Royal Belgian Institute for Space Aeronomy (BISA)

Institut royal d'Aéronomie Spatiale de Belgique (IASB)

Koninklijk Belgisch Instituut voor Ruimte-Aeronomie (BIRA)

The planned ALTIUS satellite instrument and its potential to observe stratospheric and upper tropospheric aerosols and clouds.

Filip Vanhellemont, Didier Fussen, Emmanuel Dekemper, Didier Pieroux, Ghislain Franssens, Nina Mateshvili, Quentin Errera, Christine Bingen, Charles Robert and Philippe Demoulin.

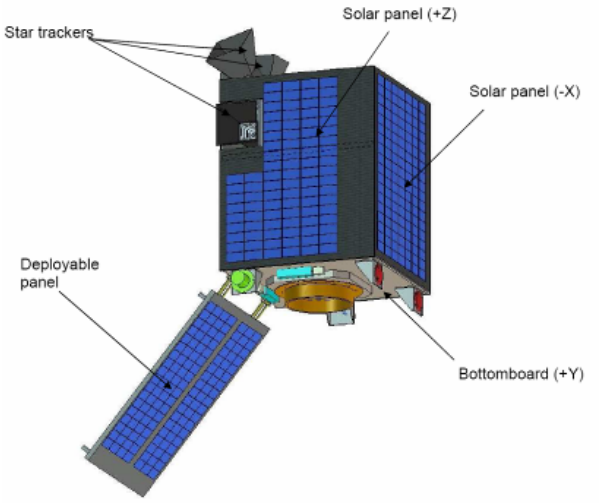
Overview of this presentation

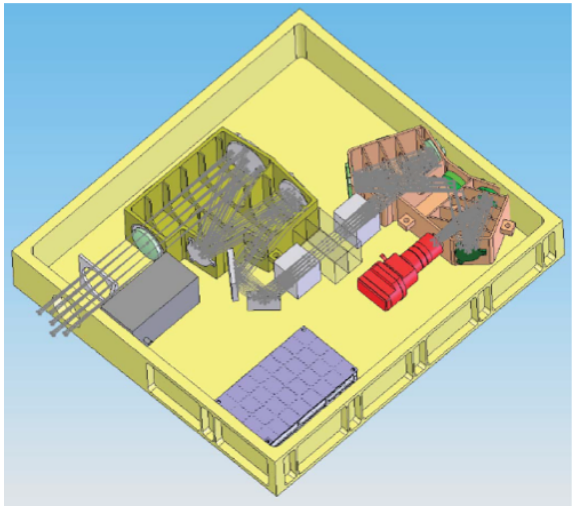
The ALTIUS mission:

- What is it?
- Recent project developments
- Measurement modes
- Performance: simulated retrievals
- Measurement campaign results

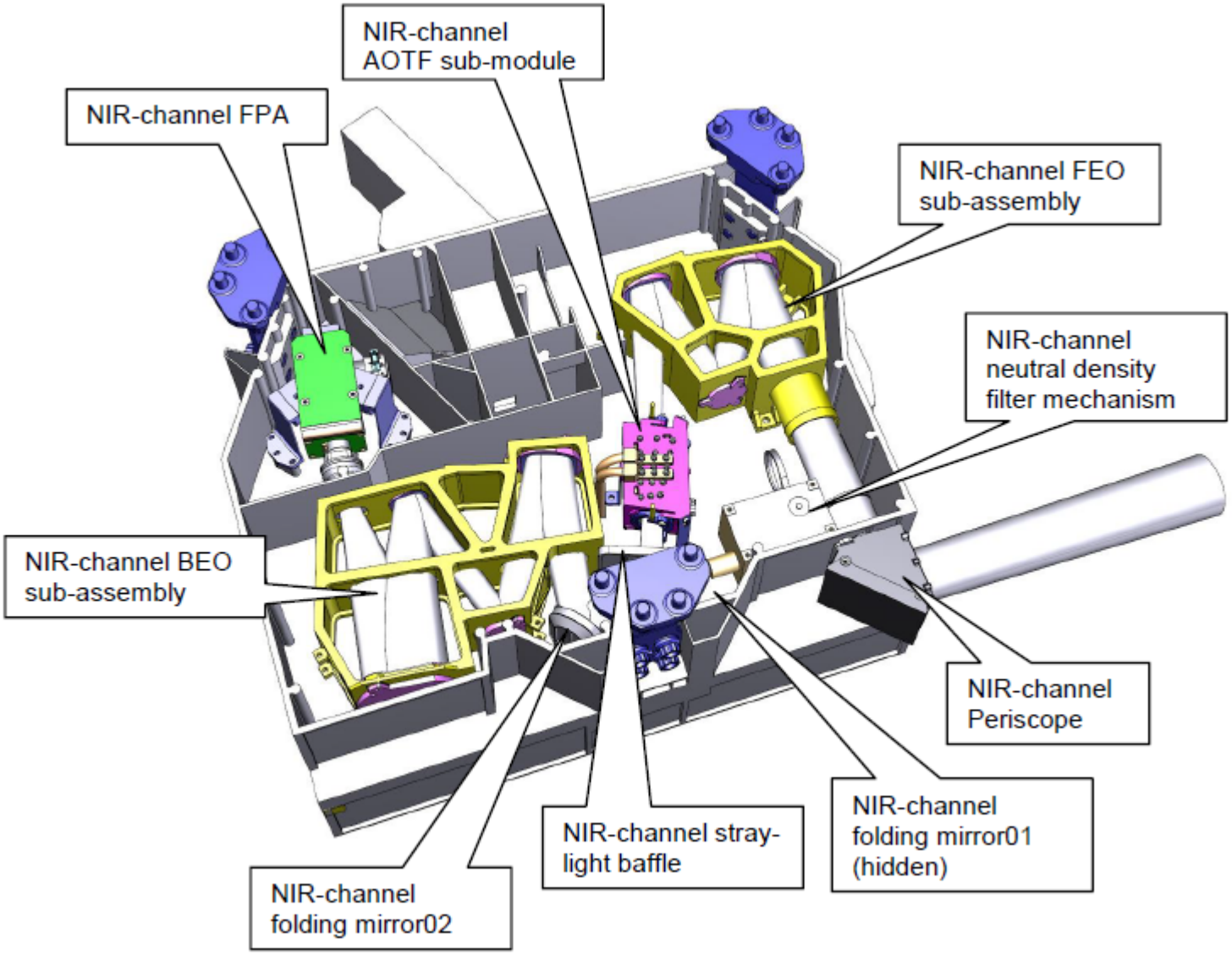
Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS)

- ALTIUS is a proposed limb imager (still in development phase)
- The instrument consists of three independent spectral camera's for the UV-Vis-NIR wavelength range (250–1800 nm).
- One individual spectral camera consists of optics + AOTF (Acousto-Optic Tunable Filter) + imaging detector. (for UV: Fabry-Perot filter)
- On board a micro-satellite (The Belgian PROBA platform) in helio-synchronous low Earth orbit
- Will operate in multi-mode — limb scatter, solar/lunar/planetary/stellar occultation.
- Main geophysical targets: strato-/mesospheric ozone profiles and minor trace constituents (NO_2, H_2O, BrO, CH_4, aerosols/clouds/PSCs/PMCs) and temperature (from refractive angle measurements)





ALTIUS instrument model at present: NIR channel



ALTIUS: recent developments

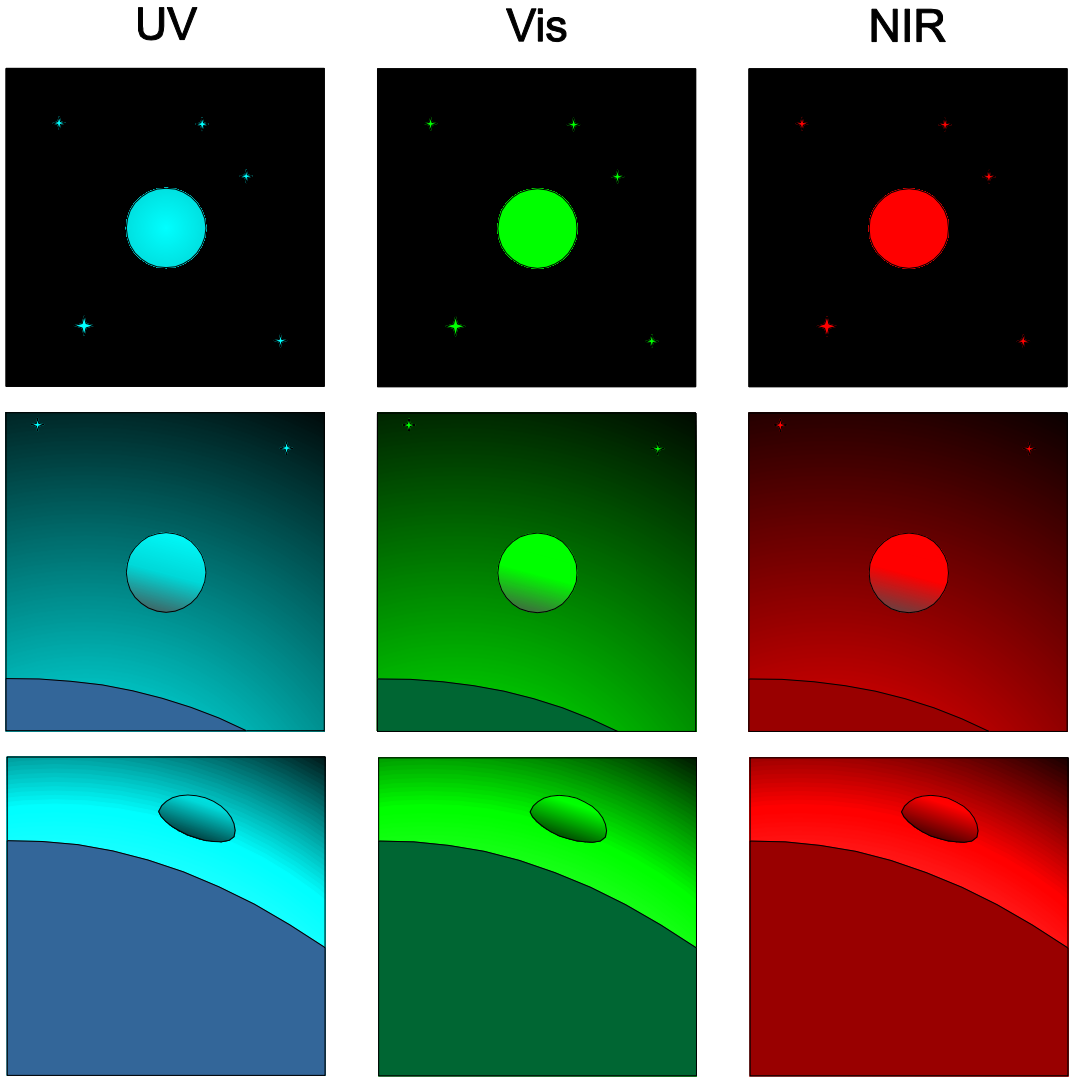
(The ALTIUS-saga started already more than 10 years ago.)

- Industrial phase B1 completed (IDR) for the payload, platform completing its PDR.
- March 2015: ESA/EO proposed to make ALTIUS an ozone monitoring mission, BELSPO (Belgian Science Policy Office) funds the OPEROZ study (definition of requirements from scientific community and operational services)
- November 2015: ESA/EO review to check the compliance of ALTIUS to the OPEROZ study.
- December 2015: A scientific added value review by an independent panel of international experts was organized. (other atmospheric species)

Feb. 11 2016: Victory! Based on the two reviews, BELSPO expressed their intention to support the ALTIUS mission, welcoming participation by other EU Member States.

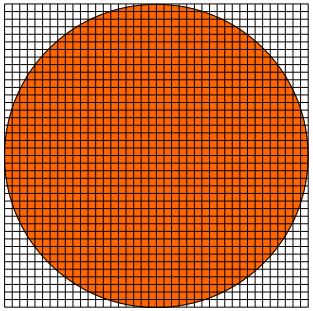
ALTIUS will most likely be implemented as an element in ESA (Earth Observation) Earth Watch Programme (monitoring missions).

Solar occultation: ALTIUS images

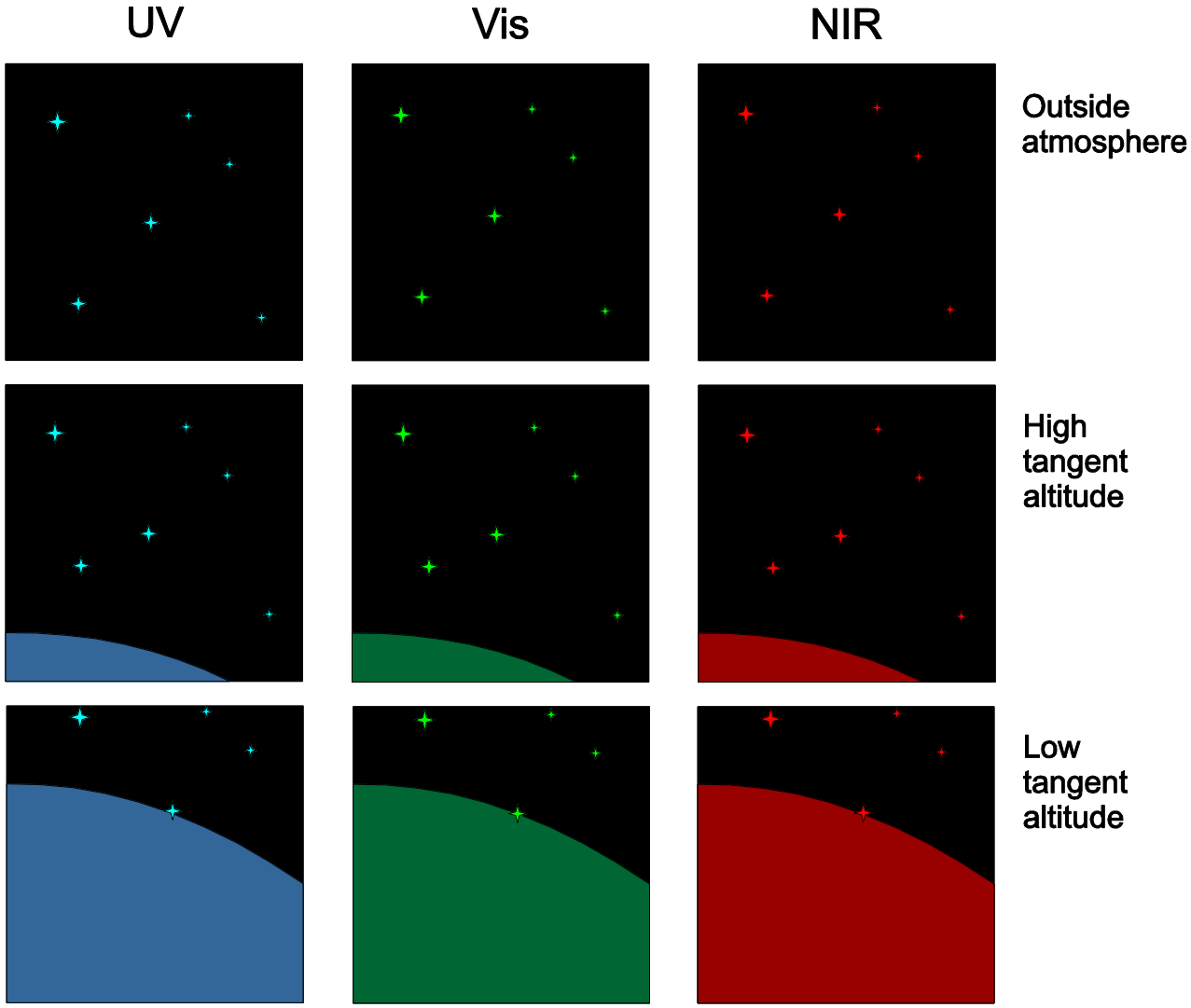


- 2 occ/orbit
- 50 obs/occ of 1 sec
- 0.1 sec per image
- # images/obs: 4 per channel x 3 channels = 12
- Total time vertical occ: 50 sec
- Total # images per orbit: 1200 (cropping!)

1 pixel	0.2 mrad	0.6 km
Solar disk	9 mrad	27 km
Full solar disk = 45 x 45 pixels		



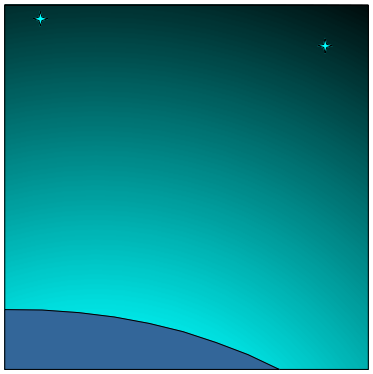
Stellar occultation: ALTIUS images



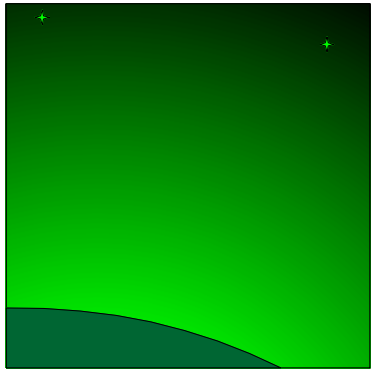
- Occultation of several stars possible (but rare).
- typically about 5 occultations per orbit
- 50 obs per occ of 2 sec
- 0.5 sec per image
- # images per observation: 4 per channel x 3 channels = 12
- Total # images per orbit: 6000

Limb observation: ALTIUS images

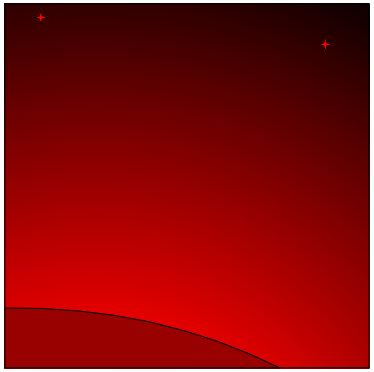
UV



Vis



NIR



All altitudes at once!

- Simplest observation mode, very complex forward model!
- About 50 observations per orbit
- # images per observation: 4 per channel x 3 channels = 12
- 1 second per image
- About 10 seconds per observation
- Total # images per orbit: about 600

A typical measurement sequence (1 orbit)

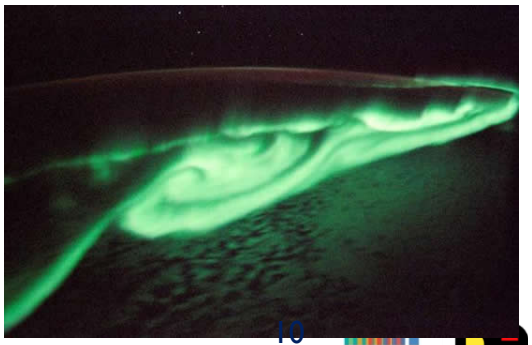
Event description	Time (s)	Sat Lat	Sat Lon	TP Lat	TP Lon
SoO (sunrise)	0	64.7	-65.1	70.8	-117.1
	65	68.4	-69.0	71.0	-137.8
	Manoeuvre				
BLObs	836	61.8	144.3	81.3	-161.5
	846	61.3	148.8	81.0	-165.2
	rest				
BLObs	896	58.3	141.9	79.4	-8.4
	906	57.7	141.6	79.0	176.9
	rest				
BLObs	956	54.8	140.0	76.7	166.9
	966	54.2	139.7	76.2	165.3
	rest				
BLObs	1016	51.2	138.3	73.6	158.7
	1026	50.6	138.1	73.1	157.6
	rest				
BLObs	1076	47.6	136.8	70.4	153.0
	1086	47.0	136.6	69.8	152.2
	rest				
BLObs	1136	44.0	135.5	67.0	148.8
	1146	43.4	135.3	66.4	148.2
	rest				
BLObs	1196	40.4	134.3	63.5	145.6
	1206	39.8	134.1	63.0	145.1
	rest				
BLObs	1256	36.8	133.2	60.0	143.0
	1266	36.2	133.1	59.4	142.6
	rest				
BLObs	1316	33.2	132.2	56.5	140.9
	1326	32.6	132.1	55.9	140.6
	rest				
BLObs	1376	29.6	131.3	52.9	139.1
	1386	29.0	131.1	52.3	138.8
	rest				
BLObs	1436	26.0	130.4	49.4	137.5
	1446	25.4	130.2	48.8	137.3
	rest				
BLObs	1496	22.4	129.5	45.8	136.1
	1506	21.7	129.3	45.2	135.9
	rest				
BLObs	1556	18.7	128.6	42.2	134.9
	1566	18.1	128.5	41.6	134.7
	rest				
BLObs	1616	15.1	127.8	38.6	133.8
	1626	14.5	127.7	38.0	133.6
	rest				
BLObs	1676	11.5	127.0	35.0	132.7
	1686	10.9	126.9	34.4	132.5
	rest				
BLObs	1736	7.8	126.3	31.3	131.7
	1746	7.2	126.1	30.7	131.6
	rest				
BLObs	1796	4.2	125.5	27.7	130.8
	1806	3.6	125.4	27.1	130.6
	rest				
BLObs	1856	0.6	124.7	24.1	129.9
	1866	0.0	124.6	23.5	129.8
	rest				

Event description	Time (s)	Sat Lat	Sat Lon	TP Lat	TP Lon
BLObs	1916	-3.0	124.0	20.5	129.1
	1926	-3.6	123.8	19.9	128.9
	rest				
BLObs	1976	-6.7	123.2	16.9	128.2
	1986	-7.3	123.1	16.3	128.1
	rest				
BLObs	2036	-10.3	122.4	13.2	127.4
	2046	-10.9	122.3	12.6	127.3
	rest				
BLObs	2096	-13.9	121.6	9.6	126.6
	2106	-14.5	121.5	9.0	126.5
	rest				
BLObs	2156	-17.5	120.8	6.0	125.9
	2166	-18.1	120.7	5.4	125.7
	rest				
BLObs	2216	-21.1	120.0	2.4	125.1
	2226	-21.7	119.9	1.8	125.0
	rest				
BLObs	2276	-24.8	119.1	-1.3	124.3
	2286	-25.4	119.0	-1.9	124.2
	rest				
BLObs	2336	-28.4	118.2	-4.9	123.6
	2346	-29.0	118.1	-5.5	123.4
	rest				
BLObs	2396	-32.0	117.3	-8.5	122.8
	2406	-32.6	117.1	-9.1	122.7
	rest				
BLObs	2456	-35.6	116.3	-12.1	122.0
	2466	-36.2	116.1	-12.7	121.9
	rest				
BLObs	2516	-39.2	115.2	-15.8	121.2
	2526	-39.8	115.1	-16.4	121.1
	rest				
BLObs	2576	-42.8	114.1	-19.4	120.4
	2586	-43.4	113.9	-20.0	120.3
	rest				
BLObs	2636	-46.4	112.8	-23.0	119.6
	2646	-47.0	112.6	-23.6	119.4
	rest				
BLObs	2696	-49.9	111.4	-26.6	118.7
	2706	-50.5	111.2	-27.2	118.5
	rest				
BLObs	2756	-53.5	109.8	-30.2	117.8
	2766	-54.1	109.5	-30.8	117.6
	rest				
BLObs	2816	-57.1	108.0	-33.8	116.8
	2826	-57.6	107.7	-34.4	116.6
	rest				
BLObs	2876	-60.6	105.8	-37.4	115.8
	2886	-61.2	105.4	-38.0	115.6
	rest				
BLObs	2936	-64.1	103.2	-41.0	114.7
	2946	-64.6	102.7	-41.6	114.5
	rest				
BLObs	2996	-67.5	99.9	-44.6	113.5
	3006	-68.1	99.2	-45.2	113.2
	rest				

Event description	Time (s)	Sat Lat	Sat Lon	TP Lat	TP Lon
BLObs	3056	-70.8	95.5	-48.2	112.1
	3066	-71.4	94.7	-48.8	111.9
	rest				
BLObs	3116	-74.1	89.5	-51.8	110.6
	3126	-74.6	88.3	-52.4	110.4
	rest				
BLObs	3176	-77.1	80.9	-55.3	108.9
	3186	-77.6	79.1	-55.9	108.6
	rest				
BLObs	3236	-79.7	67.7	-58.9	106.9
	3246	-80.0	64.9	-59.5	106.6
	rest				
BLObs	3296	-81.5	47.8	-62.4	104.5
	3306	-81.6	43.8	-63.0	104.1
	rest				
BLObs	3356	-81.9	22.3	-65.8	101.6
	3366	-81.8	18.0	-66.4	101.0
	rest				
BLObs	3416	-80.8	-1.2	-69.2	97.8
	3426	-80.4	-4.5	-69.8	97.0
	rest				
BLObs	3476	-78.5	-17.7	-72.5	92.7
	3486	-78.1	-19.9	-73.1	91.7
	rest				
BLObs	3536	-75.7	-28.5	-75.7	85.5
	3546	-75.2	-29.9	-76.2	84.0
	rest				
BLObs	3596	-72.6	-35.7	-78.5	74.8
	3606	-72.0	-36.7	-78.9	72.5
	rest				
BLObs	3656	-69.3	-40.8	-80.7	58.4
	3666	-68.7	-41.5	-81.0	54.9
	rest				
BLObs	3716	-65.9	-44.6	-81.9	35.0
	3726	-65.3	-45.2	-81.9	30.6
	rest				
SoO (sunset)	3853	-57.9	-50.6	-78.5	-78.8
	3918	-54.1	-52.7	-73.6	-74.3
	Manoeuvre				
StO, M=0.4, Hyp=87279	4188	-38.0	-58.7	-38.9	-30.1
	4386	-26.0	-61.9	-26.9	-40.8
	Manoeuvre				
StO, M=1.59, Hyp=61084	4656	-9.7	-65.6	-31.7	-68.8
	4722	-5.7	-66.5	-24.5	-69.3
	Manoeuvre				
StO, M=0.77, Hyp=60718	4752	-3.9	-66.9	-26.0	-68.3
	4818	0.1	-67.7	-18.7	-68.9
	Manoeuvre				
StO, M=0.01, Hyp=71683	4866	3.0	-68.3	-17.6	-77.0
	4888	7.3	-68.3	-8.9	-76.7
	Manoeuvre				
StO, M=1.44, Hyp=82349	5053	14.3	-70.8	8.6	-48.9
	5252	26.9	-73.7	23.4	-53.3
	Manoeuvre				
StO, M=0.4, Hyp=87279	5365	33.1	-75.3	39.6	-53.0
	5568	45.3	-79.1	53.6	-47.2
	Manoeuvre				
StO, M=1.36, Hyp=49669	5665	51.1	-81.4	70.4	-68.1
	5736	55.4	-83.4	76.5	-66.0

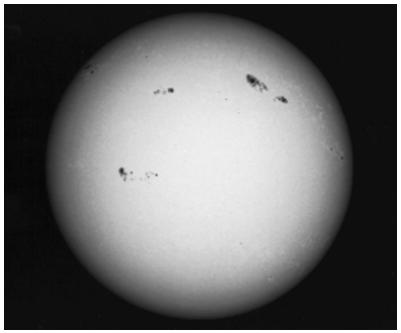
Non-nominal observation modes

- Multi-orbit tomography:
  - backward-forward + left-looking in next orbit
- Nadir:
  - 1 pixel = 140 x 140 meter
  - Total FOV: about 23 x 23 km (= scale of a city)
- Planet occultation:
  - same principle as stellar occultation
- Lunar occultation:
  - same principle as solar occultation
  - Albedo!
- Observations of optical emissions (specific wavelength tuning)
  - Aurora (555.7 nm green line)
  - nightglow (auroral green line, red lines)
- Calibration campaigns
- Special campaigns: volcanic eruptions



Simulations: forward models

- **Solar occultation:**
  - Beer-Lambert extinction law
  - Solar limb darkening
  - Refractive effects (disk flattening, dilution, refractive bending)
  - ALTIUS instrument functions (PSF, spectral response, integration time)



- **Stellar occultation:** same as solar, except:
  - Various stellar magnitudes (S/N varies)
  - Various star temperatures (spectral emission varies)
  - Point sources (No angular integration)

- **Limb observations:**
  - Full radiative transfer code ("ARTS": ALTIUS Radiative Transfer Simulator)
  - Spherical geometry
  - Vectorial (Stokes vector as output)
  - ALTIUS instrument functions

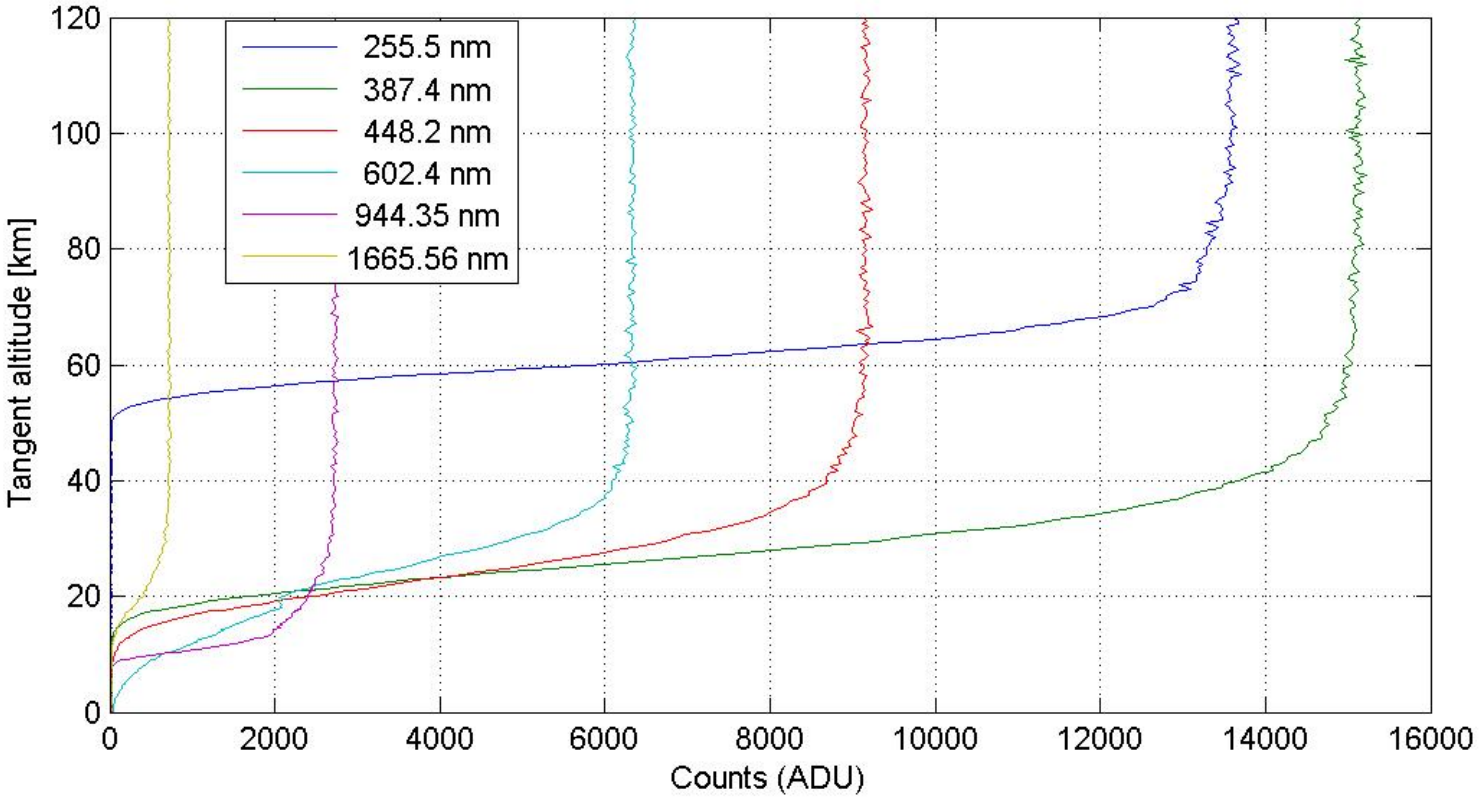
Occultation simulations: parameters

	FOV	Nb pixels	Vertical sampling	Aperture diameter	Spectral range
UV (solar)	2°	170x170	600m	9 mm	250-450 nm
UV (stellar)	0.2°			50 mm	
VIS	2°	512x512	200m	41 mm	440-800 nm
NIR	2°	256x256	400m	41 mm	800-1800 nm

Geometrical parameters	
Day of the year	# 180
Tangent point latitude	50°N
LOS azimuth angle	180° (backward looking; sunset/starset)
Local Earth radius	6366 km (from the WGS84 model)
Satellite orbital altitude	650 km

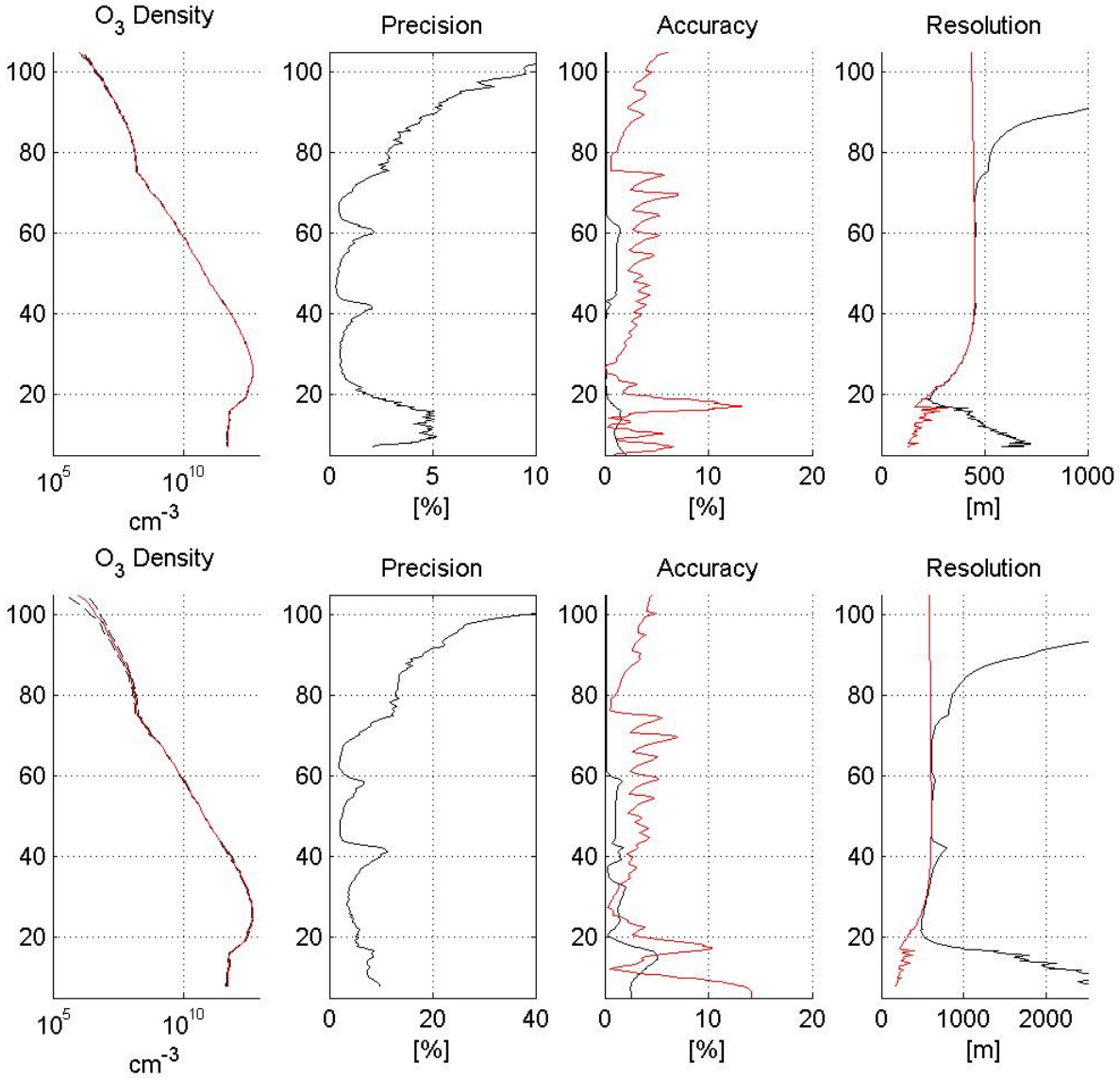
Channel	Wavelength [nm]	Constituent
UV	255.5	Ozone (Hartley band peak)
	300	Ozone (Hartley band slope)
	338.4	BrO absorption line peak
	387.4	OClO absorption line peak
Visible	448.2	NO_2 absorption line (peak)
	450.0	NO_2 absorption line (valley)
	525.0	O_3 Chappuis band (slope)
	602.4	O_3 Chappuis band (peak)
Near-infrared	944.35	H_2O absorption band
	1020.0	Stratospheric and tropospheric aerosols
	1070.0	Stratospheric and tropospheric aerosols
	1665.56	CH_4 absorption band (Q-branch)

Solar occultation: simulated signals



- Noise contributions: Poisson shot noise, digitization error (14 bit)
- Additional errors (according to instrument requirements):
  - Altitude pointing error: 150 m
  - Center of spectral bandwidth: 2σ = 0.1 nm

Occultation results: midlatitude ozone



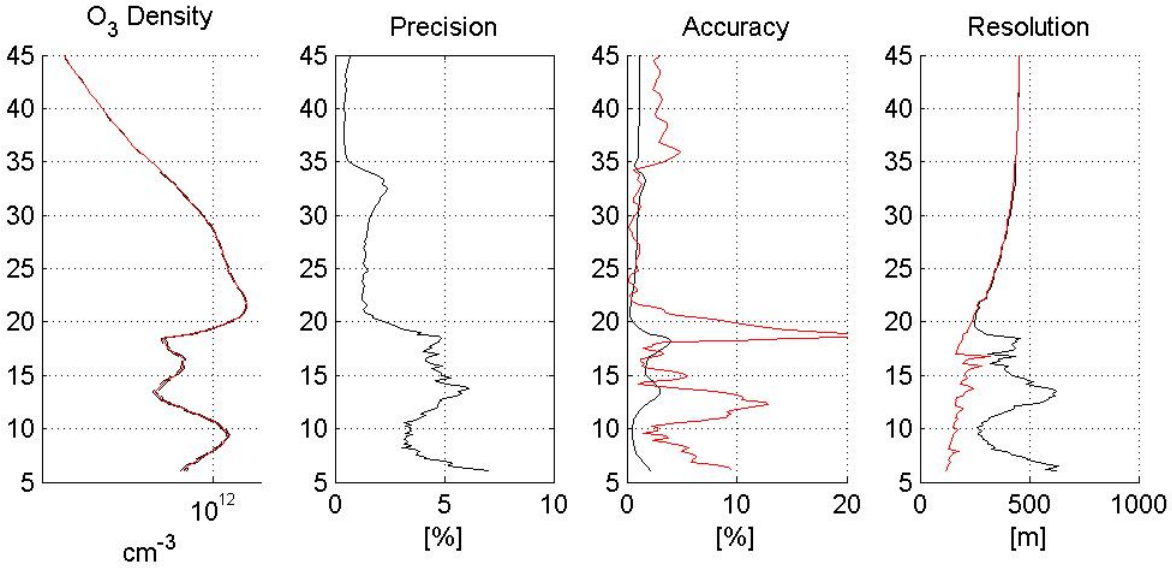
Solar occultation

Stellar occultation:

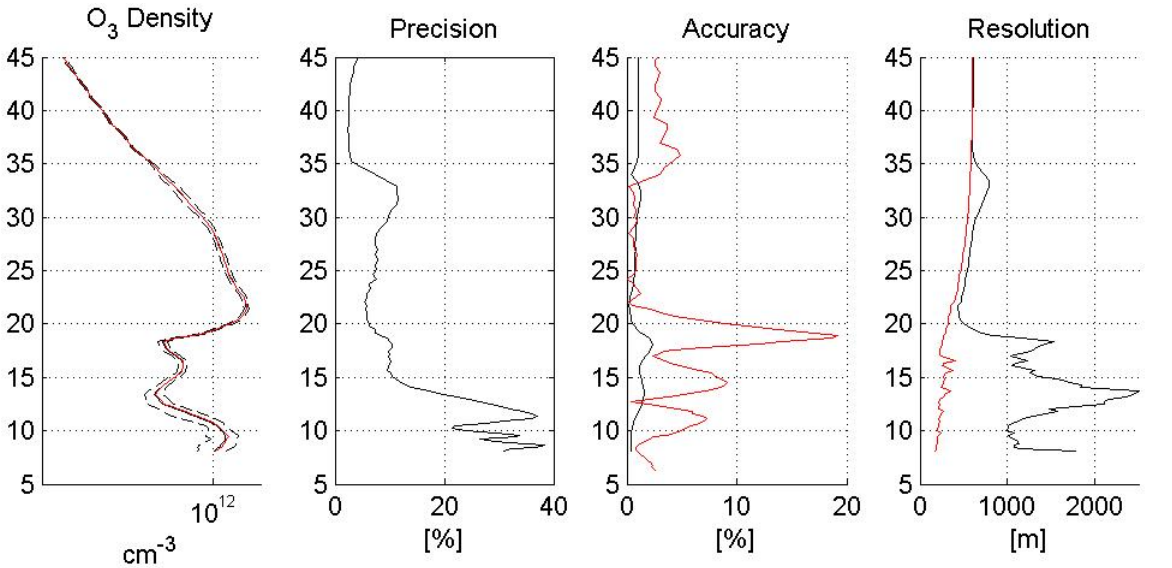
- Sirius (αCMa)
- Magnitude: -1.44
- Temp: 11000 K

Important error due to wrong pointing

Occult. results: polar ozone, Antarctic spring



Solar occultation

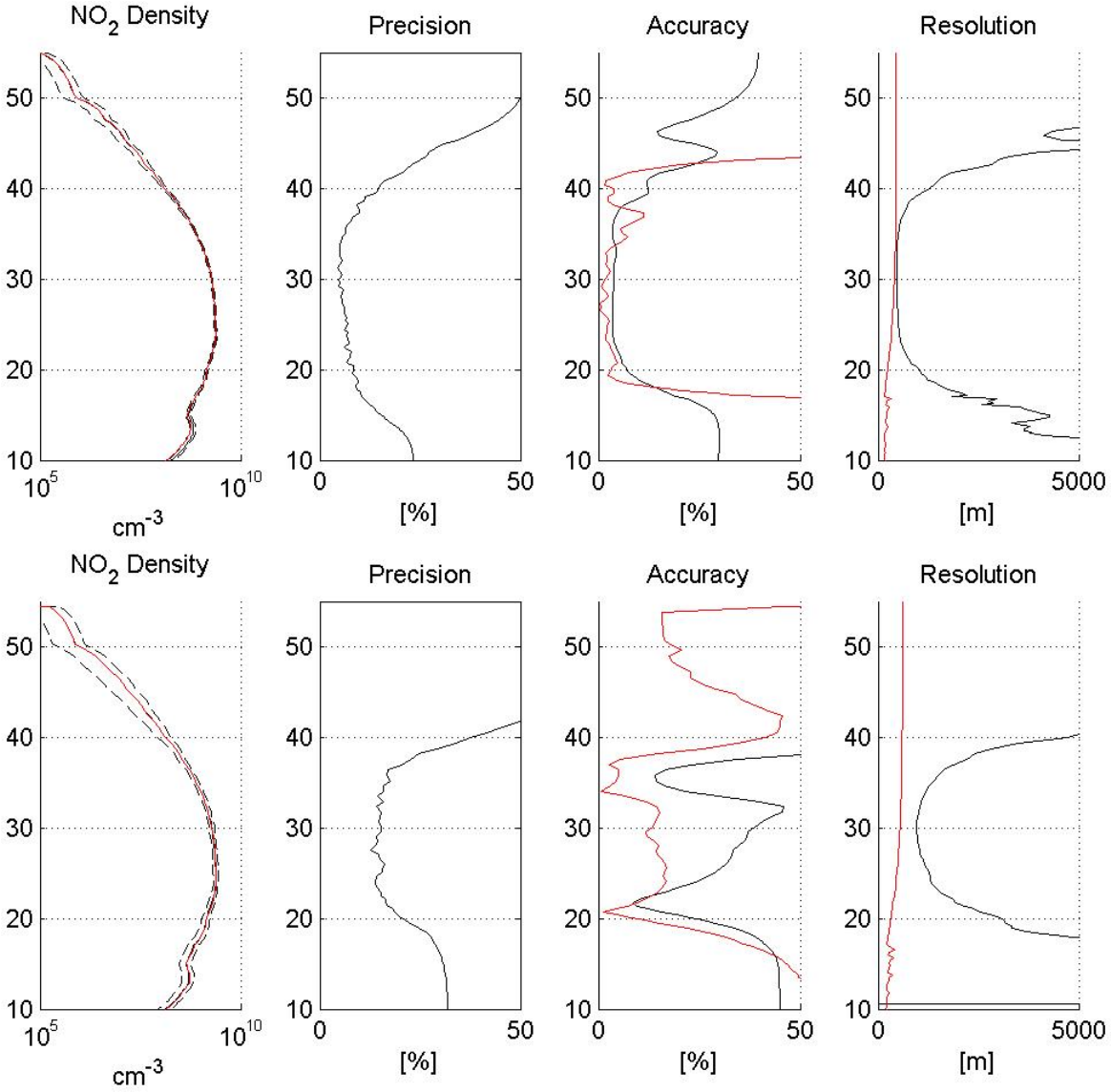


Stellar occultation:

- Sirius (αCMa)
- Magnitude: -1.44
- Temp: 11000 K

Increased error due to pointing at the top and bottom of the ozone hole

Occultation results: NO_2



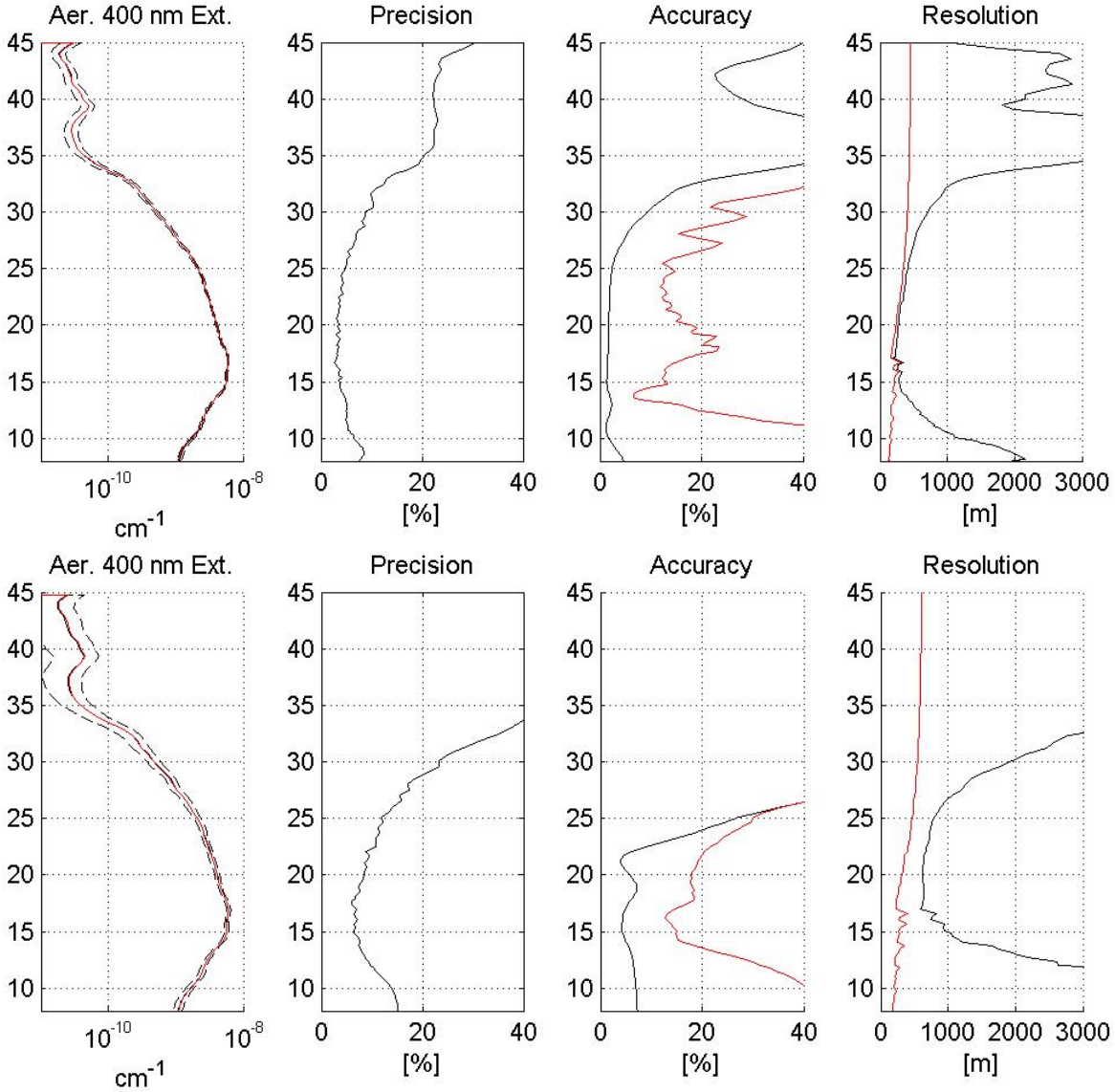
Solar occultation

Stellar occultation:

- Sirius (αCMa)
- Magnitude: -1.44
- Temp: 11000 K

For stellar occ., wavelength assignment error is very pronounced

Occultation results: Aerosol ext. at 400 nm



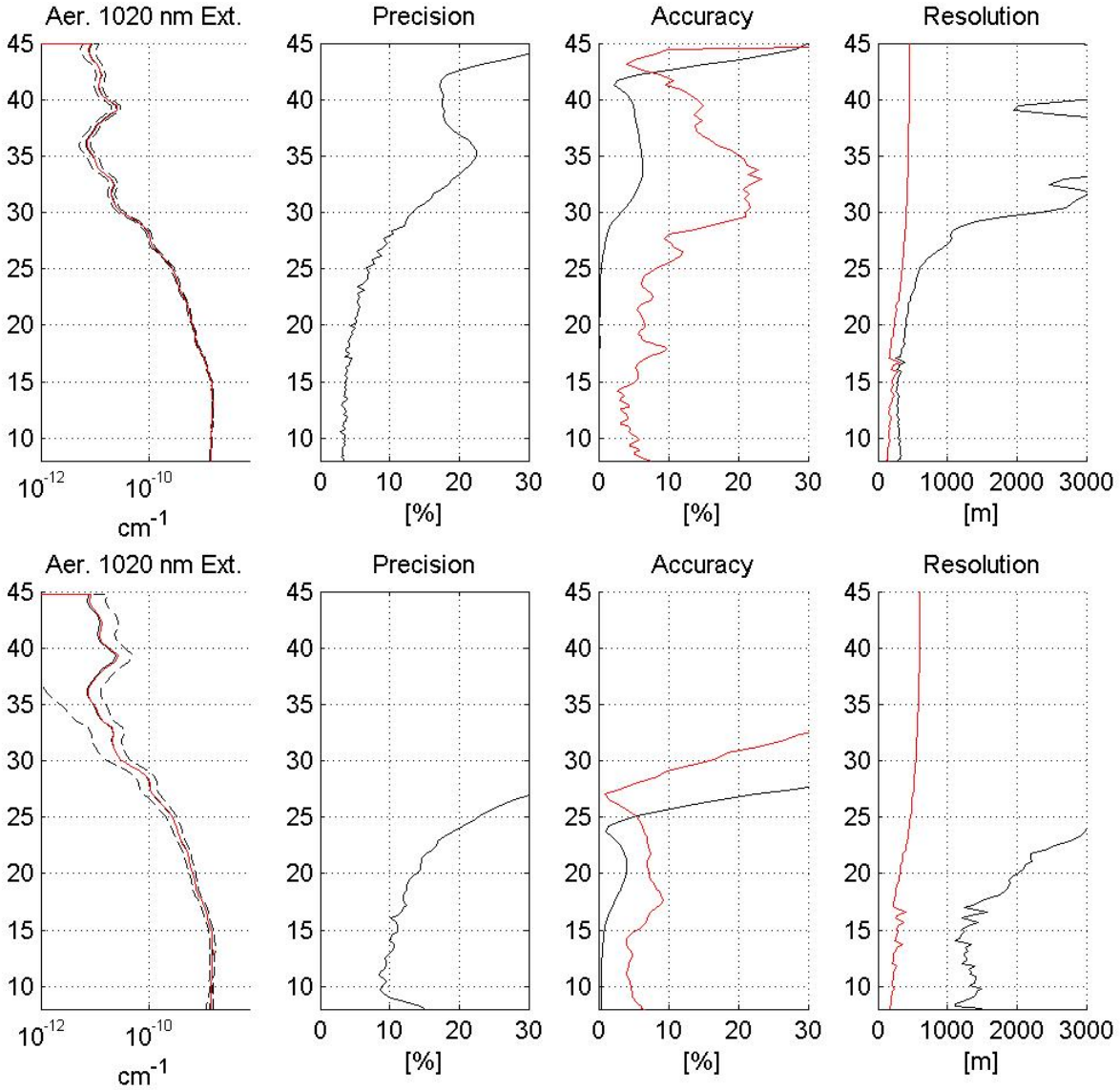
Solar occultation

Stellar occultation:

- Sirius (αCMa)
- Magnitude: -1.44
- Temp: 11000 K

Main error source: pointing error

Occultation results: Aerosol ext. at 1020 nm



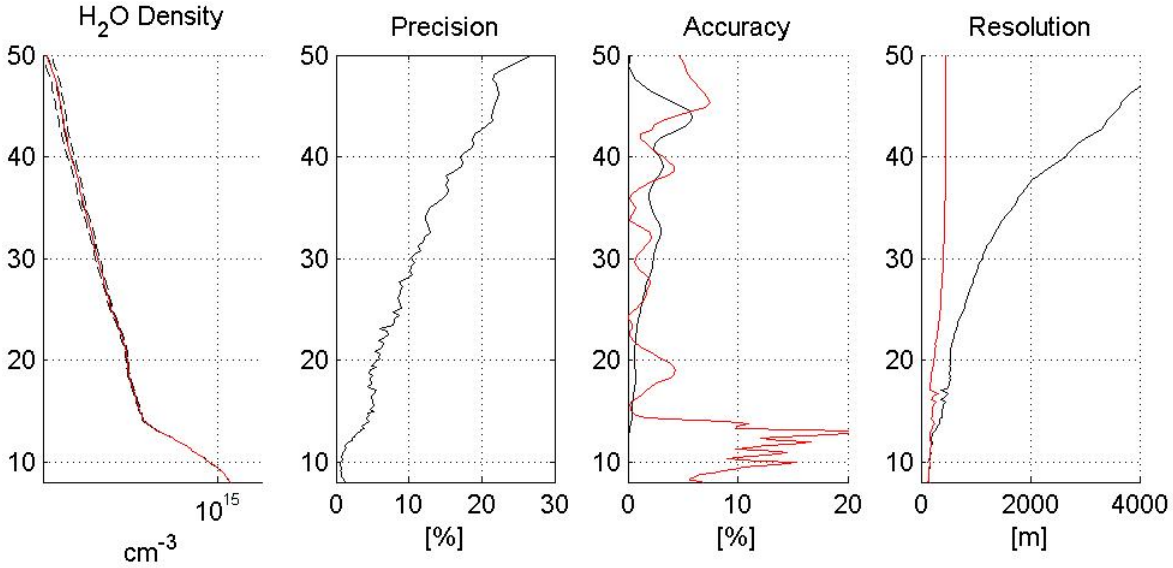
Solar occultation

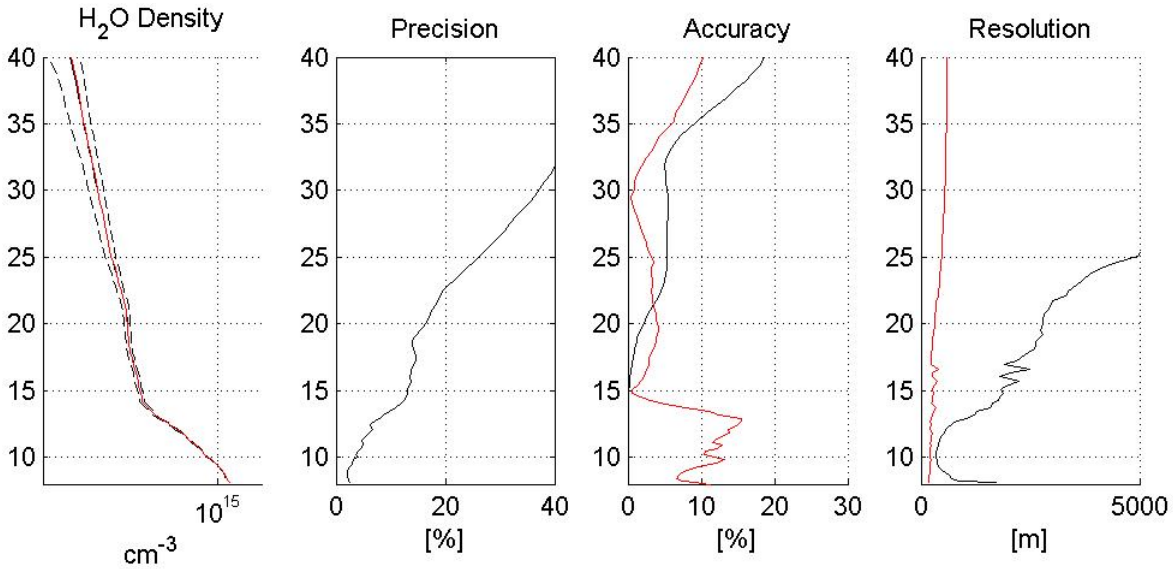
Stellar occultation:

- Sirius (αCMa)
- Magnitude: -1.44
- Temp: 11000 K

Main error sources: pointing error and detector noise

Occultation results: water vapour





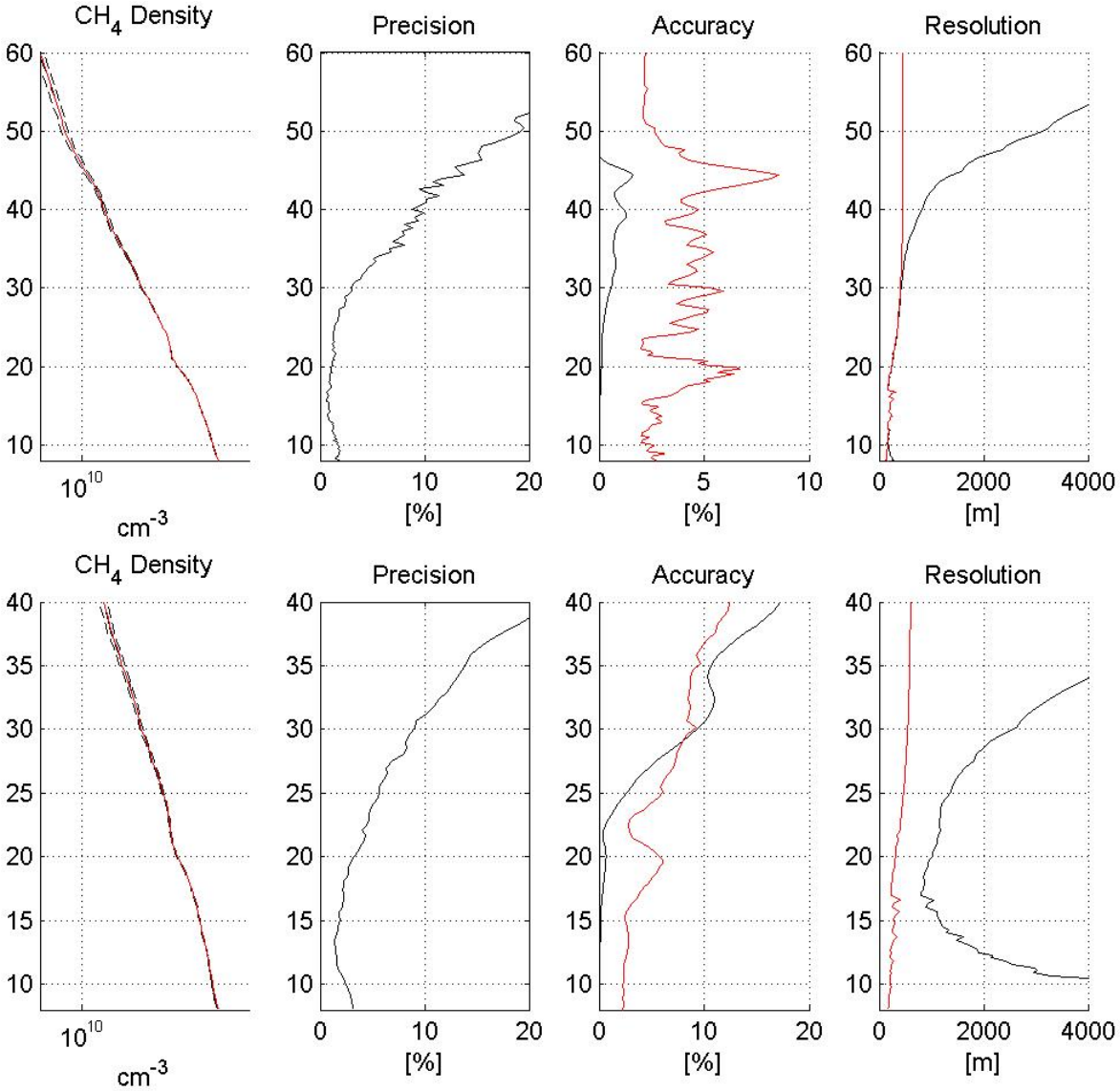
Solar occultation

Stellar occultation:

- Sirius (αCMa)
- Magnitude: -1.44
- Temp: 11000 K

Main error source (troposphere): pointing error.

Occultation results: methane



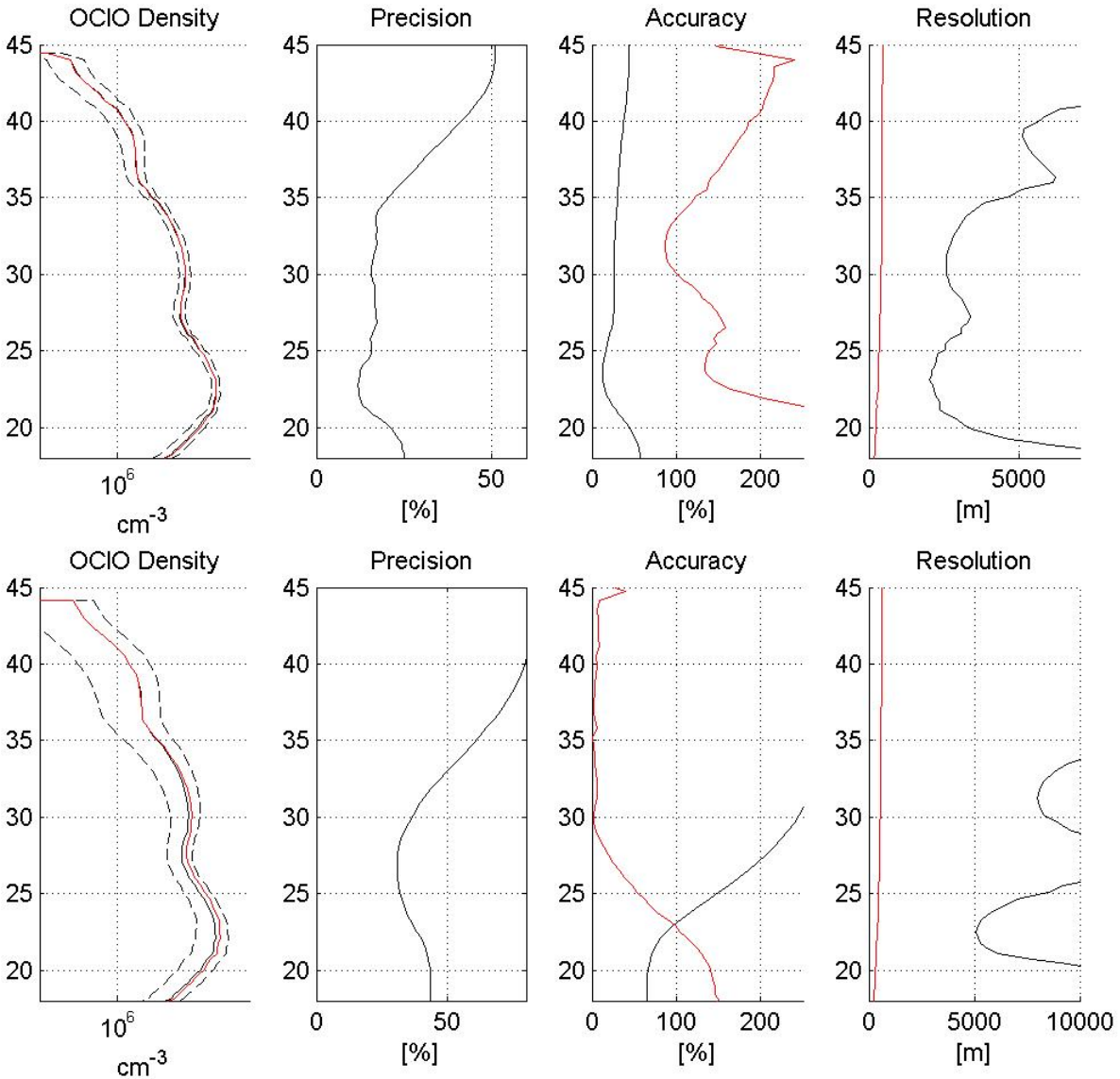
Solar occultation

Stellar occultation:

- Sirius (αCMa)
- Magnitude: -1.44
- Temp: 11000 K

Main error source: pointing error

Occultation results: OClO



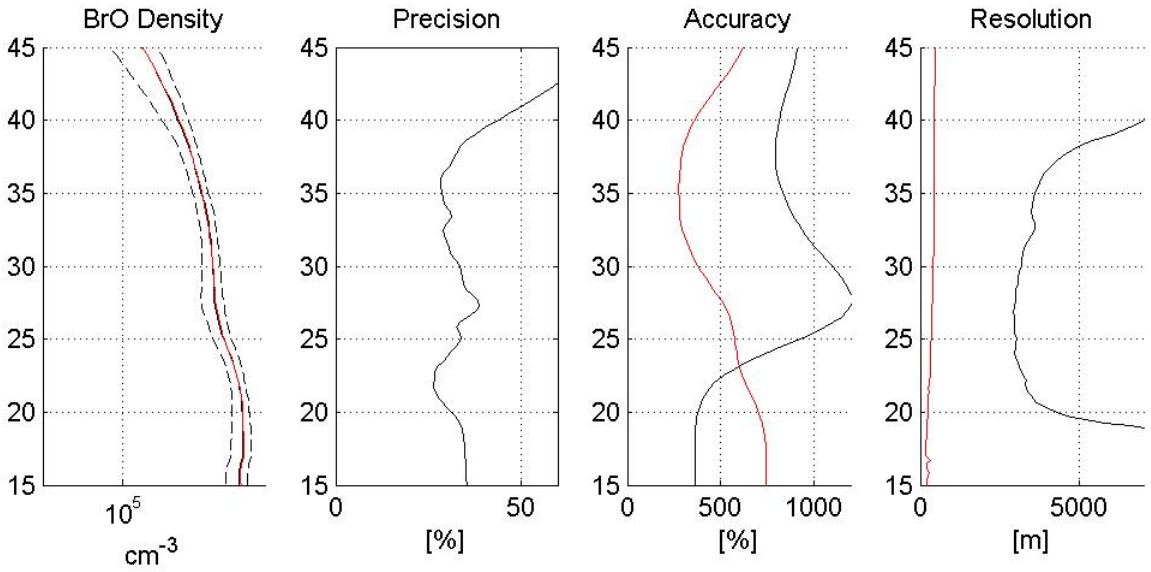
Solar occultation

Stellar occultation:

- Sirius (αCMa)
- Magnitude: -1.44
- Temp: 11000 K

Pointing error as well as wavelength assignment error are very large

Occultation results: BrO (solar occ. only)



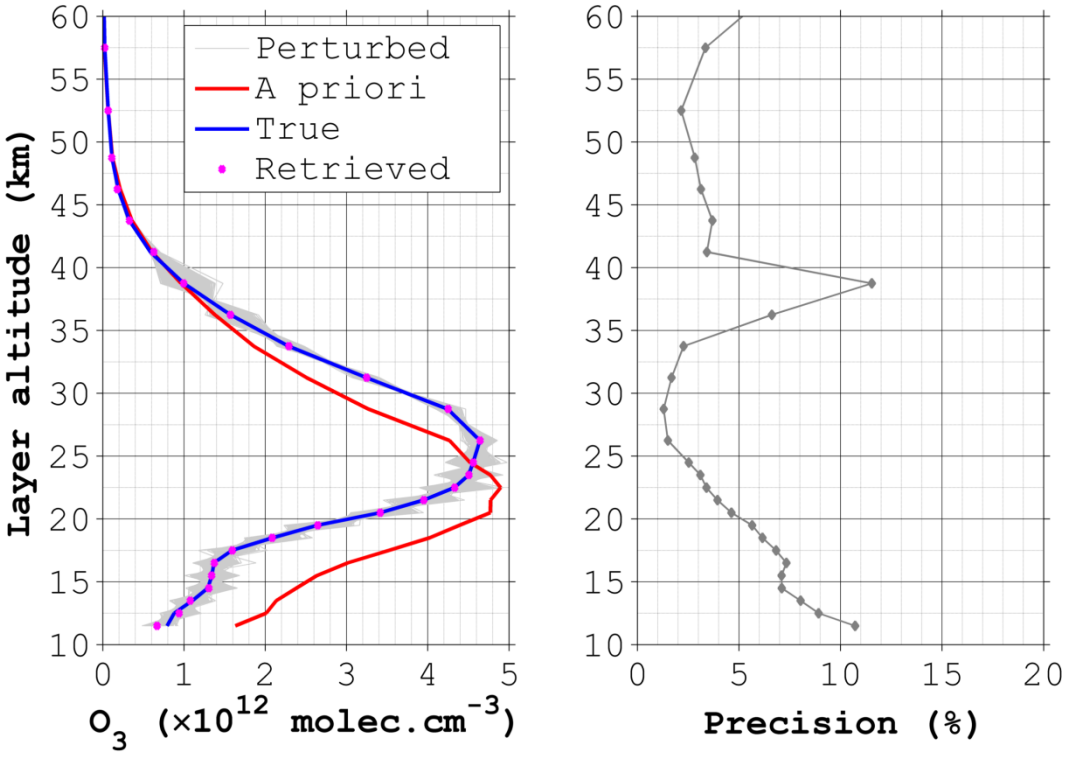
Solar occultation

Wrong wavelength assignment induces huge errors

ALTIUS bright limb O3

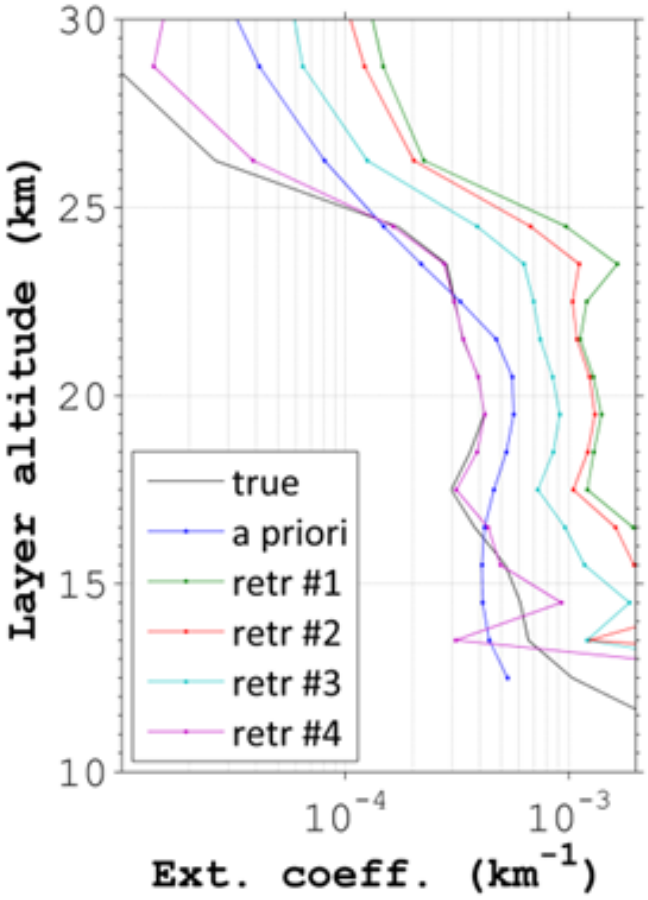
Error budget for O3 after random perturbation of the signal within the SNR requirements.

Total error budget including contribution from pointing and spectral registration.



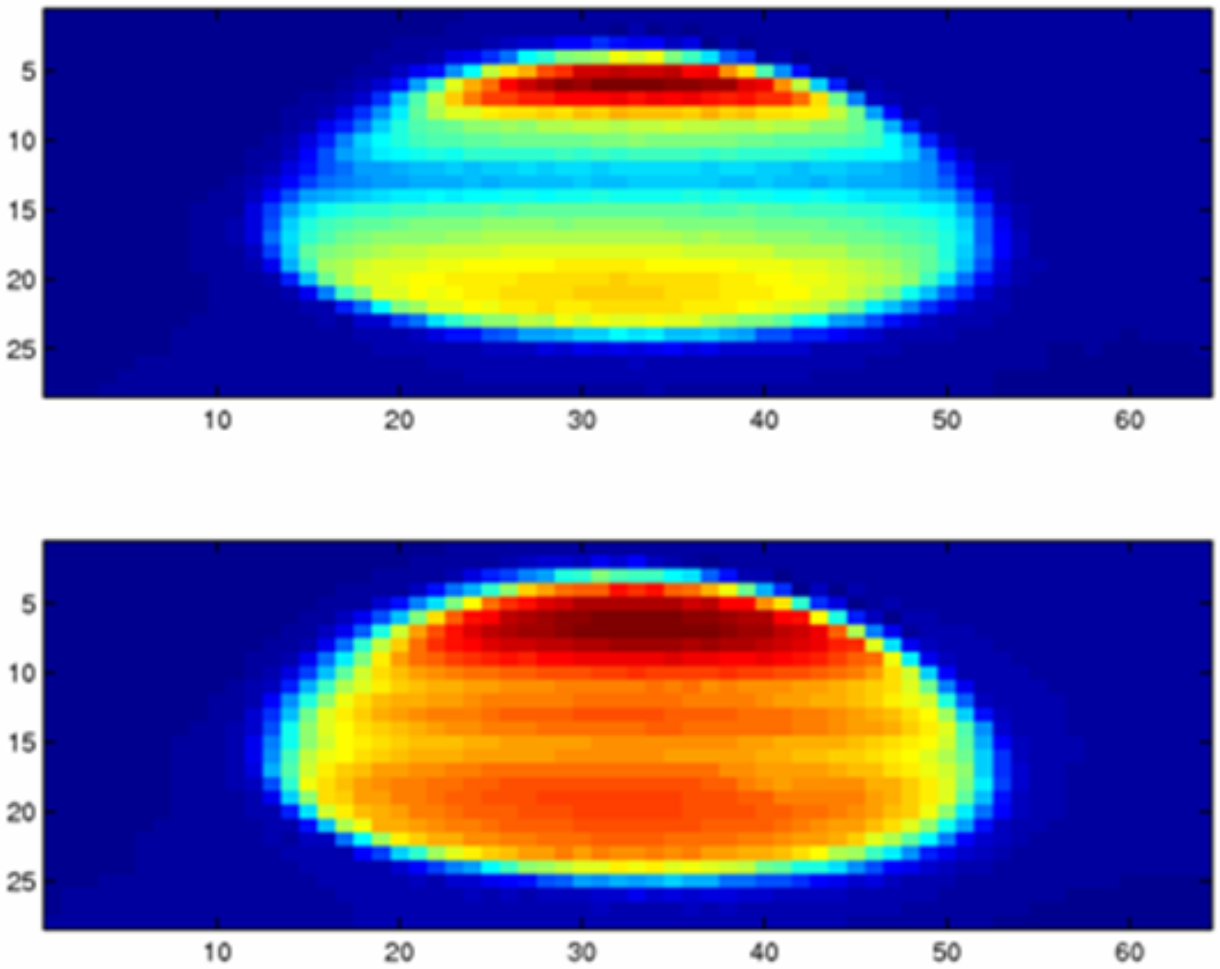
Error source	15km	20km	25km	30km	35km	40km	45km	50km	55km
SNR	7%	5%	2%	1.5%	2.5%	3%	3.5%	2.5%	2.5%
Pointing	2%	4%	1%	1%	2%	2.5%	2.5%	3%	3%
Spectral	0%	0%	0%	0%	0%	0.2%	0.4%	0.5%	0.6%
Total	**7.3%**	**6.4%**	**2.2%**	**1.8%**	**3.2%**	**3.9%**	**4.3%**	**3.9%**	**4%**

ALTIUS bright limb aerosol extinction



	Error Type	15km	20km	25km	30km
SNR	random	0.1%	0.1%	0.1%	0.1%
Pointing	bias	3%	2%	10%	10%
Spectral	bias	0%	0%	0%	0%
	Total	**3%**	**2%**	**10%**	**10%**

Major advantage of imagers: you know what you are looking at.



- Canadian ACE instrument: sunset images at 1 micrometer.
- Single and double-layer PSC
- Every cloud type has its own distinct morphology (cirrus, PSCs, PMCs, tropical anvil clouds)

Bonus: AOTF-based imagers do work!

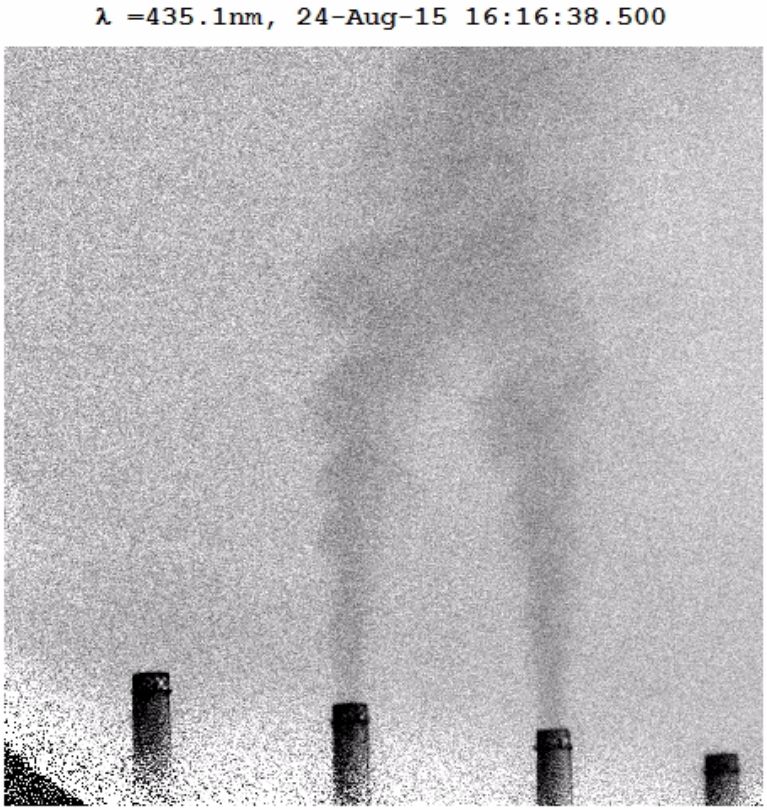
ESA-EO **AROMAT-2 campaign** in Romania in Aug 2015.

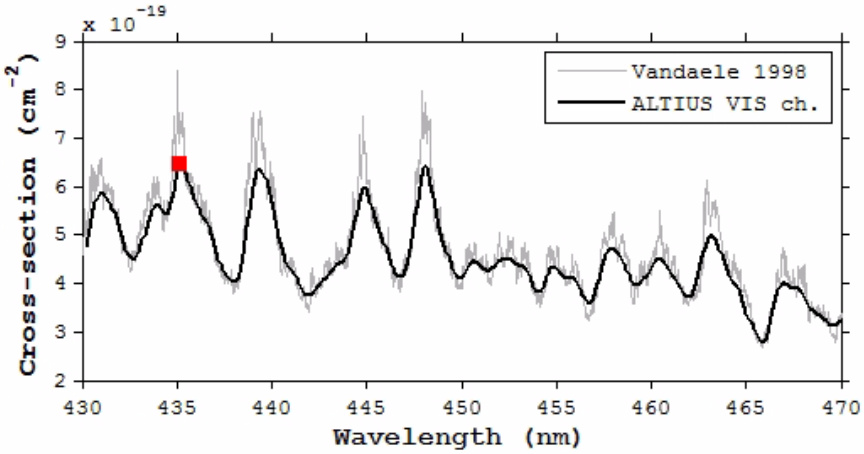
Goal: intercompare different instruments around big pollution spots in view of TROPOMI ground-based validation.

ALTIUS VIS channel breadboard was operated to retrieve NO2 SCD from the plume of the coal-burning power plant of Turceni.

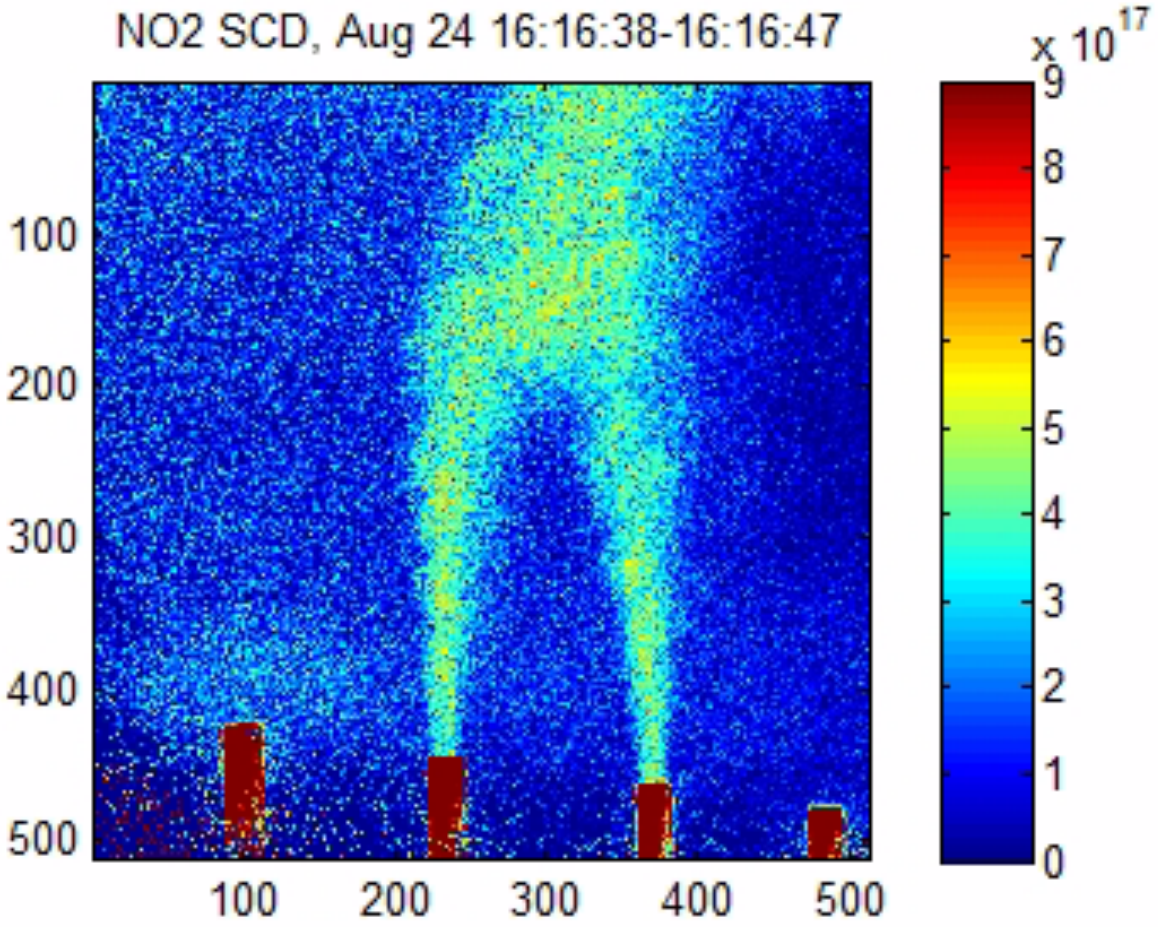
Bonus: AOTF-based imagers do work!

NO2 retrieved from the cross-section features by comparing doublets of wavelengths.





Bonus: AOTF-based imagers do work!



Thank you for your attention!

For more information: altius.oma.be