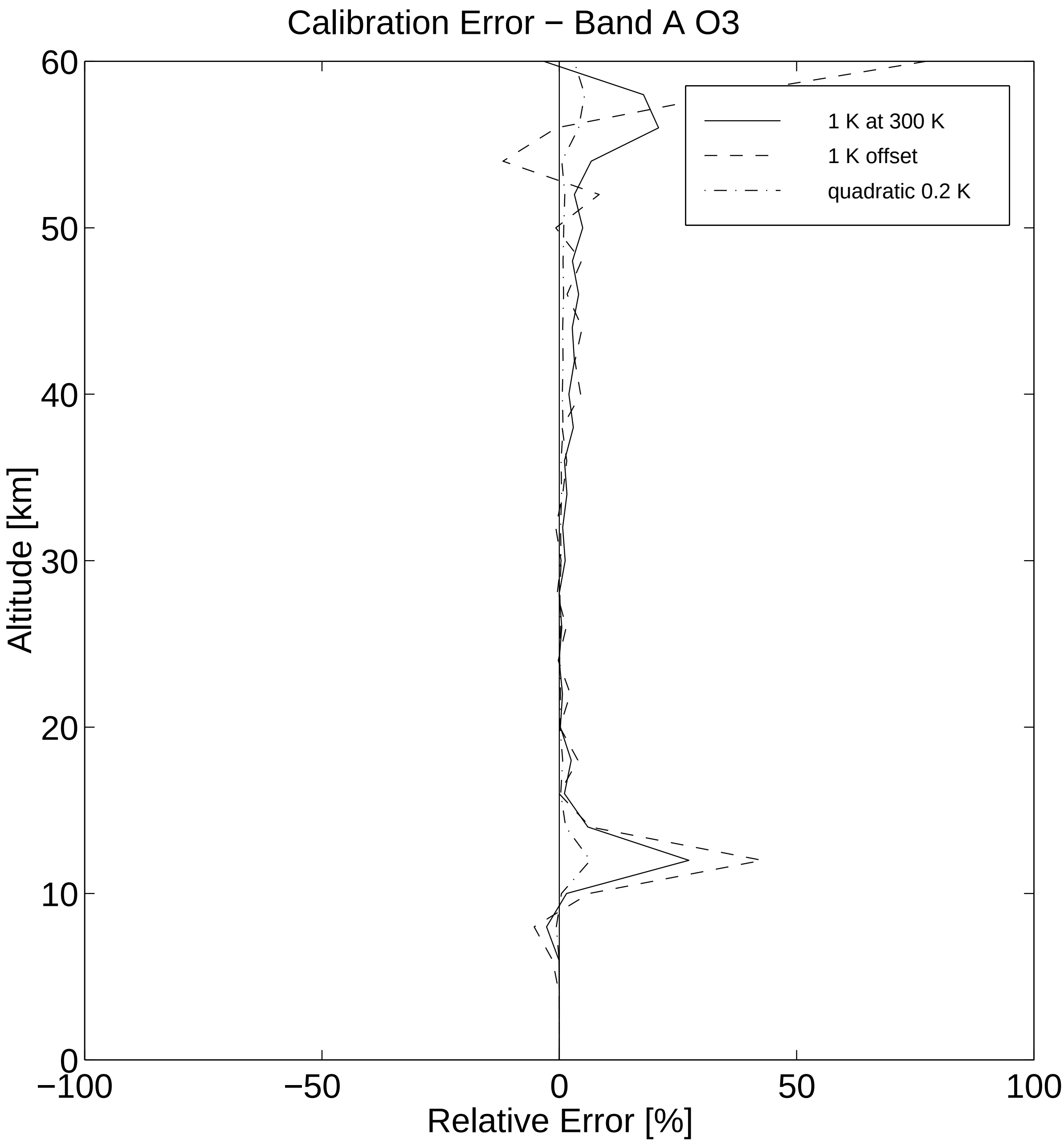
$$G = (V_a - V_c)/(V_h - V_c)$$

$$\longrightarrow \Delta T_a = \frac{T_a - T_c}{T_h - T_c}(\Delta T_h - \Delta T_c) + \Delta T_c$$

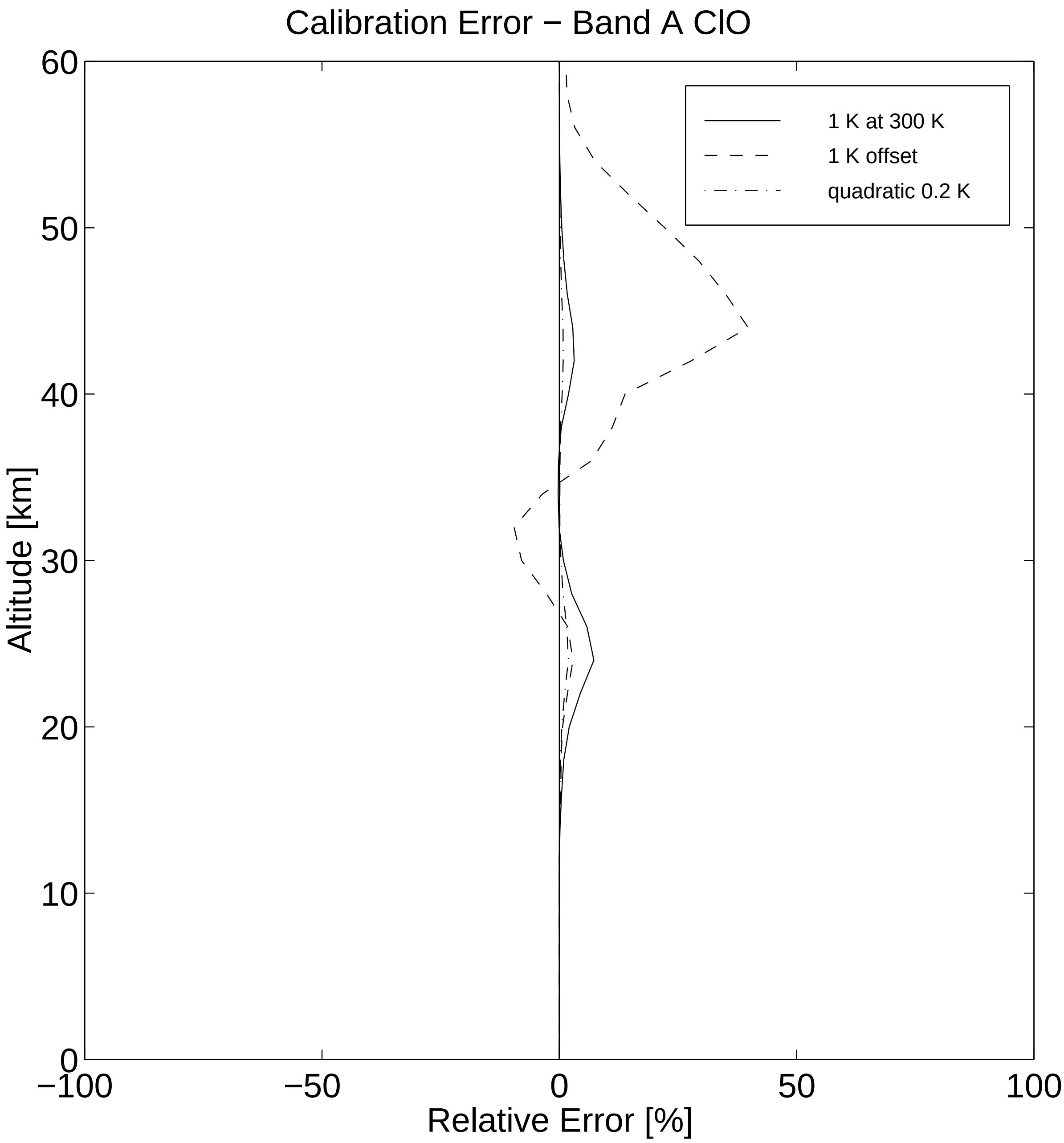
Three cases studied:

- 1 K error at 300 K
- 1 K offset
- Quadratic error of 0.2 K at 150 K

Calibration error: Ozone Band A



Calibration error: ClO Band A



Calibration error: Conclusions

- 1 K offset introduces errors of 10% and larger
- Impact of 0.2 K quadratic error is small (because the quadratic error itself is assumed to be small)

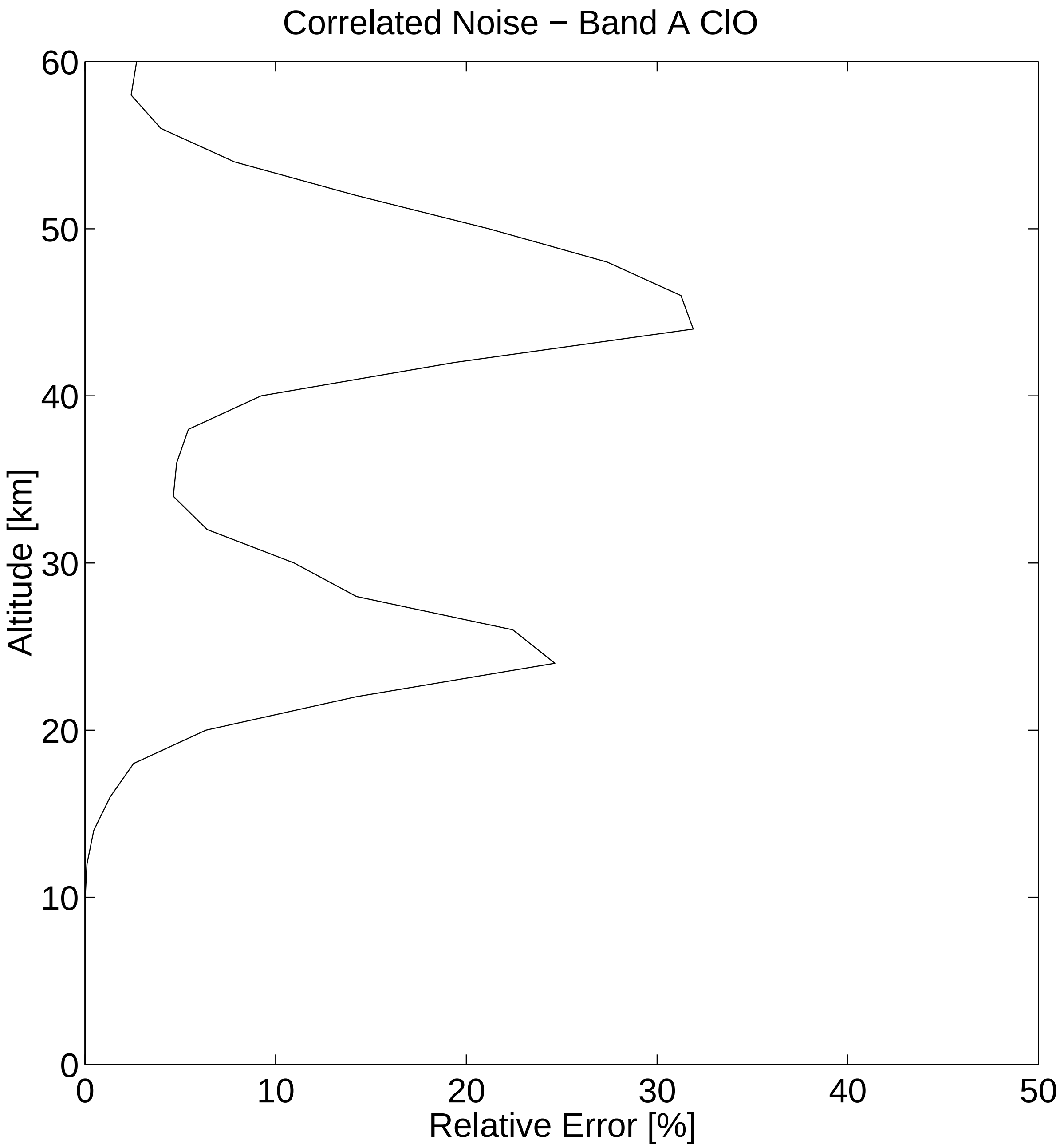
Correlated noise

- Noise on calibration measurements will be correlated for each level during one scan
- Here an integration time of 2 sec. was assumed ($10\times$ atmospheric integration time)

Result:

- Errors same order of magnitude as measurement noise
- Statistical error: Decreases with averaging

Correlated noise: ClO Band A



Temperature uncertainty

Temperature weighting function:

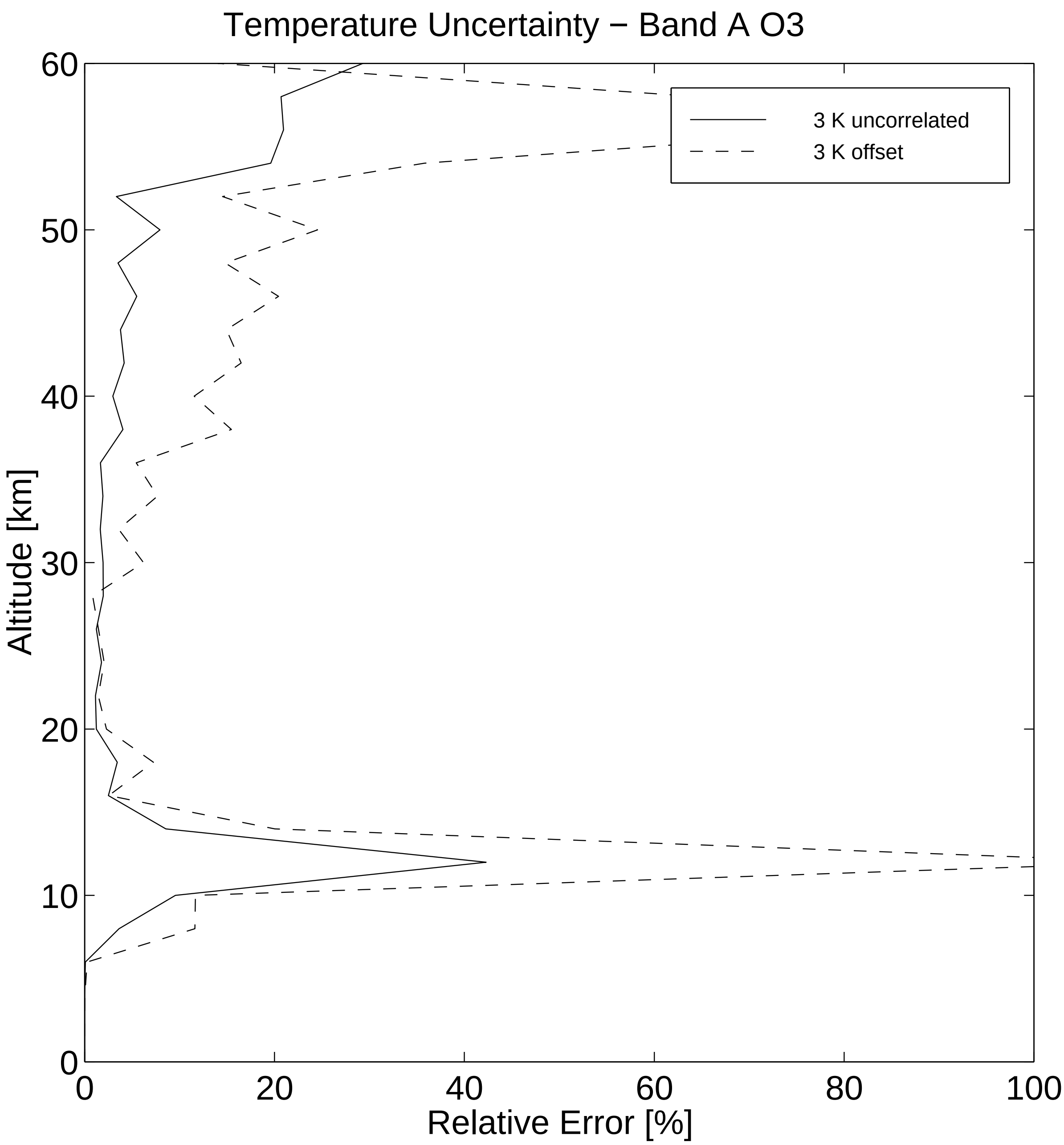
$$\mathbf{K}_b \equiv \left.\frac{\partial F}{\partial b}\right|_{b=\bar{b}}$$

$$\mathbf{S}_S = \mathbf{D}\mathbf{K}_b\,\mathbf{S}_b\,(\mathbf{D}\mathbf{K}_b)^T$$

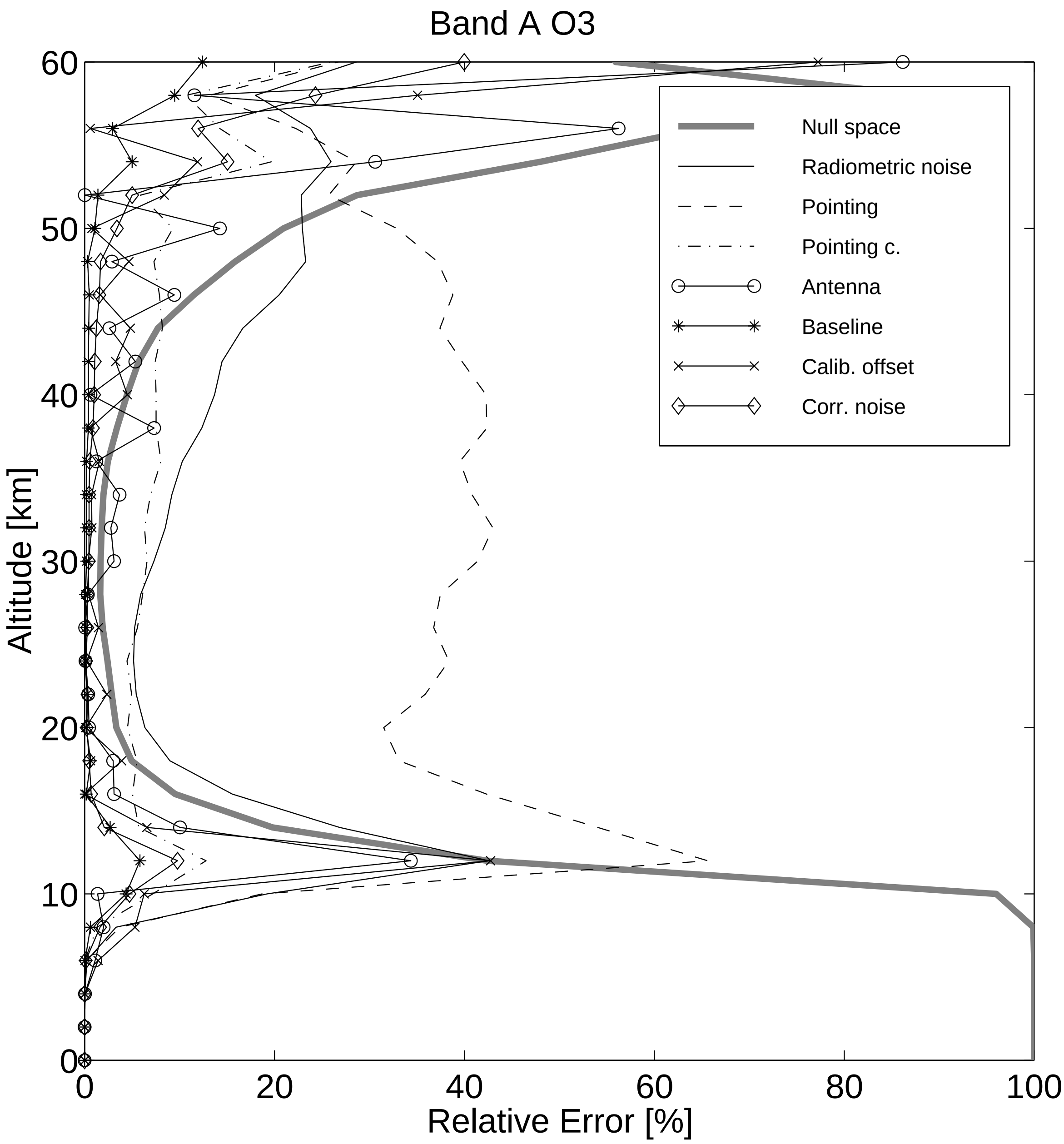
Two cases for $\mathbf{S}_b$ studied:

- 3 K uncorrelated
- 3 K offset

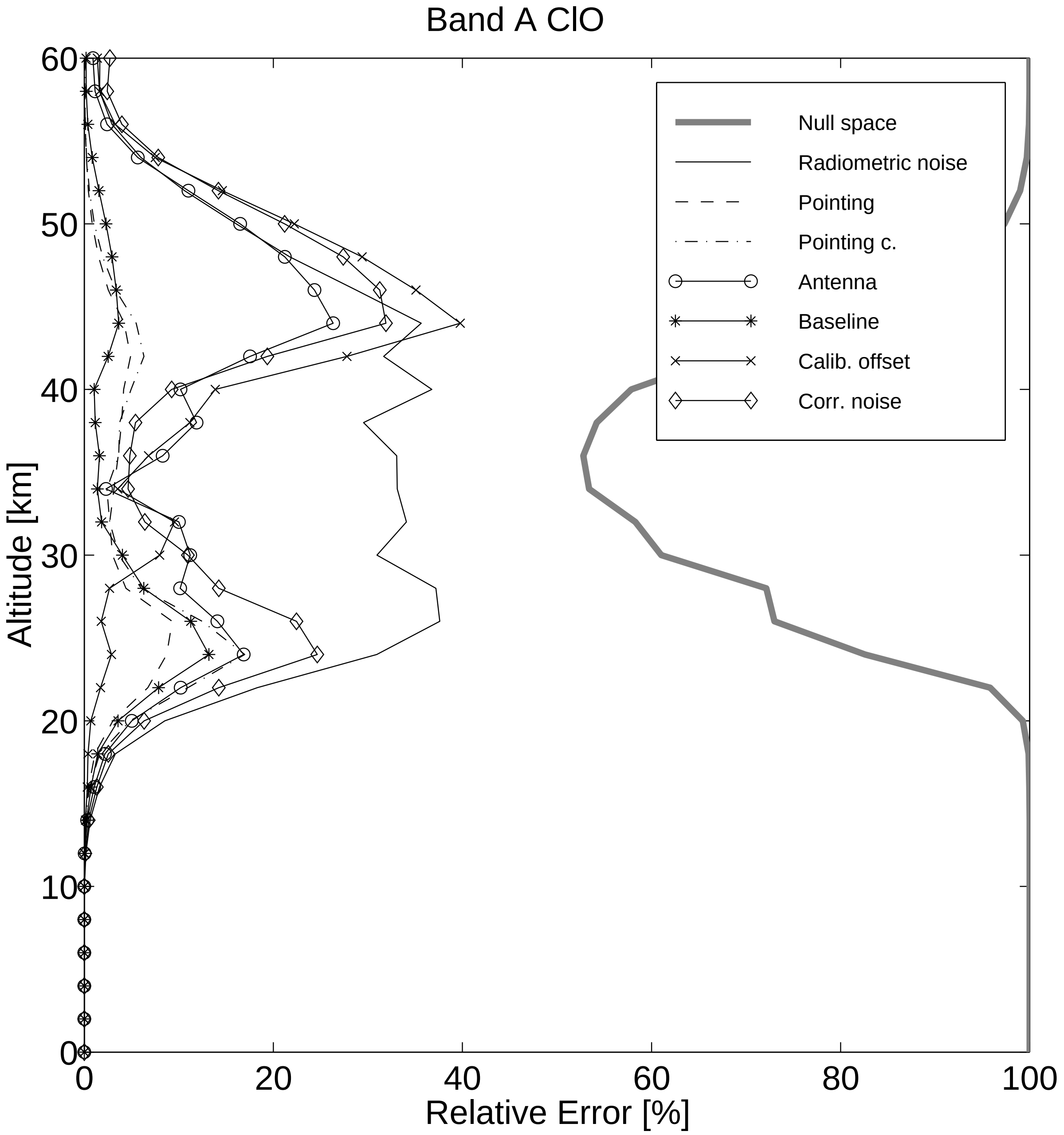
Temperature uncertainty: Ozone Band A



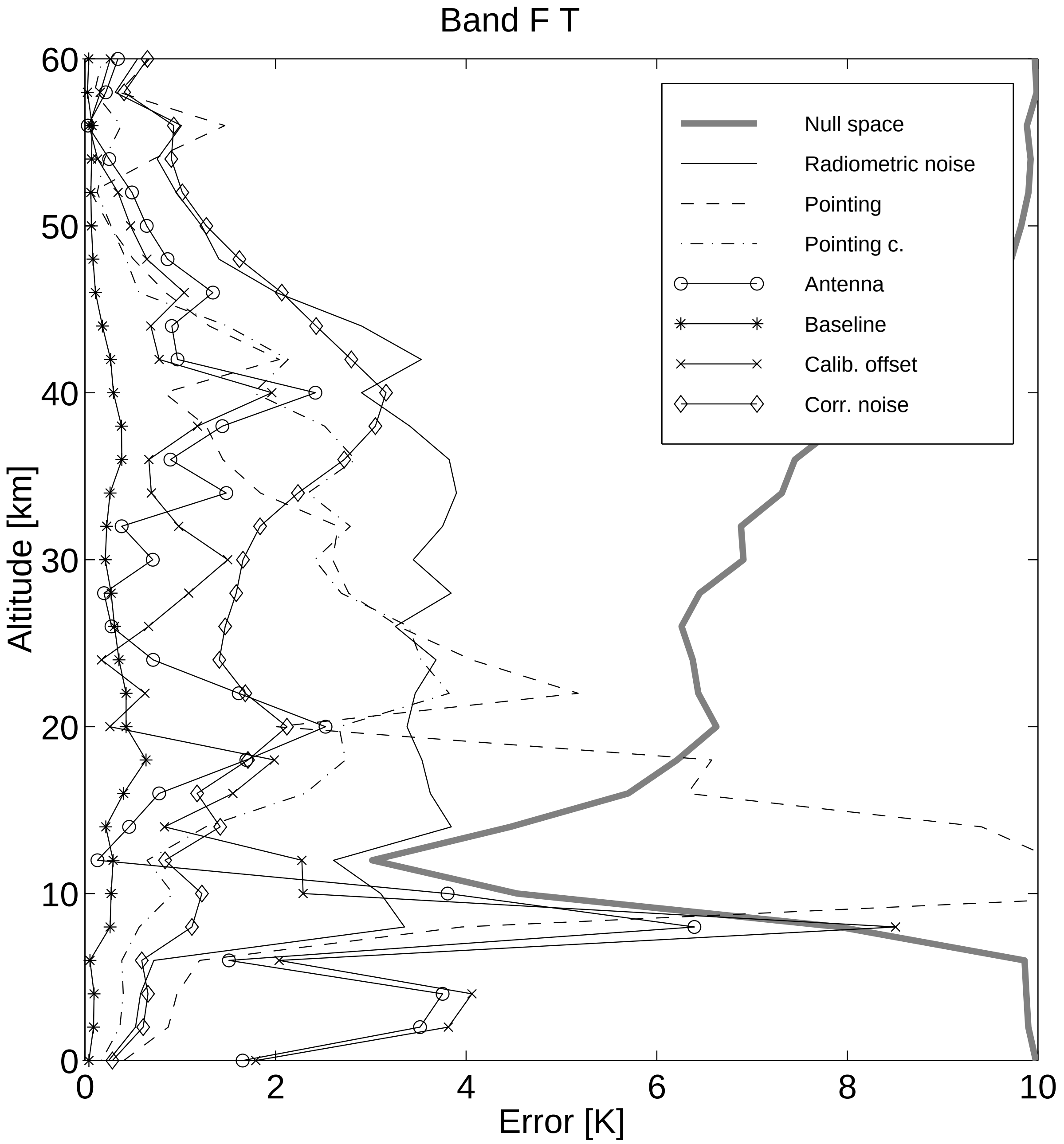
Summary: Ozone Band A (near 500 GHz)



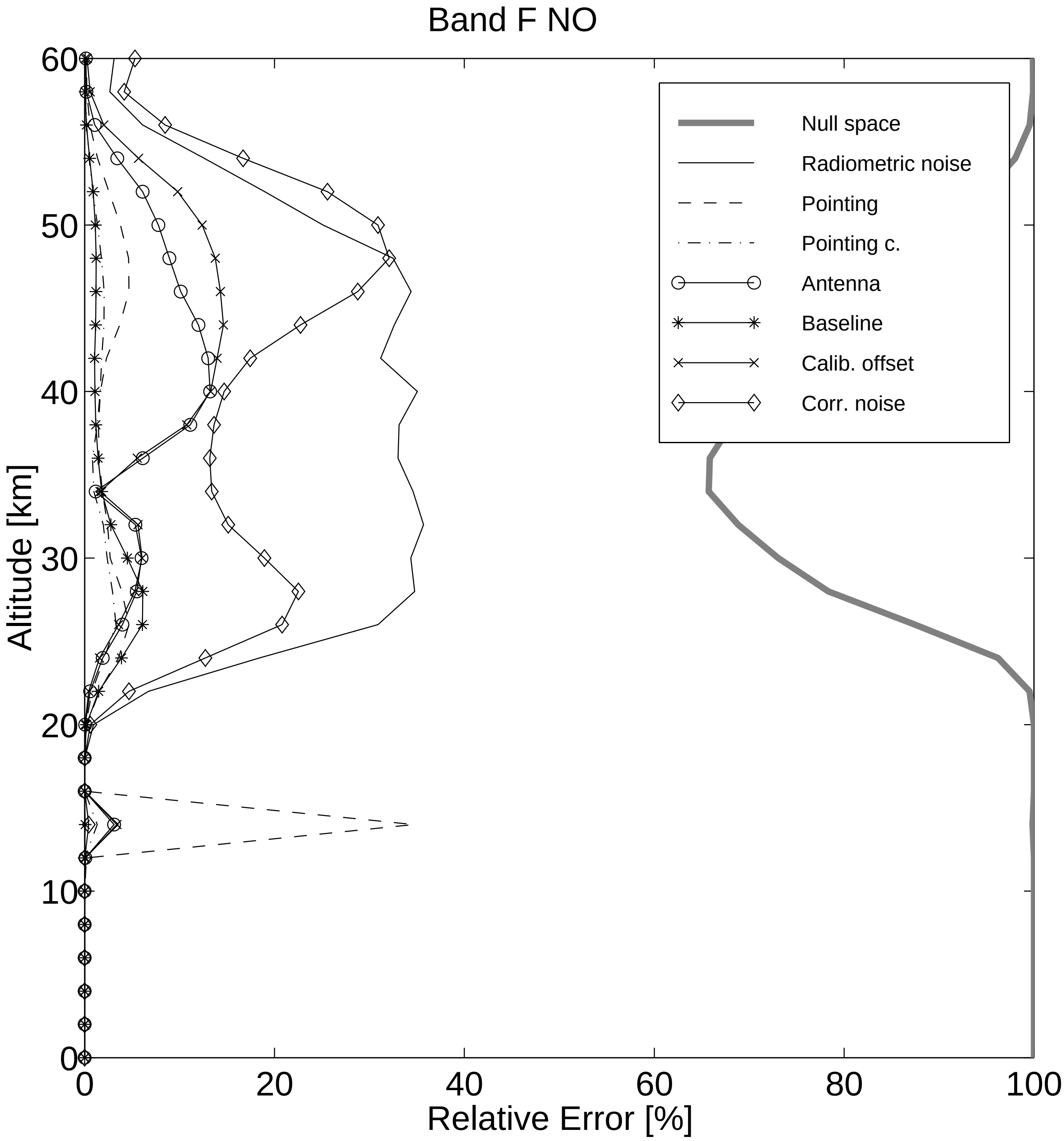
Summary: ClO Band A (near 500 GHz)



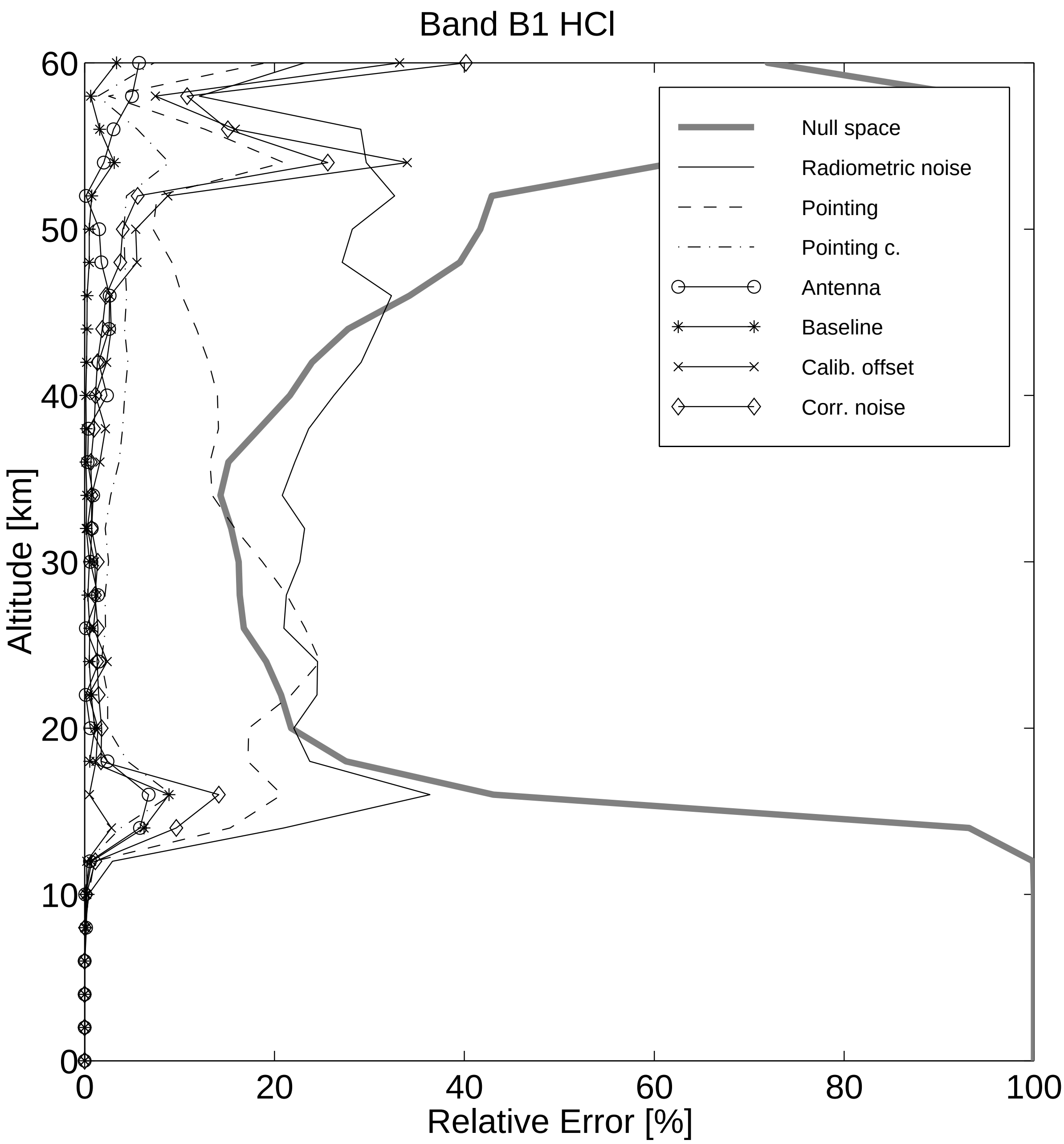
Summary: Temperature Band F (near 954 GHz)



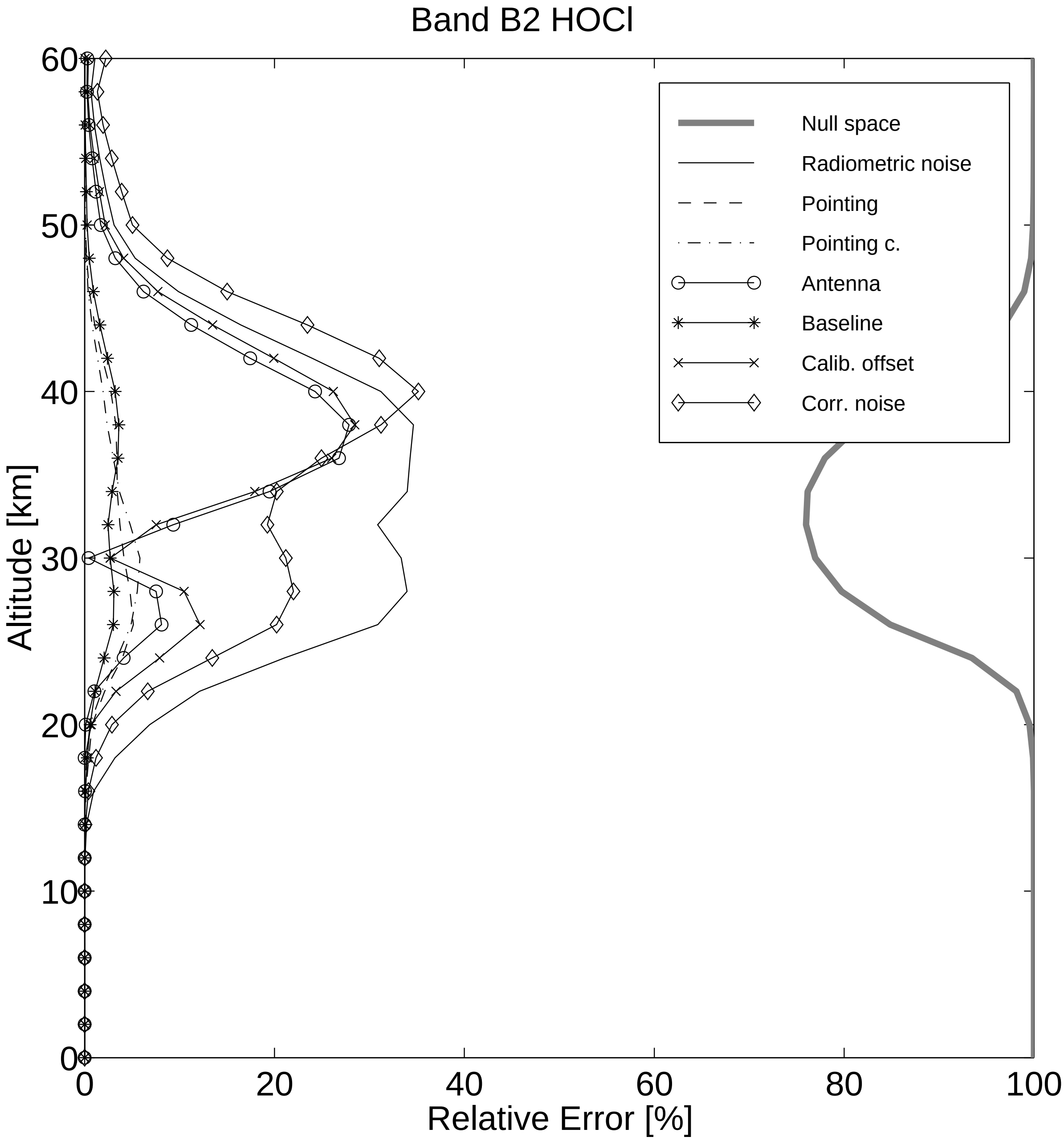
Summary: NO Band F (near 954 GHz)



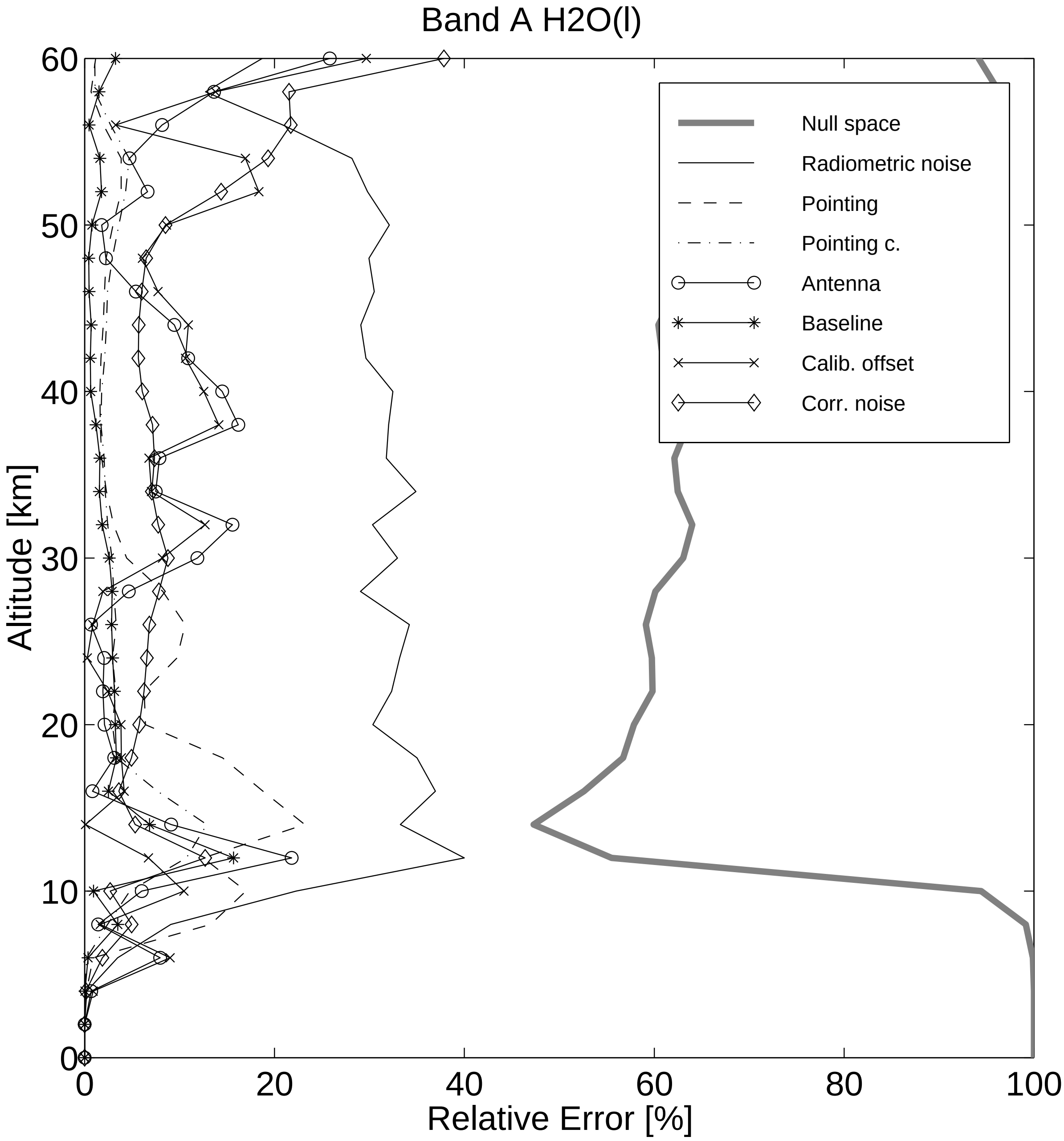
Summary: HCl Band B1
(near 626 GHz)



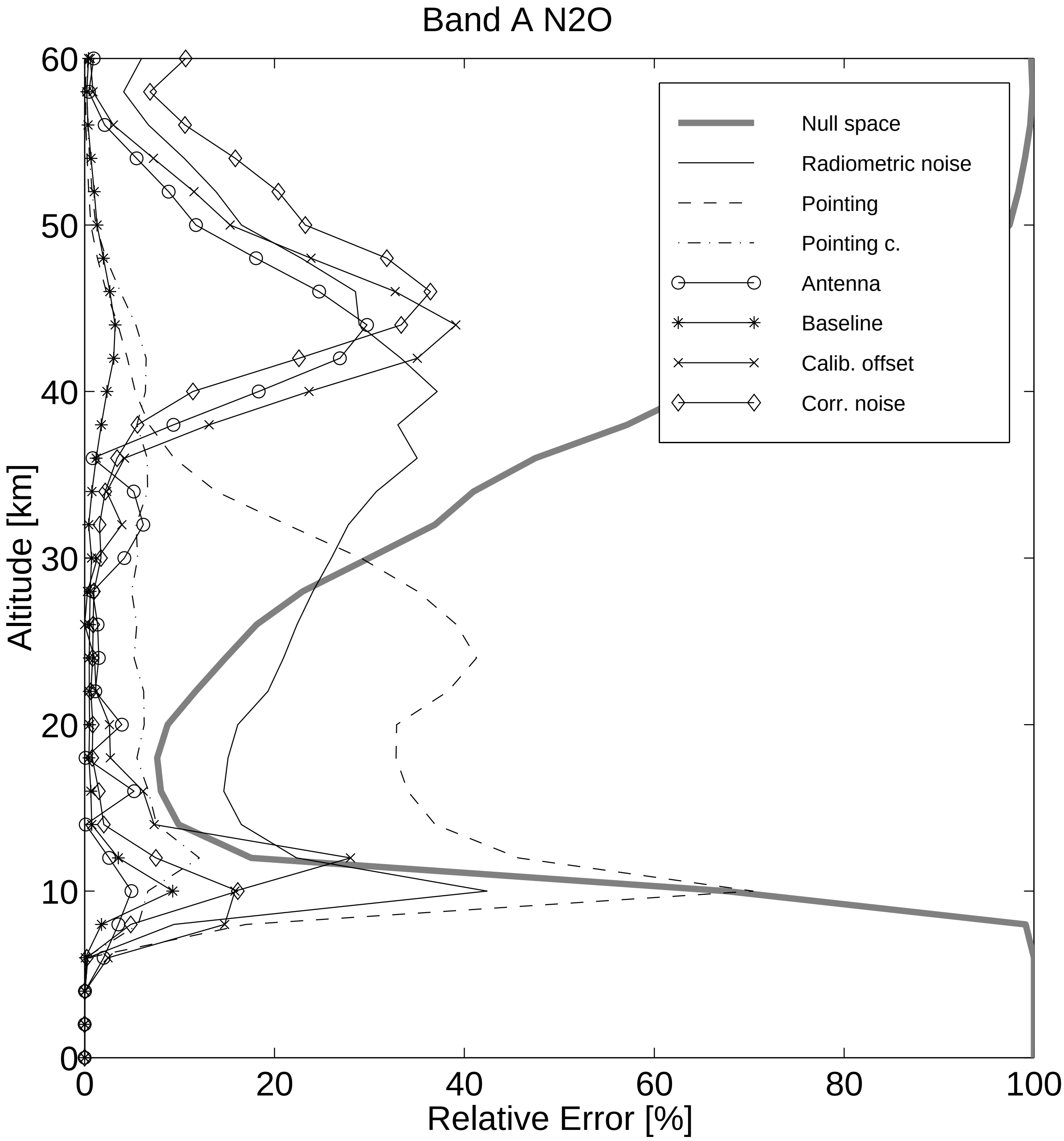
Summary: HOCl Band B2 (near 628 GHz)



Summary: H_2O Band A (near 500 GHz)



Summary: N_2O Band A (near 500 GHz)



Conclusions (1)

Most critical parameters:

- Antenna pattern knowledge (far wing must be covered, requires $\leq$ 35 dB noise)
- Pointing accuracy (should be better than $\pm$ 200 m RMS, increased delay in antenna control loop helps)
- Unwanted sideband (should be significantly better than 20 dB if there are strong lines in the sideband)
  - Can be optimized if other sideband is not used for measurements
- Atmospheric Temperature uncertainty
  - Temperature retrieval schemes are currently investigated

Conclusions (2)

Slightly less critical parameters:

- Baseline ripples
- Calibration errors

But SOPRANO radiometric requirements are stringent (one could also say optimistic):

- 0.1 K amplitude of baseline ripples
- 1 K hot and cold load temperature errors
- 0.2 K non-linearity

More significant for SMILES because radiometric noise is lower

From all our practical experience, baseline ripples are likely to be a problem with the actual instrument.

Conclusions (3)

Relatively uncritical parameters:

- Actual shape of antenna pattern (investigated 1–10 % near wing, 0–4 % far wing)
  - provided it is well known
  - provided FWHM stays the same
  - provided the scan goes down into the opaque region
- Pointing stability
  - Leads to slightly increased width of effective antenna pattern
  - $\pm$ 200 m is tolerable
- Baseline discontinuities (0.4 K every 2 GHz is tolerable)
  - Can be optimized (disc. not on line centers)
- Correlated noise
  - Same order of magnitude as measurement noise (for integration time 10 $\times$ atmospheric)
  - Statistical error, i.e., goes down when data is averaged

Conclusion of the conclusions

Crucial!

- **Pointing accuracy**
- **Baseline**
- **Knowledge** of instrument parameters, in particular
  - **Antenna pattern**
  - **Sideband ratio**

Ongoing work

The study has been extended by ESTEC. Issues:

- Temperature / pointing retrieval (in particular from bands without oxygen lines):
  IFE Bremen

- Dedicated study for the retrieval of very weak species, e.g., BrO:
  Observatoire de Bordeaux