Calibration examples from Earth observation hyperspectral instruments

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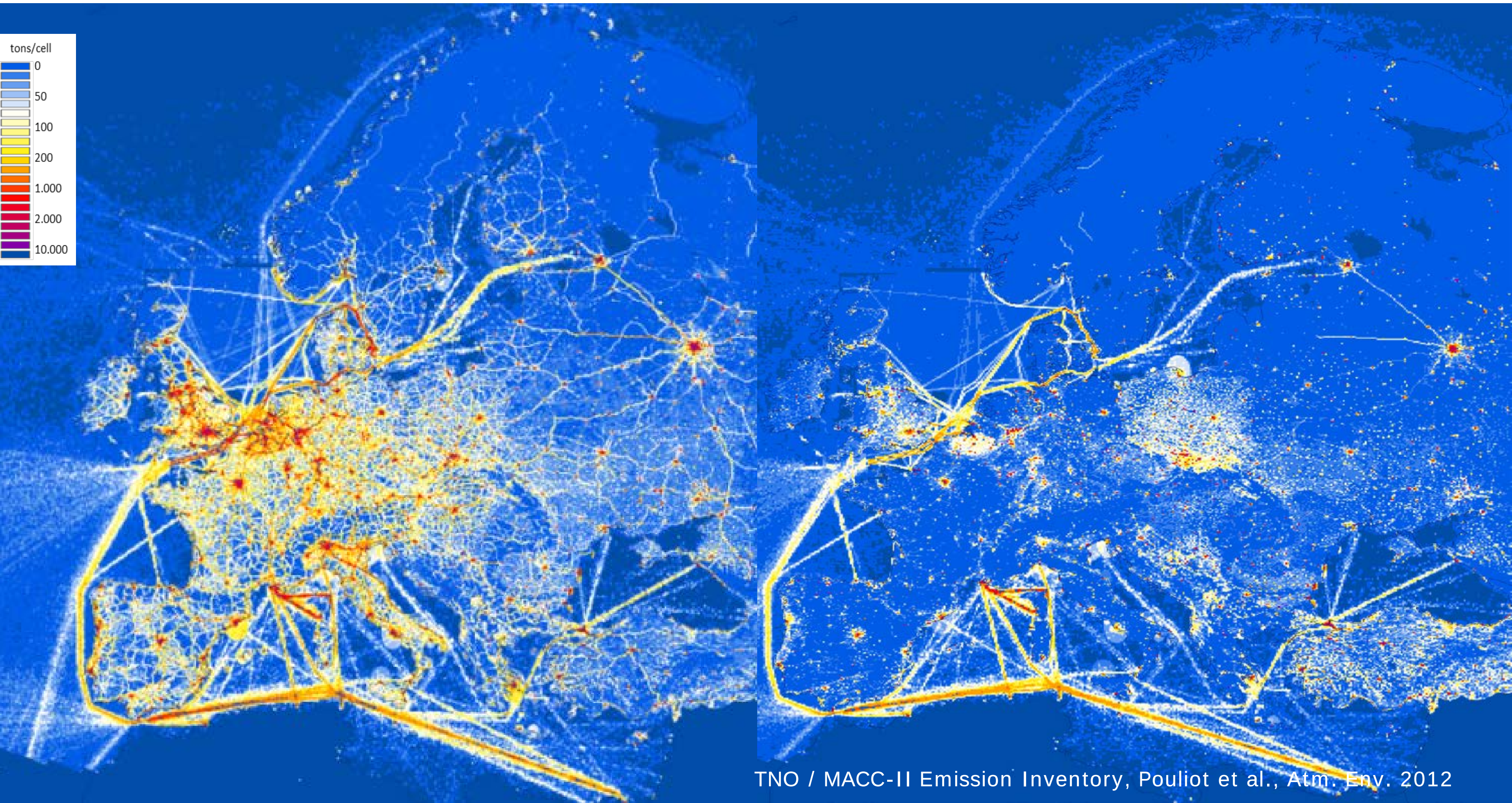
Contents

Air quality – example shipping lines

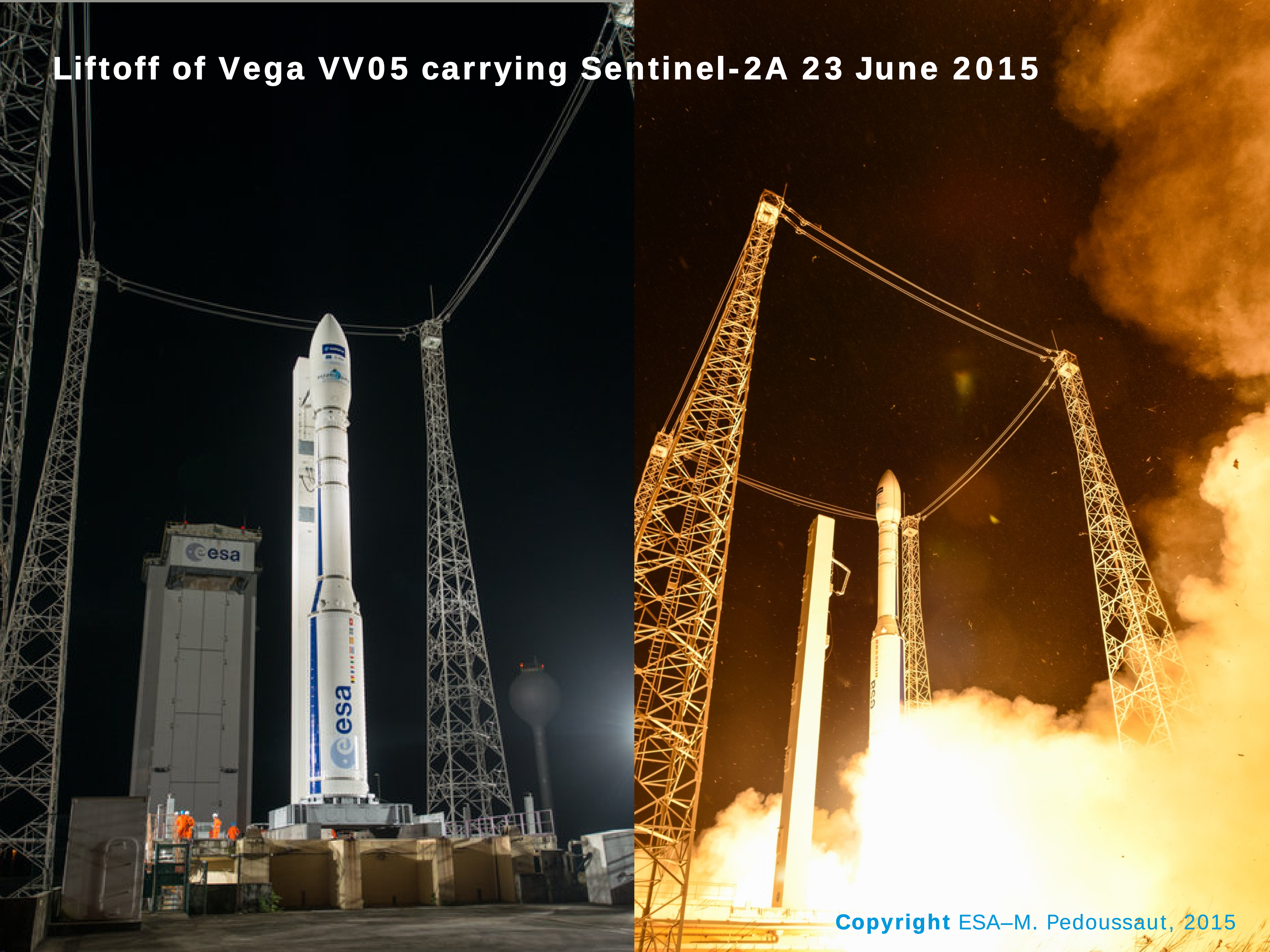
Emissions NO + NO_2

Emissions SO_2 - Year 2009, 7x7 km^2



TNO / MACC-II Emission Inventory, Pouliot et al., Atm. Env. 2012

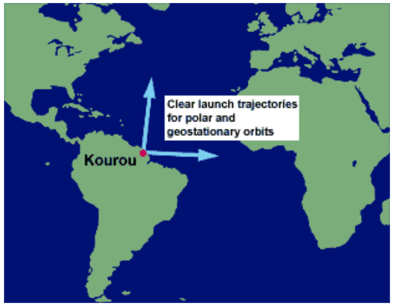
Liftoff of Vega VV05 carrying Sentinel-2A 23 June 2015



Mission architecture example MTG

Launch Segment

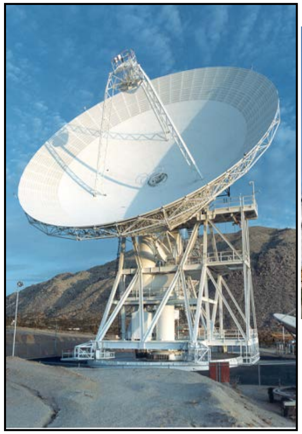
Launch Vehicle
(A5, Soyuz, Proton)



Observatory Segment

- Two MTG-Sounder (MTG-S) S/Cs
- Four MTG-Imager (MTG-I) S/Cs
- Payload
  1- Flexible Combined Imager, on MTG-I
  2- Lightning Imager, on MTG-I;
  3- Infra-Red Sounder on MTG-S;
  4- Sentinel-4/UVN, on MTG-S

Ground Segment



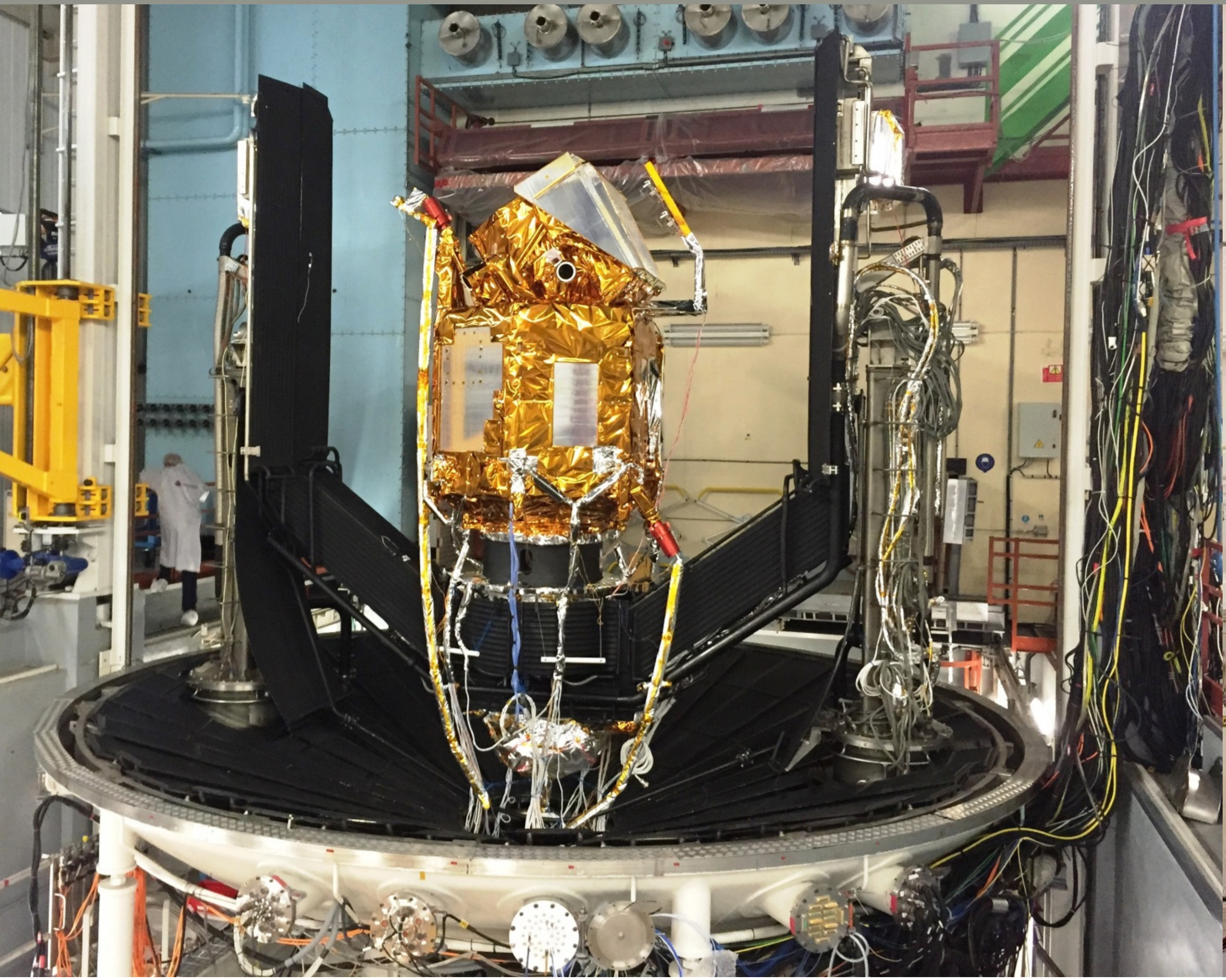
- Flight Operations Segment
- P/L Data Ground Segment
- Ground Station(s)

Orbit:
Geostationary

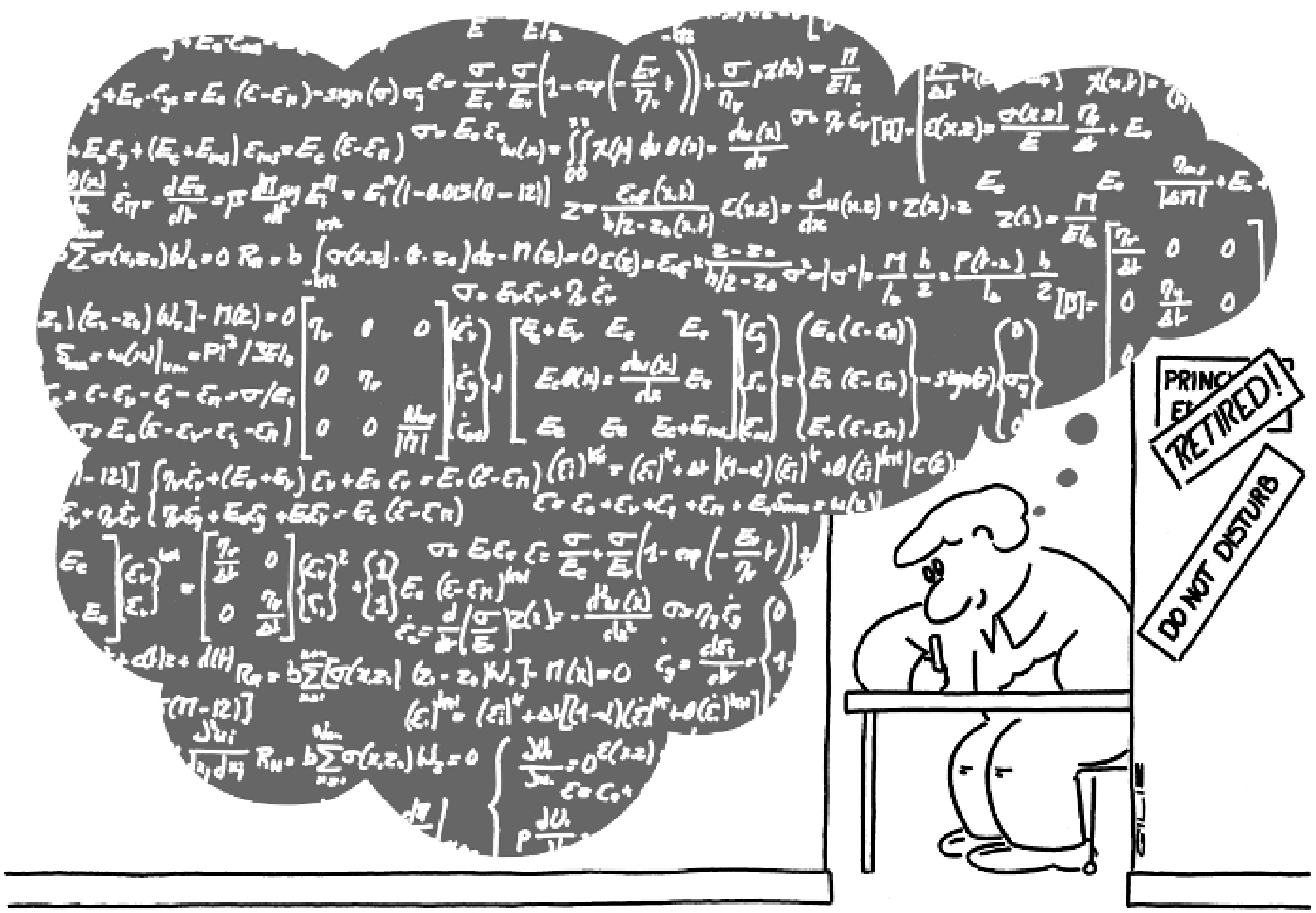
S4 / UVN on MTG-S

Image courtesy Airbus Defense & Space

Sentinel-5 Precursor in testing



Do not make it too complicated



by Gilles Labruyère

The aim of calibration is to convert instrument measured data into physical units

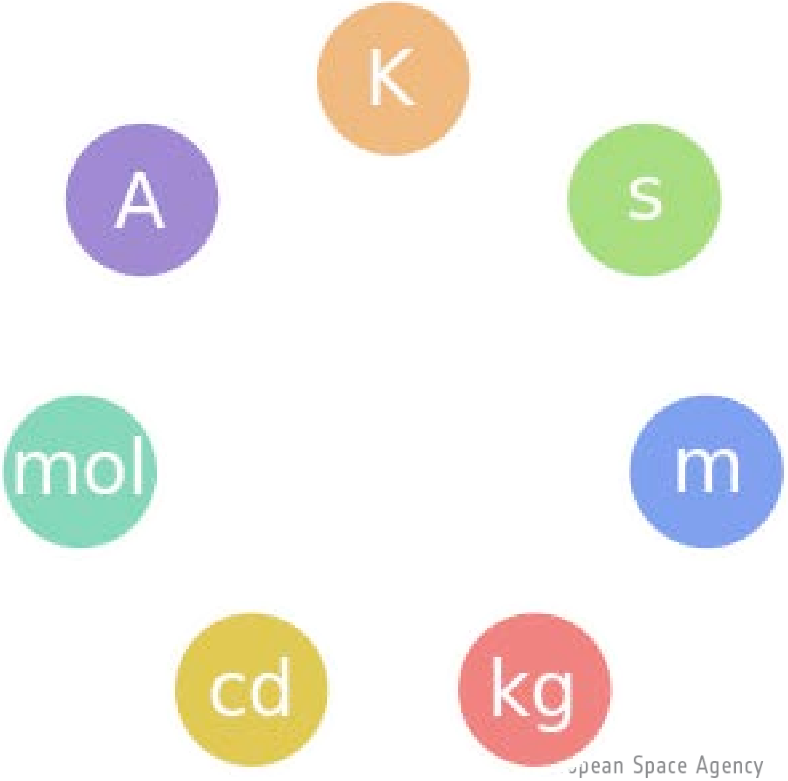
SI **International System of Units** (French: *Système International d'Unités*

- Metre [m], kilogram [kg], ampere [A], second [s], Kelvin [K], candela [cd], [mol]

Measurement = absolute calibration

- → if derived from one or more international SI standards
- → NMI (national measurement institute)

- Traceability to SI units



1 metre bar

Historical international prototype metre bar, made of an alloy of platinum and iridium, that was the standard from **1889 to 1960**.

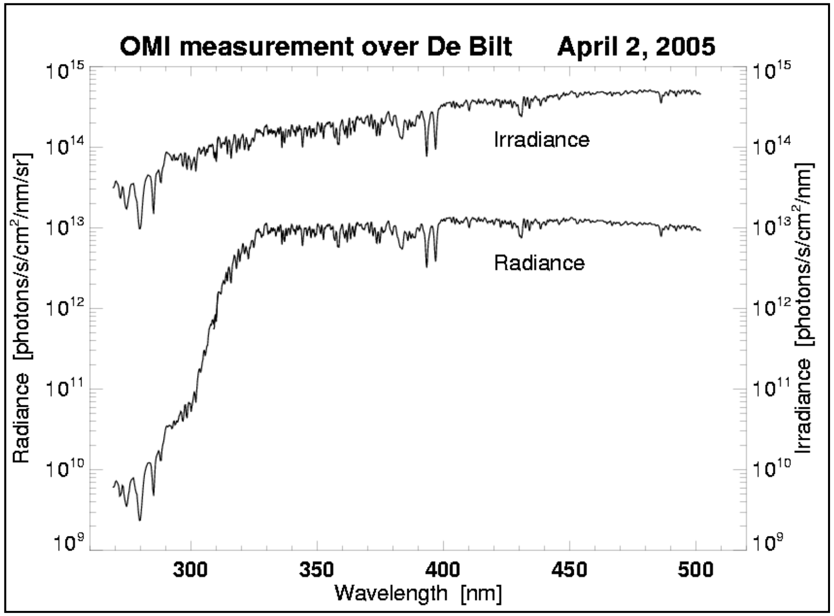
The metre was originally defined in **1793** as **one ten-millionth of the distance from the equator to the North Pole**.

In **1889**, it was redefined in terms of a prototype **metre bar**.

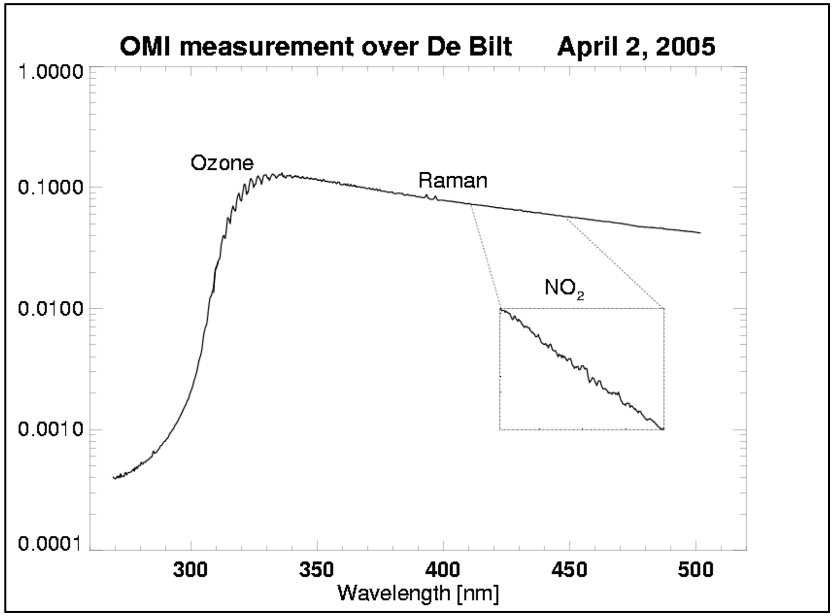
In **1960**, the metre was redefined in terms of a **certain number of wavelengths of a certain emission line of krypton-86**.

Radiance Irradiance → Reflectance

irradiance and radiance measurement

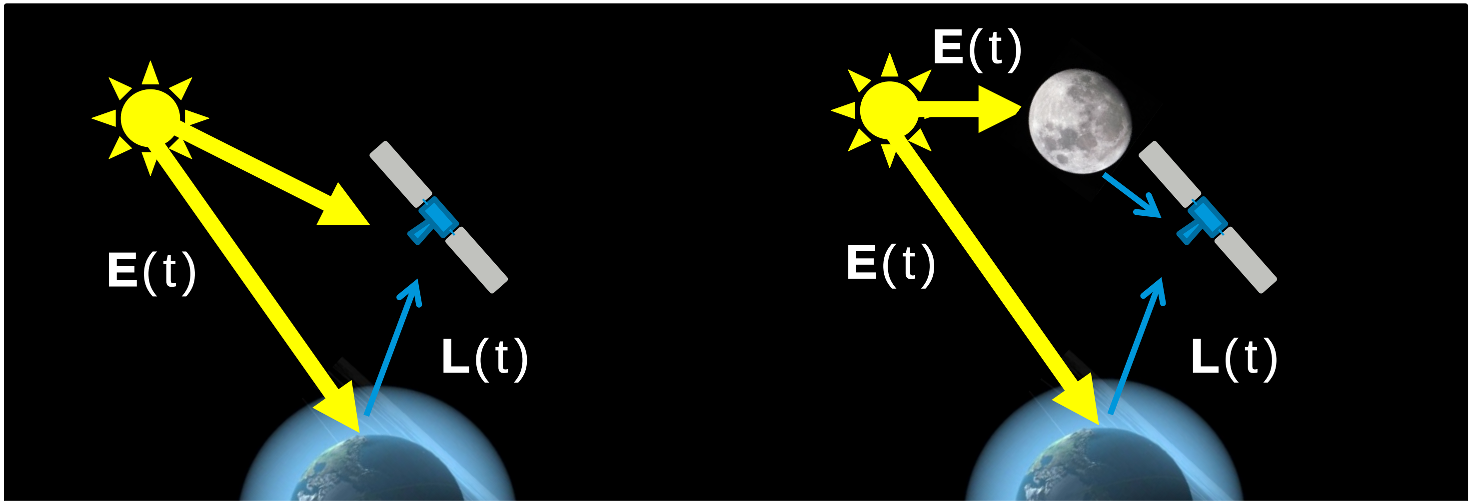


derived reflectance



Earth reflectance Top Of Atmosphere

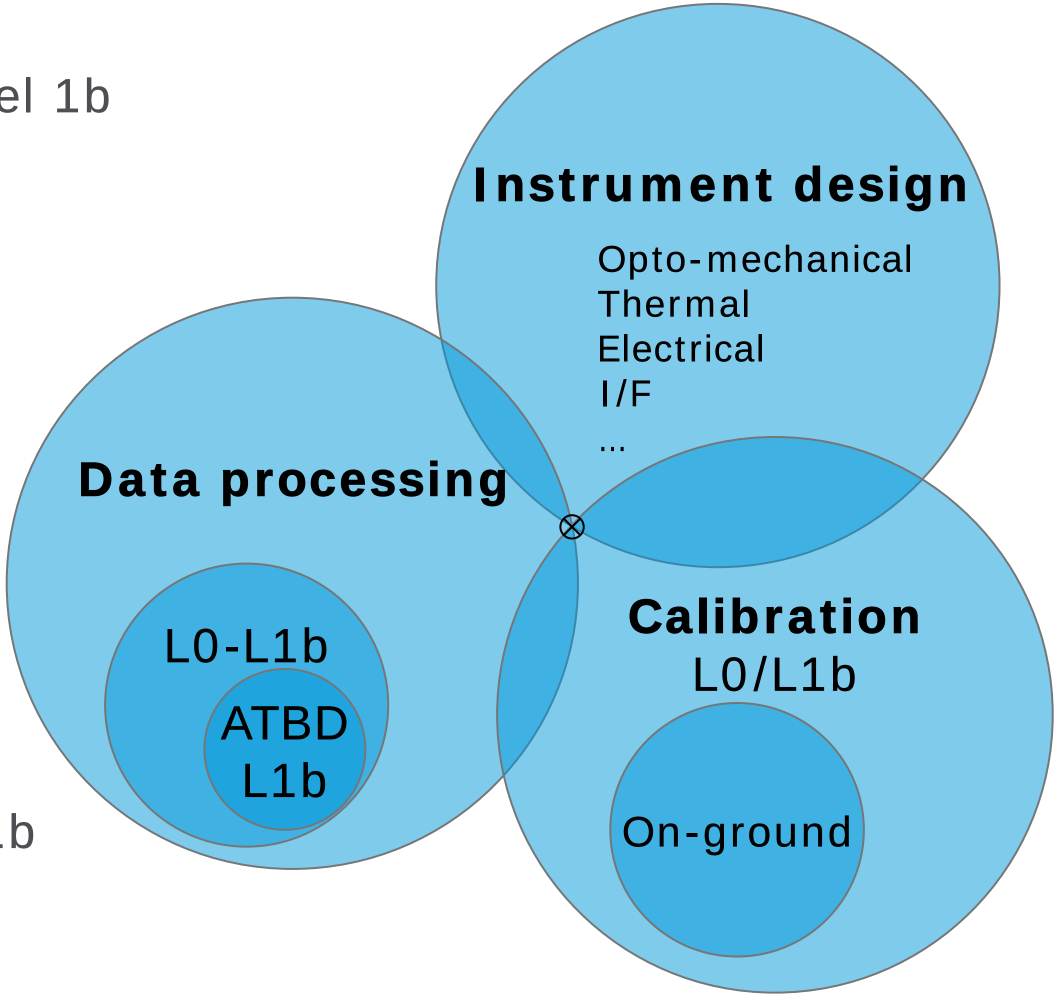
Earth’s directional reflectance (top of atmosphere) comparing to a solar reflector with known properties



Apportionment - delicate balance

space segment

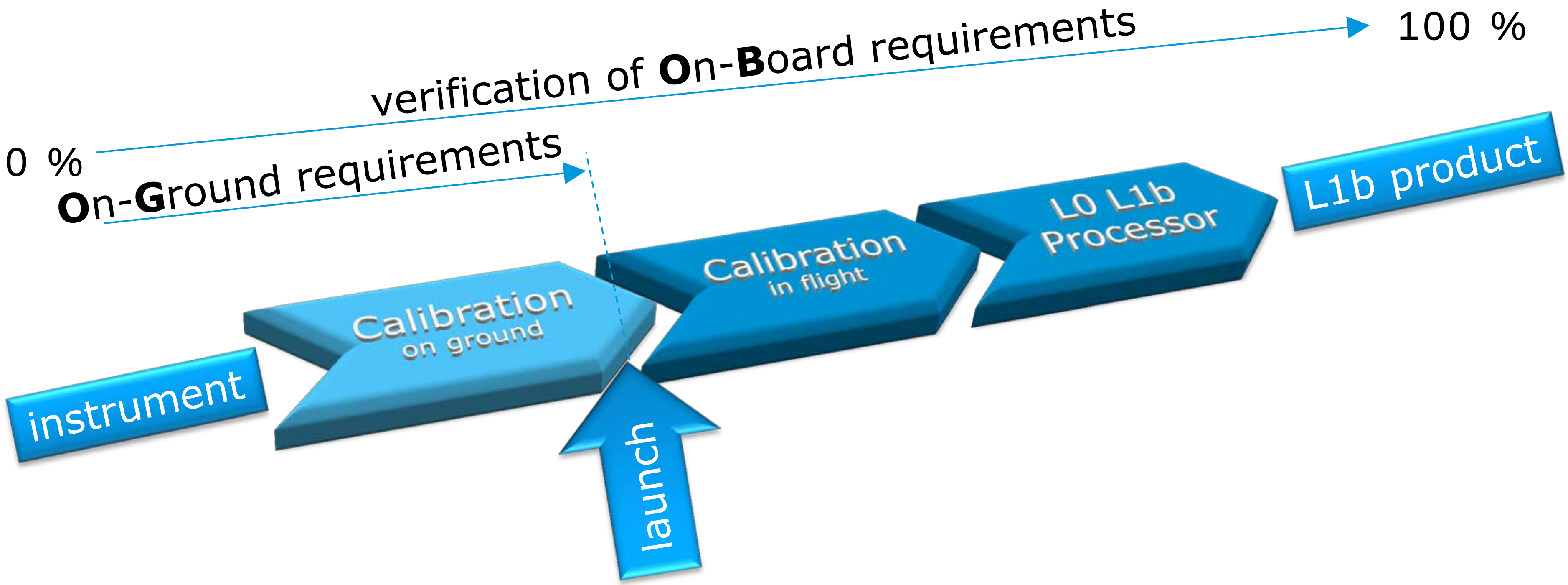
compliance with instrument Level 1b requirements at BOL and EOL



optimisation considering

- instrument performance at L1b
- accuracy budgets and
- programmatic aspects

On ground and in flight requirements



Typical instrument parameters

Spectral range	UV-VIS starting 200 – 300 nm NIR → different wavelength bands SWIR → different wavelength bands
Spectral resolution Spectral oversampling	~0.1 to 0.8 nm, wavelength band dependant ≥ 3.0 pixels
Spatial sampling	≤ a x b km^2
Number of spatial samples	Depending on instrument design achieving mission goals N/S (detector pixel) E/W (measurement samples)
Operational field of view	N/S E/W
Temporal resolution	Depending on mission
Envelope	Volume mm^3
Mass	kg
Power	W
Data rate (nominal operation/ special diagnostic operation)	Mbps

Calibration sources

EXTERNAL

Fraunhofer lines

atmospheric emission lines

Sun

moon

stars

OGSE's

vicarious

...

INTERNAL

WLS PRNU, radiometric stability, degradation

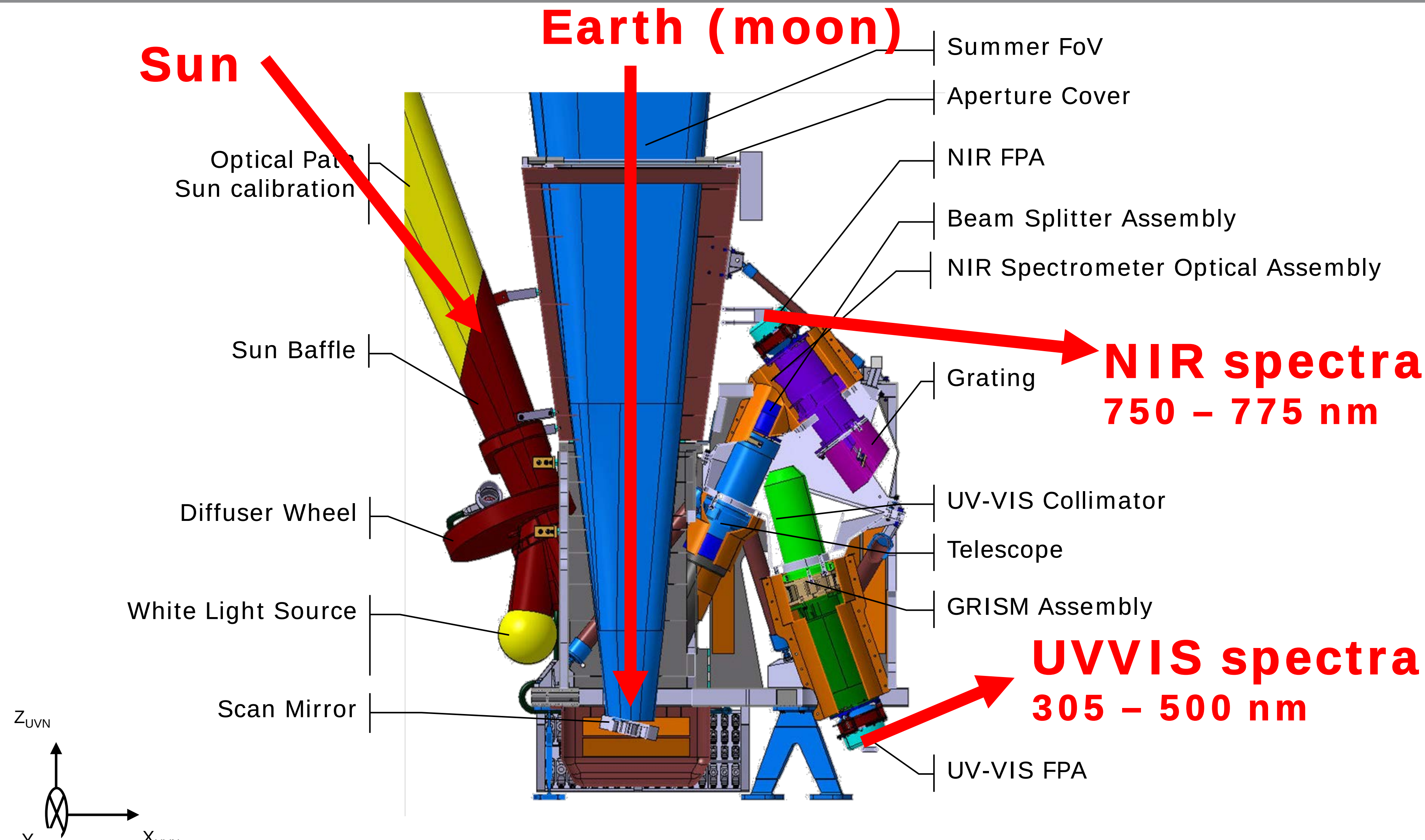
LED dead/bad pixel, pixel gain, pixel linearity

diffuser nominal/ redundant

spectral line source lamp/ laser

...

S4/UVN instrument



Courtesy of Airbus DS


SORRY THINGS GOT A LITTLE... STRANGE LAST NIGHT.
IT WAS MY FAULT. I GOT IN THE WAY.
NATHAN W PYLE
BUZZFEED COMICS

S4 / UVN calibration sources

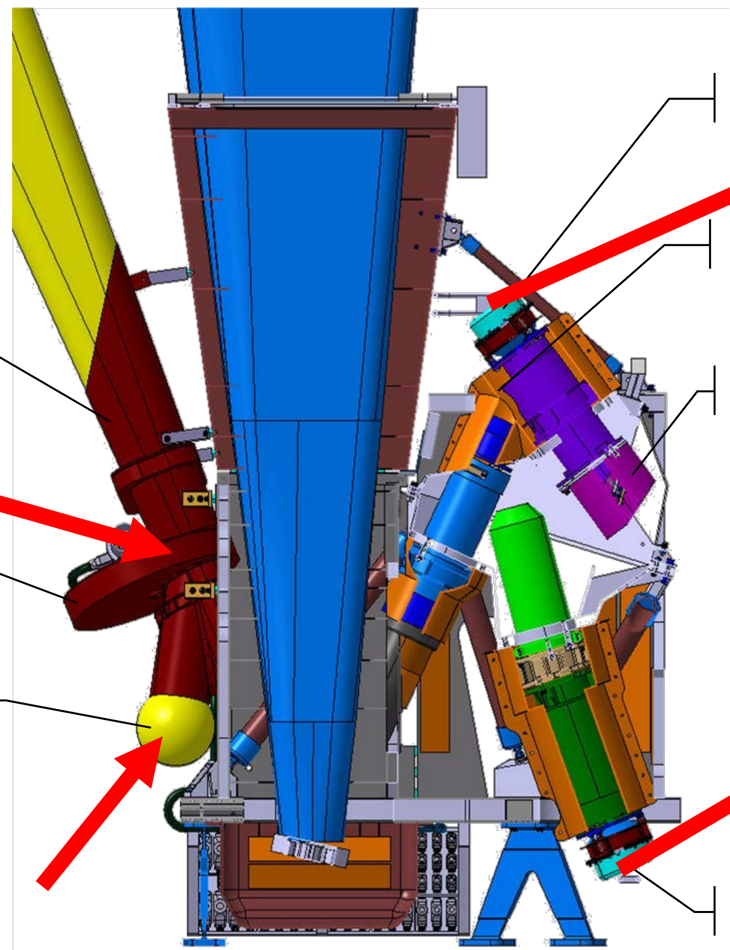
external
Fraunhofer lines
Atmospheric lines
Sun / Moon
stars
OGSE's

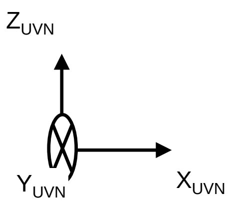
2 diffusers
daily
monthly

WLS
PRNU
radiometric stability
degradation

LED (red)
dead / bad pixel
pixel gain
pixel linearity

LED (blue)





Courtesy of Airbus DS

Characterisation / calibration

L0 performance verification / characterisation

Characterisation measurements/ parameters are to be understood as measurements/ parameters that **verify the instrument performance at level 0**, that is before applying any level 0 to level 1b data processing corrections.

Calibration (→ L1b)

Calibration measurements/ parameters are to be understood as measurements/parameters that are used to calculate and provide **calibration key data (CKD)** that are used in the level 0 to level 1b data processing algorithms and software.

Characterisation / calibration

L0 performance measurements / characterisation

1. Verification of requirements: compliant / non-compliant
2. Input for instrument model
3. Not of highest accuracy

Calibration measurements

1. Traceable to international SI-standards
2. Provide key data for the processing of raw data
3. Involve estimates of uncertainty

General consideration for on-ground testing (characterisation/ calibration)

1. Ambient vs thermal-vacuum characterisation/ calibration
2. Analysis of characterisation and calibration measurement data with level 0 to level 1b data processor
3. Level 0 to level 1b data processing software
4. Characterisation and calibration OGSE for (geostationary) Earth observing hyperspectral instruments
5. ...

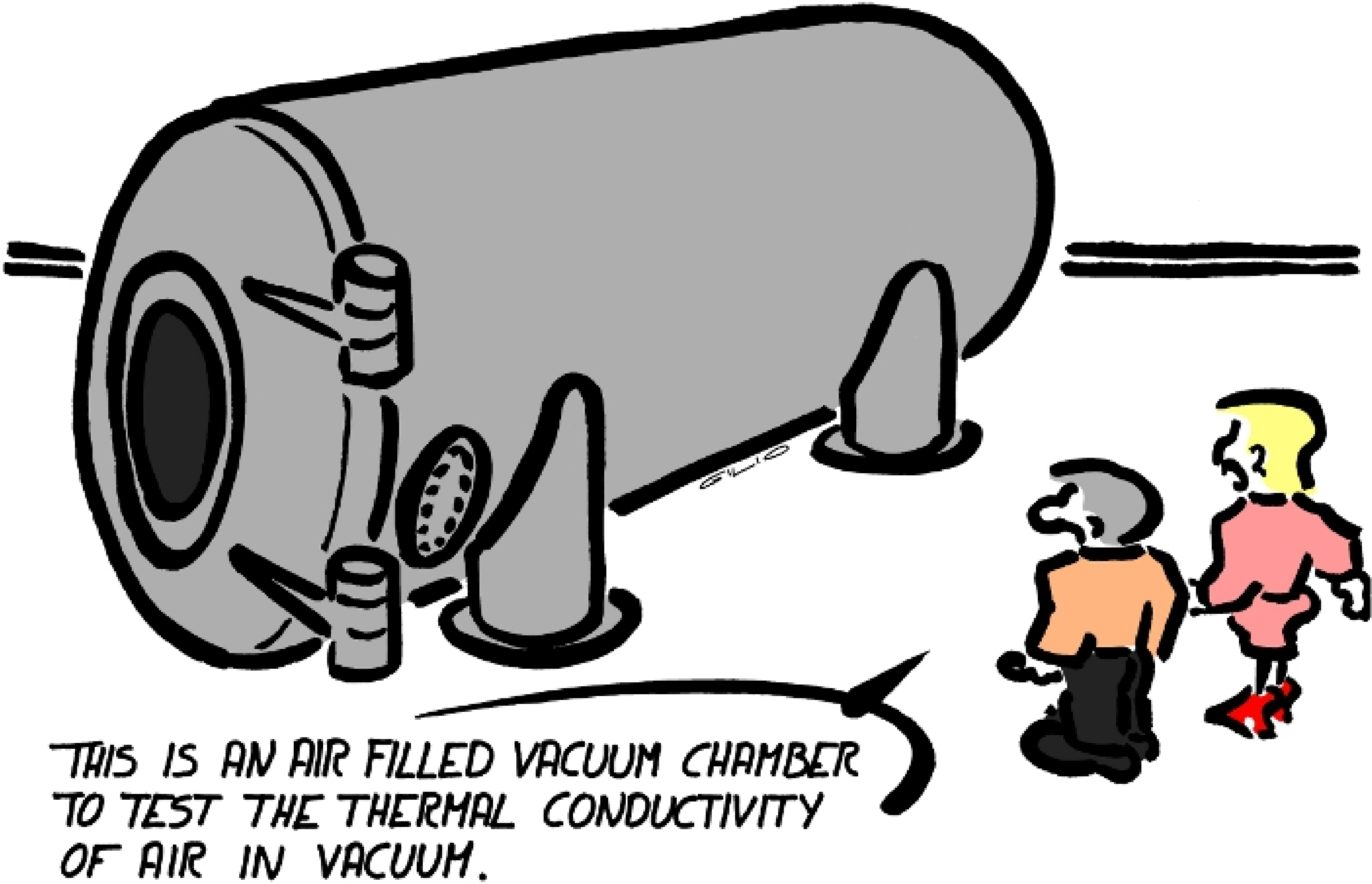
Campaign separation
L0 Performance Verification - Calibration

verification phase may necessitate changes to the instrument, OGSE, way the instrument is operated, etc., whereas the **calibration phase requires that no such changes are made**

→ otherwise traceability is lost on what has actually been calibrated and the to-be-launched-configuration differs in crucial aspects from the calibrated one

‘Test as you fly’ [with well-commissioned (=known) OGSE]

→ redoing parts of the calibration every time a change is made to the test configuration is very likely not going to be feasible



by Gilles Labruyère

L0 performance and calibration parameters

- → **radiometric calibration** Earth spectral radiance, Sun spectral irradiance and Earth reflectance (radiance/irradiance)
- → **spectral calibration**
  - wavelength scale for uniform and non-uniform ground scenes
  - Instrument Spectral Response Function (ISRF)
  - optical bench temperature (gradient) dependencies
- → spectral/ spatial **straylight**
- → **electronic** and **detector** calibration parameters
- → **geometric** parameters, co-registration, Image Navigation and Registration (INR), geolocation
- → **polarisation** correction, verification at level 0 that instrument is sufficiently insensitive to incident polarisation or polarisation calibration
- → at level 0: no **spectral features** in instrument response that interfere with atmospheric gas absorptions

Flow down to component level

1. **component**

   e.g. characterisation of diffuser, scan mirror

   (transmission, angle dependence, radiation, ...)

2. **sub-system**

   e.g. Focal Plane Assembly sub-system

   (full video chain: detector, FEE, FPA housing, ...)

3. **system**

   instrument models

   (EQM, PFM, FM)

Further flow down

- Optical-, Mechanical- and Electrical **Ground Support Equipment** requirements specification, along with their
  - accuracies,
  - commissioning needs and
  - commissioning accuracies, etc.
- requirements for a calibration facility.

Throughout the processes described above it is important to maintain a proper **system overview**, covering all relevant aspects, from **instrument performance** via **calibration** to **L0 to L1b data processing** and **operation**.

Absolute radiometric accuracy

accounting for all **error contributions** (straylight, polarisation, smear,...) at level 1b (after corrections) → 2% achievable

Calls for building-up an **error budget** accounting for contributions from:

- instrument design
- instrument on-ground & in-flight L0 performance verification and calibration
- signal processing L0 to L1b

similar requirements exist for on-ground measurements

- instrument response in Sun calibration
- instrument response in Earth observation
- instrument response in Earth reflectance

Radiometric calibration parameters

1. absolute Earth spectral **radiance**
2. absolute Sun spectral **irradiance**
3. **Earth** viewing **angle dependency**

   North-South on detectors and scan mirror (OMI and OMPS have no scan mirror)
4. **Sun** viewing **angle dependency**
5. absolute Earth **reflectance**: Earth radiance/ solar irradiance, using dedicated sources optimised for this parameter

In orbit, relative radiometric **degradation** monitoring and quantification primarily with **Sun irradiance** measurements, but also with **WLS** and **LED,** Earth **radiance** and **moon** measurements.

Radiometric measurements

	OGSE	Radiance	Irradiance
1	FEL	1R	1I
2	SBS	2R	2I
3	Integrating Sphere	3R	3I

Using different radiometric sources is absolutely essential to obtain required radiometric accuracy and to quantify measurement uncertainties.

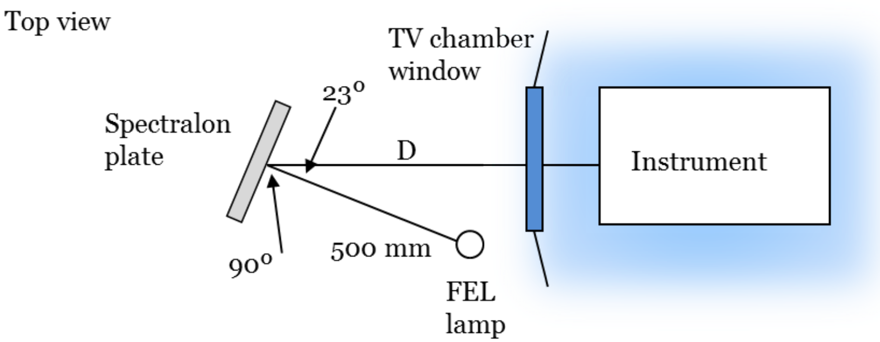
Measurement sequence include:

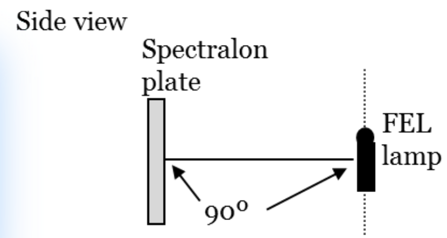
- Absolute radiance/ irradiance/ reflectance
- Irradiance goniometry
- Radiance angular dependency

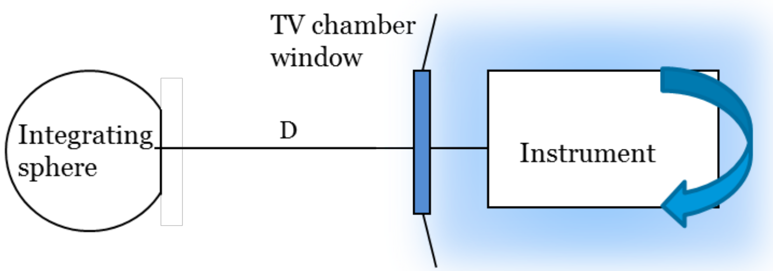
Product	Msm	Comment
Refl	2I/2R	Best (calibration keydata)
Refl_FEL	1I/1R	Analysis result from measurement expected to be less good
Abs_Rad	1R	Calibration keydata (expected to be the most accurate key parameter to be used for L0 to L1b processing)
Abs_Irrad	Abs_Rad x Refl	Best (expected to be the most accurate key parameter to be used for L0 to L1b processing)
Abs_Irrad_FEL	1I	Analysis result from measurement expected to be less good
Ang_dept _sphere	3R	Radiance angular dependence
Refl_sphere	3I/3R	Instrument BSDF
Abs_Rad´	3R	Radiance angular dependency & calibration keydata (to be used in L0 to 1 processing in case more accurate than Abs_Rad)
Abs_Irrad’	Abs_Rad’ x Refl	Calibration keydata (to be used in L0 to 1 processing in case more accurate than Abs_Irrad)

Absolute radiometric radiance calibration - on ground

Absolute radiometric radiance calibration measurements using calibrated sources (FEL lamp, integrating sphere) and **radiance angle dependency calibration** measurements under flight-representative thermal-vacuum conditions

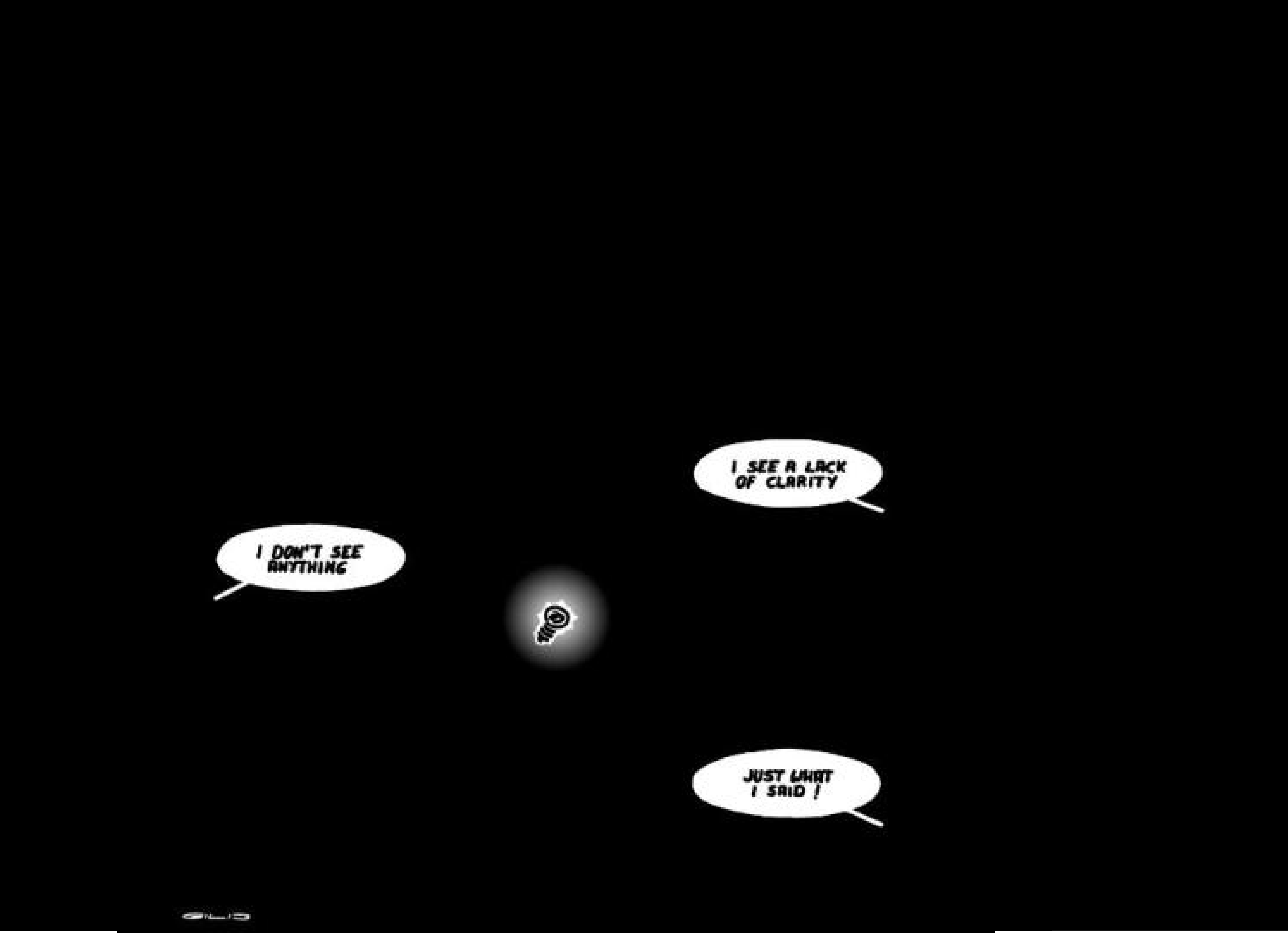






FEL lamp as part of OGSE

OMI calibration at TNO



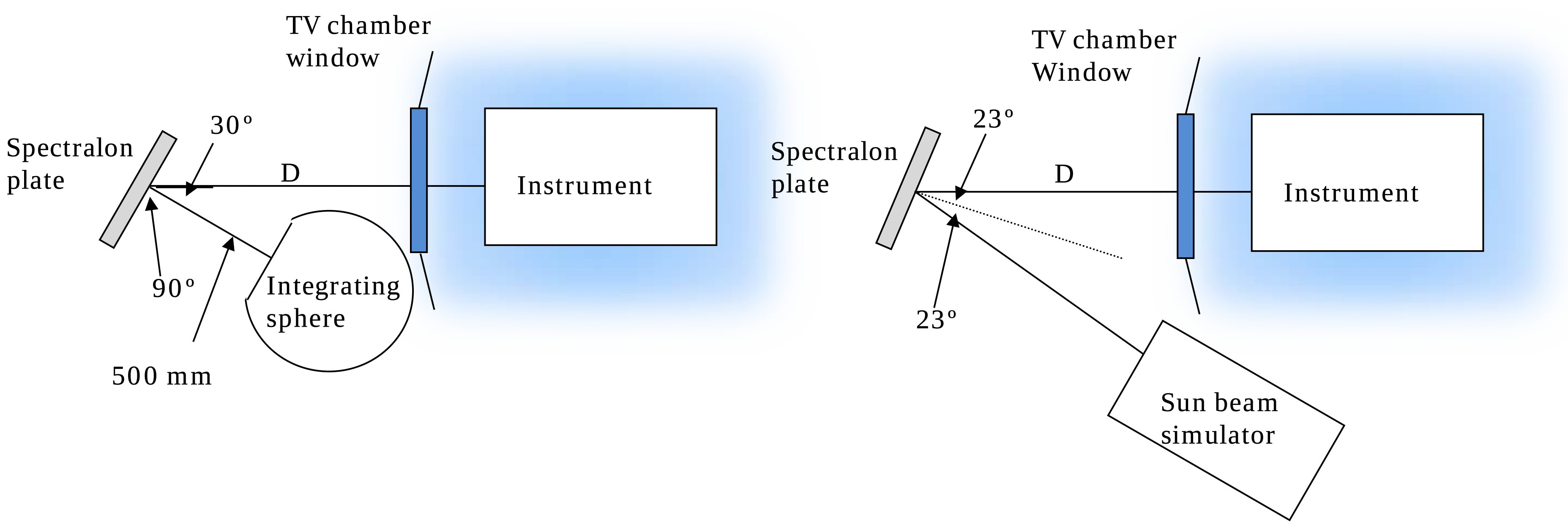
by Gilles Labruyère

Diffuser as part of OGSE

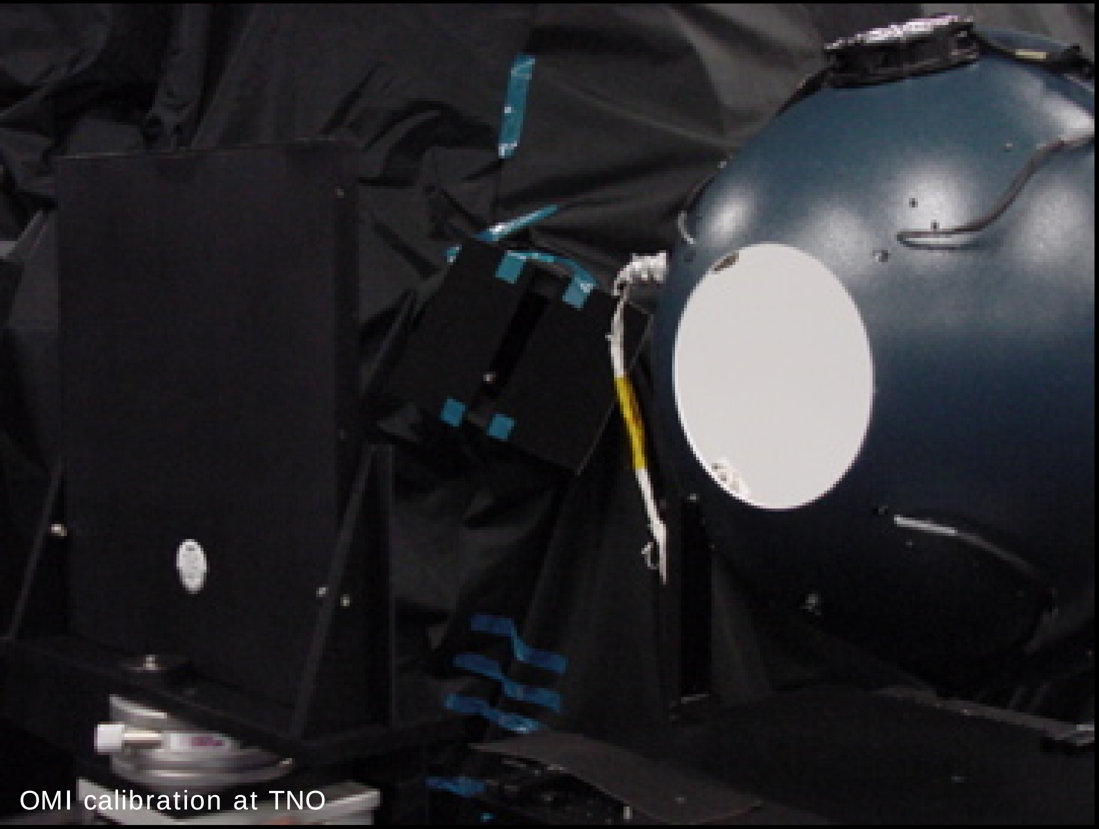
OMI calibration at TNO

Absolute radiometric radiance calibration - on ground

Absolute radiometric radiance calibration measurements using calibrated source **cross calibration** with respect to FEL lamp

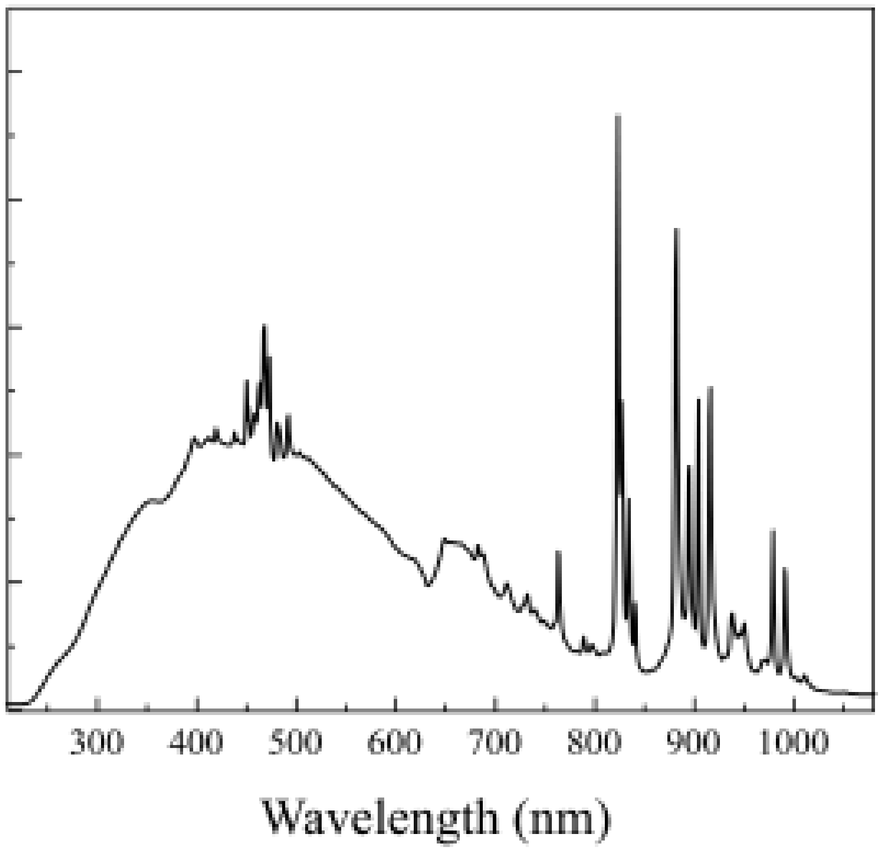


Integrating sphere as part of OGSE


OMI calibration at TNO

... and do not forget Theo(dolite)!

Xenon arc lamp



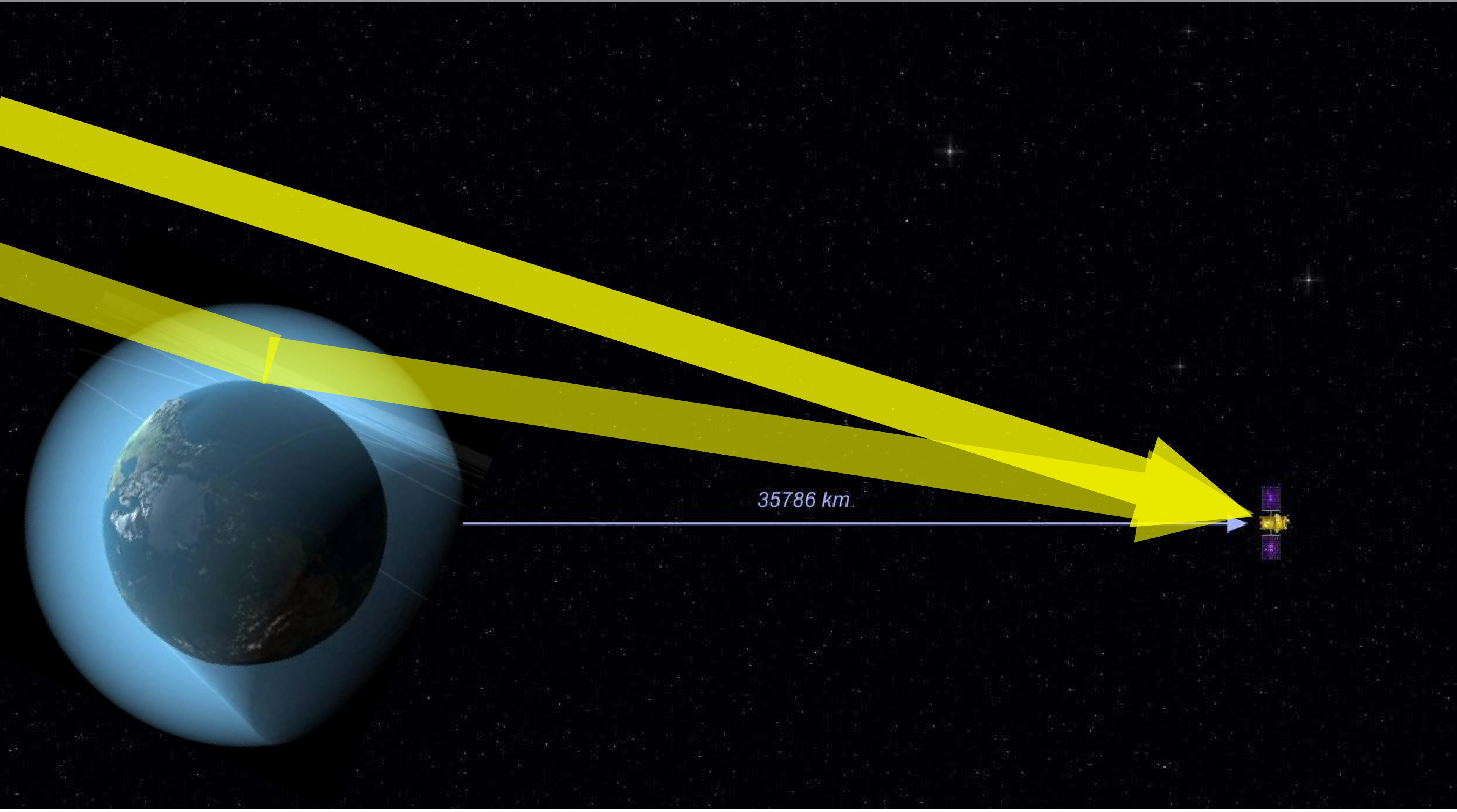
Spectral features originating from light source

Radiometric measurements

	OGSE	Radiance	Irradiance
1	FEL	1R	1I
2	SBS	2R	2I
3	Integrating Sphere	3R	3I

Product	Msm	Comment
Refl	2I/2R	**Best** (calibration keydata)
Refl_FEL	1I/1R	Analysis result from measurement expected to be less good
Abs_Rad	1R	Calibration keydata (expected to be the most accurate key parameter to be used for L0 to L1b processing)
Abs_Irrad	Abs_Rad x Refl	**Best** (expected to be the most accurate key parameter to be used for L0 to L1b processing)
Abs_Irrad_FEL	1I	Analysis result from measurement expected to be less good
Ang_dept _sphere	3R	Radiance angular dependence
Refl_sphere	3I/3R	Instrument BSDF
Abs_Rad´	3R	Radiance angular dependency & calibration keydata (to be used in L0 to 1 processing in case more accurate than Abs_Rad)
Abs_Irrad'	Abs_Rad' x Refl	Calibration keydata (to be used in L0 to 1 processing in case more accurate than Abs_Irrad)

Straylight - Reflection of Sun light on Earth surface and/or limb measurements



Straylight

It is impossible to meet the required accuracy for straylight (radiometric accuracy) at L1b by improving straylight performance at L0 alone, i.e. on-ground calibration of straylight is essential.

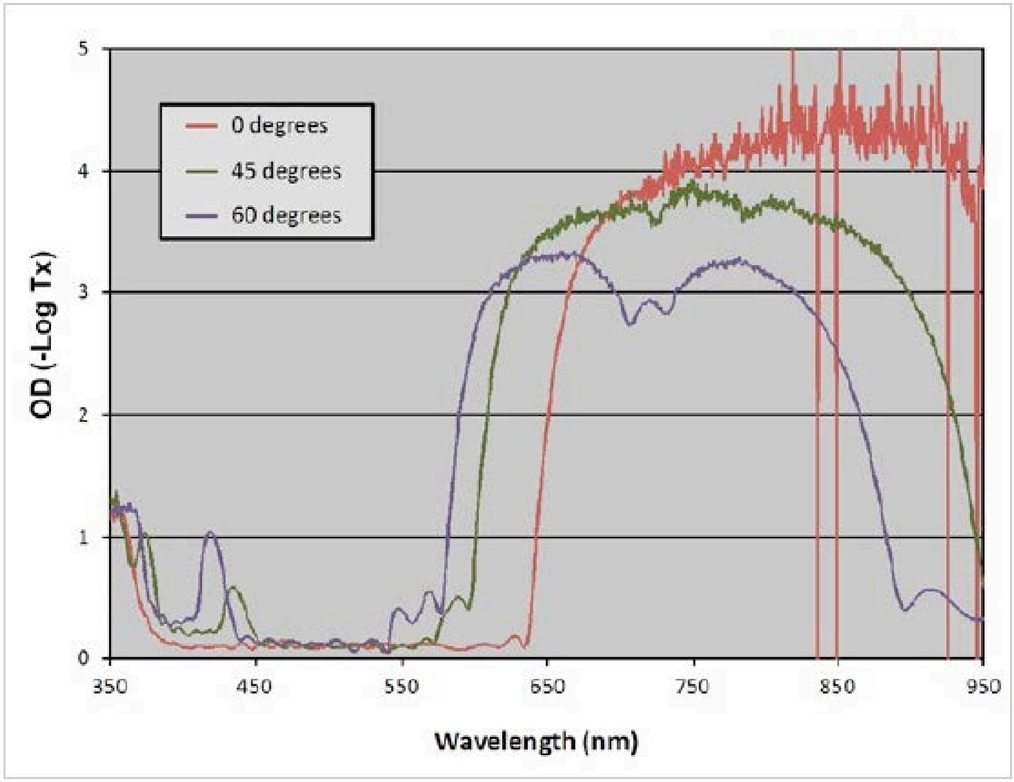
- L0 straylight verification incl. **OOF** straylight, **OOB** straylight, L0 straylight req. verification
- L1b straylight calibration incl. **uniform in-field straylight**, **ghosts**

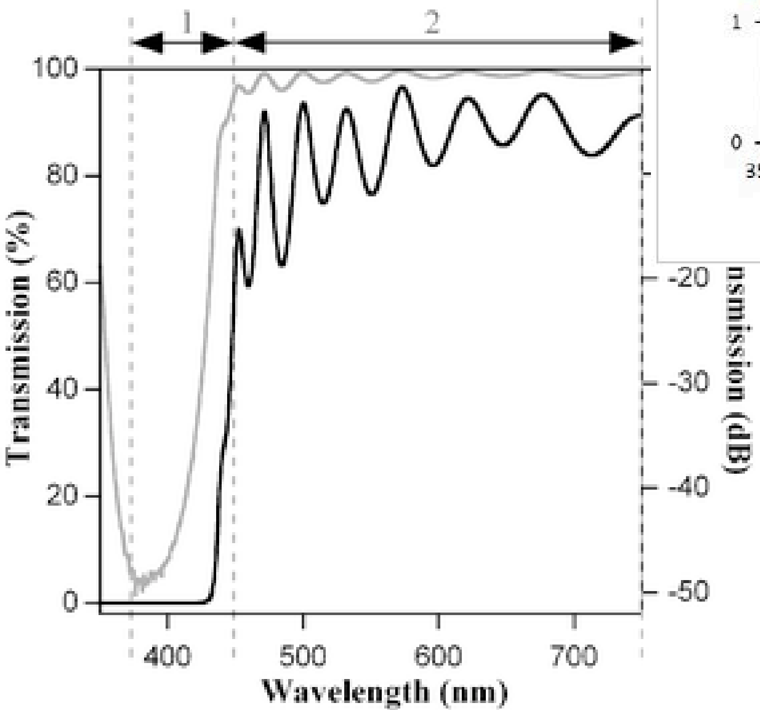
➔ inputs algorithms and calibration key parameters come **solely from on-ground calibration measurements.**

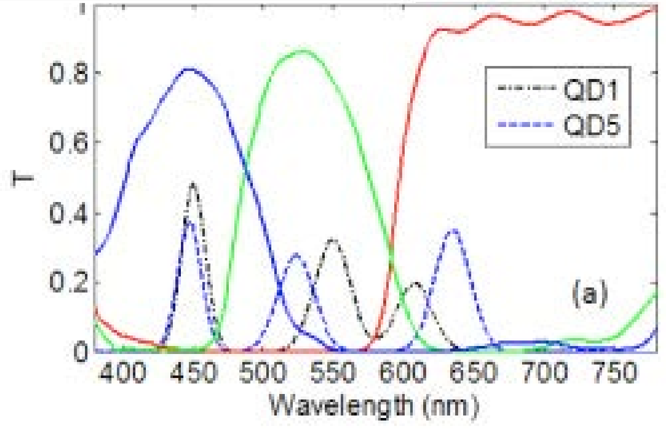
➔ goal measurements: build a 4x4 straylight correction matrix for correction of in flight observations

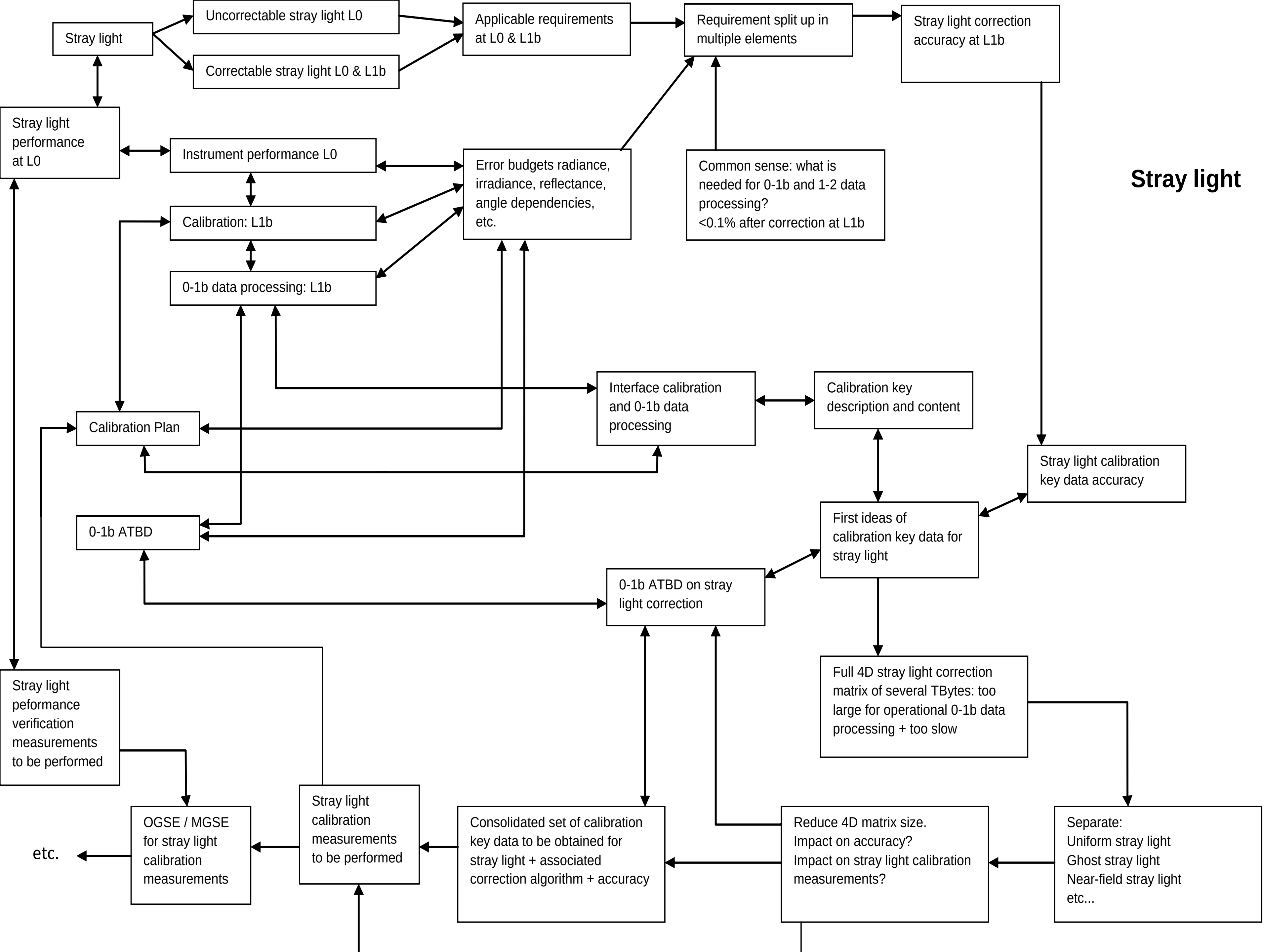
#	Straylight measurement	OGSE	Objectives
1	straylight ISRF-type measurements: full slit and ¼ of the slit	straylight monochromatic "ISRF-type" OGSE	measure the wings of the straylight kernels
2	straylight monochromatic point source ("laser-type") measurements	same as above except that the object target is a pinhole instead of a slit	determination of core of the straylight kernel
3	straylight broadband point source OGSE	Broadband (with filters to limit bandwidths) illuminates a few pixels in the spatial direction.	2D verification of the limited variation of the straylight kernels along the spatial range of the CCD
4	straylight broadband full slit	monochromatic "ISRF-type" OGSE Combined with broadband filters	same as 3 with more straylight (far field)

Filters, dichroic, coatings, diffusers etc








Stray light
Stray light
Uncorrectable stray light L0
Correctable stray light L0 & L1b
Applicable requirements at L0 & L1b
Requirement split up in multiple elements
Stray light correction accuracy at L1b
Stray light performance at L0
Instrument performance L0
Error budgets radiance, irradiance, reflectance, angle dependencies, etc.
Common sense: what is needed for 0-1b and 1-2 data processing? <0.1% after correction at L1b
Calibration: L1b
0-1b data processing: L1b
Interface calibration and 0-1b data processing
Calibration key description and content
Calibration Plan
Stray light calibration key data accuracy
0-1b ATBD
First ideas of calibration key data for stray light
0-1b ATBD on stray light correction
Full 4D stray light correction matrix of several TBytes: too large for operational 0-1b data processing + too slow
Stray light peformance verification measurements to be performed
OGSE / MGSE for stray light calibration measurements
Stray light calibration measurements to be performed
Consolidated set of calibration key data to be obtained for stray light + associated correction algorithm + accuracy
Reduce 4D matrix size. Impact on accuracy? Impact on stray light calibration measurements?
Separate: Uniform stray light Ghost stray light Near-field stray light etc...
etc.

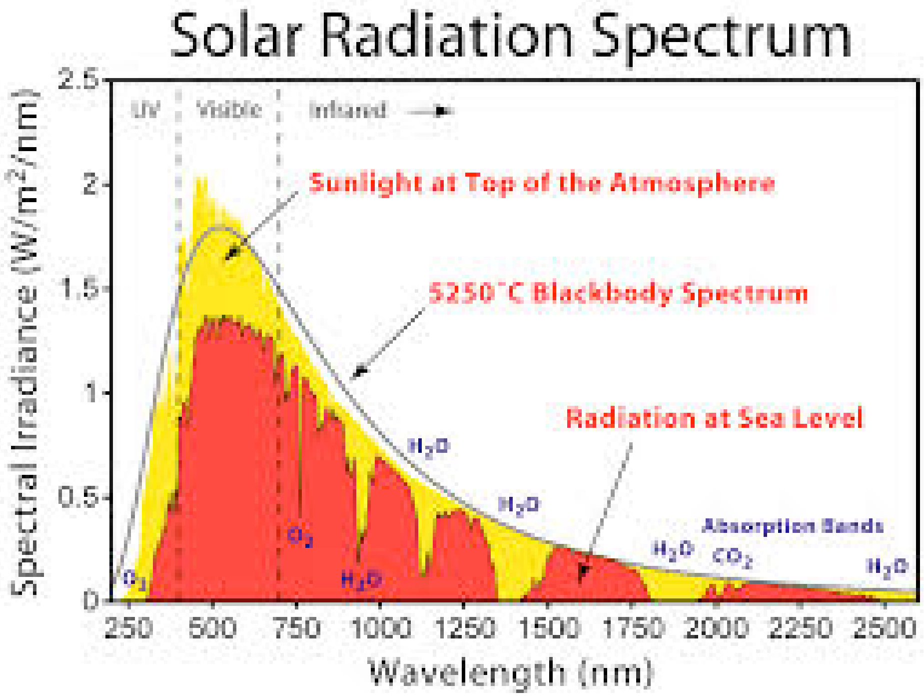
Spectral

ISRF: Measurement performed with a tuneable laser with sub pixel step size. Measurements are done for all N/S angles simultaneously on each spectral pixel of UV/VIS to NIR. The step in the spectral direction being 1/10th of pixel.

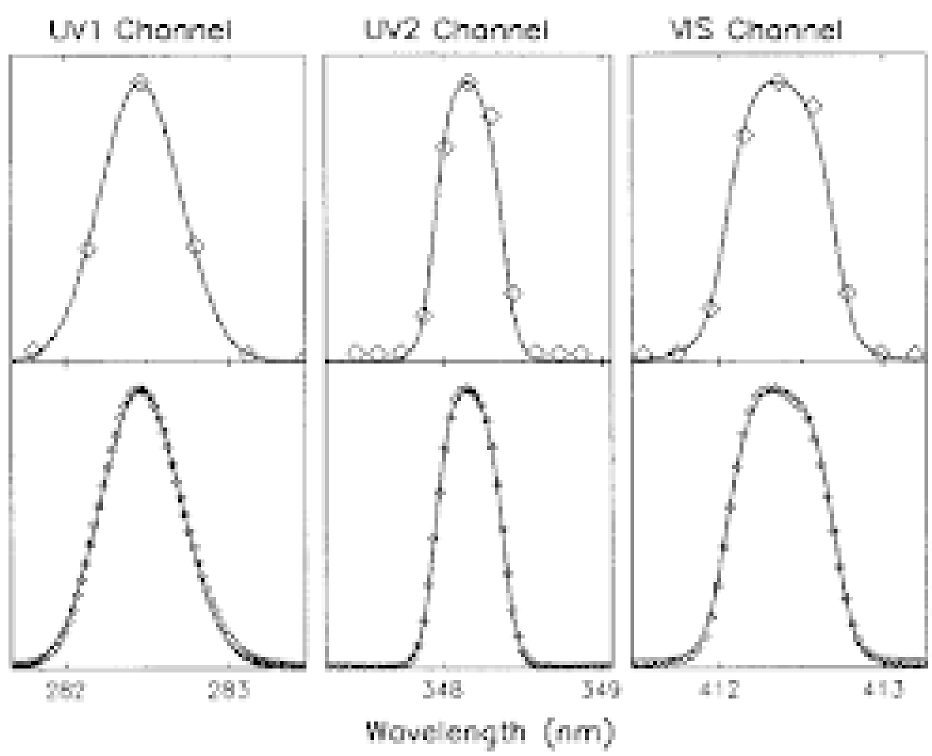
➔ *Choice of the OGSE is fundamental since selection of the 'wrong' OGSE can lead to an increase by factor 2-4.*

Spectral calibration: with PtCrNeAr hollow cathode lamp performed with a fully illuminated slit. Fraunhofer lines, gas cell spectra, tuneable lasers…

Spectral - slitfunction



Spectral line source vs. echelle grating



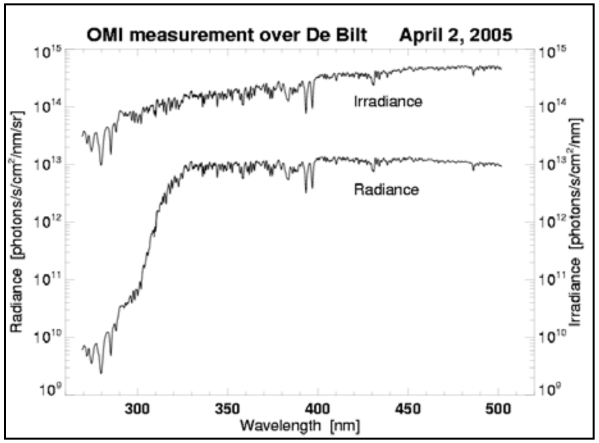
OMI calibration Dobber et al. IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 44, NO. 5, MAY 2006.

Polarisation measurements

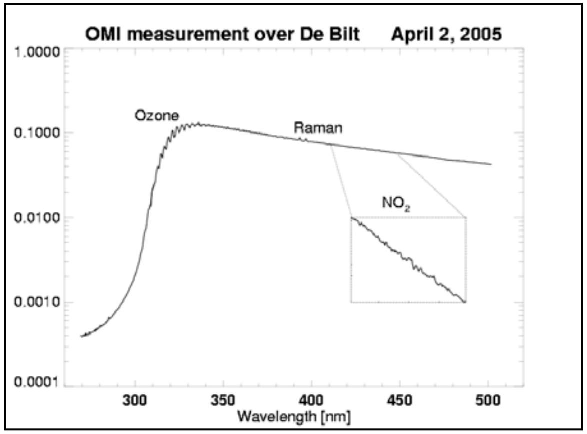
- C&C polarisation OGSE used with continuum light source
- Measurement performed by rotating the polarisation state at the exit of the polarisation optic
- Polarisation spectral features: polarisation OGSE used with monochromatic tuneable source (monitored down to 0,01% → very challenging)

S4 / UVN spectral features

Irradiance and radiance measurement

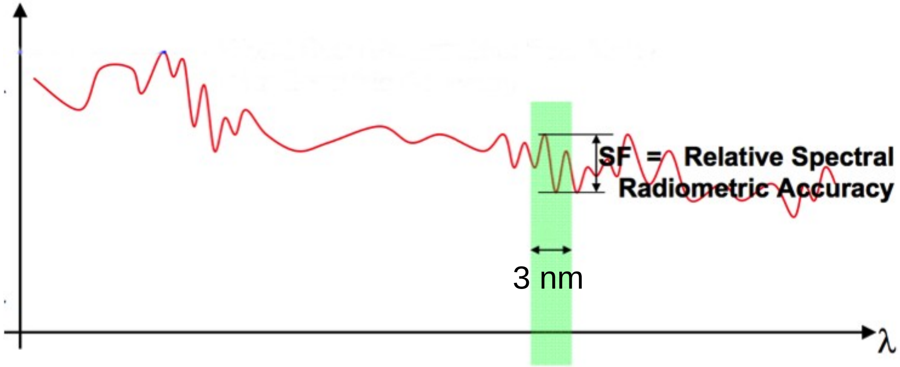


Derived reflectances



Note how small the NO_2 features are! We are talking about 0.01% signal strength of the total signal

Contributors to these **spectral features** are: polarisation scrambler, coatings, gratings, sun diffuser, straylight, gain change, ...



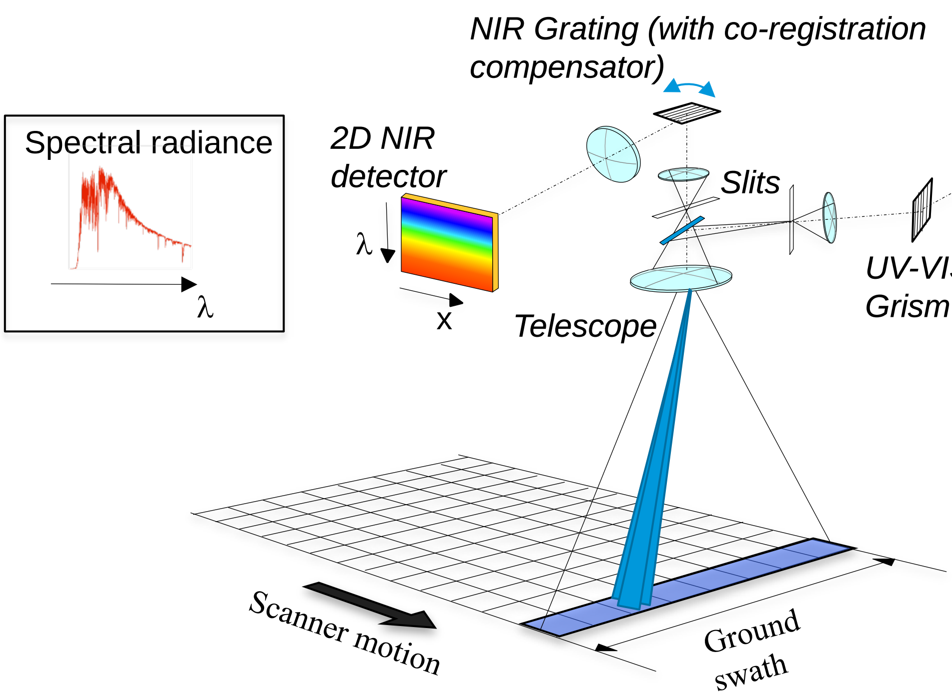
< 0.05 %!

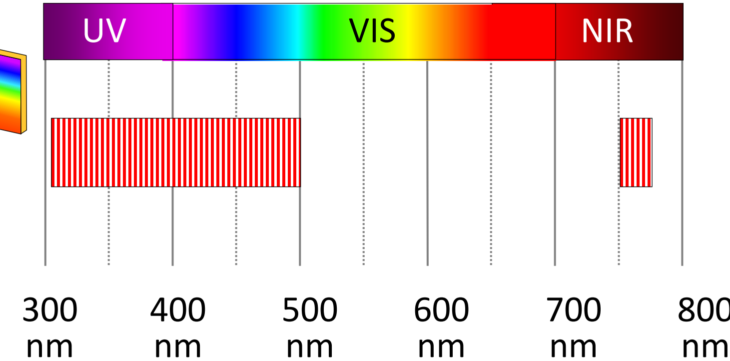
Co-registration and instrument alignment

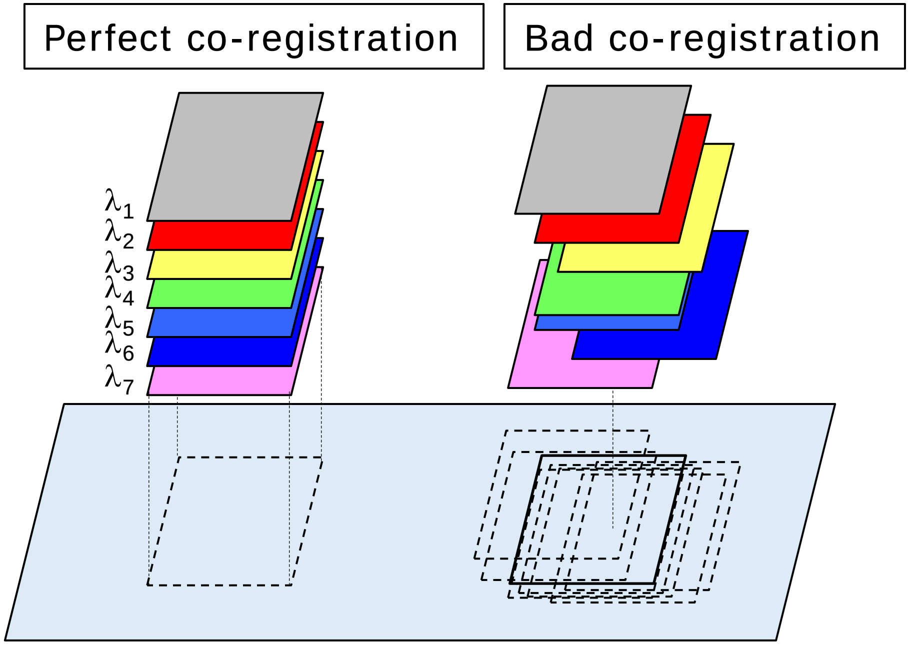
Objectives: co-registration compensator alignment & characterisation of the nominal **pointing direction of the scan mirror and ref. coordinate** system wrt alignment cubes

- Broadband star stimulus based: several point sources equally spaced across the N/S direction (same as PSF)
- Sub-pixel E/W scan
- Sub-pixel N/S scan

S4/UVN spatial co-registration requirements







Co-registration

- 0.1 SSD intra-band
- 0.2 SSD inter-band.

→ corresponds to a particularstability in spatial direction

Data flow for calibration and L0 to L1b prototype data processing

calibration key data required for L0 to L1b data processing and their accuracies determined by interface between

- calibration (and the **Calibration Plan**) and
- L0 to L1b data processing software **Algorithm Theoretical Baseline Document**

time-dependent **calibration keydata** (during nominal operation)

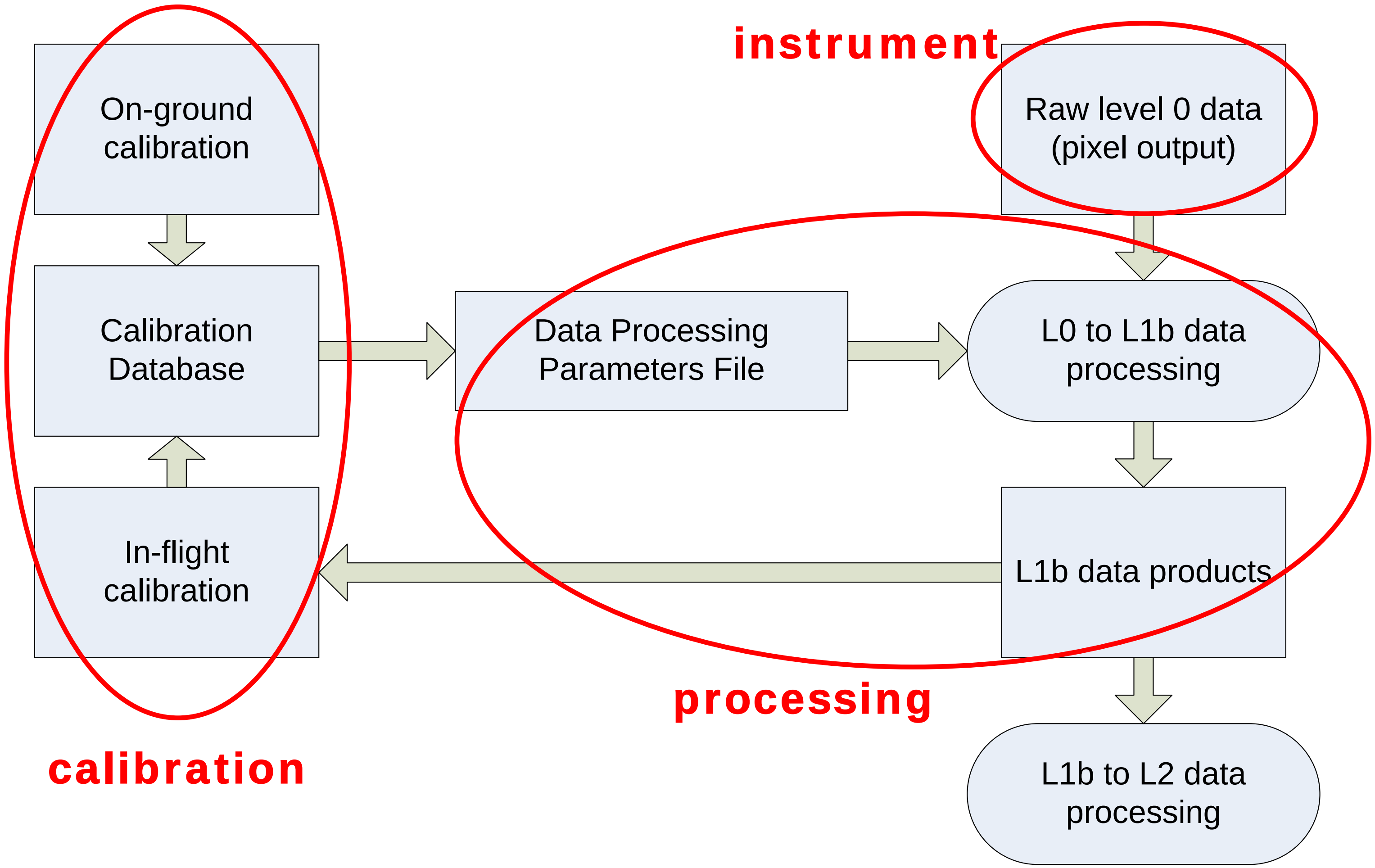
changes that are important within one day/ orbit, e.g. spectral changes or other changes originating from thermal changes and heterogeneous scenes

- Daily,
- Weekly,
- Monthly and
- Yearly resolution

Level 1b data products

1. Top Of Atmosphere **spectral radiance** in photons.s^{-1}.cm^{-2}.nm^{-1}.sr^{-1}
2. Extra-terrestrial **spectral** solar **irradiance** in photons.s^{-1}.cm^{-2}.nm^{-1}
3. Calibration data
   a. Incl. measurements e.g. WLS, dark, LED
4. Data Processing Parameters File
   a. (time-dependant) calibration keydata
   b. Instrument performance trend monitoring parameters (incl. long term)
   c. All other necessary additional parameters
5. Star measurement
6. ...

Data flow for calibration and L0 to L1b data processing



Measurement classes, ICIDs

Msm Class	ICID	Type of Measurement	ICIDVer
0 (Earth)	0	Earth Noon	0
			1
			2
0 (Earth)	1	Earth Morning / Evening	0
			1
			2
0 (Earth)	2	Earth Dawn / Dusk	0
			1
			2
			3
4 (Dark)	3	Background Noon	0
			1
			2
			3
4 (Dark)	4	Background Morning / Evening	0
4 (Dark)	5	Background Dawn / Dusk	0
			1
			2

Msm Class	ICID	Type of Measurement	ICIDVer
1 (Sun)	6	Sun Daily Diffuser	0
			1
			2
			3
4 (Dark)	7	Background Sun Daily Diffuser	0
3 (LED)	8	LED stability	0
4 (Dark)	9	Background LED stability	0
3 (WLS)	10	White Light Source stability	0
4 (Dark)	11	Background White Light Source stability	0
5 (Moon)	12	Moon	0
….			

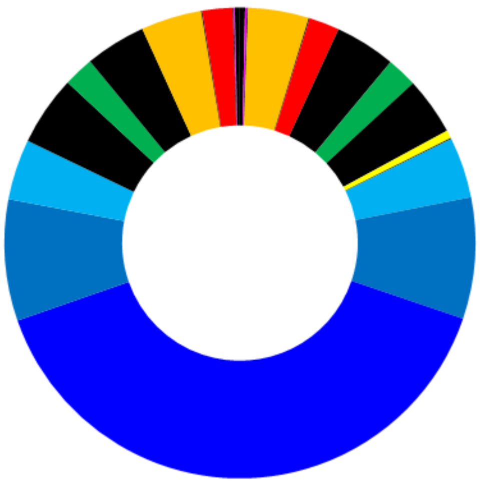
‘sun glint’ Carl Rottmann Greece

Commissioning phase in flight

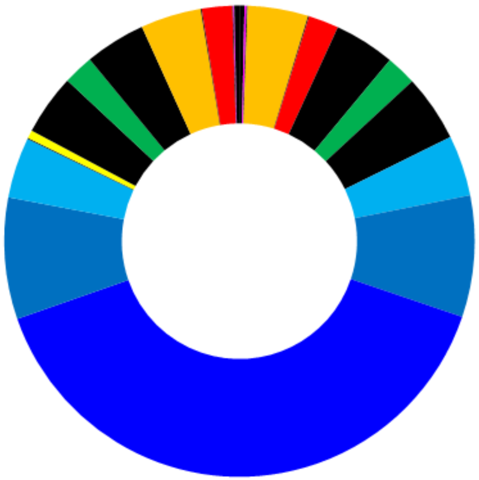
1. All **nominal** measurements, possibly at **different temperatures**
2. ICIDs with **different exposure times** (e.g. WLS to find optimum around expected/ analysed/ predicted ground tested exposure times
3. ICID for **read-out register**, **offset correction**
4. Extreme East/West **scan**, North/South viewing, faster scan, **step-and-stare**
5. Aperture covers open during **background** measurements
6. Coadding/ binning
7. Follow sun/ moon/ stars
8. 24h/ orbit dark measurements
9. ...

Operational sequence

Daily (winter) timeline



Daily (summer) timeline



Starting time [min]	Duration	Name	ICIDs
T0	5m	Idle	
T0+5	1m	LED stability	16,17
T0+6	1m	Idle	
T0+7	30m	Dark measurements for dark current, offset, RTS, bad and dead pixels	92,93,94
T0+37m	1m	Idle	
T0+38m	1h	Earth dusk/dawn background, normal scanning, Earth morning / evening background, normal scanning, Earth noon background, normal scanning	1,3,5
T0+1h38m	1h	Idle	
T0+2h38m	30m	Star observations, scanning	145,146
T0+3h08m	1h09m	Idle	
T0+4h17m	1h	Earth dusk/dawn, nominal scanning	0
T0+5h17m	2h	Earth morning/evening, nominal scanning	2
T0+7h17m	9h28m	Earth noon, nominal scanning	4
T0+16h45m	2h	Earth morning/evening, nominal scanning	2
T0+18h45m	1h	Earth dusk/dawn, nominal scanning	0
T0+19h45m	1m	Idle	
T0+19h46m	8m	Daily sun measurements at sunset (winter) with daily (regular) diffuser. Timing of illuminated sun measurements is critical and shall be checked. Background measurements prior to illuminated measurements.	6,7
T0+19h54m	57m	Idle	
T0+20h51m	30m	Star observations, scanning	145,146
T0+21h21m	1h	Idle	
T0+22h21m	30m	Dark measurements for dark current, offset, RTS, bad and dead pixels	92,93,94
T0+22h51m	1m	Idle	
T0+22h52m	1h	Earth dusk/dawn background, normal scanning, Earth morning / evening background, normal scanning, Earth noon background, normal scanning	1,3,5
T0+23h52m	1m	Idle	
T0+23h53m	2m	LED bad/dead pixels	10,11
T0+23h55m	5m	Idle	
T0+24h		Sequence of event finished	

Measurement statistics per orbit / day

Measurement	Percentage	Remarks
Earth radiance	65%	optimised ICIDs for light condition
Sun irradiance	1%	Sun background measurements counted as sun irradiance measurements. Regular diffuser exposure time: ~4 minutes
Dark / background calibration	12%	
LED calibration	<1%	LED on time: 90 seconds LED on switches: 2
Star observations	4%	
Idle	18%	
Diffuser mechanism movements	1 time	to diffuser position and back
Earth aperture cover movements	1 time	open and close

Cumulated status of life limited items per timeline

	Daily	Weekly	Monthly	Yearly
WLS on time (seconds)	0	120	120	720
WLS switches	0	3	3	4
LED on time (seconds)	90	120	420	420
LED switches	2	3	4	4
Diffuser mechanism movements	1	1	1	1
Earth aperture cover movements	1	1	1	1
Regular diffuser exposure (seconds)	240	240	0	0
Backup diffuser exposure (seconds)	0	0	240	240

Lessons learnt from instruments

On ground 'Test as you fly'

- i.e. thermal vacuum environment with flight representative conditions for pressure, temperatures for detectors and 'optical bench'

EQM prior to flight model

- calibrated in dry-run campaign, elimination of non-conformances

On ground and in flight

- several parameters can only be measured with sufficient accuracy on ground, e.g. polarisation, straylight and ISRF
- clear split between L0 performance verification and calibration

Instrument built as designed?

- L0 performance verification

Calibration

- retrieve calibration key parameters for L0 to L1b processing

Lessons learnt from predecessor instruments

In view of predecessor missions, these critical performance requirements are leading the complexity of the measurement / verifications, specifically:

- measurements are very **time** consuming due to the **spectral range** in the **UV**
- **polarisation** sensitivity (polarisation scrambling vs. calibration)
- on-ground **radiometric accuracy** & **budgets**
- measure **ISRF** with required accuracy, verify via both sun port and Earth port
- measure **straylight** with required accuracy
- irradiance **goniometry**: time consuming, also to obtain sufficient signal-to-noise

Post long term storage calibration

Why calibrating the instrument after storage?

Note: calibration shall not be confused with L0 performance verification

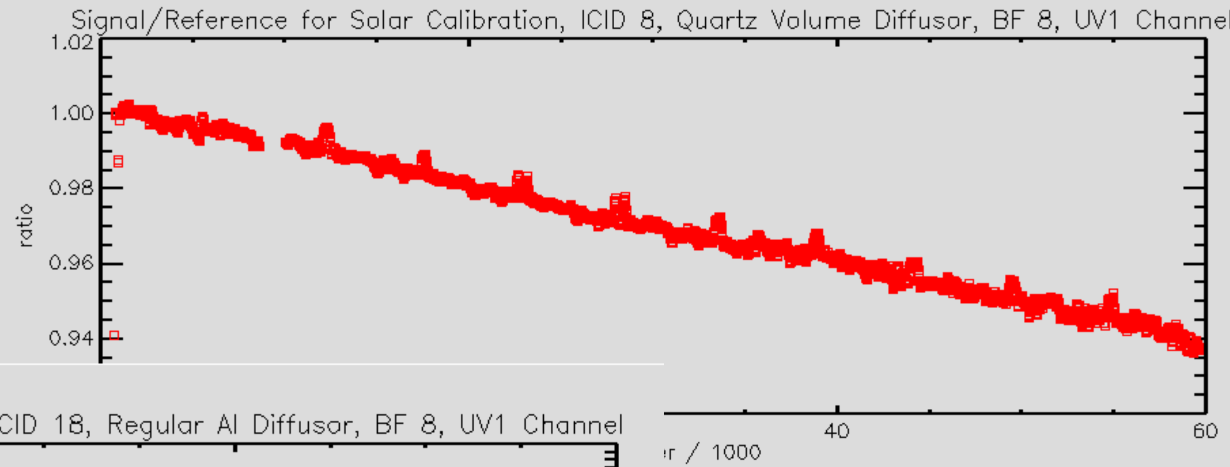
- these missions rely on an instrument **calibration transfer from ground to in orbit**

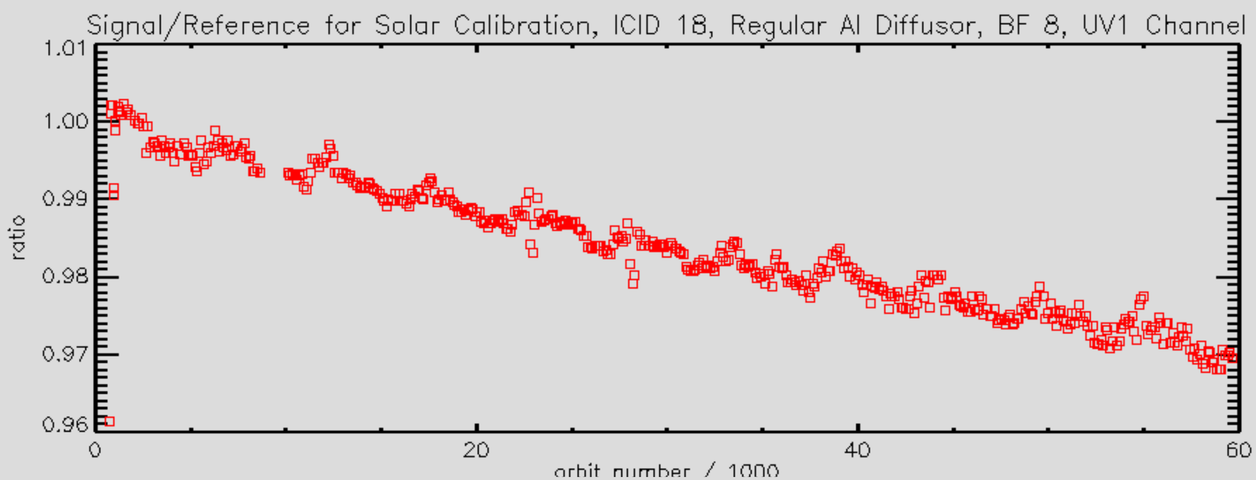
- L1b processing **requires accurate knowledge** of instrument **calibration key parameters** (e.g. spectral response function, straylight)

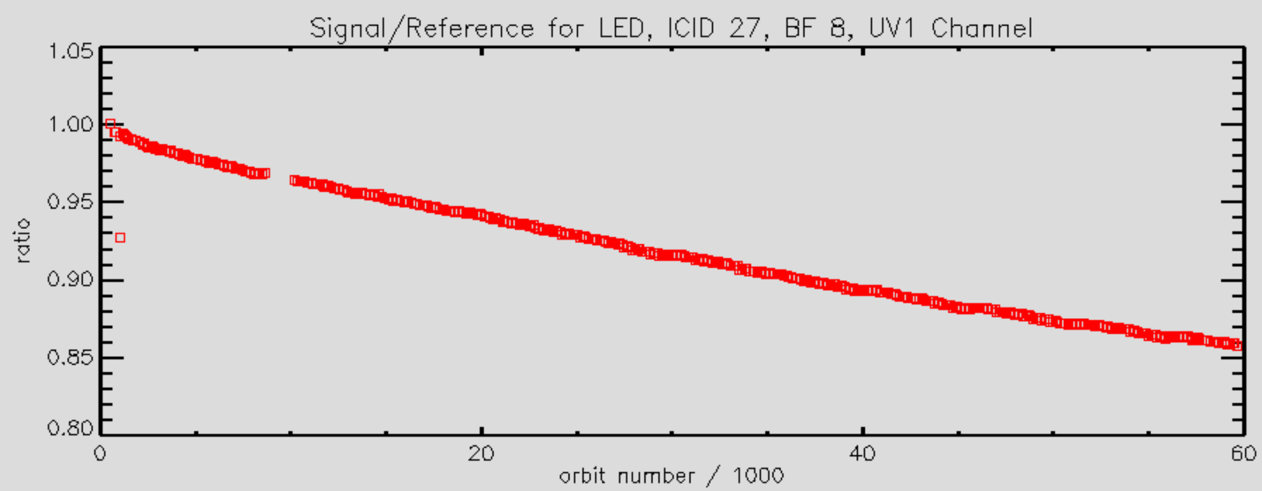
- therefore an accurate and representative **on-ground calibration** is mandatory

- instrument performance are subject to evolution during the long on-ground storage (e.g. GOME-2 FM2 experienced a **4% variation in radiometric calibration** during storage

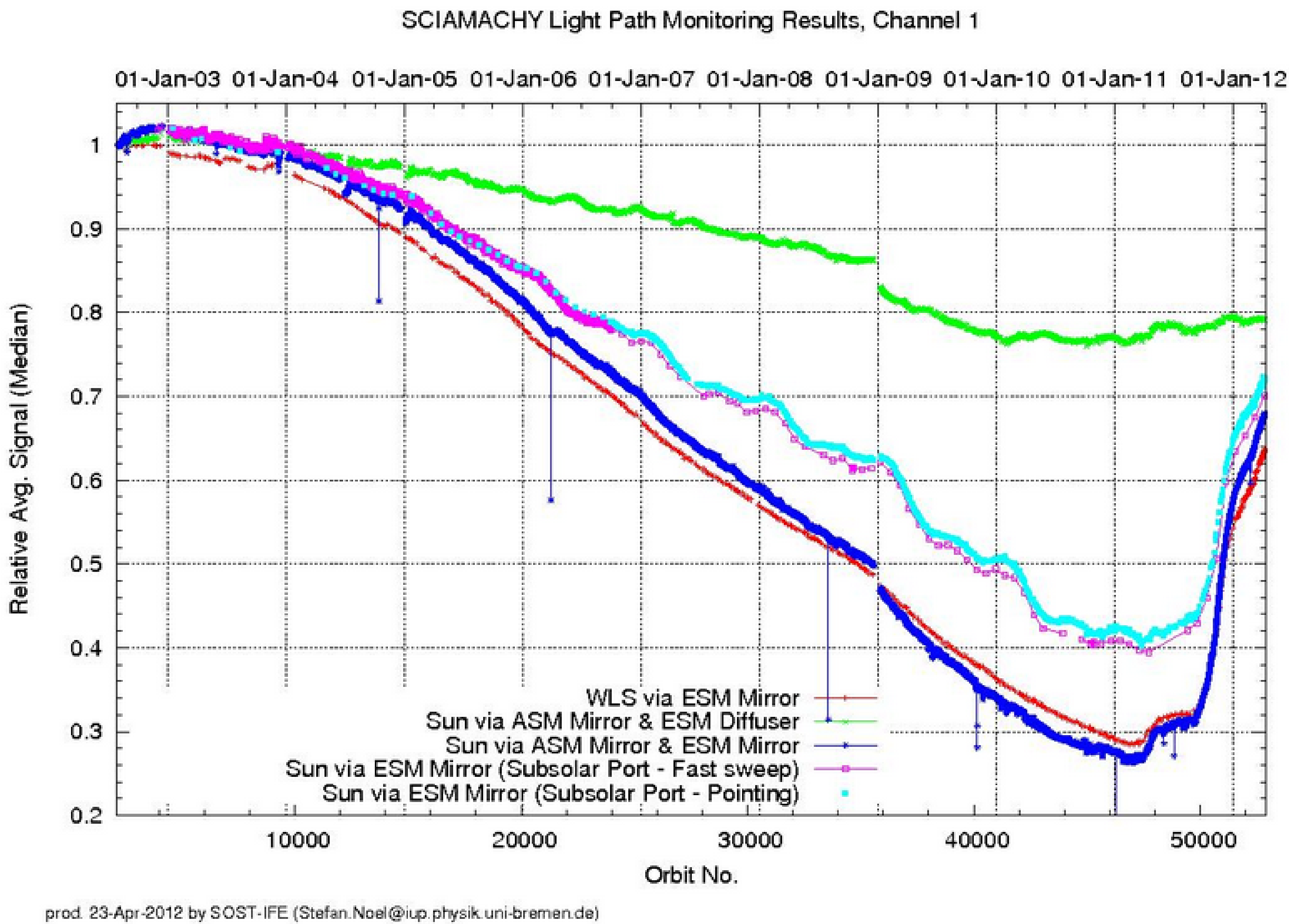
Internal







http://projects.knmi.nl/omi/research/calibration/instrument_status_v3/



SCIAMACHY Light Path Monitoring Results, Channel 1
01-Jan-03
01-Jan-04
01-Jan-05
01-Jan-06
01-Jan-07
01-Jan-08
01-Jan-09
01-Jan-10
01-Jan-11
01-Jan-12
Relative Avg. Signal (Median)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
10000
20000
30000
40000
50000
Orbit No.
WLS via ESM Mirror
Sun via ASM Mirror & ESM Diffuser
Sun via ASM Mirror & ESM Mirror
Sun via ESM Mirror (Subsolar Port - Fast sweep)
Sun via ESM Mirror (Subsolar Port - Pointing)
prod. 23-Apr-2012 by SOST-IFE (Stefan.Noel@iup.physik.uni-bremen.de)

Decontamination measures to prevent optical degradation (examples)

- **bake-out** of all hardware incl. after launch (additional heater power)
- protection optical components from e.g. **solar flux**
- **warm-up** possibilities independently for detectors/optical bench
- **protection solar diffusers**
    - no measurements several weeks after launch
    - no measurements after yaw flip
    - no measurements after thrusters' usage
- **purging** until launch
- avoidance **humidity**
- avoid **materials degrading** under space environment (e.g. relevant light fluxes, atomic oxygen, radiation, TV, molecular contamination)

Lessons learnt

It is possible to build and fly UV instruments with low degradation

→ low degradation improves long-term calibration accuracy

→ limiting solar measurements is an important component

Thermal control should be standard equipment

→ wavelength shifts cause many downstream problems

→ optics temperature should remain constant from laboratory to orbit

Lessons learnt

Of paramount importance is that at the start of a programme,

- **scientists**,
- **calibration specialists**,
- **instrument operators** and
- **system and software developers**

closely work together to identify the

- measurement types,
- the frequency of scheduling,
- the required corrections steps that are applied and
- data products

Conclusion

Attention for **balance** between **instrument design**, L0 **performance**, **calibration** (on ground and in flight), level 0 to 1b **data processing** and **operation** to deliver L1b data products within the required specification at End of Life.

OGSE and **on-board calibration hardware** have to be carefully selected.

Operation and **contamination prevention** from early start of programme.

Thermal control should be standard equipment

It is possible to build and fly UV instruments with low degradation!

Thank you for your attention!

Korean Peninsula at night, shown in a 2012 composite photograph from NASA