Atmospheric **L**imb **T**racker for the **I**nvestigation of the **U**pcoming **S**tratosphere

The ALTIUS mission: Operational and Scientific Objectives

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ESA-EO

LPS / 23-May -2022

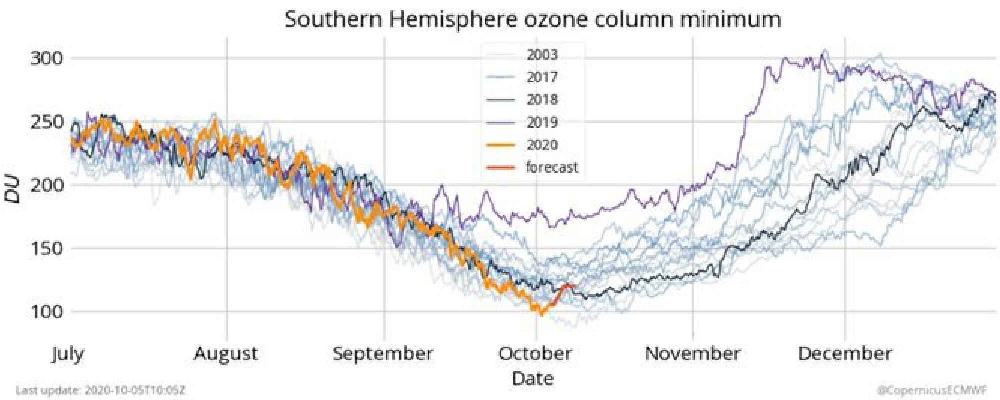
WMO 2018 Scientific Assessment of Ozone Depletion

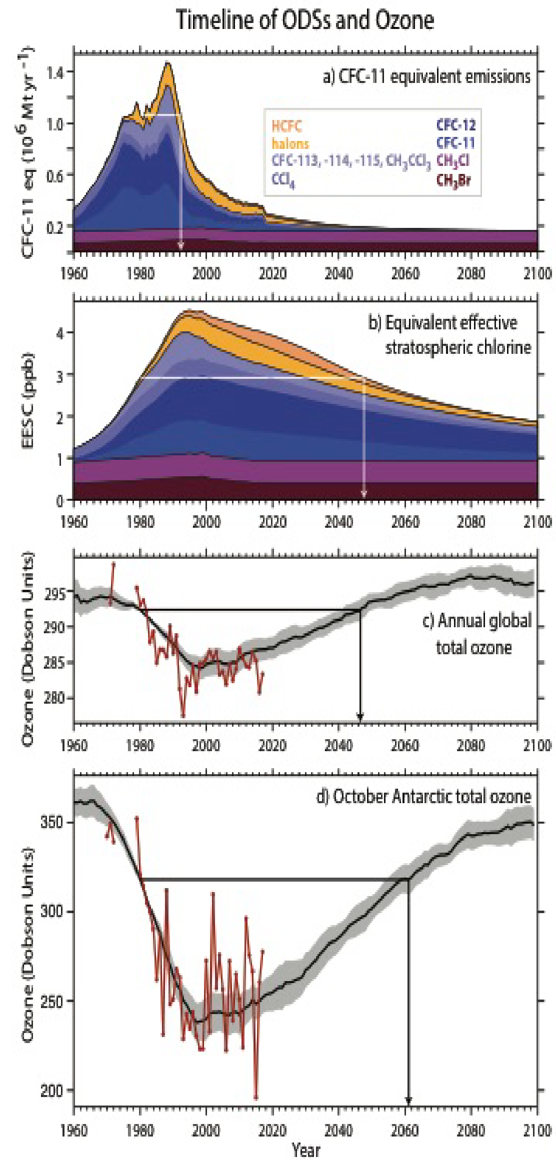
(Executive Summary published in November 2018)

ALTIUS

"Actions taken under the **Montreal Protocol** have led to decrease ozone-depleting substances (ODSs) and **the recovery of stratospheric ozone has started**:

- The **Antarctic O_3 hole is recovering**, while continuing to occur every year.



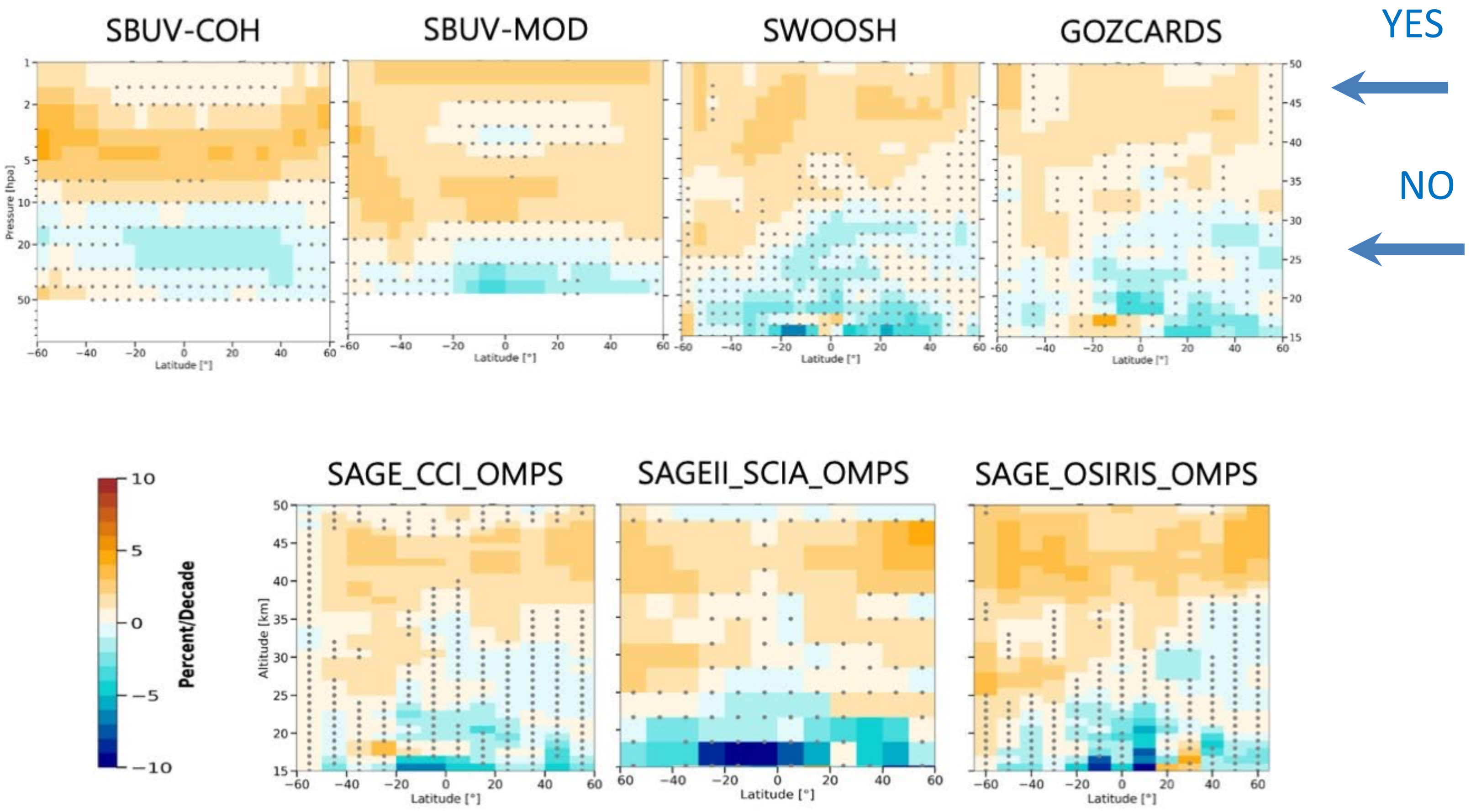


- **O_3 layer changes in the latter half of this century will be complex.**

The monitoring of stratospheric O_3 is still essential

ALTIUS

Is ozone recovering in mid-latitudes and tropics?



courtesy of S. Solomon

Godin-Beekman et al., 2022, ACPD; updating LOTUS from Petropavlovskikh et al.

Some Key Conclusions from Susan Solomon in a recent lecture (SPARC 30th anniversary webinar on 21st April 2022)

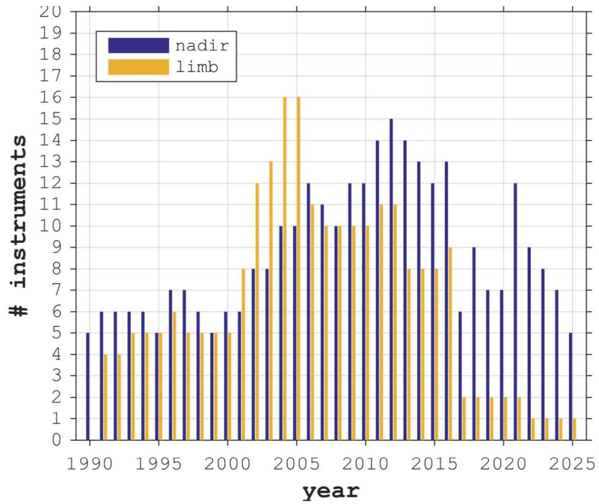
- UTLS mid-lat and tropical ozone changes →challenges for SPARC in the mid- to late-1990s and again now. **Why isn't LS ozone recovering** and what are the implications for climate?

- Understanding of the role of heterogeneous chemistry on sulfates, incl not only big also small volcanoes in the mid to late-1990s, but also liquid PSCs. **New challenges in PyroCb**: Field, lab, theory.

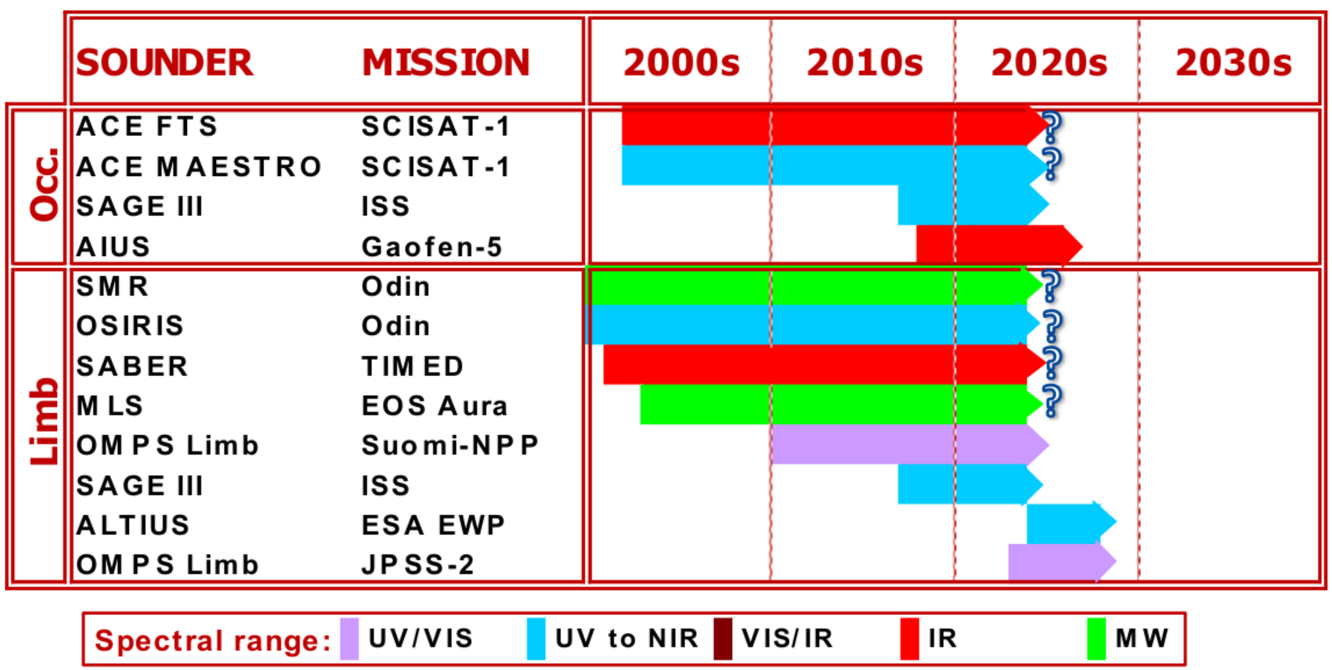
- **Role of Bry, Cly**. Full inclusion of these and het chem in models an ongoing challenge; also in linear regressions.

- **Stratosphere-troposphere coupling**: Antarctic to Arctic, range of time scales → challenges for predictions and projections. Need for fully interactive chemistry/radiative damping; not included in many models. Interactive ocean coupling?

ALTIUS: Why?



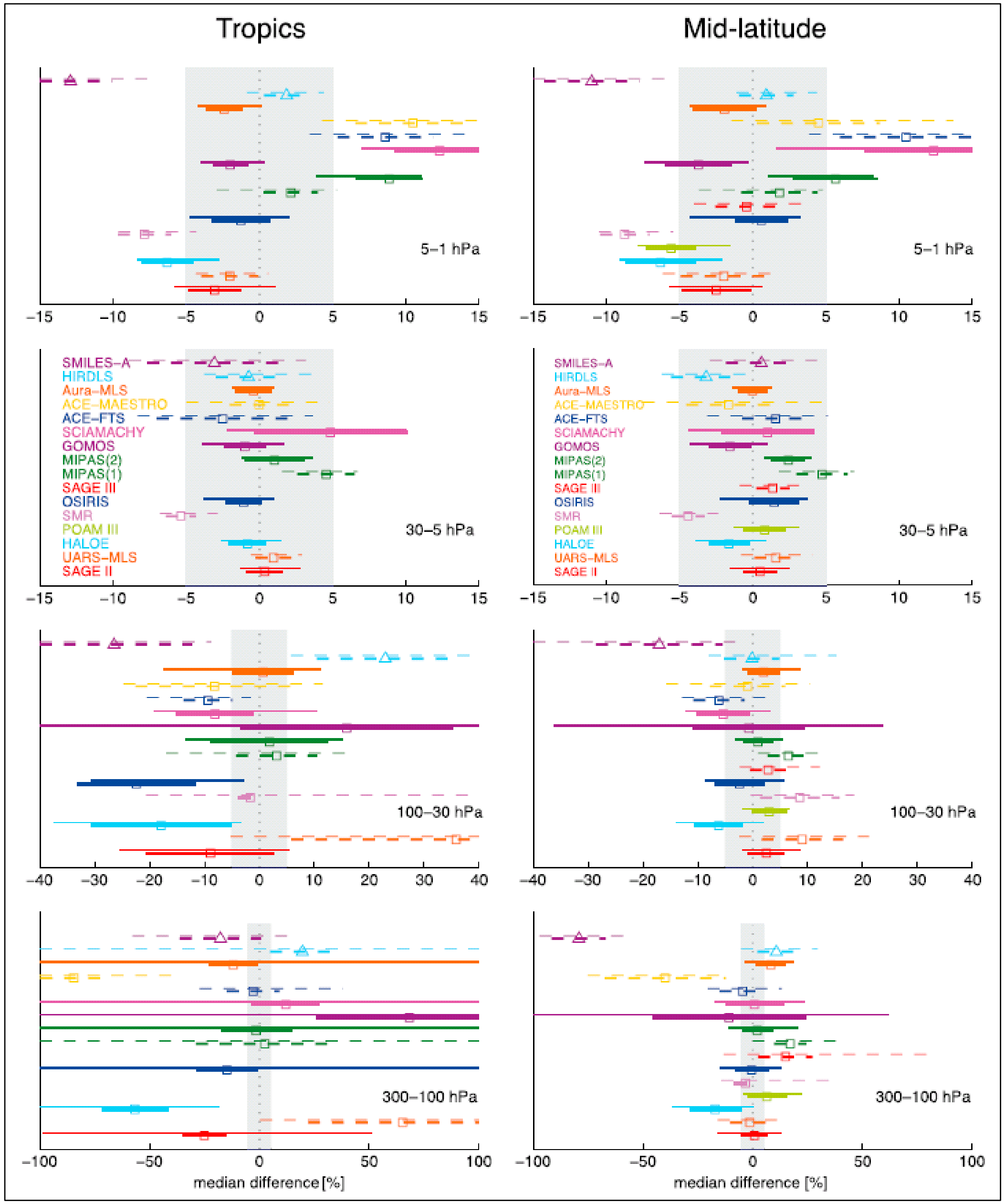
The ALTIUS mission concept was proposed by the Royal Belgian Institute for Space Aeronomy in 2005, as an anticipated solution to the « gap ».
The mission was approved in 2017 by BELSPO and implemented by ESA as an Earth Watch element



Credit: JC Lambert's team BISA - 2021

ALTIUS

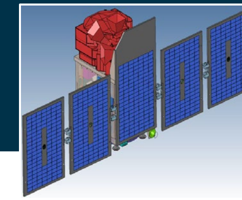
esa
ESA-DEVELOPED EARTH OBSERVATION MISSIONS
2010
2015
2020
2025
2030
ERS-1
ERS-2
Envisat
MetOp-A
Proba-1
SMOS
GOCE
CryoSat
Swarm
Proba-V
Meteosat 10 (MSG)
MetOp-B
Meteosat 11 (MSG)
Sentinel-1A
Sentinel-1B
Sentinel-2A
Sentinel-2B
Sentinel-3A
Sentinel-3B
Sentinel-5P
Sentinel-1C
Sentinel-1D
Sentinel-6 Michael Freilich
MetOp-C
Sentinel-2C
Sentinel-3C
Sentinel-2D
Sentinel-3D
Sentinel-6B
MTG-I1
Sentinel-5A MetOp-SG-A1
Arctic Weather Satellite
MetOp-SG-B1
Sentinel-4A MTG-S1
MTG-I2
CO2M-A
CO2M-B
CRISTAL-A
CIMR-A
ROSE-L-A
LSTM-A
CHIME-A
CRISTAL-B
CIMR-B
ROSE-L-B
LSTM-B
CHIME-B
MTG-I3
Sentinel-4B MTG-S2
Sentinel-5B MetOp-SG-A2
MetOp-SG-B2
Aeolus
ALTIUS
EarthCARE
Biomass
FLEX
Scout-1
TRUTHS
FORUM
Earth Explorer-10
Earth Explorer-11
Sentinel-1
Sentinel-2
Sentinel-3
Sentinel-6
Continuation of Sentinel Next Generation Mission
Science
esa
Copernicus
Meteorology
EUMETSAT

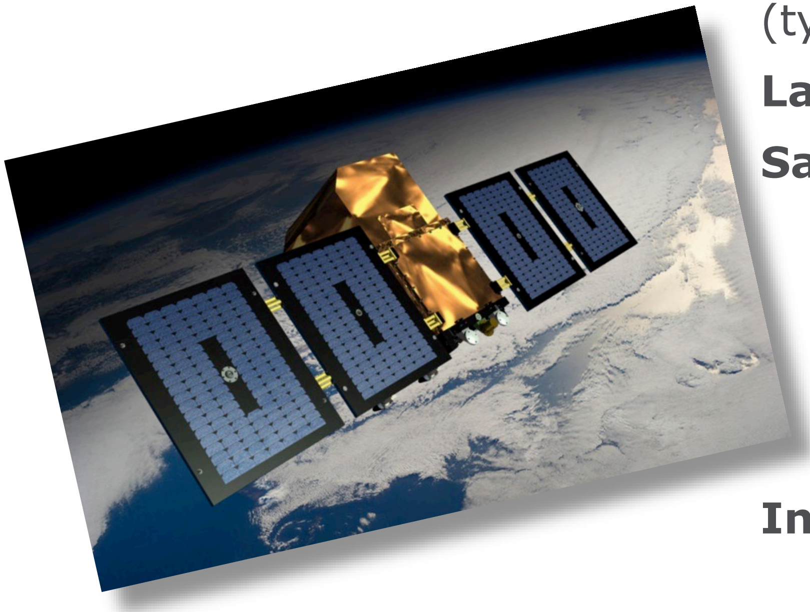


Summary of ozone differences for 1996–2010. Over a given latitude and altitude region, the median (squares), median absolute deviation (MAD, thick lines), and the standard deviation (thin lines) of the monthly mean relative differences between an individual instrument climatology and the MIM are calculated. **[S. Tegtmeier et al. , JGR, 2013]**

- **To go below 5 % is difficult : stability may be more important**
- **We need several overlapping missions**

Technical Overview





Mission duration: > 3 years (phase E2)

Operational Orbit: standard low Earth orbit (typically 668km – 10:30)

Launch Vehicle: Co-passenger (including VEGA-C)

Satellite:

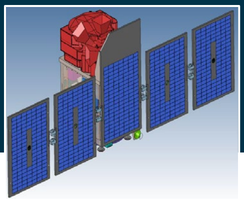
- < 300 kg
- Volume 1 x 0.8 x 1.3 m^3
- < 250 W
- Autonomous, agile, several pointing modes

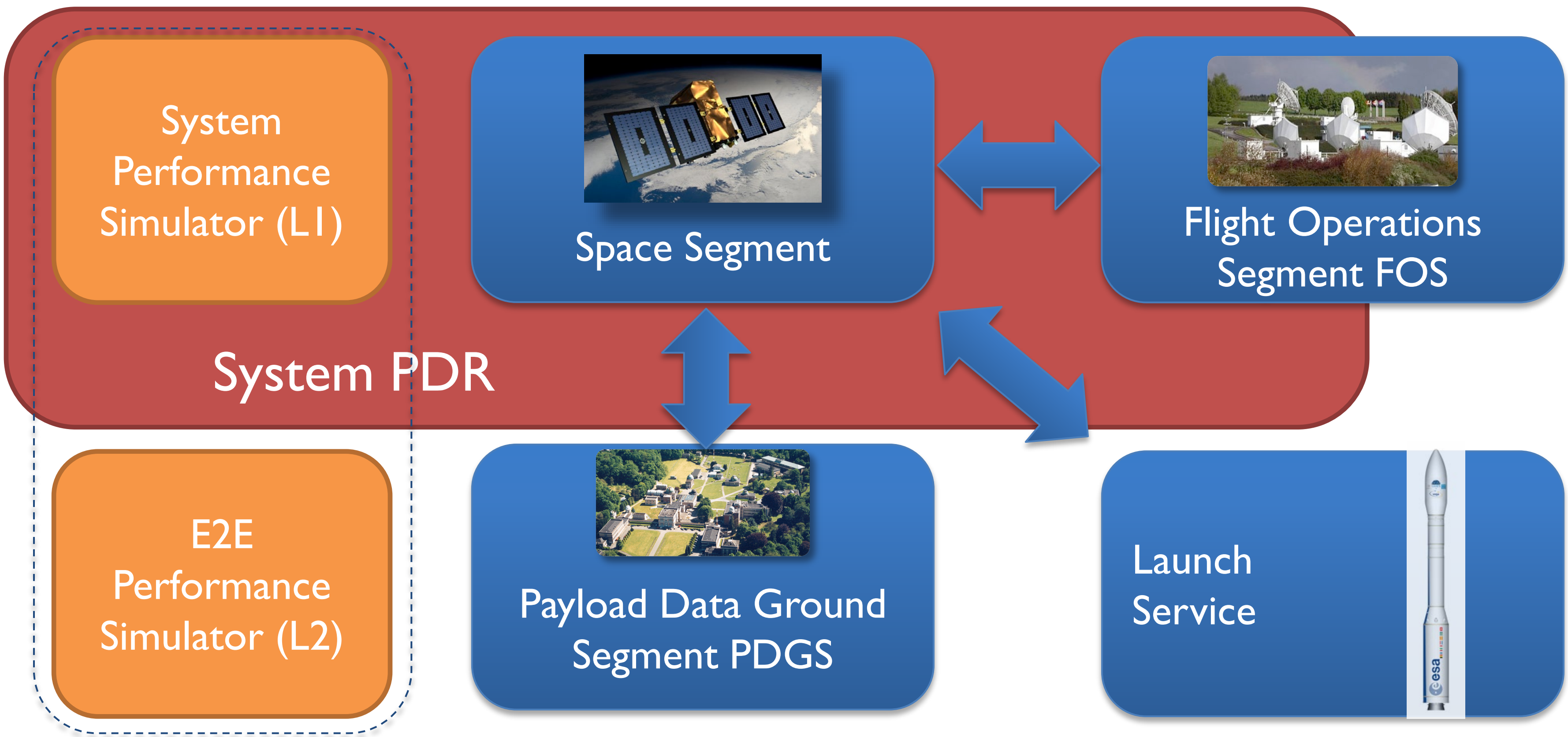
Instrument: 2D spectral imager (limb sounder)

- Ultraviolet, Visual, Near Infrared

key concept: agility

Technical Overview - System

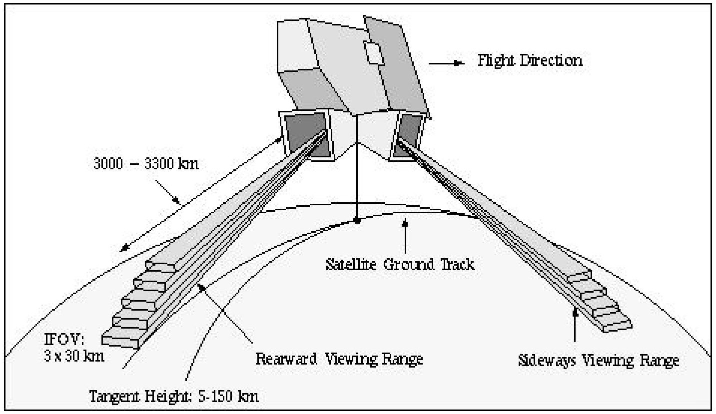


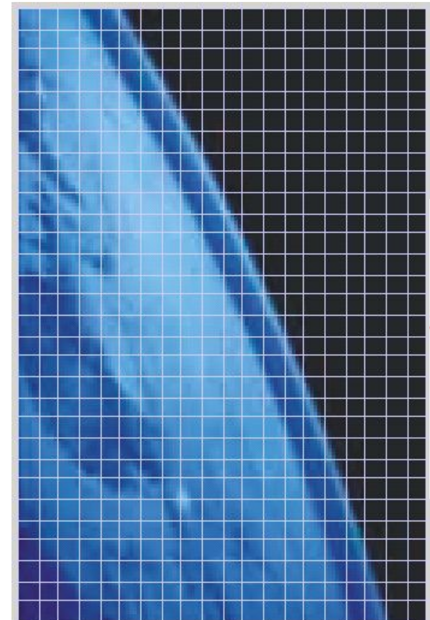


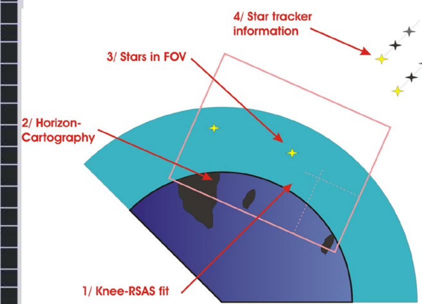
PDGS @ Brussels to support operational (NRT) and consolidated (CP) processing for L0,L1,L2

To solve the tangent altitude registration issue

ALTIUS







Limb scan	Full 2-D limb imaging
Filter or grating spectrometers	Acousto-optical and FP filters

(wavelength x space) x space **=**

↓

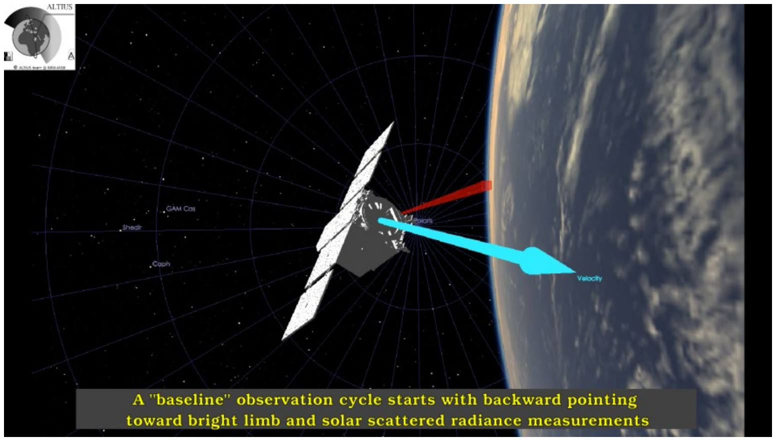
wavelength **x (space x space)**

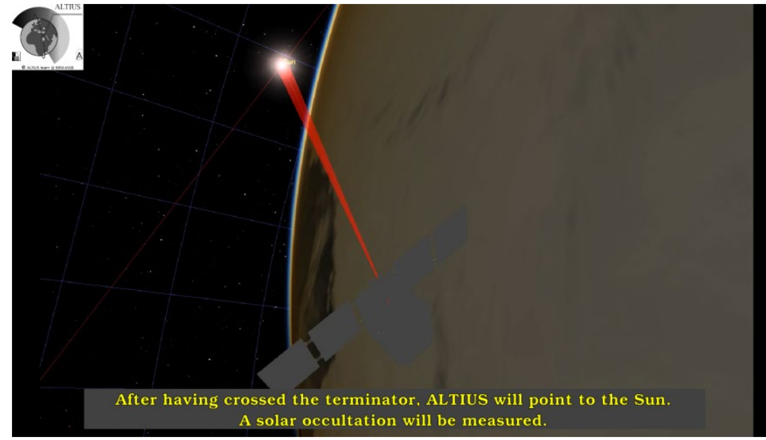
↓

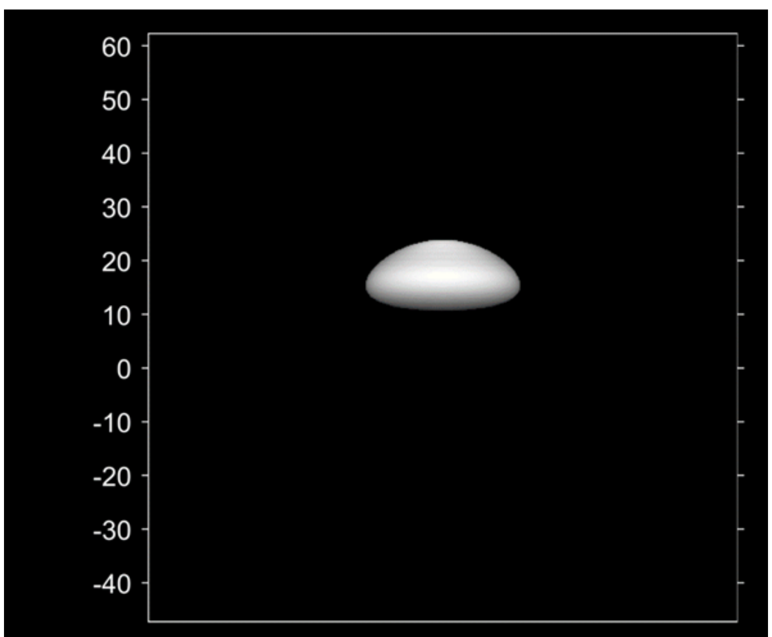
[250-1020 nm] x [0.5 km x 0.5 km]

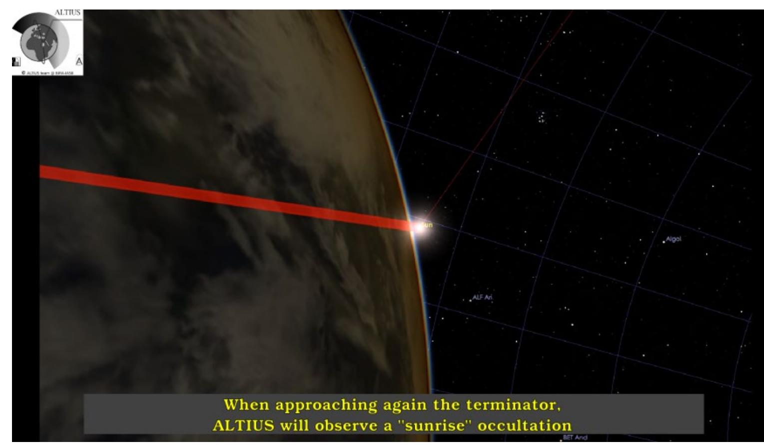
NIR -> SWIR

Spectral imaging has a serendipitous property: it allows for occultation observations by simple **inertial pointing** .

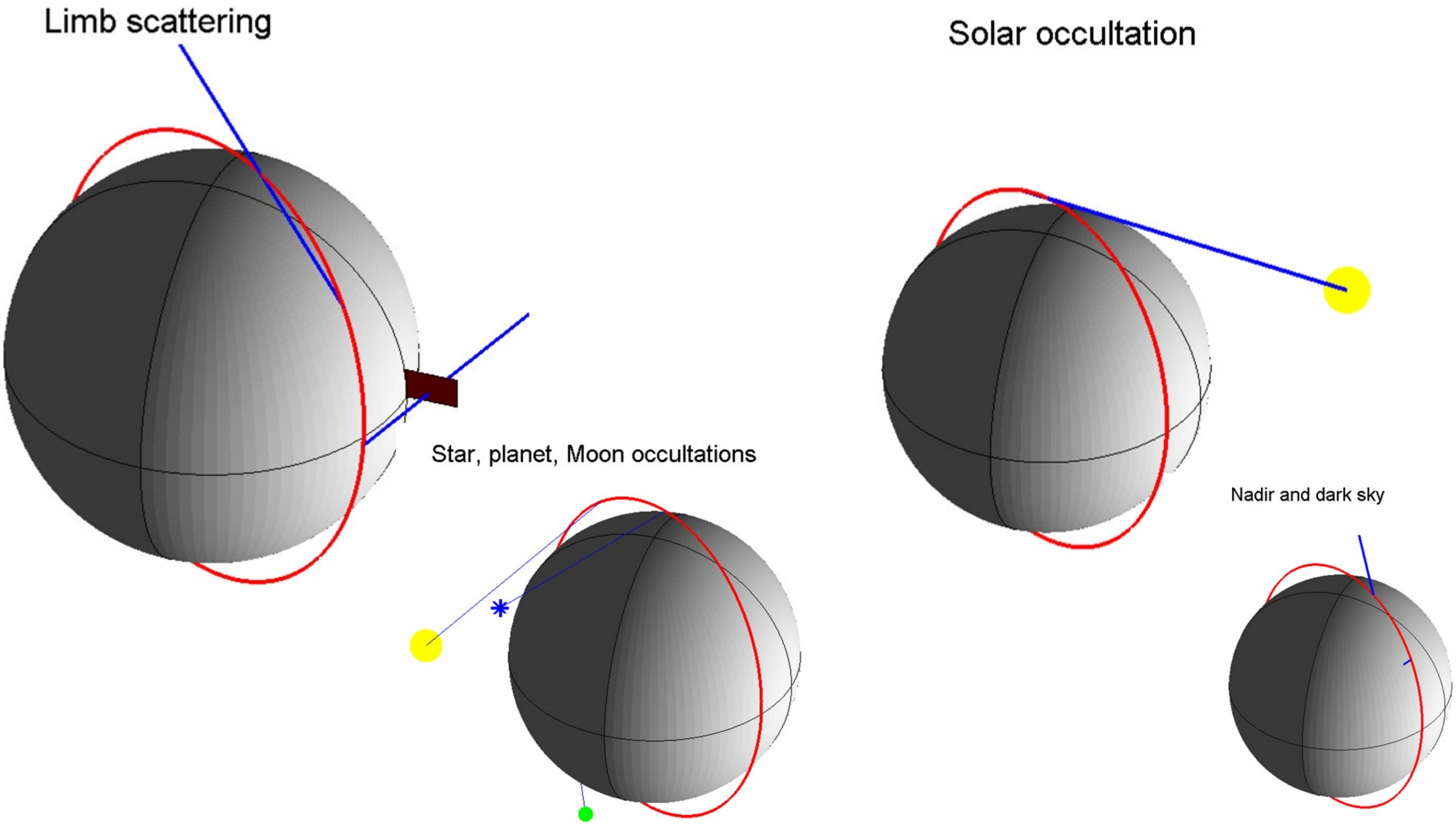




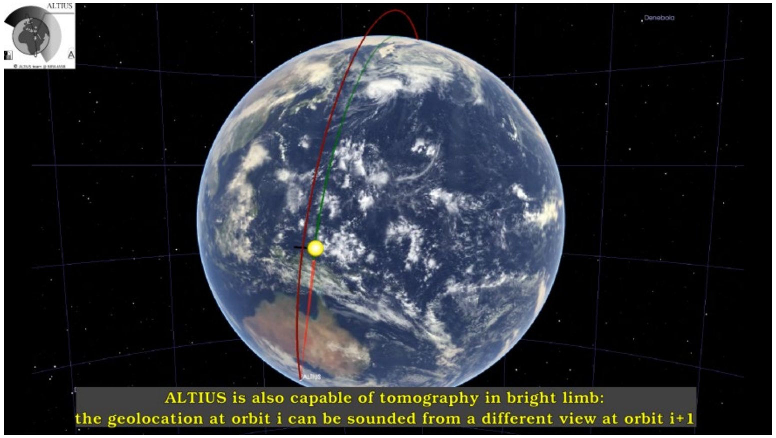


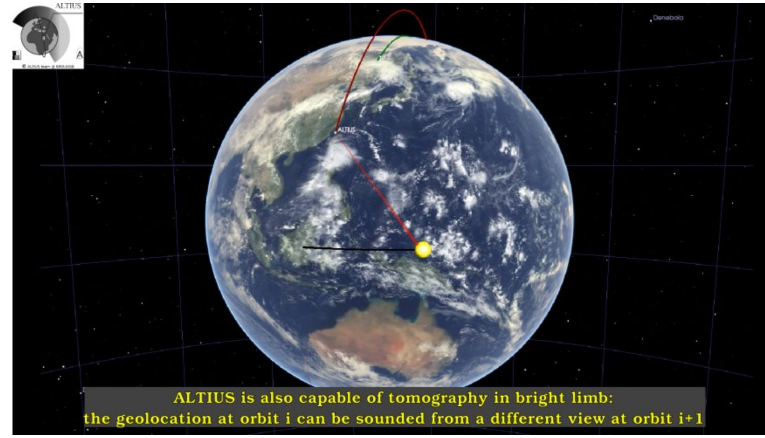


Innovative ALTIUS concept: multimode observations



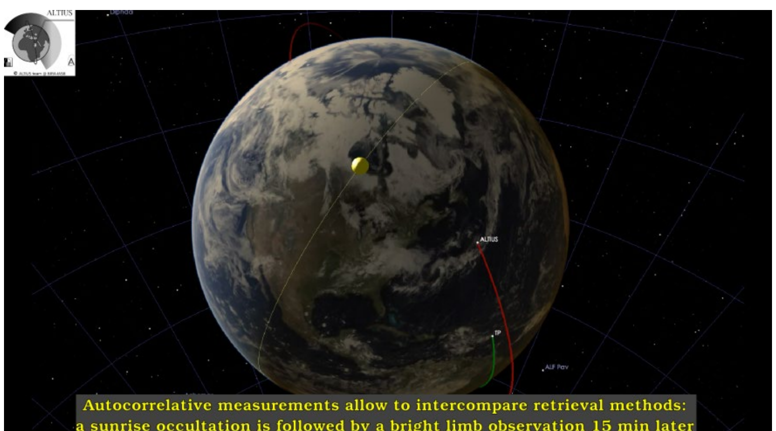
20 % of mission time will be used for calibration and dedicated observations.

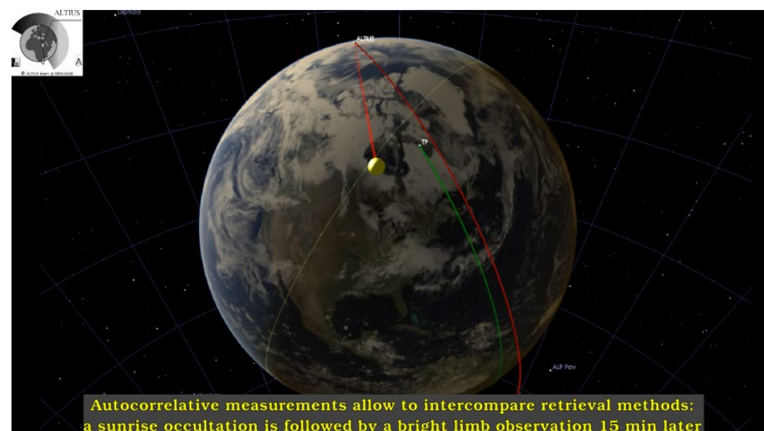




Stereoscopic sounding ↑

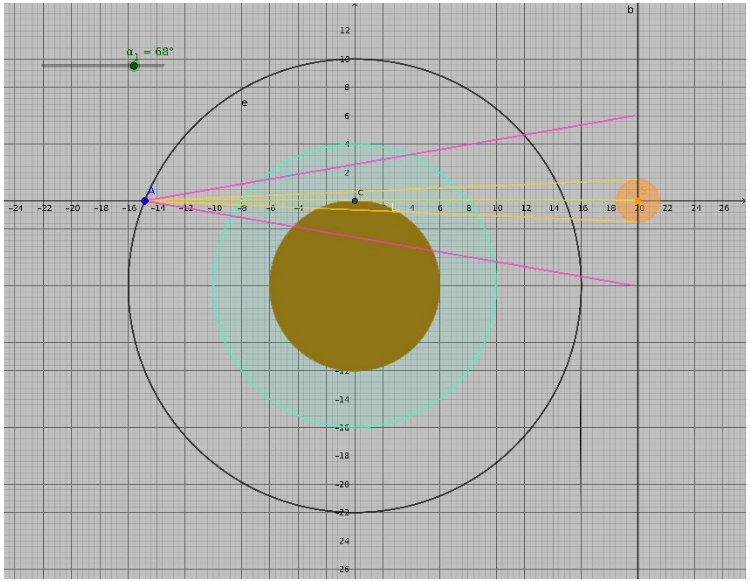
Self-validation ↓

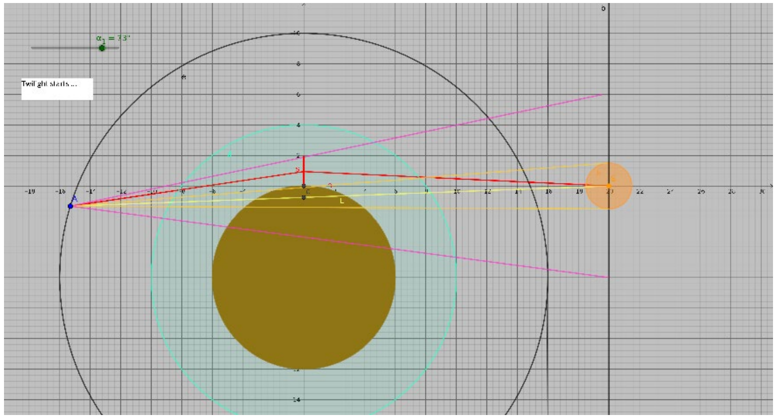


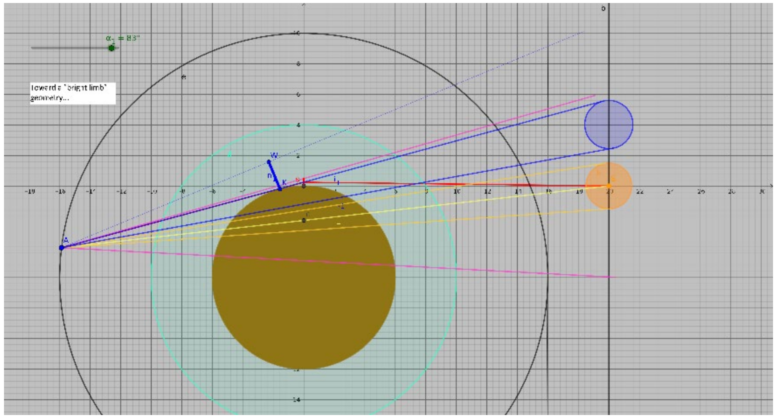


New feature: self-validation by twilight observations

end of occultation







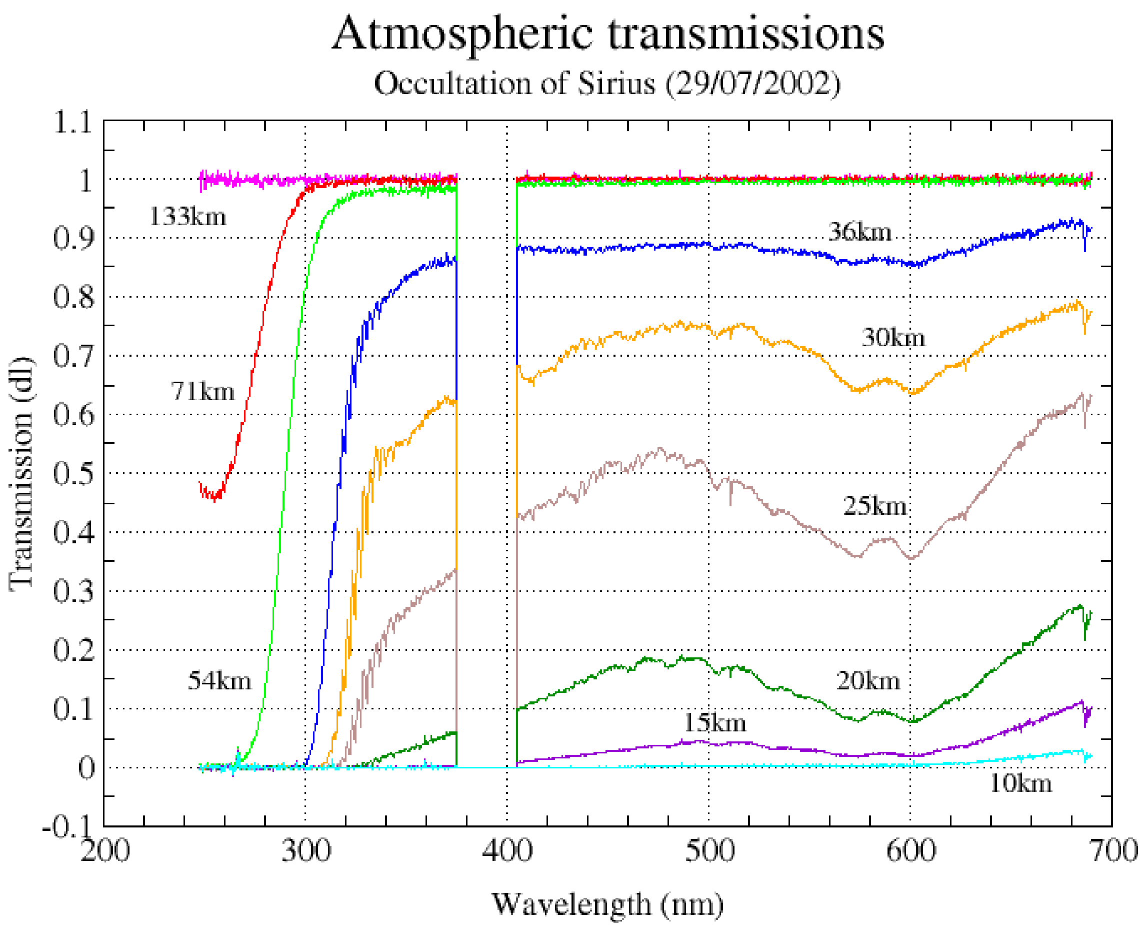
natural twilight

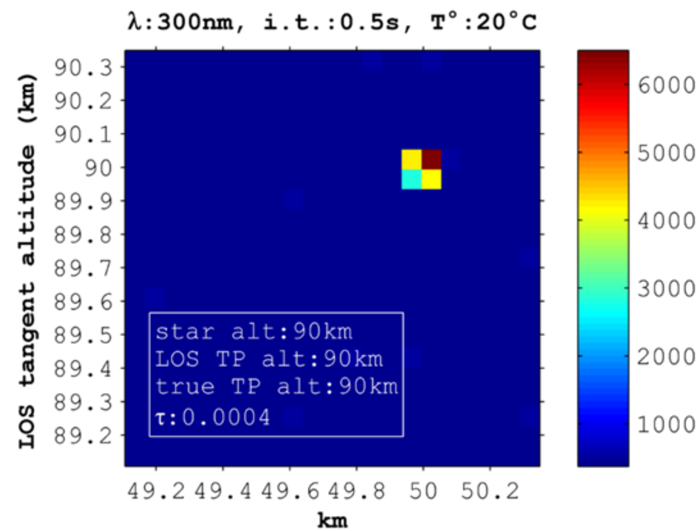
extended twilight

Credit: ISS astronaut Don Pettit (2012) [https://earthobservatory.nasa.gov/images/147990/stars-in-motion]

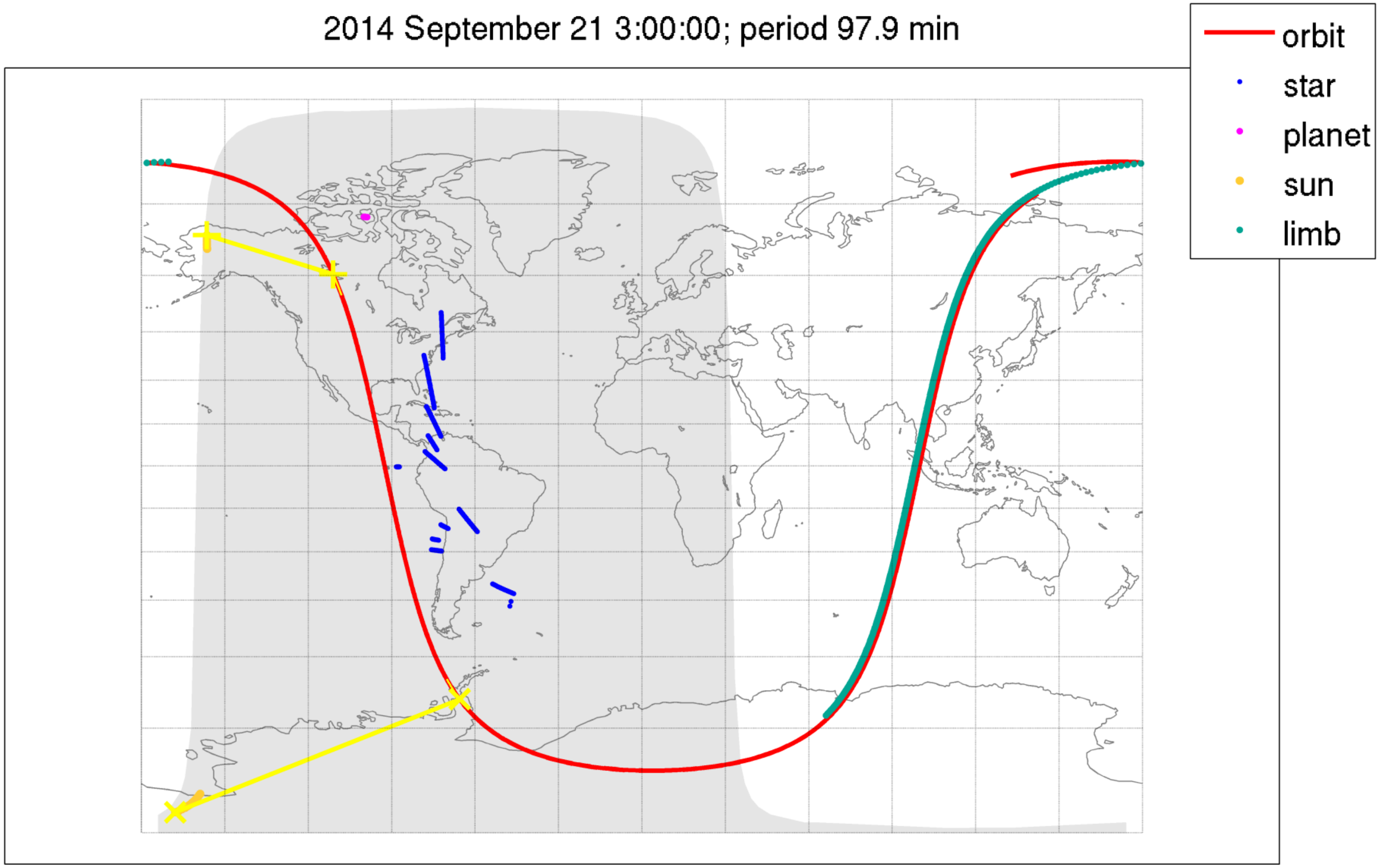
ALTIUS

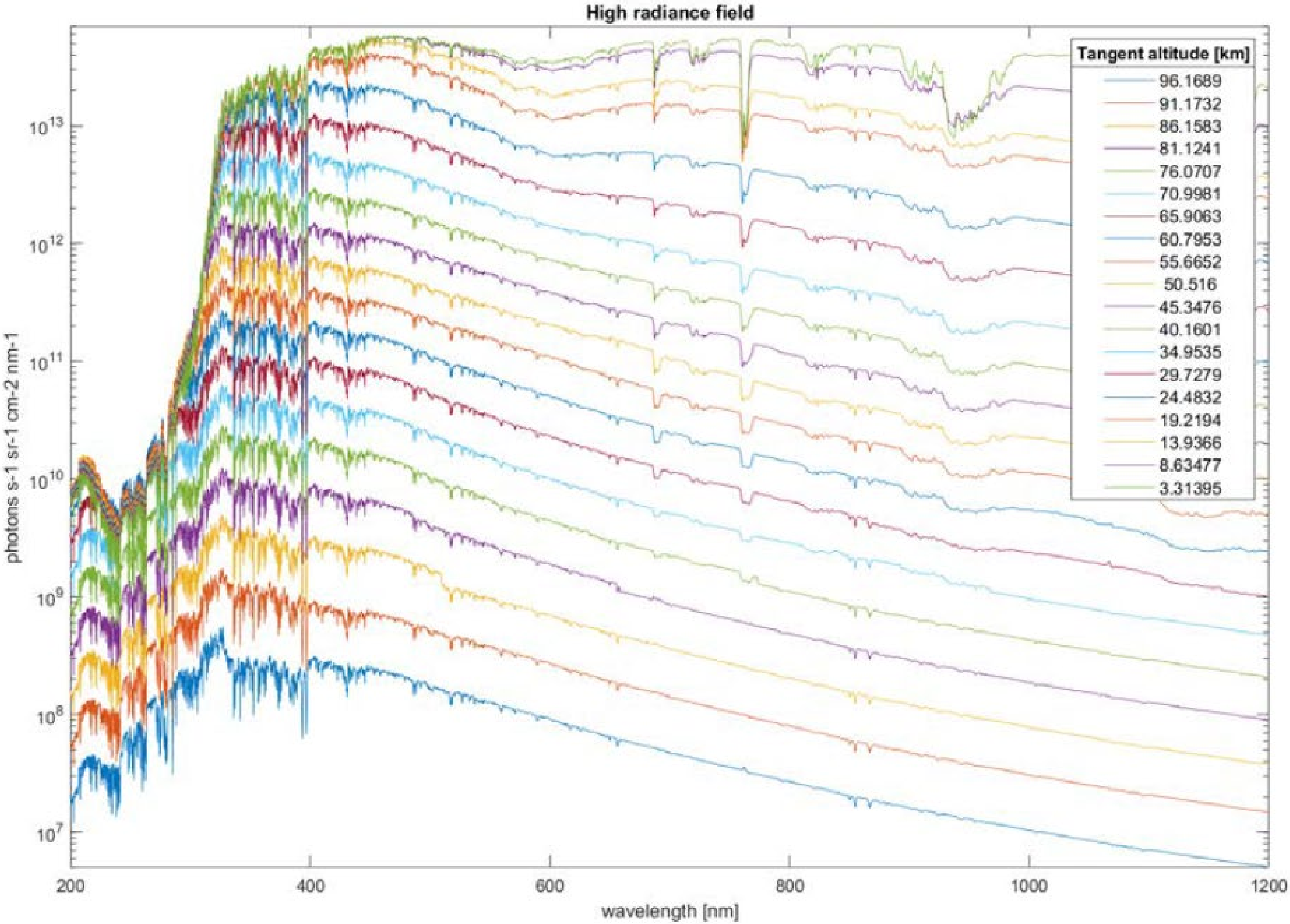
Transmission spectra





2014 September 21 3:00:00; period 97.9 min

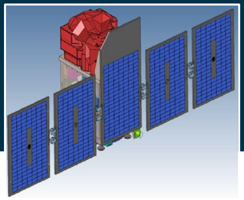


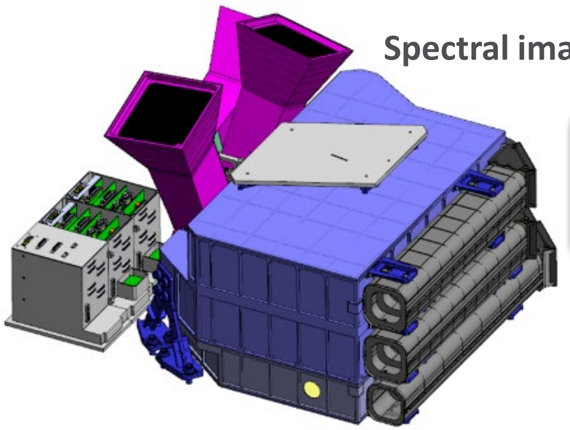

High radiance field
Tangent altitude [km]
96.1689
91.1732
86.1583
81.1241
76.0707
70.9981
65.9063
60.7953
55.6652
50.516
45.3476
40.1601
34.9535
29.7279
24.4832
19.2194
13.9366
8.63477
3.31395
photons s-1 sr-1 cm-2 nm-1
wavelength [nm]
200
400
600
800
1000
1200

Scientific requirements

	Molecule	Vertical Region	Target/Threshold Tot. Error (%)
SR1	O3	UT/LS	5/20
SR2	O3	US	3/10
SR3	O3	UT/LS polar	10/30
SR4	O3	MS	10/20
SR5	NO2	Strato	15/40
SR6.1	H2O	UT/LS	5/20
SR6.2	~~CH4~~	~~UT/LS~~	~~2/5~~
SR7	Aerosol	UT/LS	10/100
SR8	PSC	UT/LS	30/100
SR9	PMC	MS	30/100
SR10.1	OClO	Strato	20/50
SR10.2	BrO	UT/LS	5/10
SR10.3	NO3	UT/LS night	15/40
SR11	T	UT-MS	0.5/2 (K)
SR12	Tomo	UT/LS	15/40

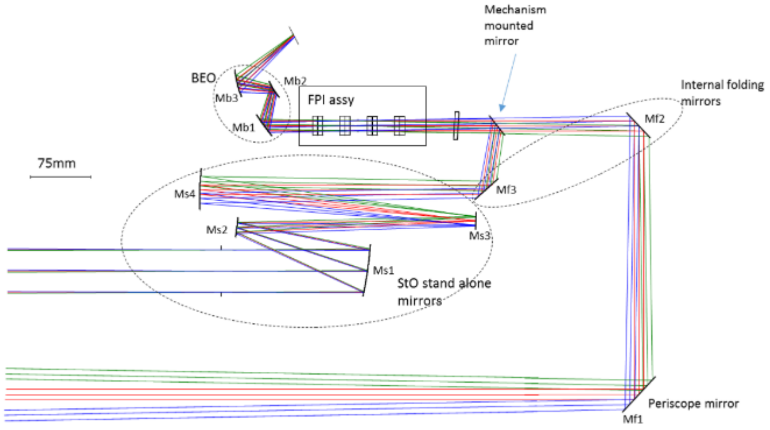
Technical Overview - Instrument

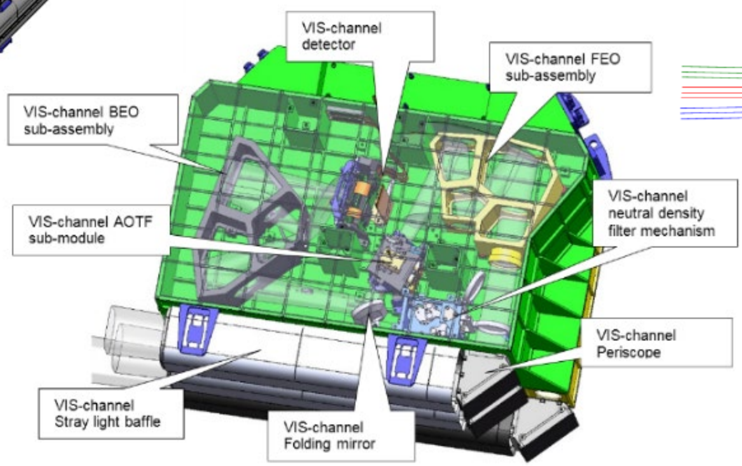


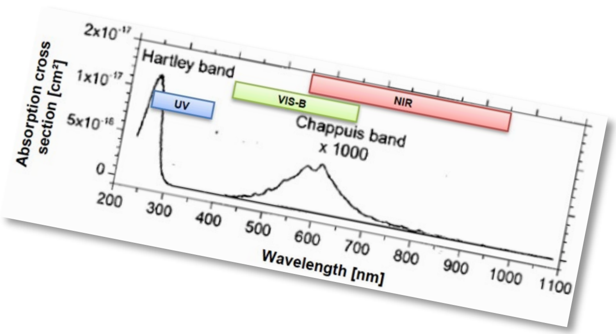


Spectral imager with 3 independent channels:

UV (250 – 355nm)
VIS-B (440-675nm)
NIR (600 - >1020nm)

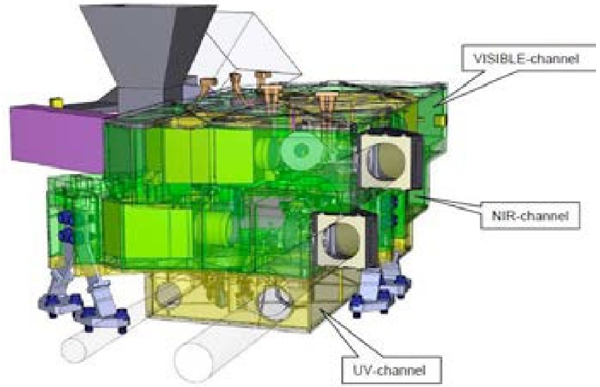


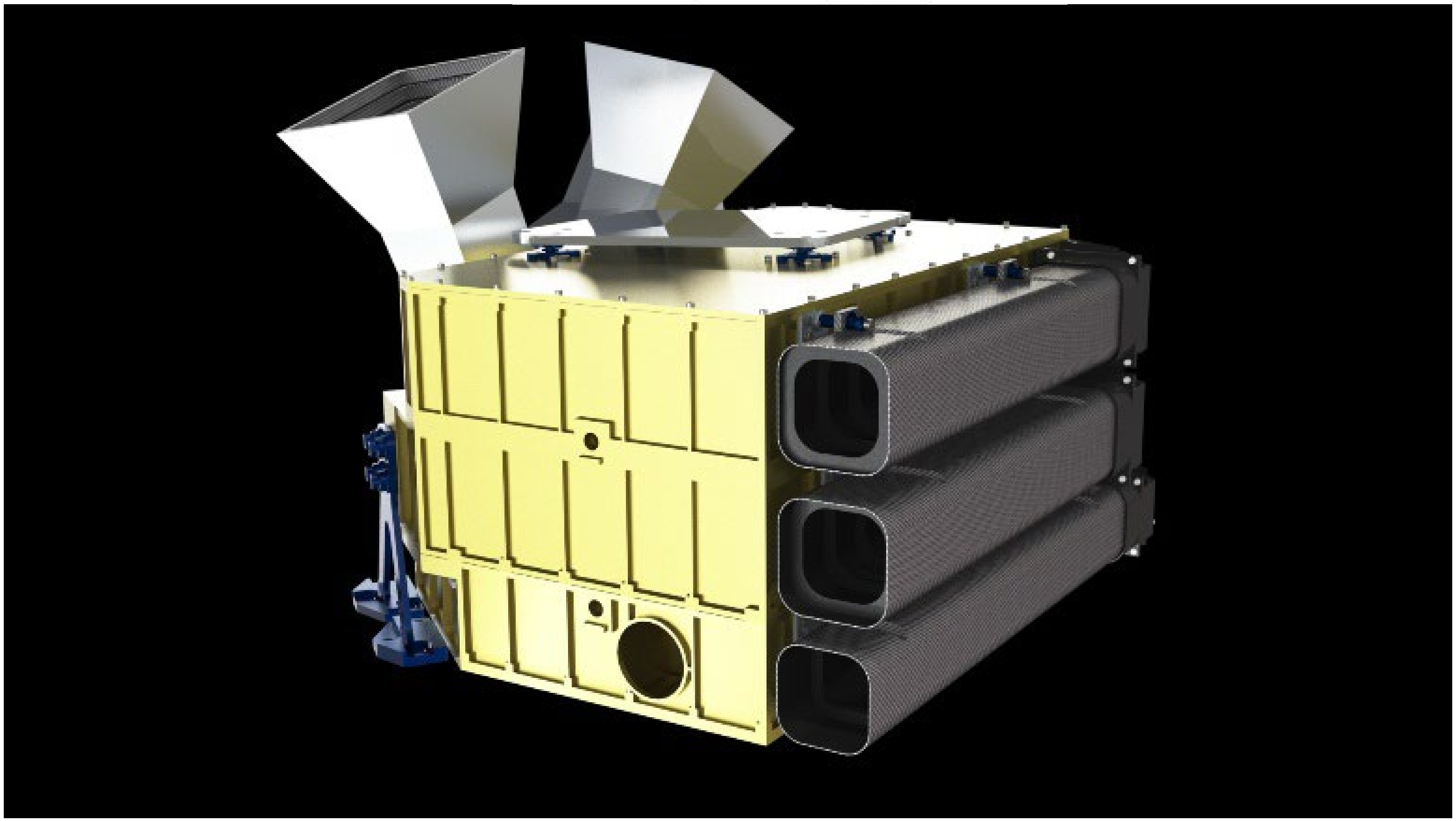




Spectral filters:

AOTF for VIS-B/NIR
FPI for UV


VISIBLE-channel
NIR-channel
UV-channel



ALTIUS Stray Light (U. SASK.)

In-field stray light

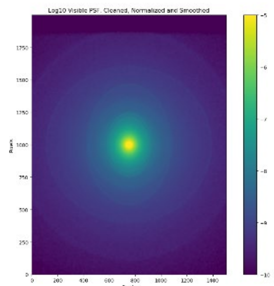
The PSF is spatially variant and does not permit standard deconvolution. We build a linear matrix formulation relating the contribution of every pixel to every other pixel.

$$Y = AX$$

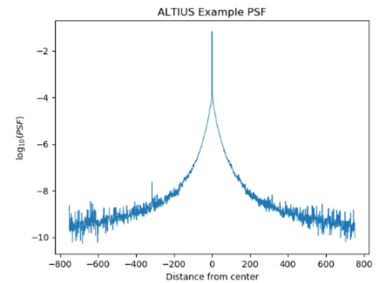
This is solved using standard linear algebra.

$$X = A^{-1}Y$$

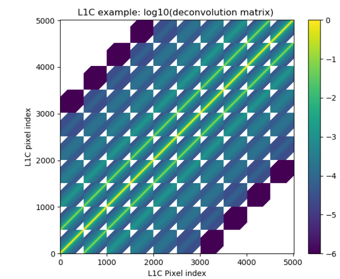
The matrix A can be very large with over 1 trillion elements. This is too large for most computers, and we limit the matrix to around 5,000 x 5,000 elements by vertically binning by a factor of 3 and horizontally binning to 10 vertical profiles. The solution is very quick once matrix **A** is calculated. Calculating **A** can take 3 hours for simple cases using multi-threaded C++ code and noticeably longer for more detailed cases.



Example PSF image



PSF slice

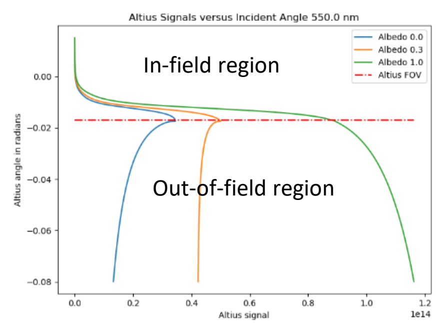


Convolution Matrix, A

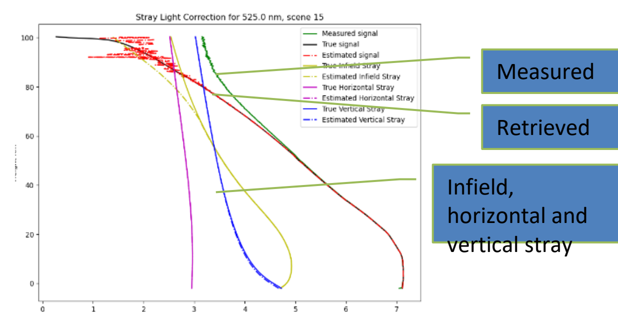
Out-of-field stray light

The Earth's surface is a bright region located within the near-out-of-field region of the ALTIUS field of view: it cannot see the detector directly but may illuminate the front-end optics. The fall-off of atmospheric signal in altitude is faster than the stray light curve. The low altitude, out-of-field signal dominates the measured high-altitude signal. This is a **High-Altitude Proxy** for stray light.

The low altitude, out-of-field signal is approximated with a lower order polynomial and adjusted until we have a good fit with the high-altitude proxy. The inferred stray light is then removed from all altitudes.

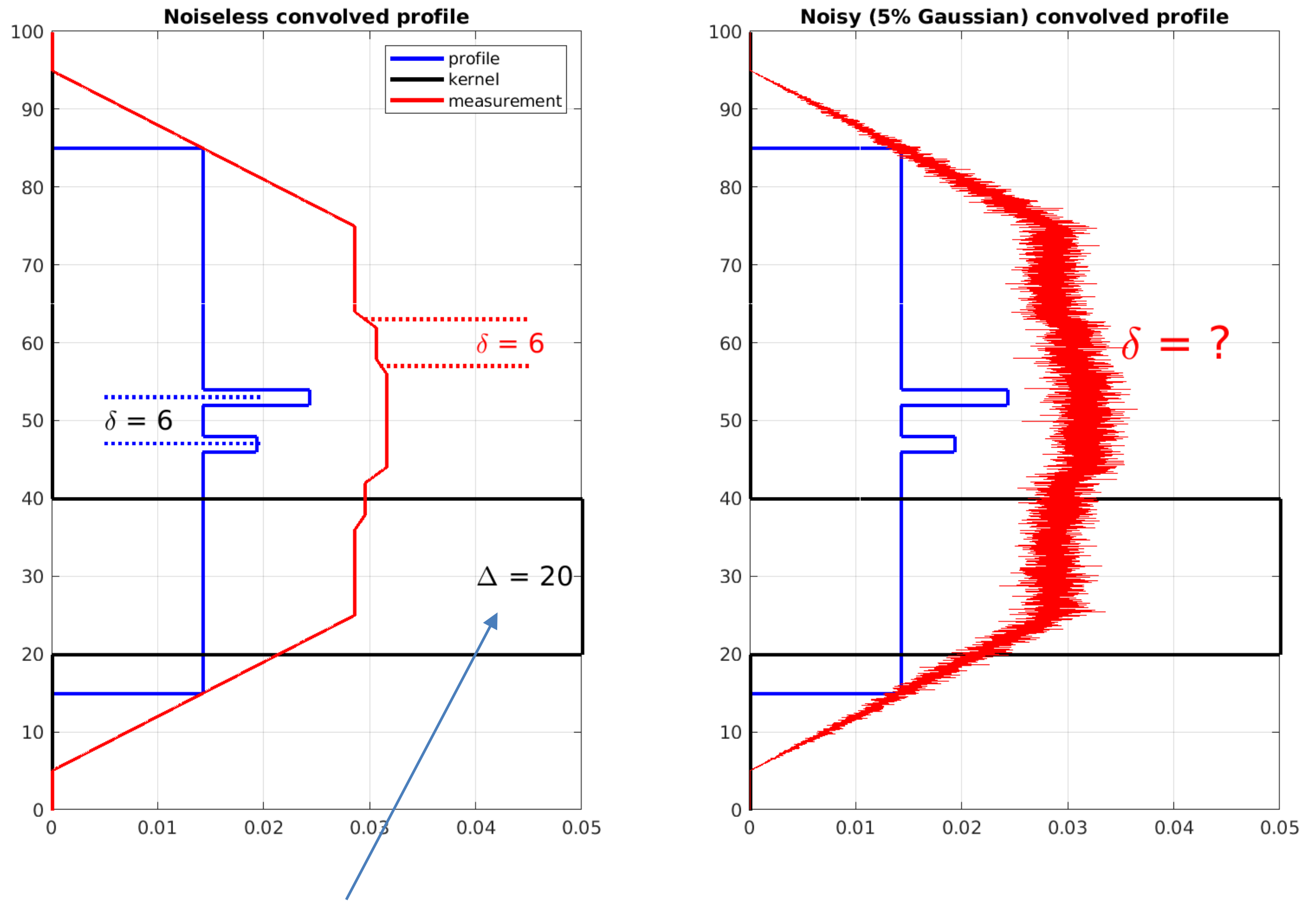


There is a significant contribution from the radiance in the low altitude out-of-field region to the signals measured in the infield region



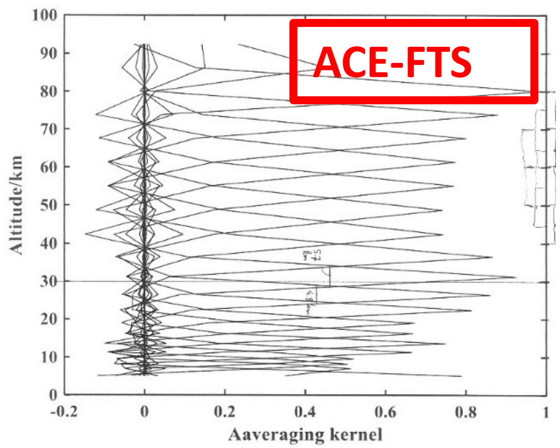
The high-altitude proxy allows low altitude stray light to be estimated and removed.

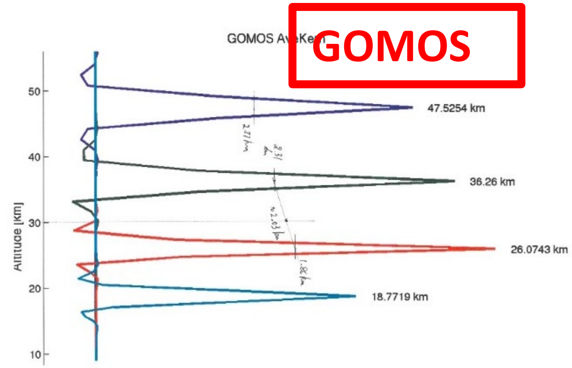
Impact of SNR on vertical resolution

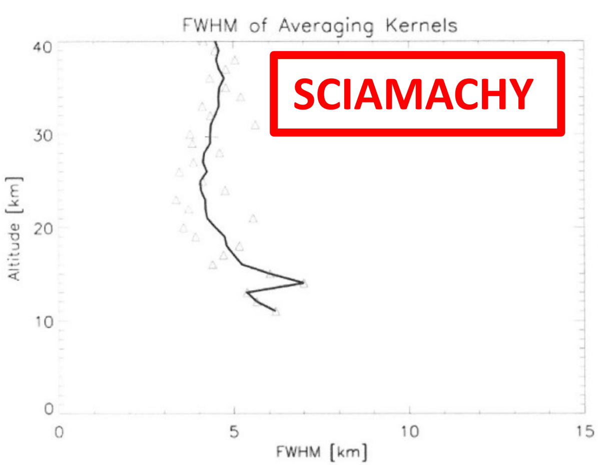


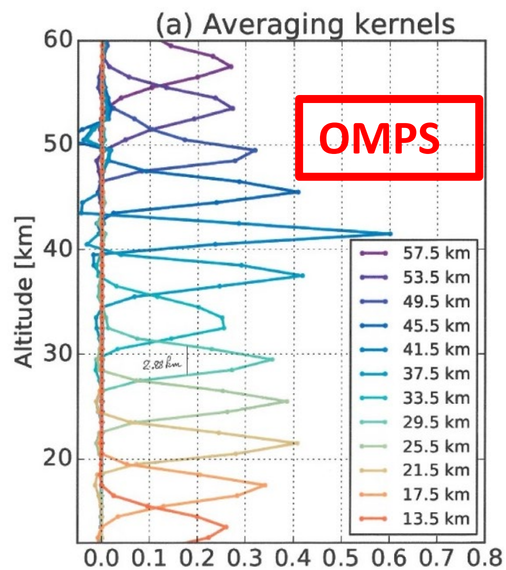
f.i. solar or lunar occultations

ALTIUS









SOUNDER	FWHM (@30km)
ACE-FTS (solar occ.)	~5.5 km
SCIAMACHY (limb)	~4.3 km
ALTIUS (#PC=20/SNR=500) **(limb)**	**~3.6 km**
OMPS (limb)	~2.9 km
OSIRIS (limb)	2.2(?) km <x<3.5 km
GOMOS (stellar occ.)	~2.0 km

ALTIUS in a nutshell

- **ALTIUS** is a limb spectral imager (3 channels / 250 nm-1020 nm) operating in several observation geometries from a microsatellite platform (PROBA), with a target vertical resolution of 0.5-1.0 km in the range 10-100 km.
  - Operational objective : NRT stratospheric ozone/aerosol monitoring.
  - Scientific objectives: O_3, NO_2, H_2O, aerosols, temperature, tomography, airglow,…
- Global coverage through a standard heliosynchronous LEO orbit with a 3-day revisit cycle. NRT and Consolidated products. Need for assimilated L3 data.

STATUS

- ALTIUS is alive as an **Earth Watch** mission (May 2025)
- Phase B2-C-D started
  system PDR done
  PDGS PDR in 2021
- Preliminary algos exist for ozone NRT in bright limb and occultations.
- Mission performances are strongly linked with the convergence of instrument performances.
- A lot of technical/scientific questions are still open: in-flight calibration methods, self-validation, airglow, instrumental convolutions, ...