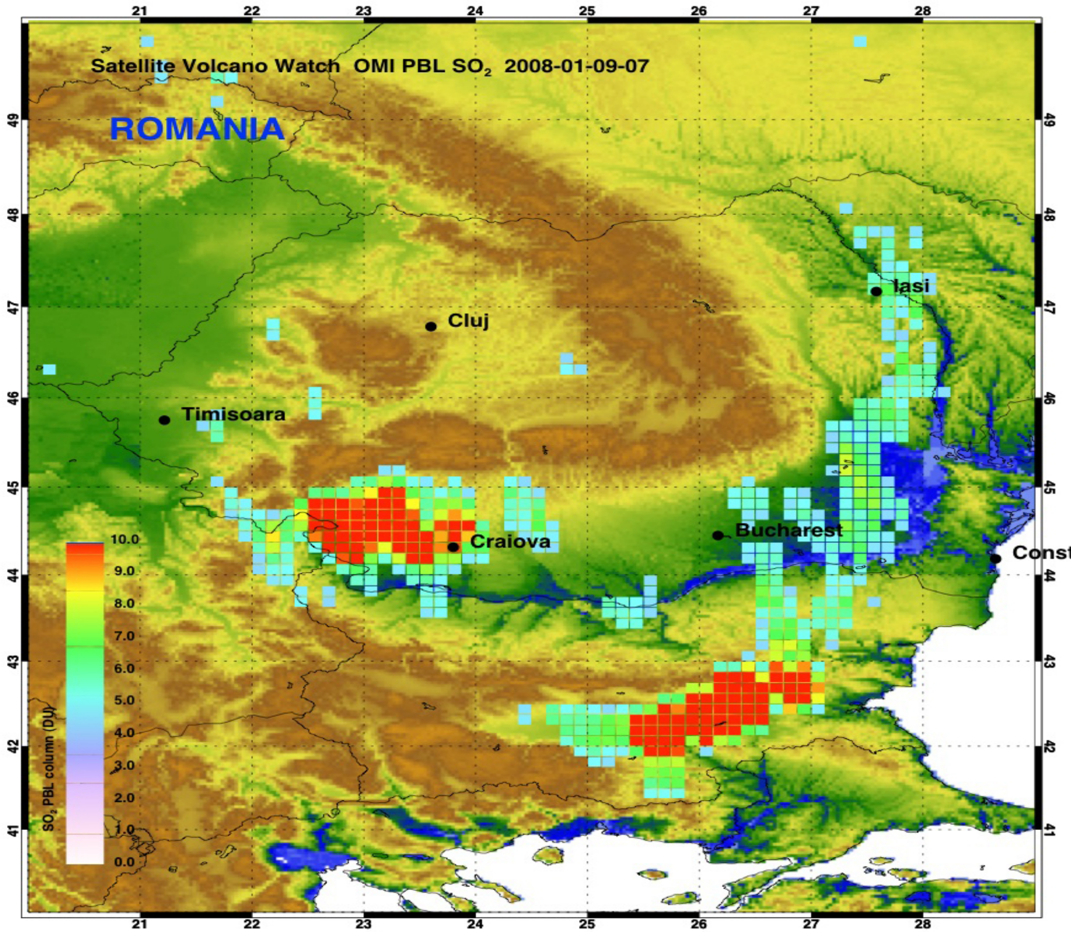
Imaging cameras for monitoring of SO_2 plumes

Kerstin Stebel, Fred Prata, Cirilo Bernado,
Franck Dauge, and Rolf Haugen
NILU – Norwegian Institute for Air Research

& RADO team

Norsk institutt for luftforskning



Bulgaria's Maritza Iztok 3 t-plant has become the cleanest in Eastern Europe, the plant's operator Enel declared. Photo by Alexander Markov (Sofia News Agency)

Left: OMI Planetary Boundary Layer SO_2 for Romania and Bulgaria on 1–7 Sept.2008. Units are Dobson units (DU) and each 0.25 x 0.25 degree box contains SO_2 a mounts accumulated over the period of 7 days, i.e. the first week of September 2008 in this case.

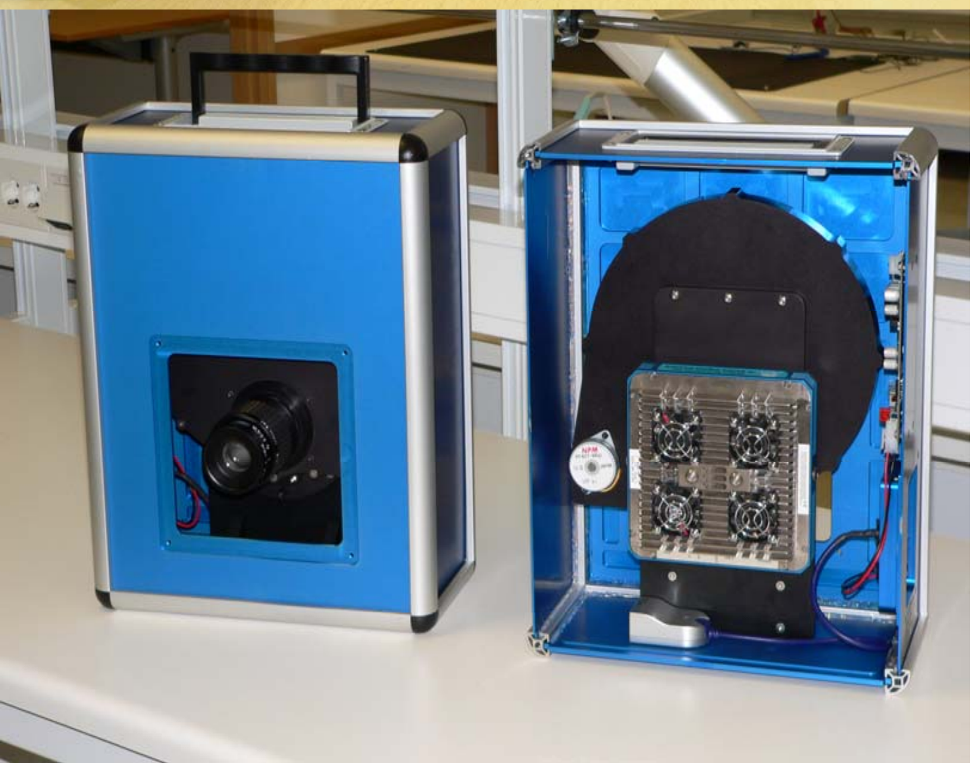
High SO_2 concentrations

* Industrial emissions in the Craiova area
* Source of plume over Bulgaria source from ‘‘clean’’ Maritza power plants
* Emissions following topography of Carpathian mountains

Romanian Atmospheric research 3D Observatory - RADO

NILU's role:

- technical and scientific support for the implementation of the project
- training of Romanian researchers at NILU and at RADO
- **develop 5 IR and 5 UV cameras** for SO_2, particles, volcanic plumes, and to implement them at the 5 stations of the observatory



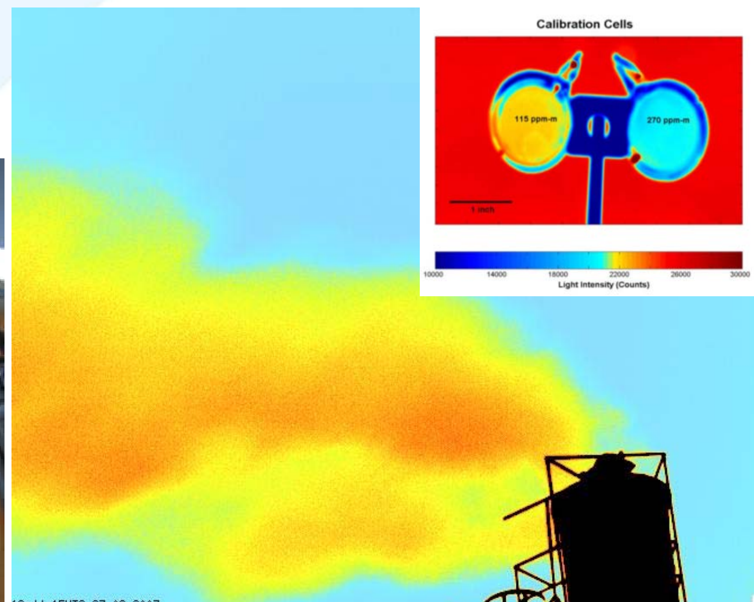
UV camera

Detector	Apogee e2V CCD47-10 back illuminated QE ~60% at 320 nm cooled
Pixels	1024x1024 13 µm square
Filterwheel	max. 9 filters 310, 315,325 and 330 nm 10 nm FWHM
UV lens	50, 78, 105 mm, F/3.5, F/3.8, F/4.0
Digitisation	16 bits
FOV	15.2° - 7.23°
Detection range	~10 km
Accuracy (SO_2)	0.1 gm^{-2}

SO_2 camera development:

Mori T, Burton MR (2006) The SO_2 camera: a simple, fast and cheap method for ground-based imaging of SO_2 in volcanic plumes. Geophys Res Lett 33:L24804. doi:10.1029/2006GL027916

Bluth GJS, Shannon JM, Watson IM, <u>Prata AJ</u>, Realmuto VJ (2007), Development of an ultra-violet digital camera for volcanic SO_2 imaging. J Volcanol Geotherm Res 161:47–56



Portable UV imaging camera for industrial and anthropogenic gas emission monitoring and assessment

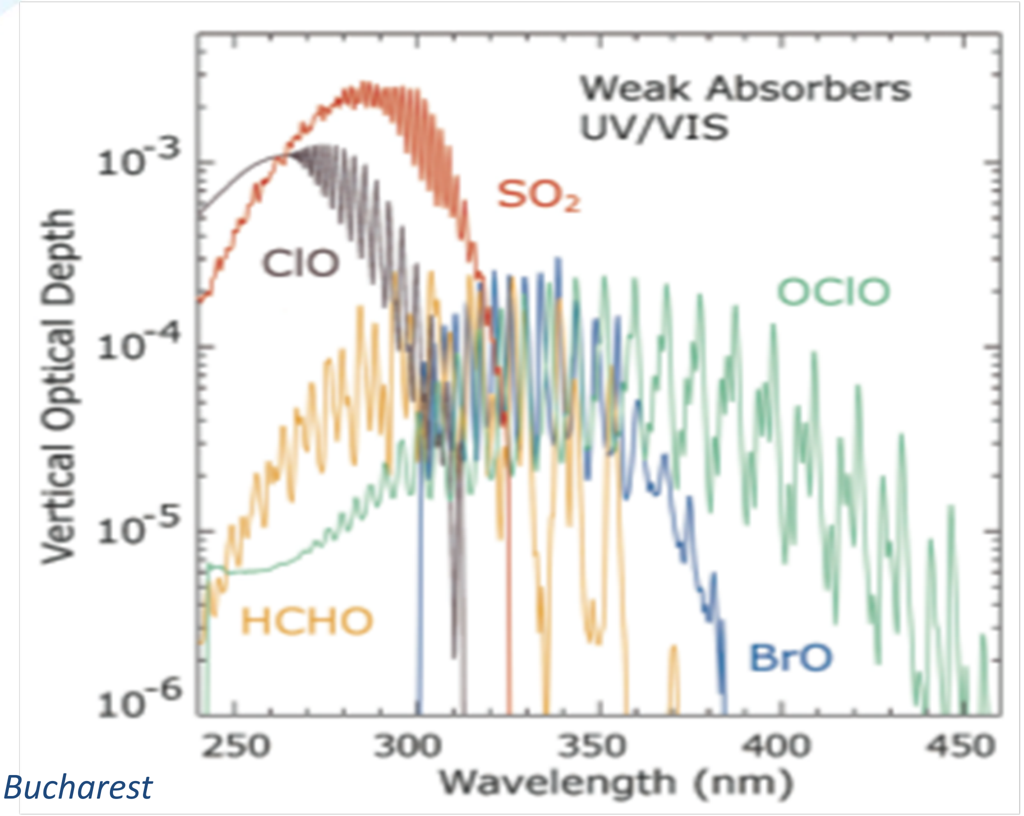
Measurement and calibration principle:

Beer-Bougier-Lambert-law

$$I_A(\lambda) = I_{0,A}(\lambda) \cdot \exp(-k_{\lambda} \cdot \rho \cdot L)$$

$$\mathrm{Ln}(I / I_{0,A}) = -k \cdot S$$

k: extinction coefficient
ρ: gas concentration
L: pathlength
S: path concentration



Calibration:

Quartz glass cells filled with known amounts of SO_2

NILU

Measurement principle, cont.

$$\tau_A = \tau_{SO_2} + \tau_{SCAT}$$

↓

$$\tau = \tau_A - \tau_B$$

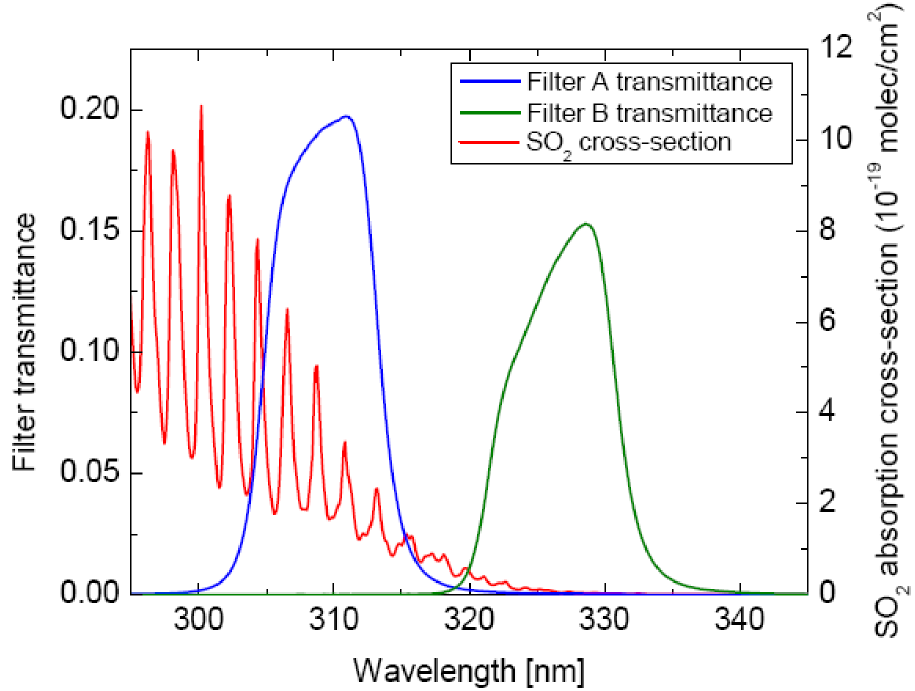
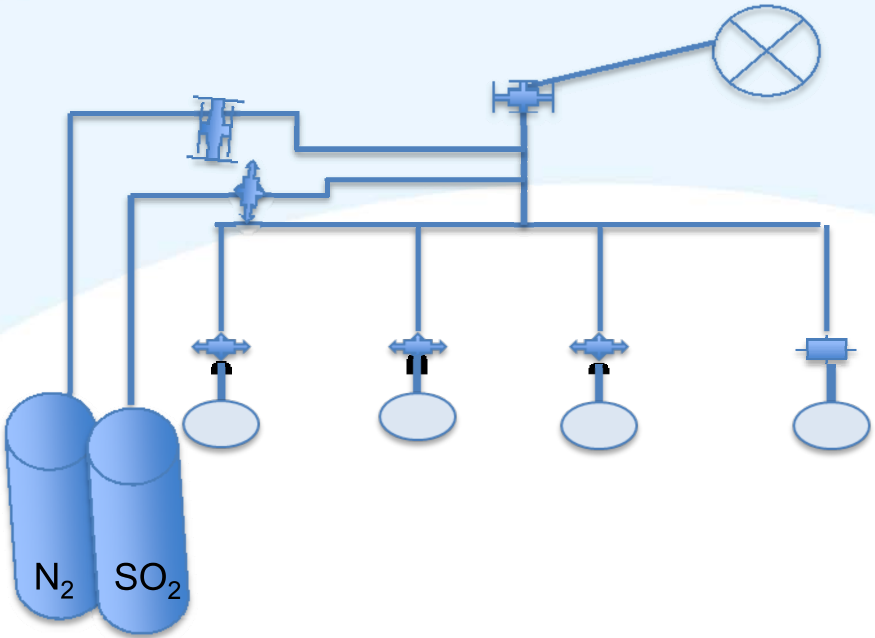


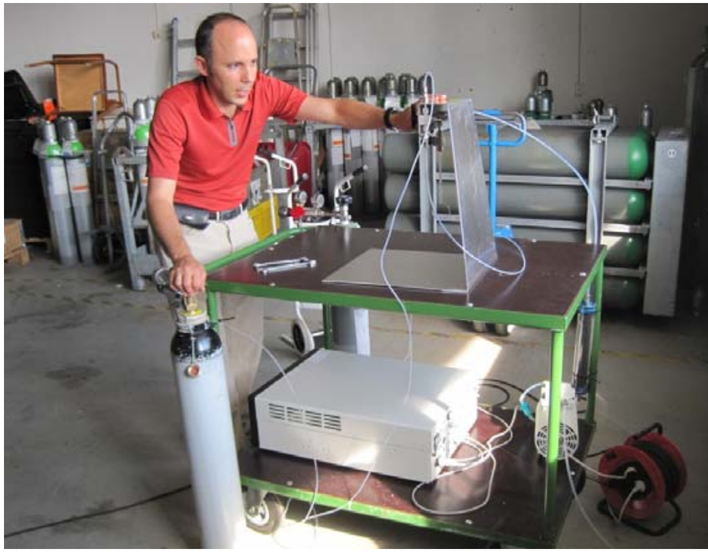
Fig. 4.11 – Measured transmittance of the two band-pass filters used for construction of the SO_2-camera prototype. Also shown (red) is the absorption cross-section of SO_2 (*Bogumil et al. 2003*). (Adapted from *Kick 2008*)

[from Kern, AMTD, 2010]

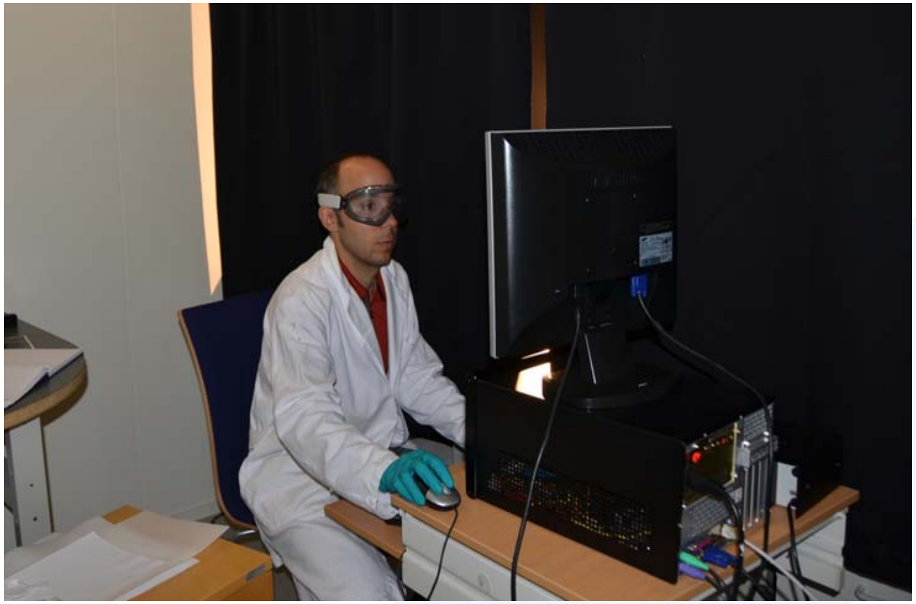
Quartz glass calibration cells 50 mm diameter [100 – 1500 ppm·m] [<5000 ppm·m]

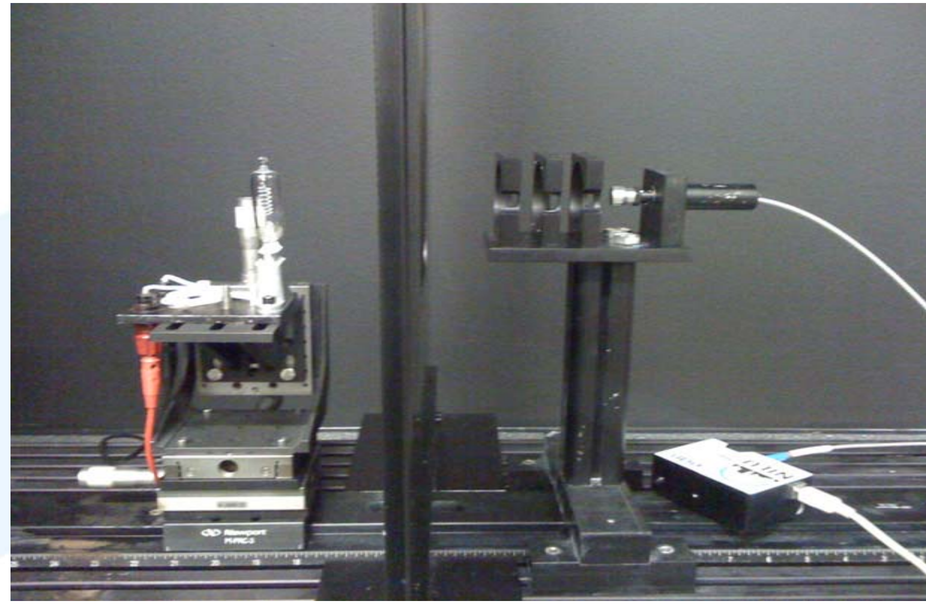


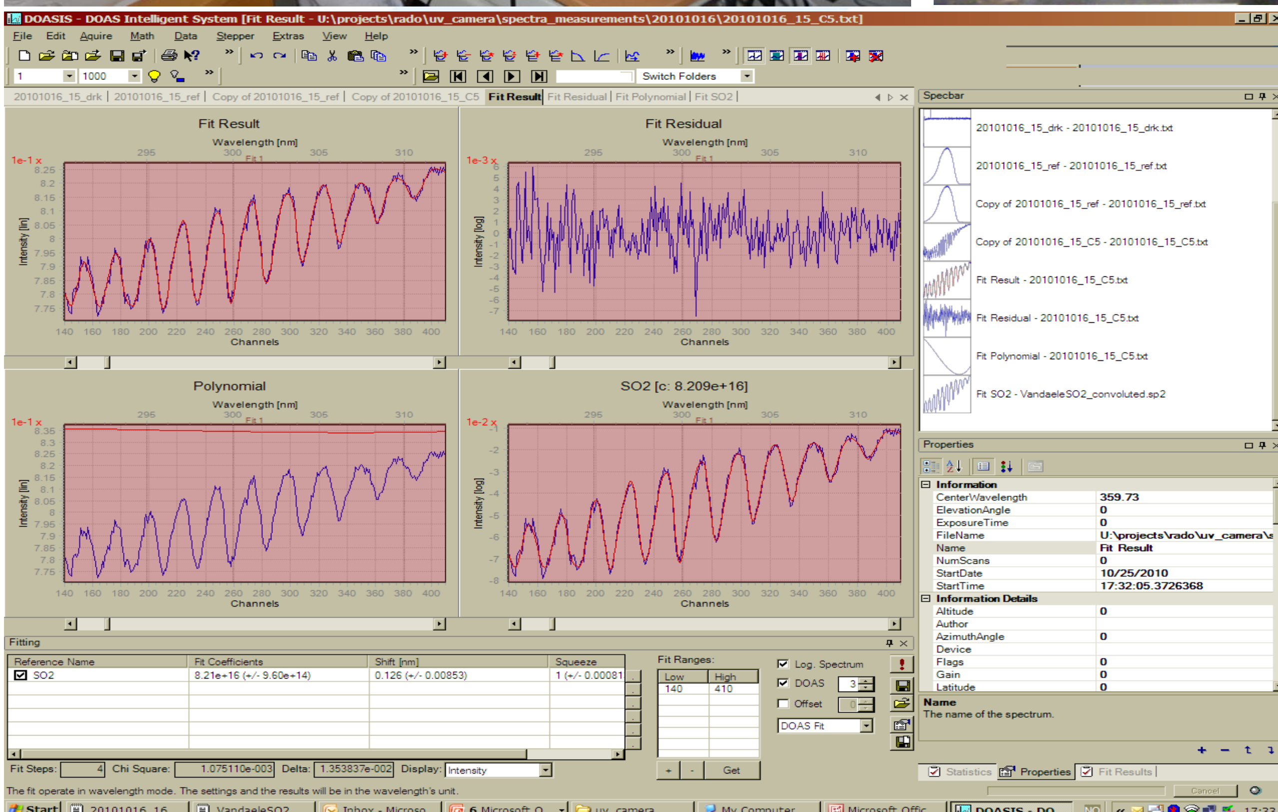
1. heat at 100°C, flush with N_2 for one hour
2. evacuate, fill with mixture of SO_2 and N_2
3. sealing by glass blower



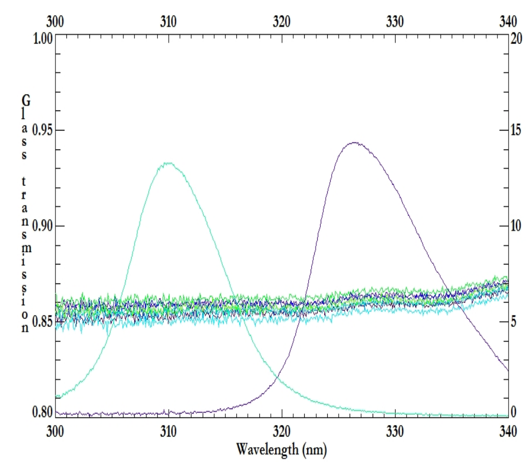
NILU

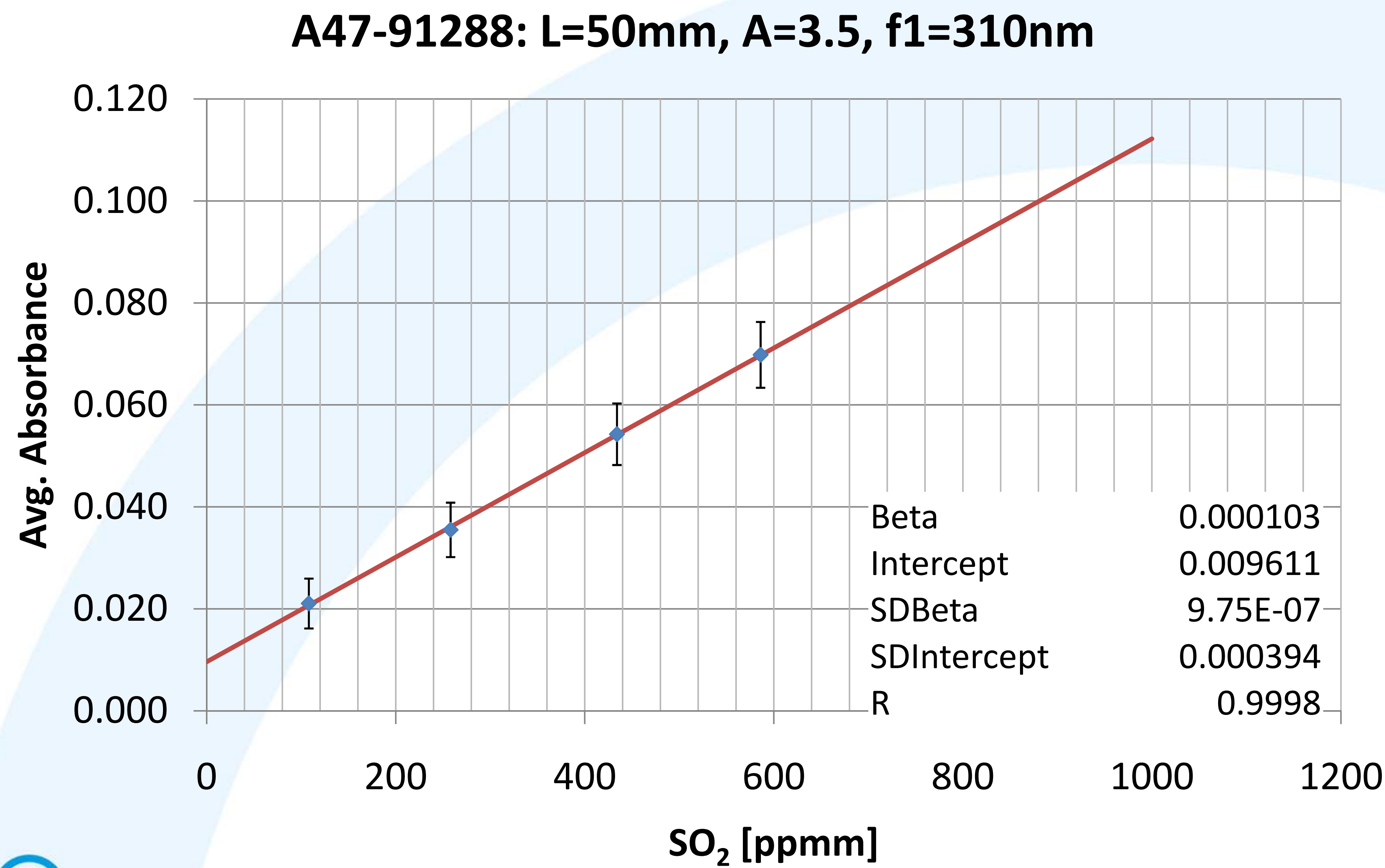






$$T_{glass,\,310\,nm} - T_{glass,\,330\,nm} < 0.01$$

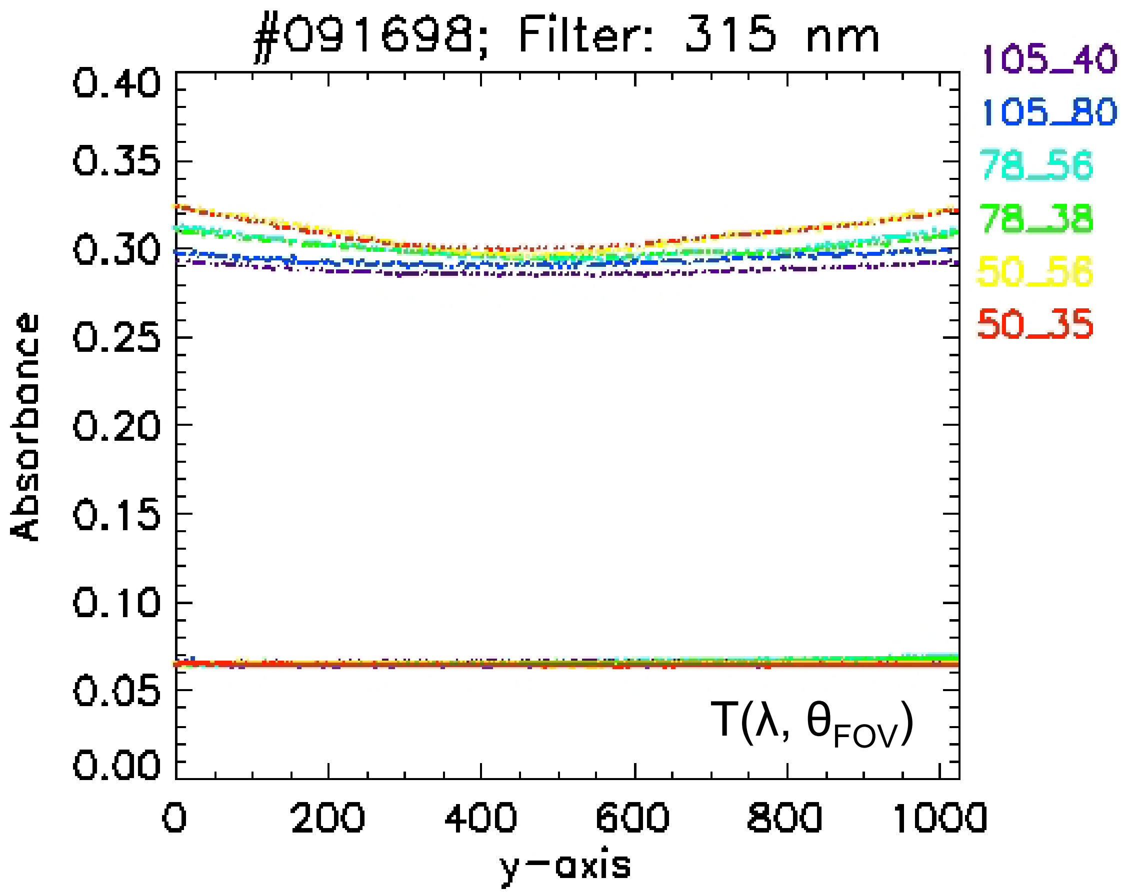


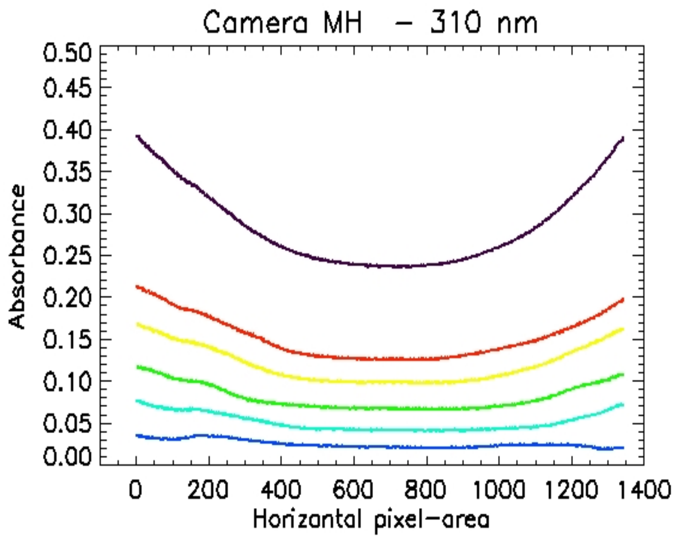

A47-91288: L=50mm, A=3.5, f1=310nm
0.120
0.100
0.080
0.060
0.040
0.020
0.000
Avg. Absorbance
0
200
400
600
800
1000
1200
SO2 [ppmm]
Beta 0.000103
Intercept 0.009611
SDBeta 9.75E-07
SDIntercept 0.000394
R 0.9998

Calibration corrections

$$\hat{\tau}_A = -\ln\left(\frac{\int_\lambda I_S(\lambda, SZA)\cdot T_A(\lambda,\theta)\cdot Q(\lambda,\beta)\cdot T_O(r_{1..n})\cdot \exp(-\sigma(\lambda)\cdot S(\lambda))\cdot d\lambda}{\int_\lambda I_S(\lambda, SZA)\cdot T_A(\lambda,\theta)\cdot Q(\lambda,\beta)\cdot T_O(r_{1..n})\cdot d\lambda}\right)$$

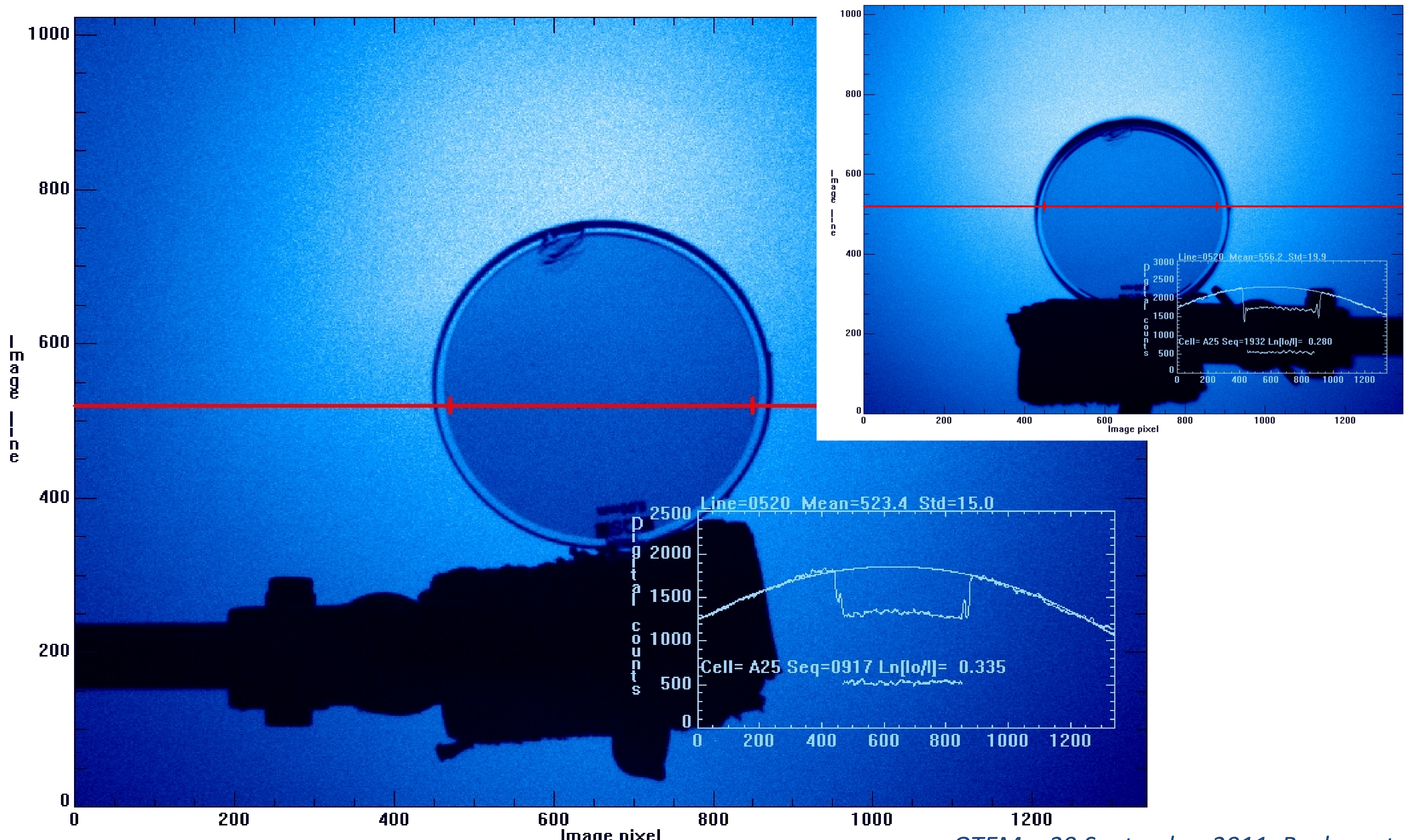
from Kern, AMTD, 2010





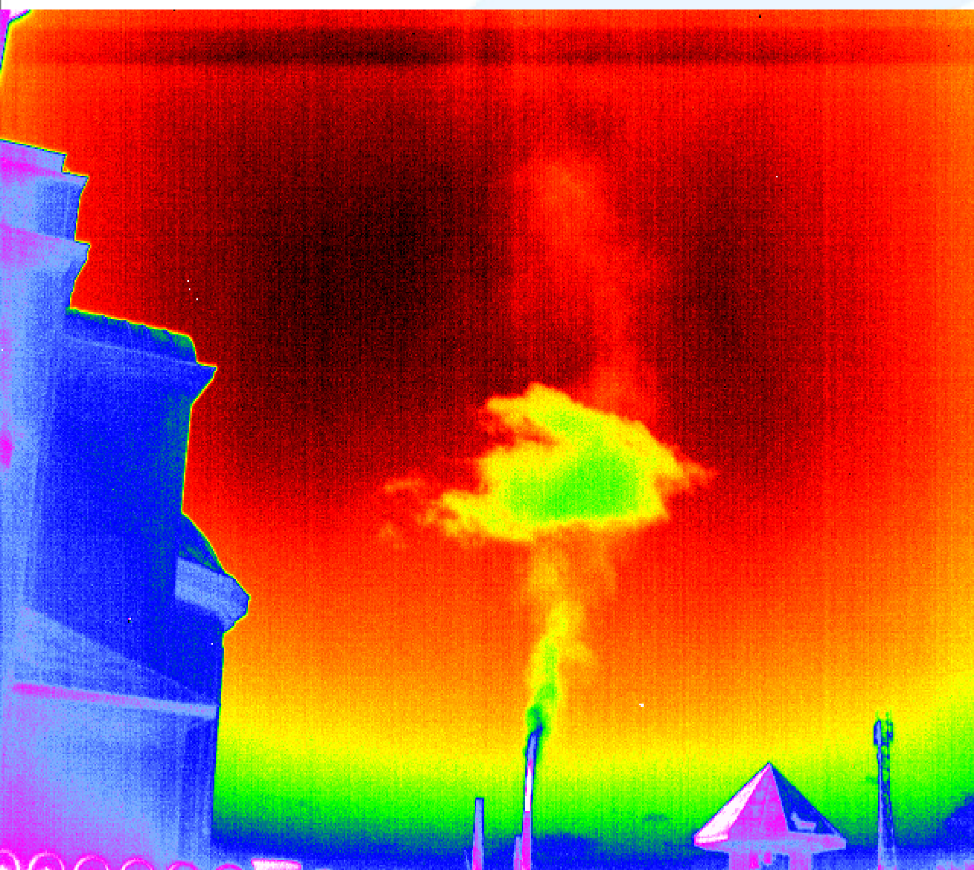
Calibration cell A25 (~1600ppmm) - at 09:17 LT $\tau_{A\_so_2 + glass} = 0.335$

at 19:32 LT $\tau_{A\_so_2 + glass} = 0.280$

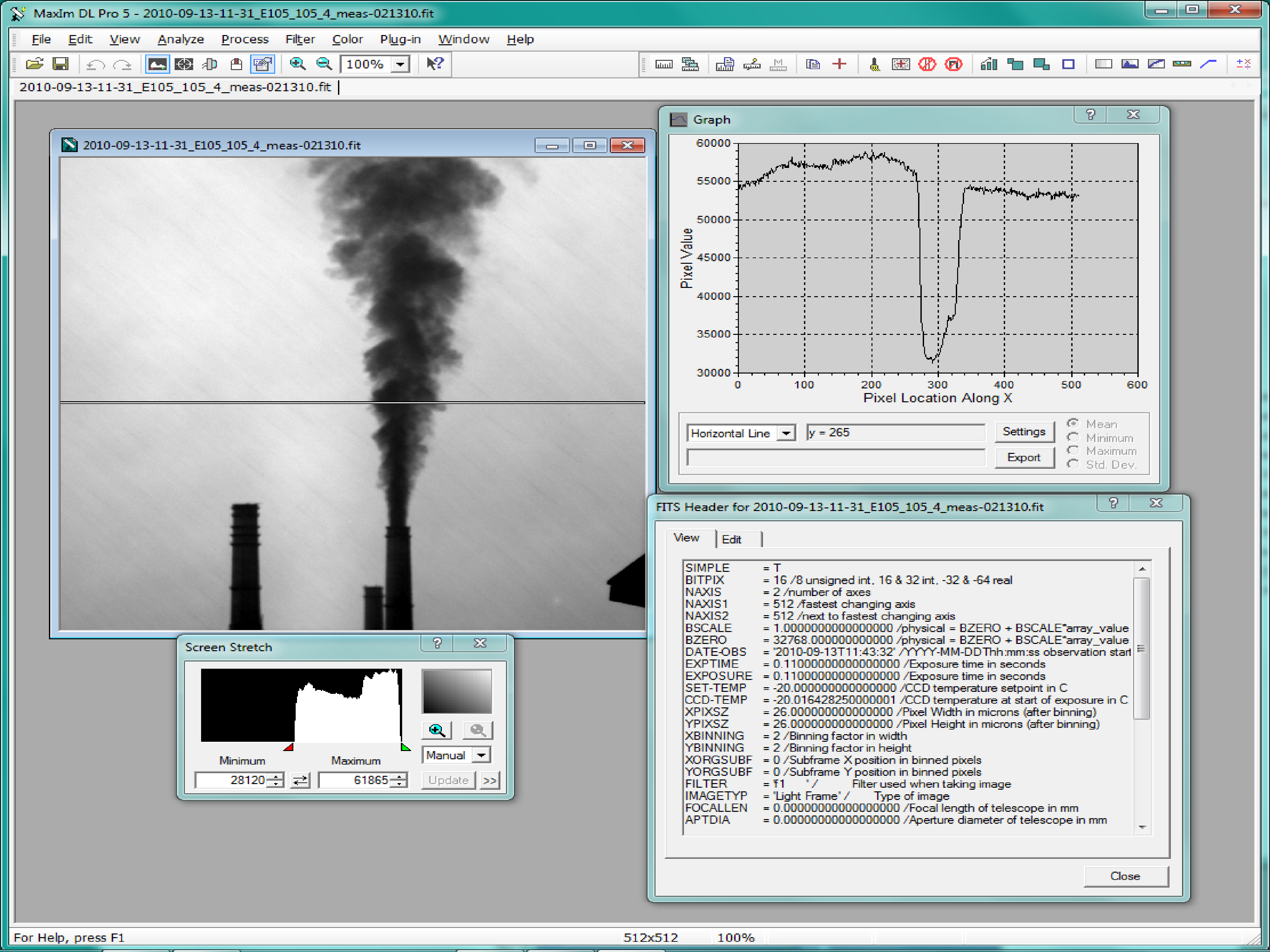


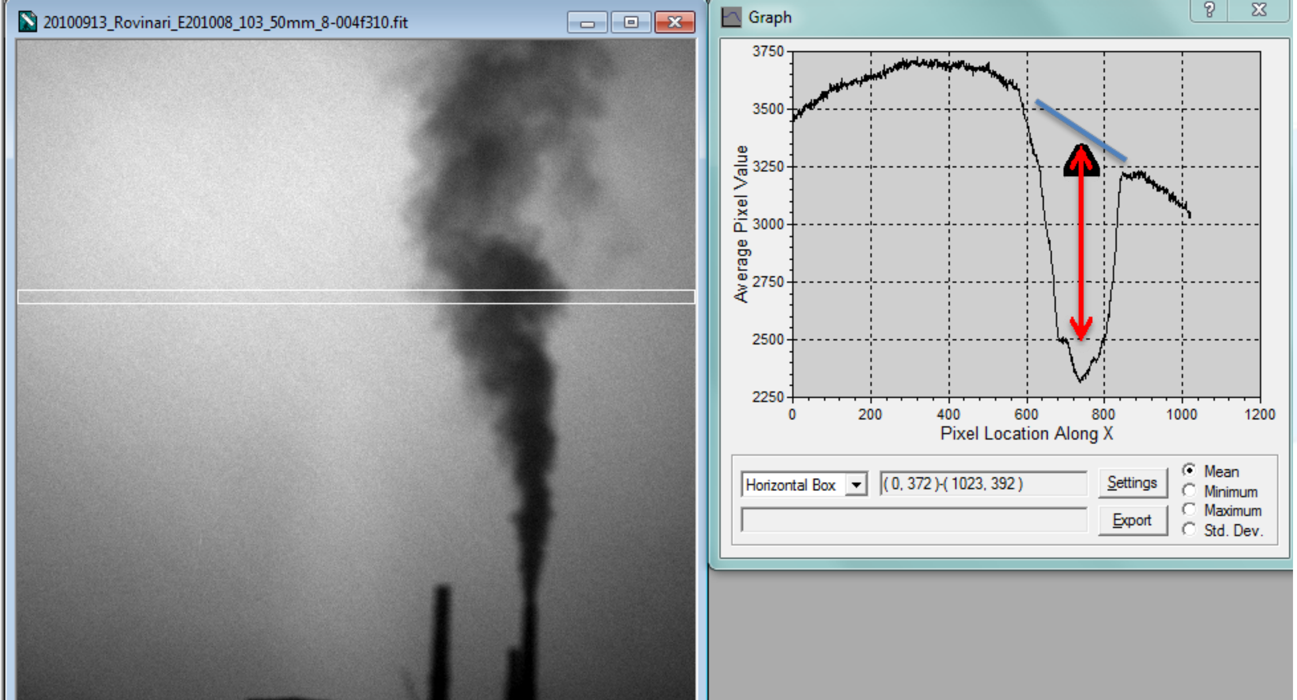
Romanian Atmospheric research 3D Observatory - RADO

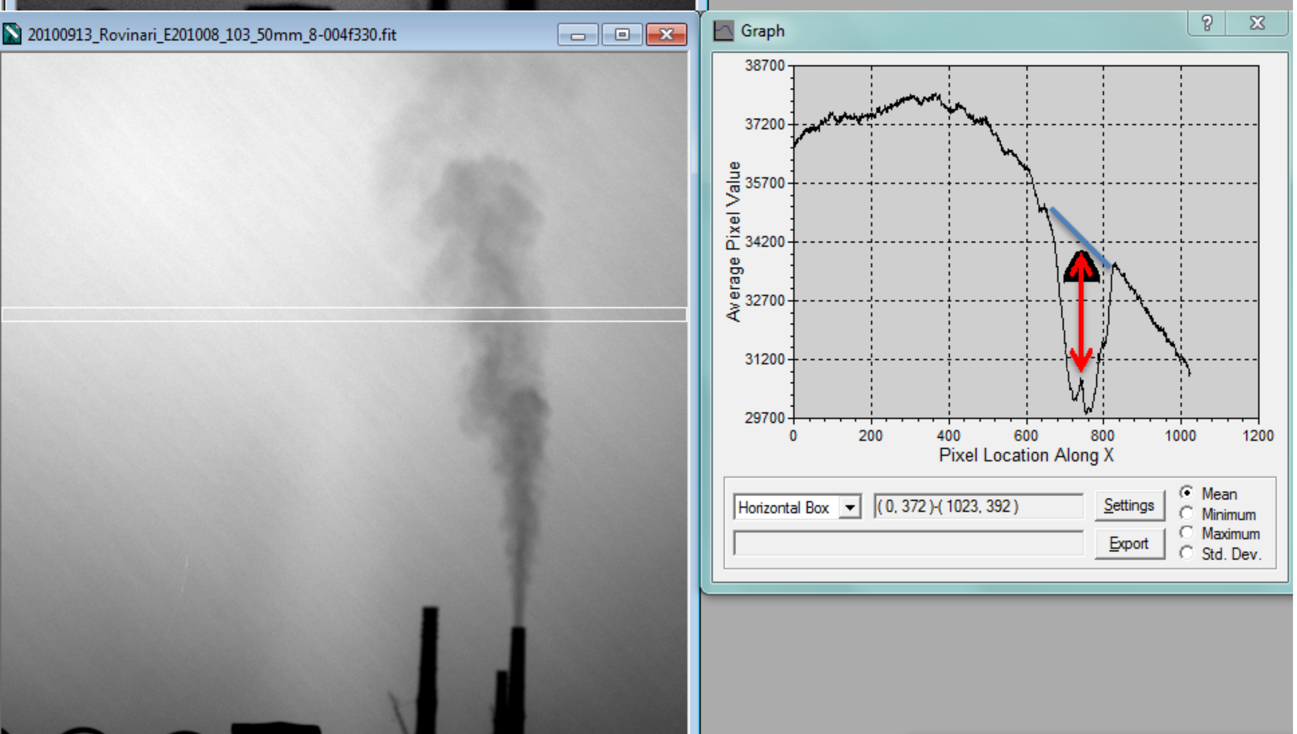
Rovinari field training site



1 – 15 September 2010


MaxIm DL Pro 5 - 2010-09-13-11-31_E105_105_4_meas-021310.fit
File Edit View Analyze Process Filter Color Plug-in Window Help
100%
2010-09-13-11-31_E105_105_4_meas-021310.fit
2010-09-13-11-31_E105_105_4_meas-021310.fit
Graph
60000
55000
50000
45000
40000
35000
30000
Pixel Value
0 100 200 300 400 500 600
Pixel Location Along X
Horizontal Line
y = 265
Settings
Export
Mean
Minimum
Maximum
Std. Dev.
Screen Stretch
Minimum
Maximum
28120
61865
Manual
Update
>>
FITS Header for 2010-09-13-11-31_E105_105_4_meas-021310.fit
View
Edit
SIMPLE = T
BITPIX = 16 /8 unsigned int, 16 & 32 int, -32 & -64 real
NAXIS = 2 /number of axes
NAXIS1 = 512 /fastest changing axis
NAXIS2 = 512 /next to fastest changing axis
BSCALE = 1.0000000000000000 /physical = BZERO + BSCALE*array_value
BZERO = 32768.000000000000 /physical = BZERO + BSCALE*array_value
DATE-OBS = '2010-09-13T11:43:32' /YYYY-MM-DDThh:mm:ss observation start
EXPTIME = 0.11000000000000000 /Exposure time in seconds
EXPOSURE = 0.11000000000000000 /Exposure time in seconds
SET-TEMP = -20.000000000000000 /CCD temperature setpoint in C
CCD-TEMP = -20.016428250000001 /CCD temperature at start of exposure in C
XPIXSZ = 26.000000000000000 /Pixel Width in microns (after binning)
YPIXSZ = 26.000000000000000 /Pixel Height in microns (after binning)
XBINNING = 2 /Binning factor in width
YBINNING = 2 /Binning factor in height
XORGSUBF = 0 /Subframe X position in binned pixels
YORGSUBF = 0 /Subframe Y position in binned pixels
FILTER = 'f1 ' / Filter used when taking image
IMAGETYP = 'Light Frame' / Type of image
FOCALLEN = 0.00000000000000000 /Focal length of telescope in mm
APTDIA = 0.00000000000000000 /Aperture diameter of telescope in mm
Close
For Help, press F1
512x512
100%





Principle:

$- \text{Log} (I_0 - I_d / I - I_d)$

310 nm filter

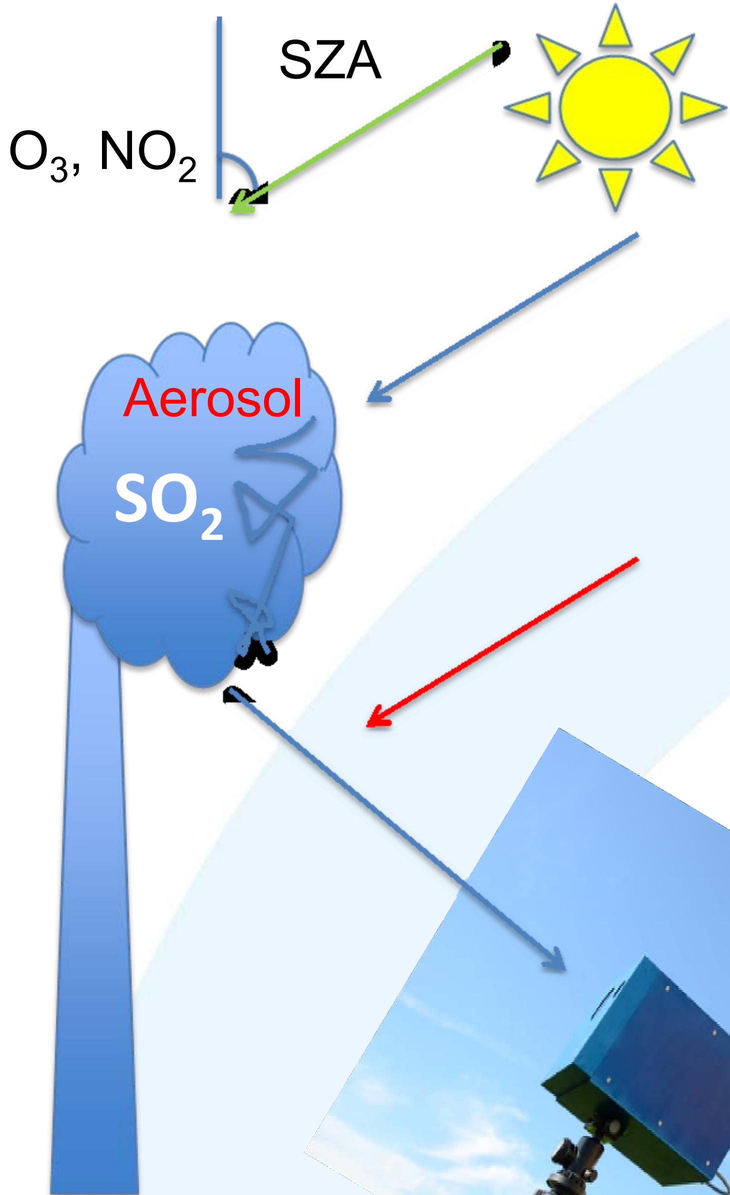
$-\text{Log} (3275 - 1300 / 2260 - 1300) = 0.31$

330 nm filter

$-\text{Log} (34200 - 1300 / 29700 - 1300) = 0.06$

$AA_{SO2} = 0.31 - 0.06 = 0.25$

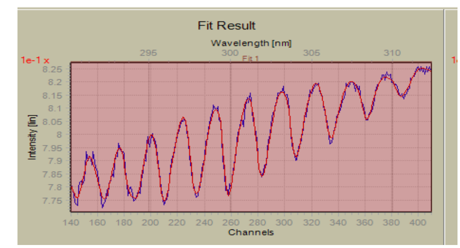
SO_2 : ~ 3000 pppm·m

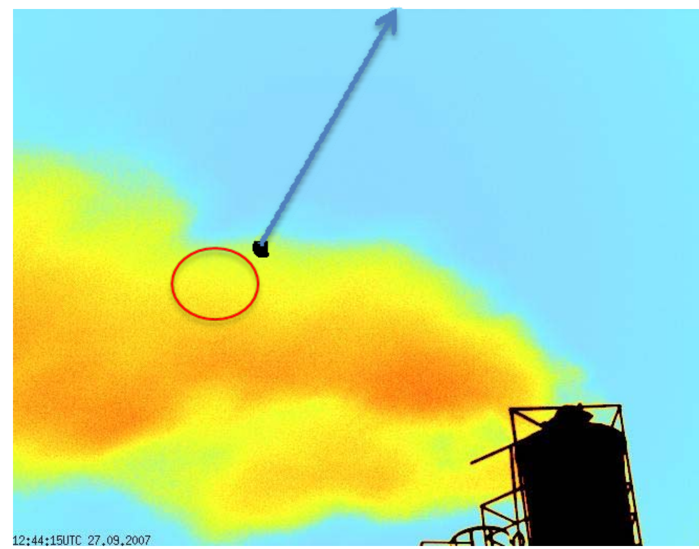


Atmosphere

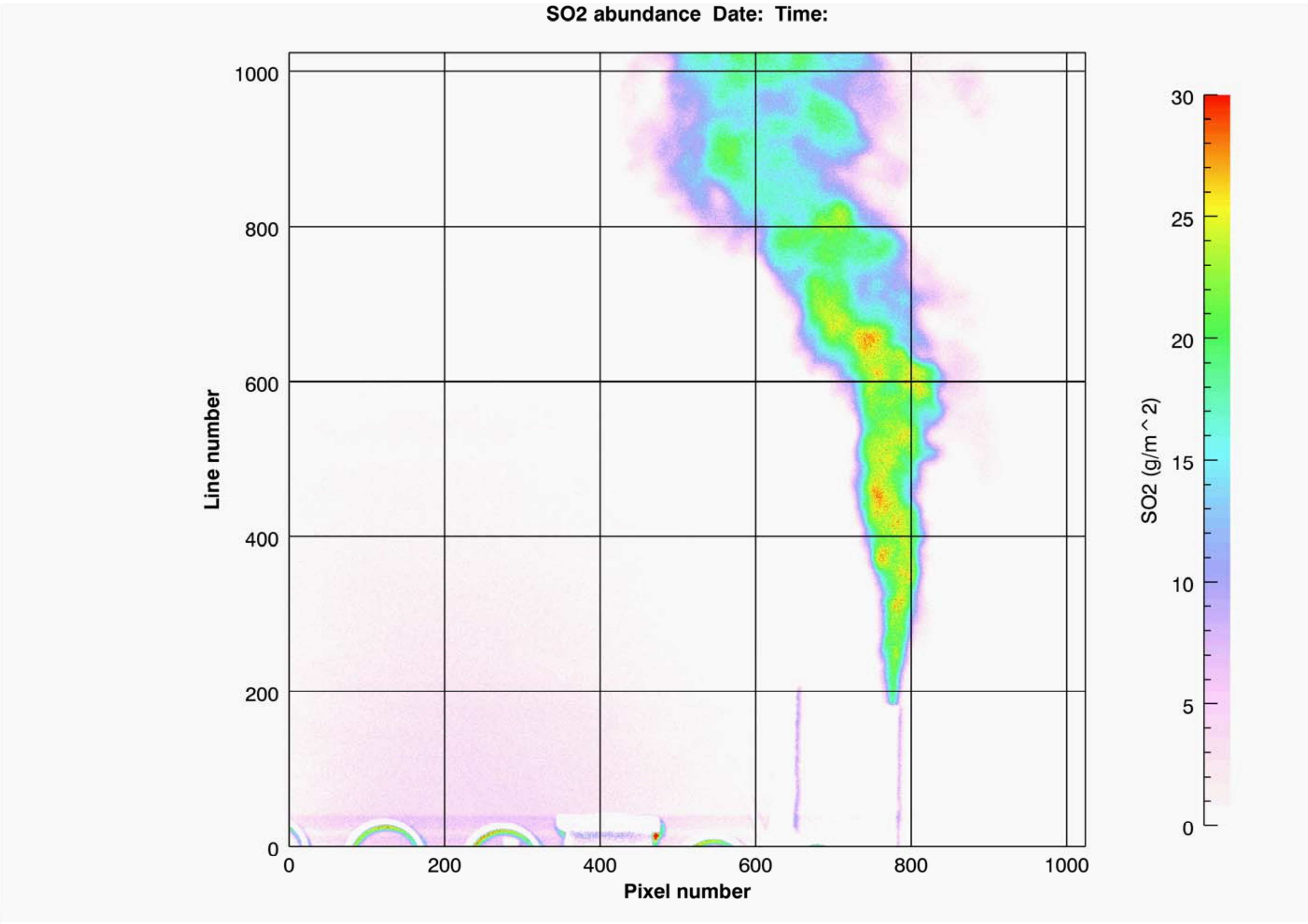
- Dilution
- Multiple scattering

Combine camera and *spectrometer*
& *RT modelling*



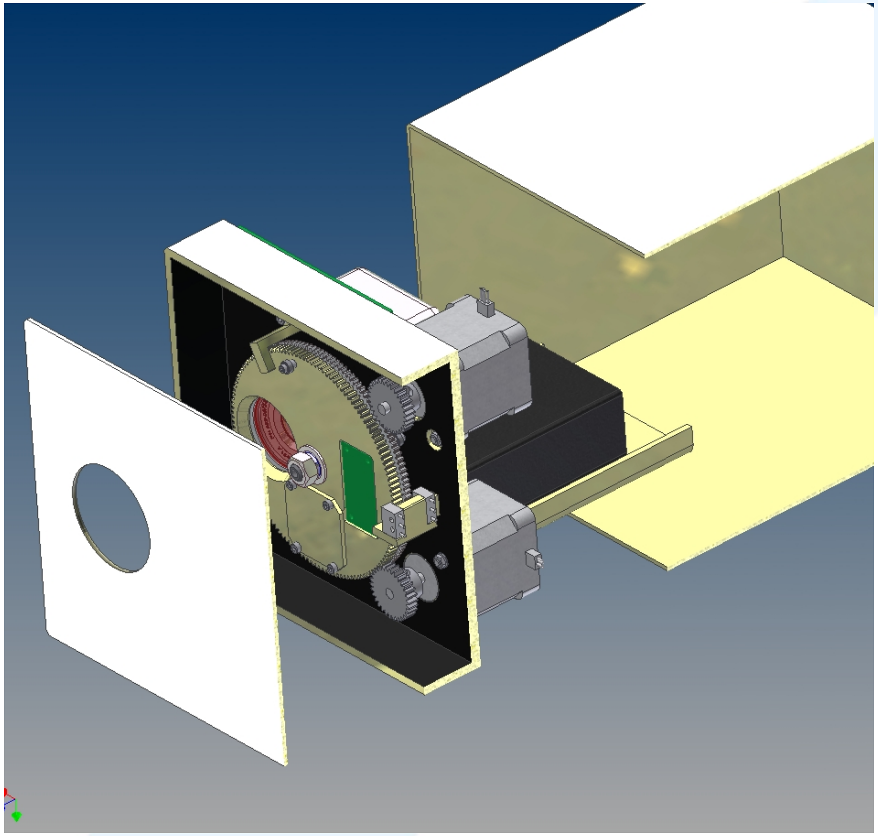


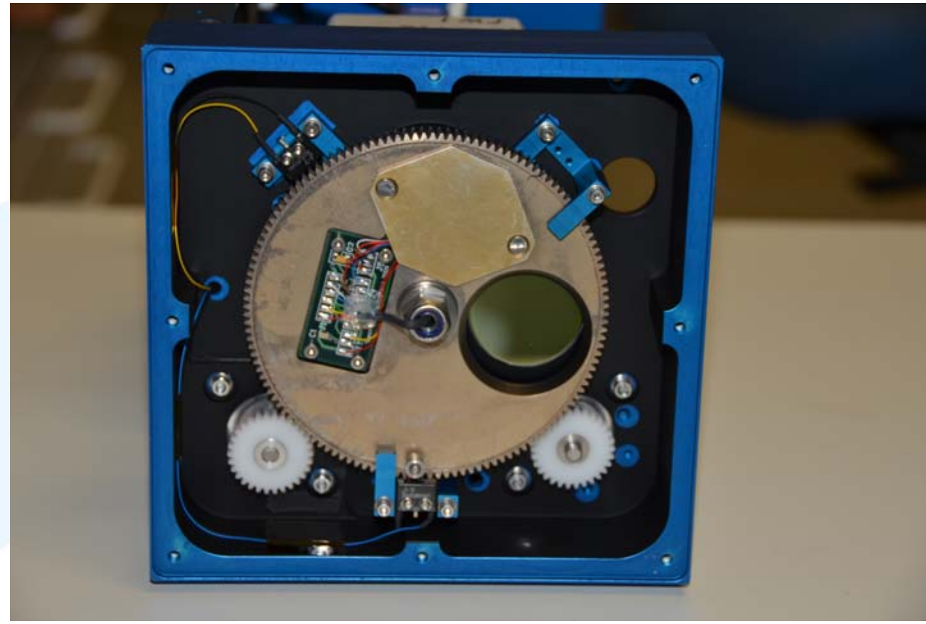
NILU


SO2 abundance Date: Time:
Line number
Pixel number
SO2 (g/m ^ 2)
0
200
400
600
800
1000
0
5
10
15
20
25
30

IR camera

schematics & specification





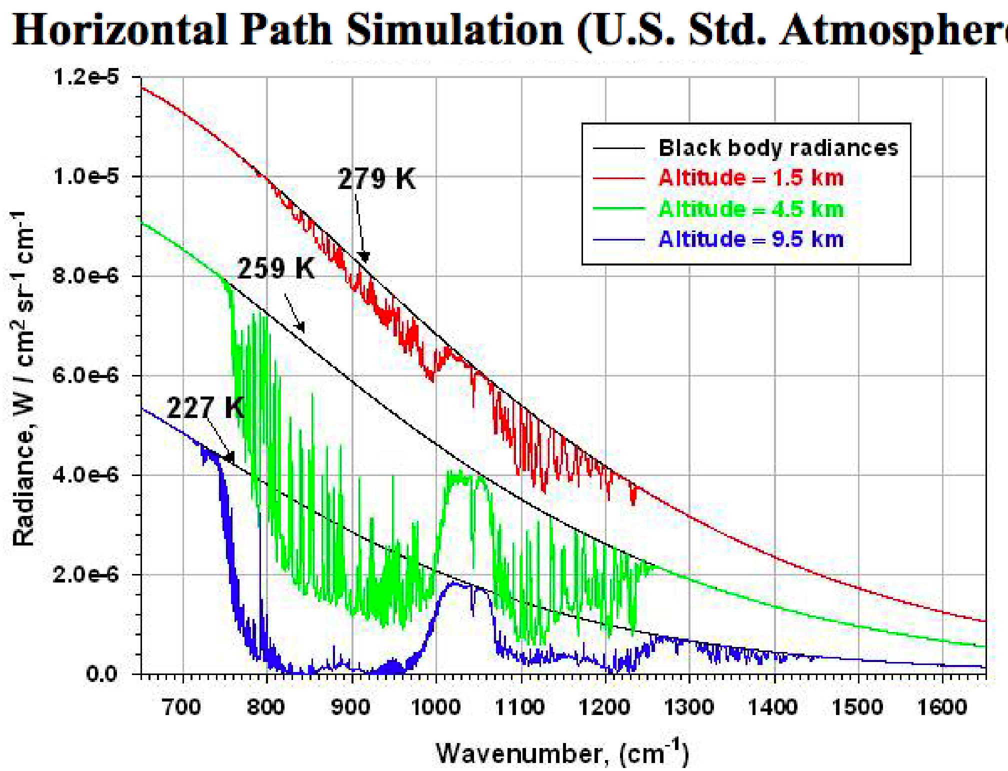
Total field-of-view	43°
Optics	25 mm F1.4 Ge lens
Image size	640 x 512 pixels
Number of filters	up to 4
Filter 1 (SO_2)	8.6 μm
Filter 2 (Plume temperature)	10.0 μm
Filter 3 (Ash)	11.0 μm
Filter 4 (Ash)	12.0 μm
Sampling rate (max)	~7 Hz
Detector	Uncooled microbolometer
NEΔT Filter 1	500 mK @ 250 K
NEΔT Filter 2	200 mK @ 250 K
NEΔT Filter 3	200 mK @ 250 K
NEΔT Filter 4	200 mK @ 250 K
Power requirements	12 V, 3 A, 40 W peak
Accuracy (SO_2)	$\pm$0.2 g m^{-2}
Accuracy (Silicate particles)	$\pm$0.5 g m^{-2}
Detection range	~10 km

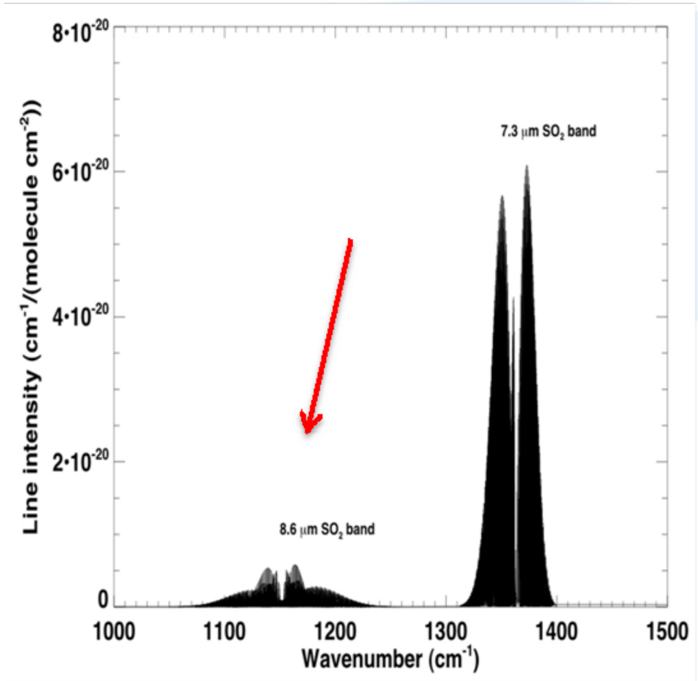
Calibration

- laboratory: black body
- black body shutter

NILU

7.3 µm and 8.6 µm SO_2 bands

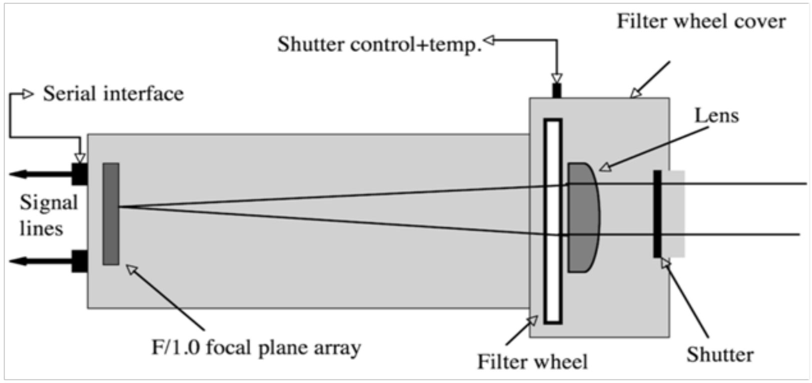




Line intensities from HITRAN-2000 database (Rotheman et a al, 2003)

Table 1.1: Channel number, central wavelength, bandwidth, purpose and required noise equivalent temperature difference (NEΔT) for NicAIR.

Channel No	Wavelength μm	Purpose	NEΔT mK
1	8.65	SO_2/plume imaging	300
2	10.00	SO_2 and volcanic ash/particles	100
3	10.87	Volcanic ash/particles	100
4	12.00	Volcanic ash/particles	100

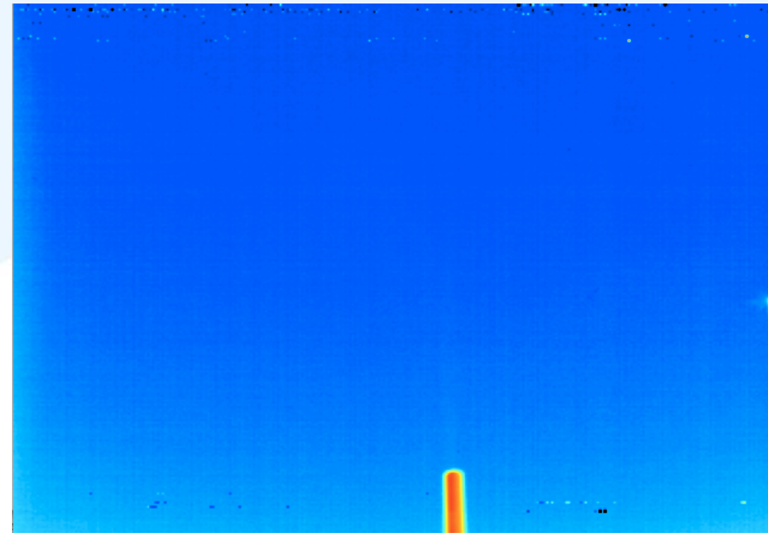


Prata, A. J., and C. Bernardo (2007) Retrieval of volcanic SO_2 column abundance from Atmospheric Infrared Sounder data, J. Geophys. Res.,112, D20204, doi:10.1029/2006JD007955.

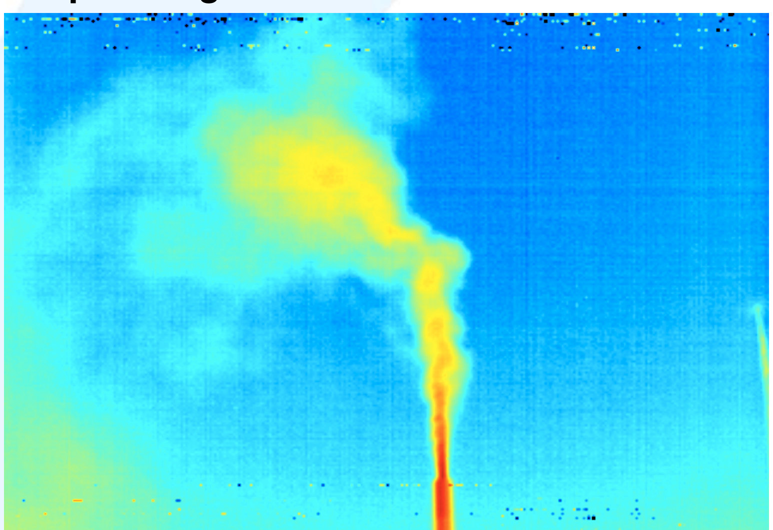
Stack measurements

Broadband image

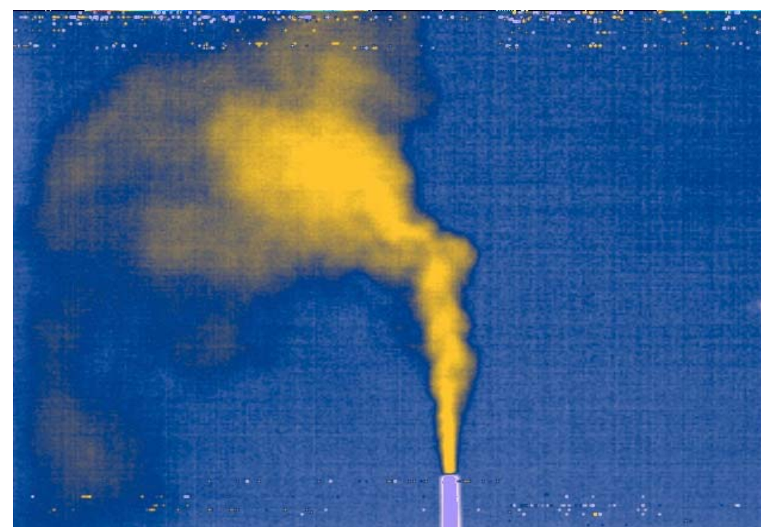
11 µm image



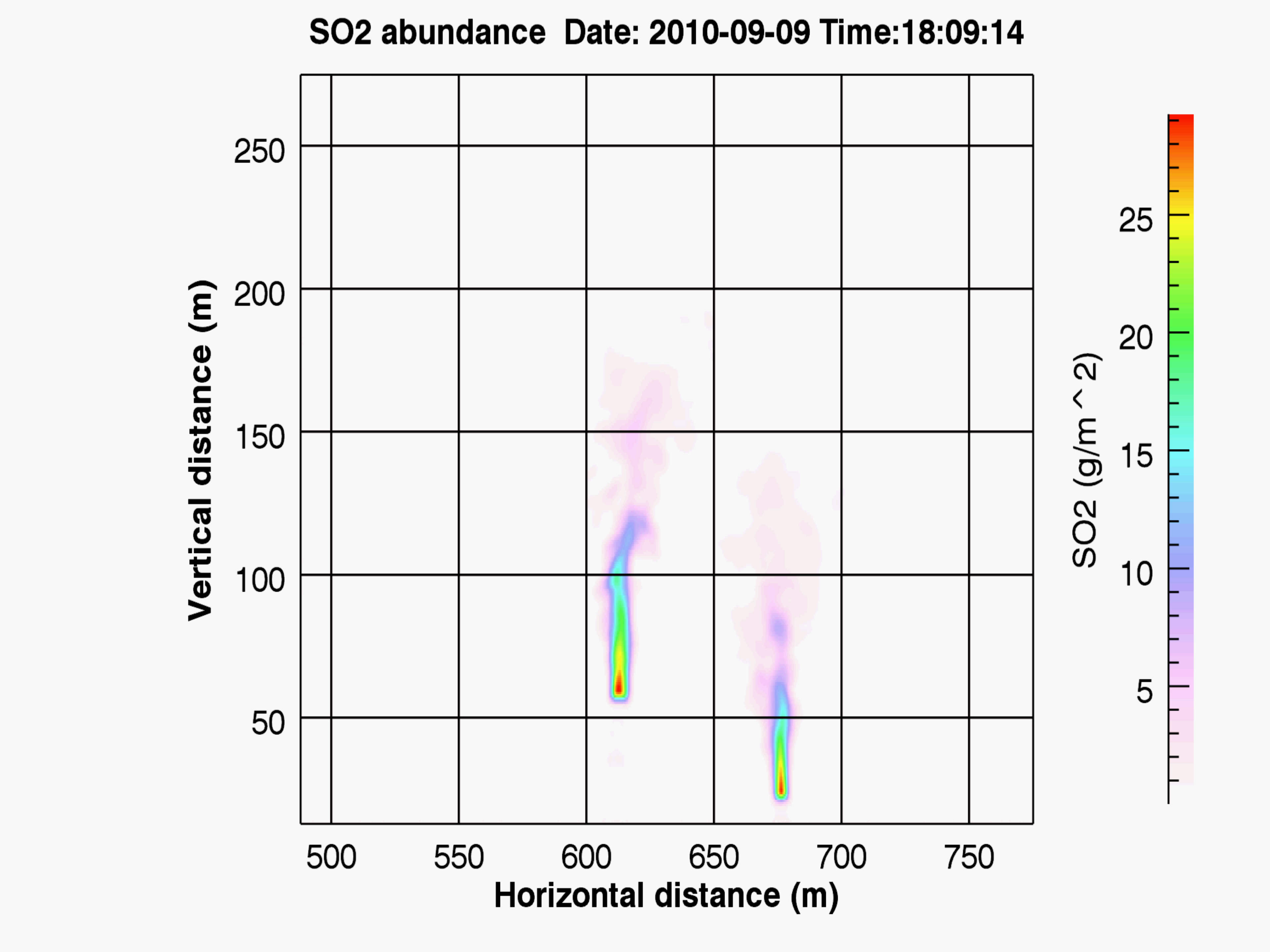
8.6 µm image



8.6-11 µm image (ΔT_{SO_2})



NILU


SO2 abundance Date: 2010-09-09 Time:18:09:14
Vertical distance (m)
250
200
150
100
50
500
550
600
650
700
750
Horizontal distance (m)
SO2 (g/m ^ 2)
25
20
15
10
5