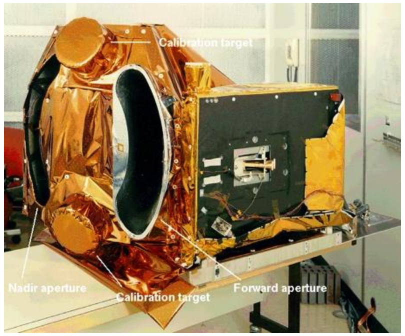
(A)ATSR and SLSTR VIS/SWIR Channels Calibration

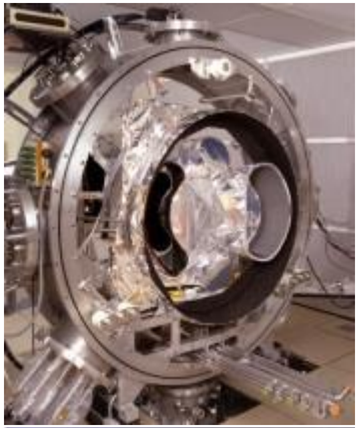
Dave Smith & Mireya Etxaluze

ATSR Series

1991-2000 ATSR-1



1995-2008 ATSR-2



2002-2012- AATSR

SLSTR Series

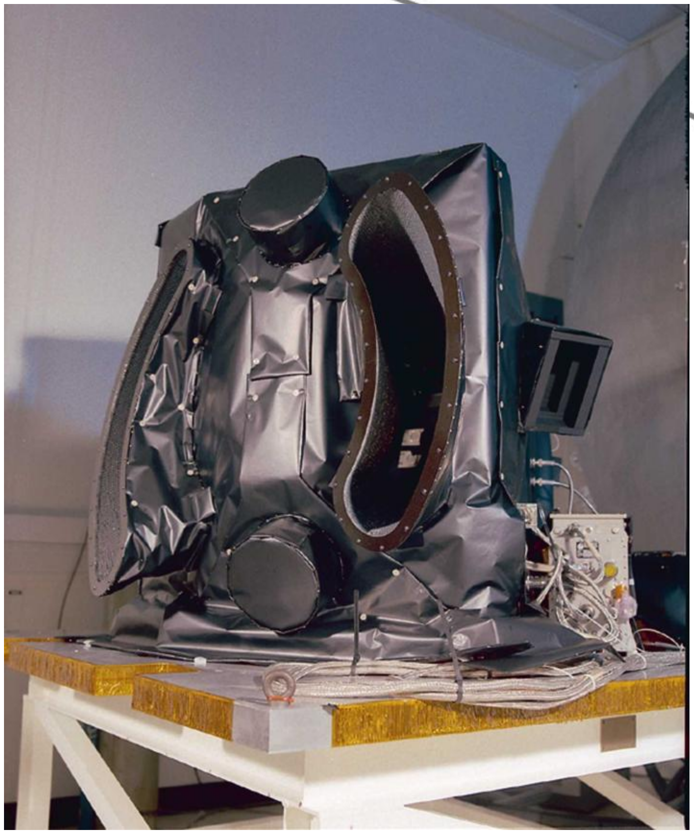
2016 – Sentinel 3A

Launched 16-Feb-2016 ☺

- 2018 – Sentinel 3B
- 2021 – Sentinel 3C
- 2023 – Sentinel-3D
- etc.

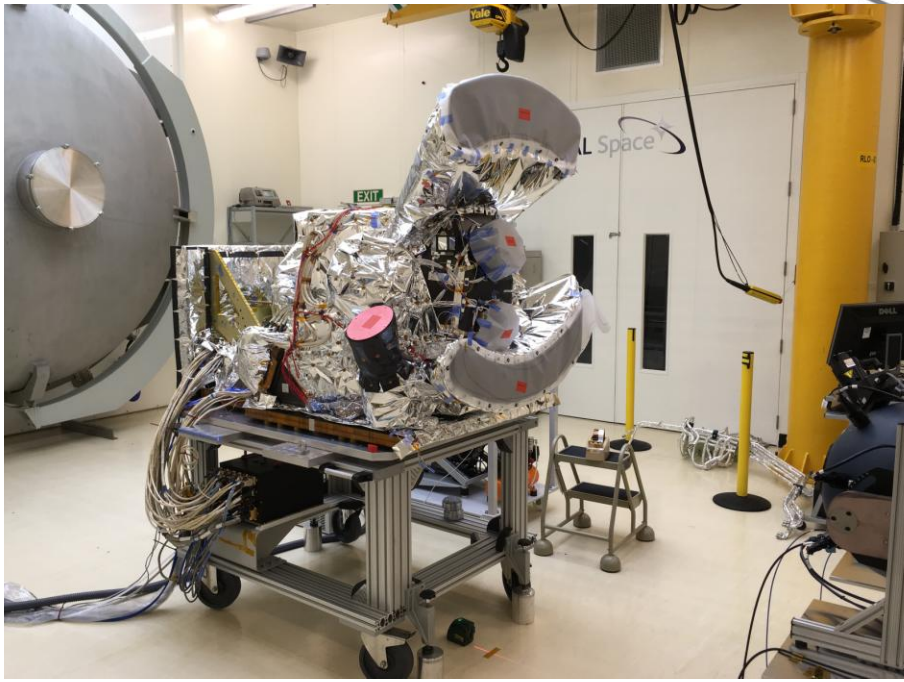
(A)ATSR instrument

Nadir swath	<22° (512km swath)
Dual view swath	22° (512km swath)
One telescope	Φ110 mm / 800mm focal length
Spectral bands	TIR : 3.74μm, 10.85μm, 12μm SWIR : 1.61μm VIS: 555nm, 659nm, 859nm (ATSR-2/AATSR Only)
Spatial Resolution	1km at nadir
Radiometric quality	NEΔT 30 mK (LWIR) – 50mK (MWIR) SNR 20 for VIS - SWIR
Radiometric accuracy	0.2K for IR channels 3% for Solar channels relative to Sun



SLSTR instrument

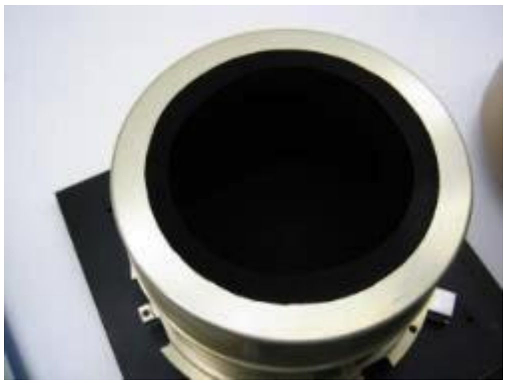
Nadir swath	>74° (1400km swath)
Dual view swath	49° (750 km)
Two telescopes	Φ110 mm / 800mm focal length
Spectral bands	TIR : 3.74μm, 10.85μm, 12μm SWIR : 1.38μm, 1.61μm, 2.25 μm VIS: 555nm, 659nm, 859nm
Spatial Resolution	1km at nadir for TIR, 0.5km for VIS/SWIR
Radiometric quality	NEΔT 30 mK (LWIR) – 50mK (MWIR) SNR 20 for VIS - SWIR
Radiometric accuracy	0.2K for IR channels 2% for Solar channels relative to Sun

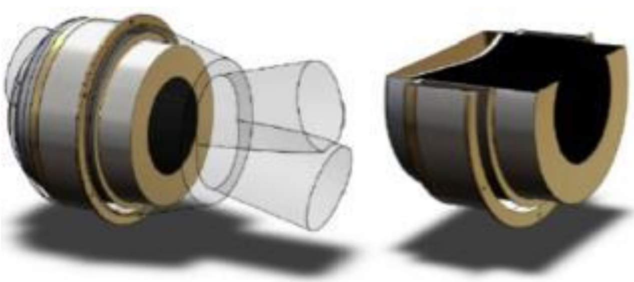


On-Board Calibration systems

Thermal InfraRed

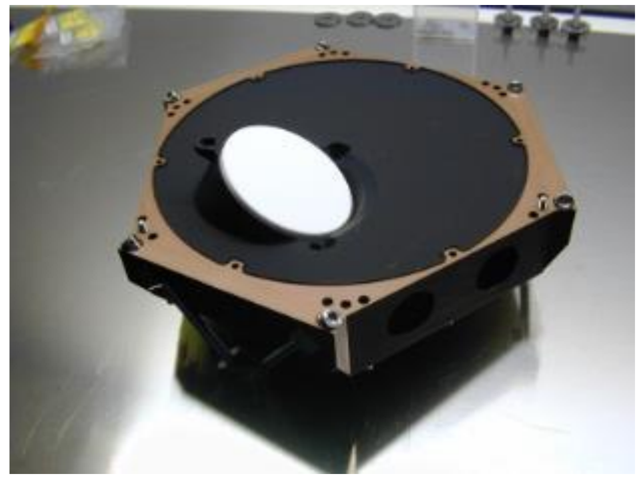
Blackbodies





VIS-SWIR Channels

VISCAL



Effective e >0.998
T non-uniformity < 0.02 K
T Abs. Accuracy 0.07 K
T stability < 0.3 mK/s
8 PRT sensors + 32 Thermistors

Zenith diffuser +
relay mirrors
Uncertainty <2%

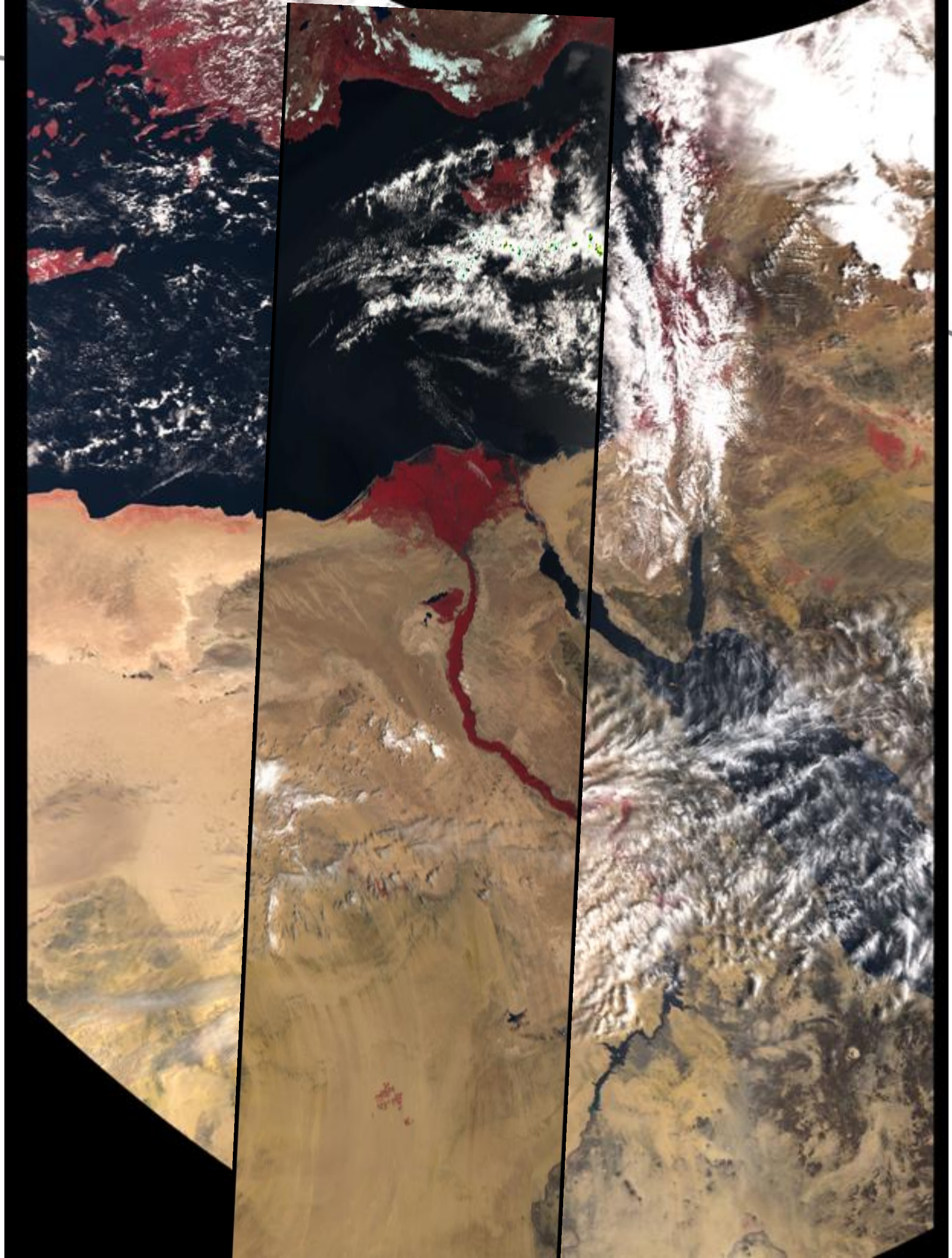
AATSR vs SLSTR Key Differences

RAL Space

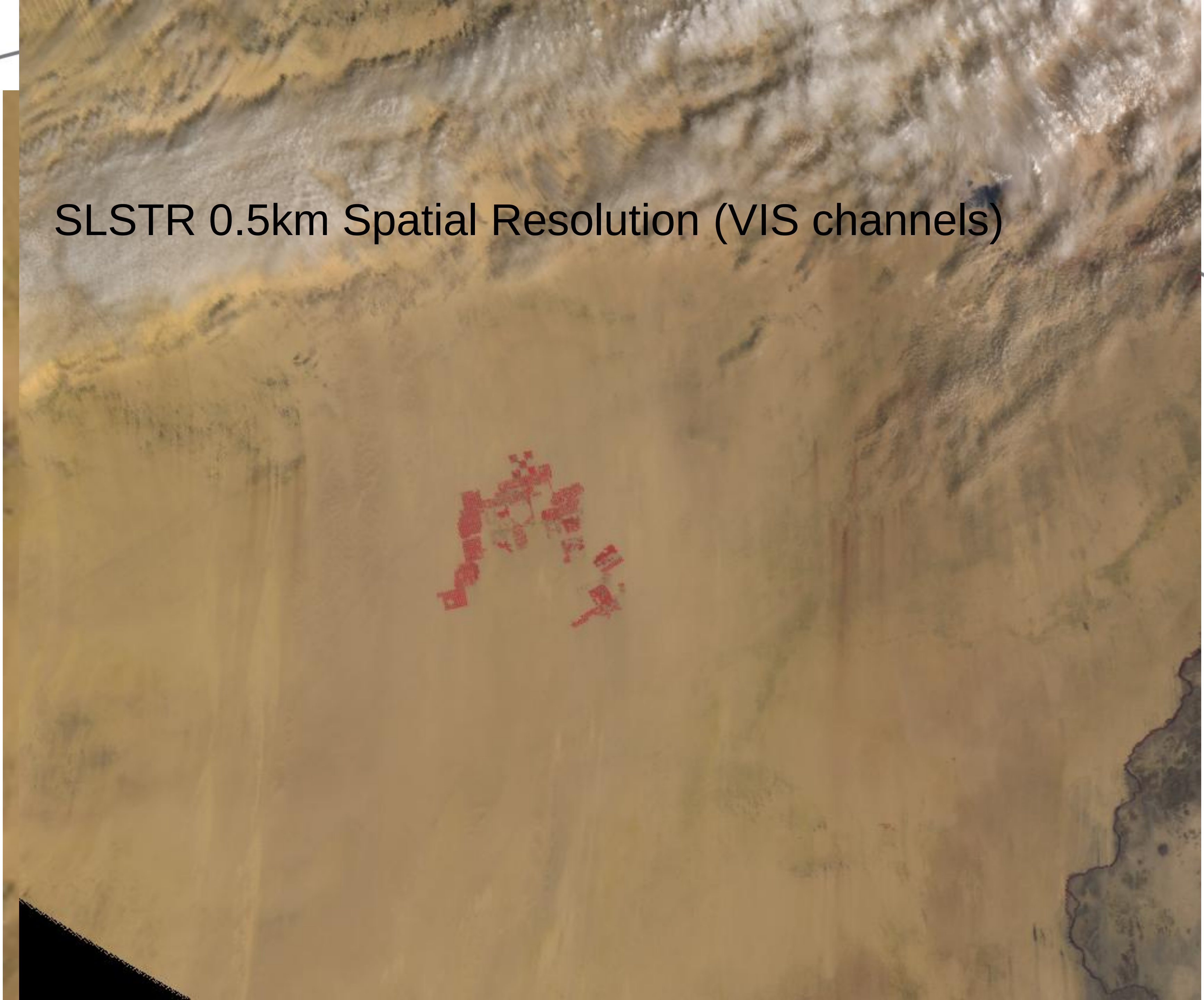
AATSR	SLSTR
Single detector for each channel	Multiple detectors per channel
Adjustable Gain (12 bit ADC)	Fixed Gain (14 bit ADC)
All channels aligned behind common field stop.	No common field stop
Single Telescope + Scanner	Two telescopes + scanners
Telescope aperture completely filled by detector	Telescope aperture filled by VIS channels. Partially filled by SWIR
Matt Russian Opal Diffuser	Zenith Diffuser
2 relay mirrors (all flat) – bare aluminium	3 relay mirrors (for each view) – first mirror is concave – protected silver coated

Sentinel-3 SLSTR
First Image over
Egypt 03/03/2016

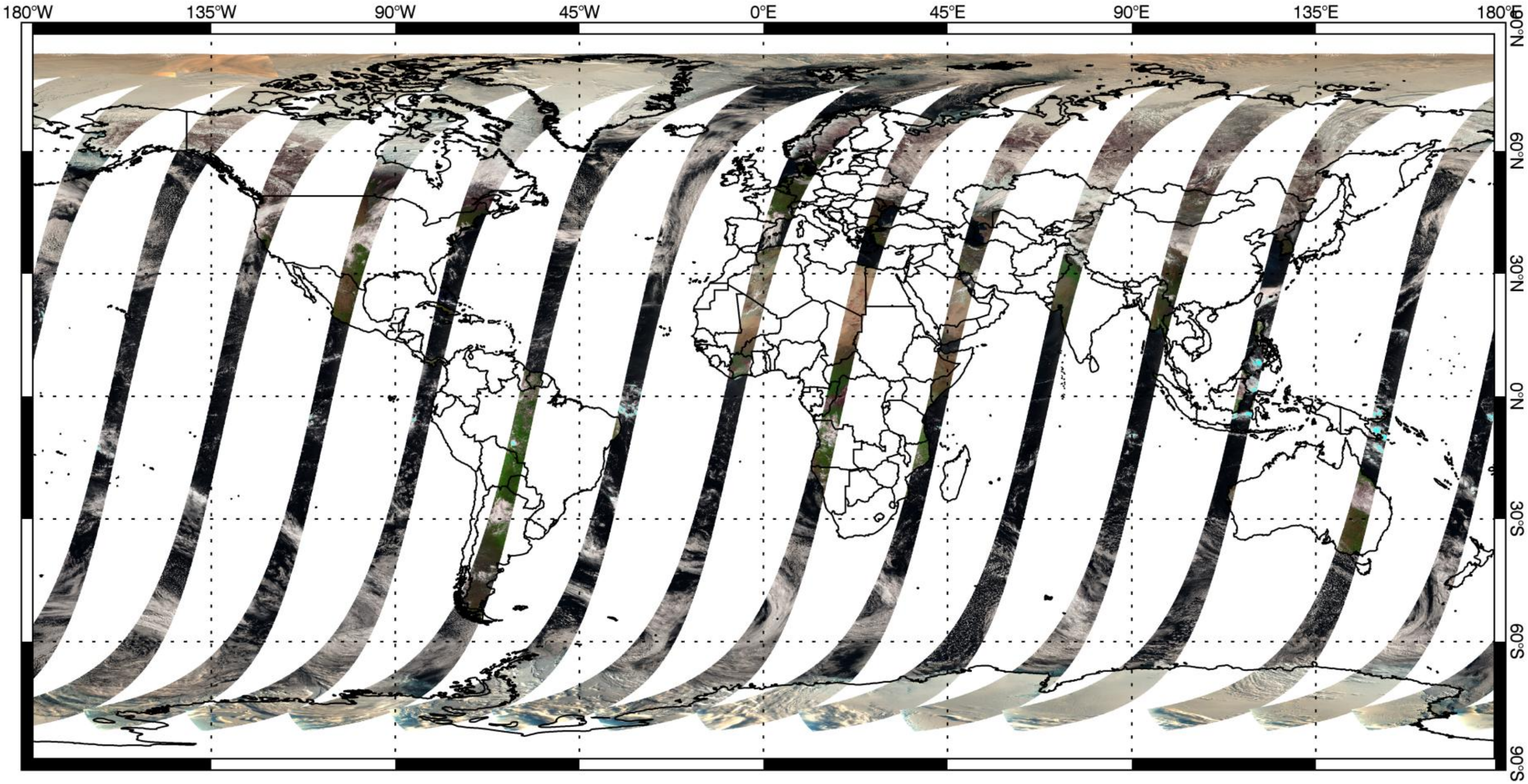
+
Last AATSR image
over Egypt
07/04/2012



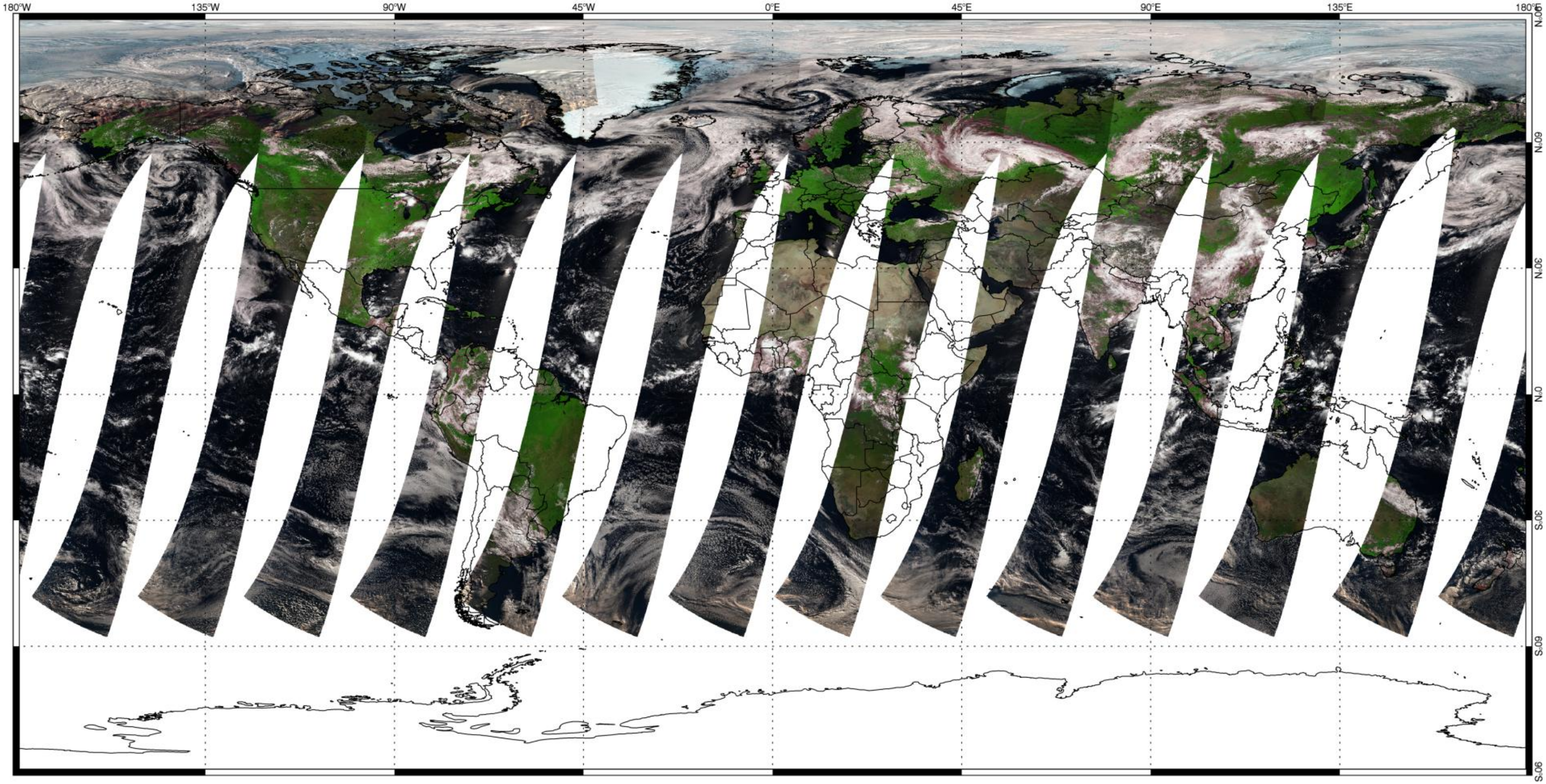
SLSTR 0.5km Spatial Resolution (VIS channels)



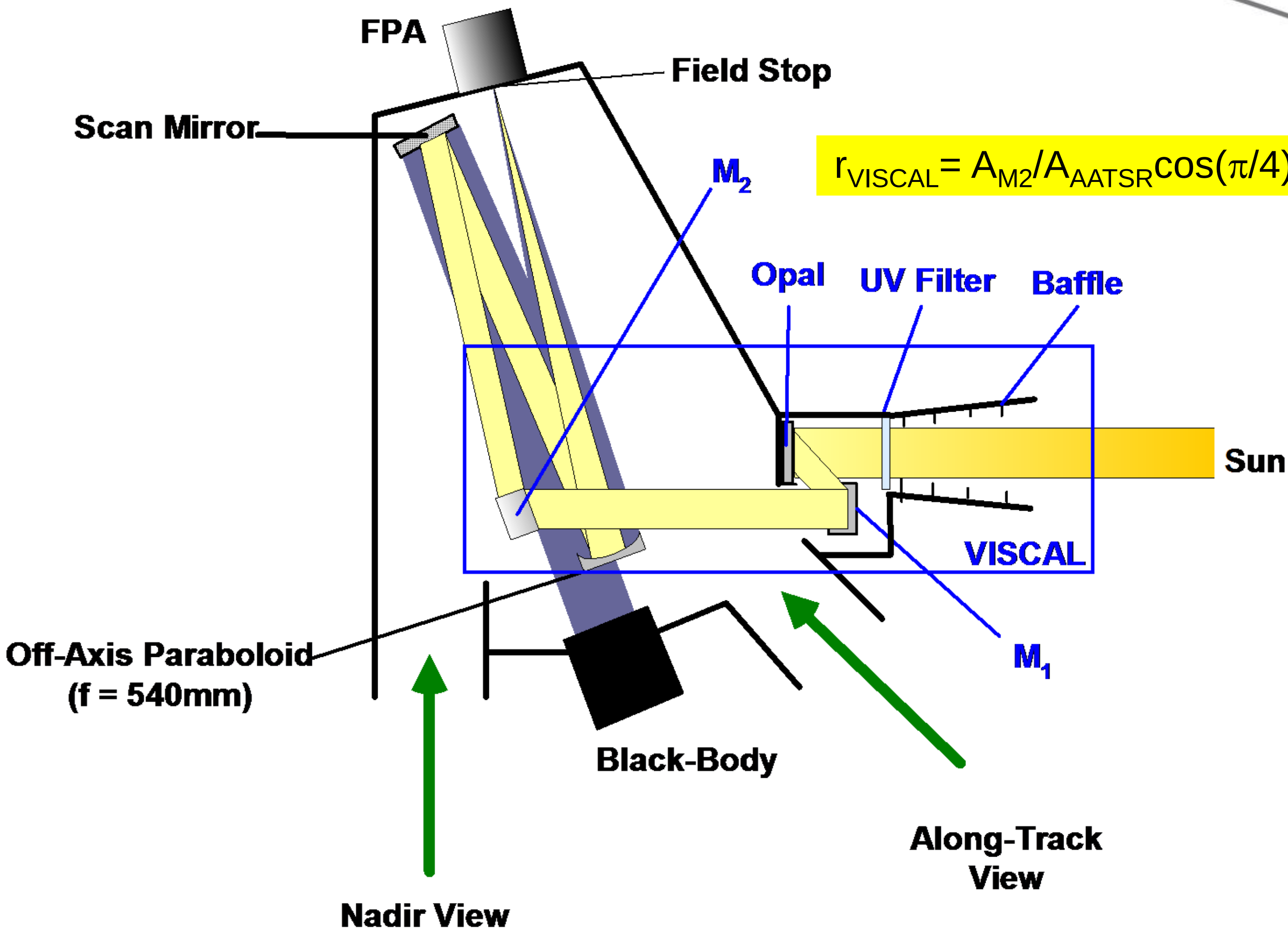
L3 from L1 data (AATSR)



L3 from L1 data (RSB Channels)



AATSR VISCAL



$r_{VISCAL} = A_{M2}/A_{AATSR}\cos(\pi/4)\, r_{M1} r_{M2} \tau_{UV} RI(0,\pi/4)$

SLSTR has additional relay mirror and separate chains for nadir/oblique

VIS/SWIR Calibration Model

$$L_{scene} = CalSlope.(DN_{scene} - DN_{dark})\ I_{sun} / (\pi \cos(\theta_s))$$

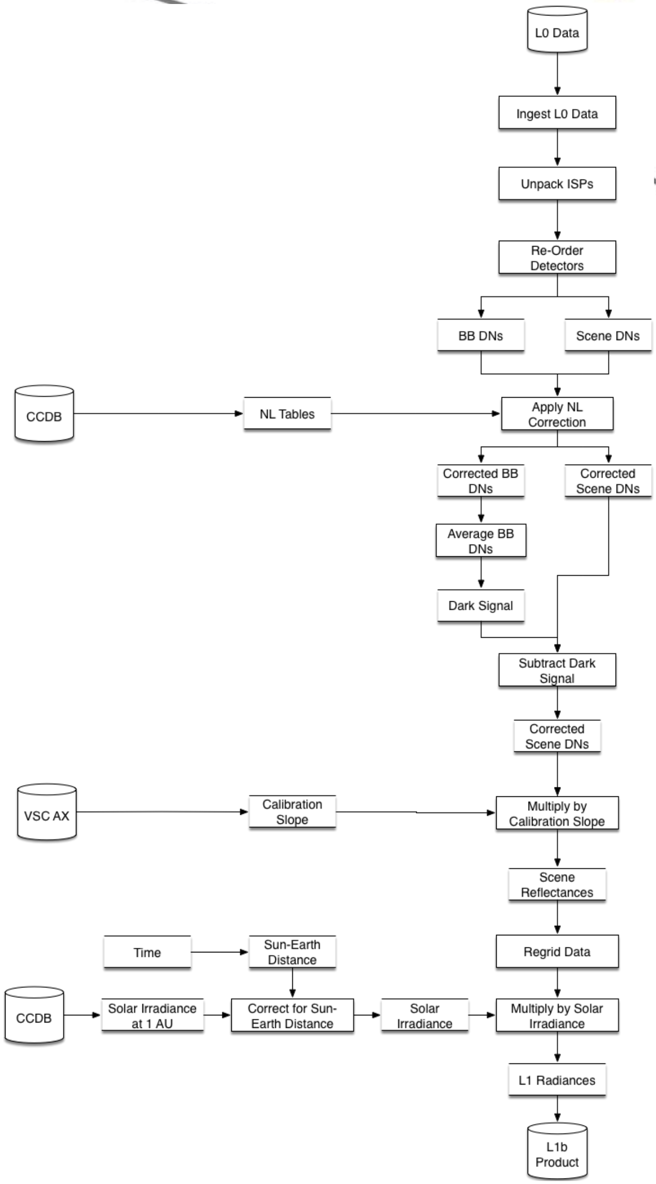
$$CalSlope = R_{cal} / (DN_{cal} - DN_{dark})\ K_{drift}$$

CalSlope is in VISCAL auxiliary files generated for same orbit no.

DN are adjusted for non-linearity

Key external inputs are:

- DNs from instrument source packets in L0 data
- R_{cal} = VISCAL reflectance factor from pre-launch calibration in CCDB
- I_{sun} from CCDB derived from Thuillier Solar Irradiance spectrum and spectral responses
- Time – needed for computation of sun-earth distance
- K_{drift} – Determined from vicarious calibration (assumed 1.0 at launch)



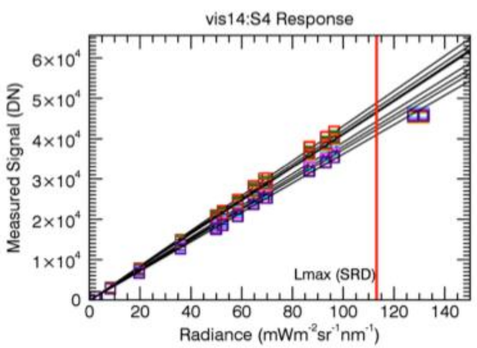
VISCAL Calibration Factors

Several methods are employed to derive calibration factors, R_{vcal}, for the VISCAL system:

- Application of component level measurements (Diffuser BRDF, Mirror reflectances, UV window transmission, geometric factors) to radiometric model.
  - This is not a direct measurement – reliant on witness measurements and modelled geometric factors.
- Instrument level tests – comparing response from VISCAL to those from earth view.
  - Direct method – Results used in CCDB
  - Problem with low signals at VISCAL - light source is not bright enough.
- In-orbit measurements – here we use the radiometric response of the instrument from on-ground measurements using a calibrated integrated sphere.
  - Traceable to SI units
  - Assumes that the detector response is same on orbit.
- Vicarious calibration using stable reference sites (e.g. CNES, DIMITRI).

Pre-Launch Calibration

Measurement Equation

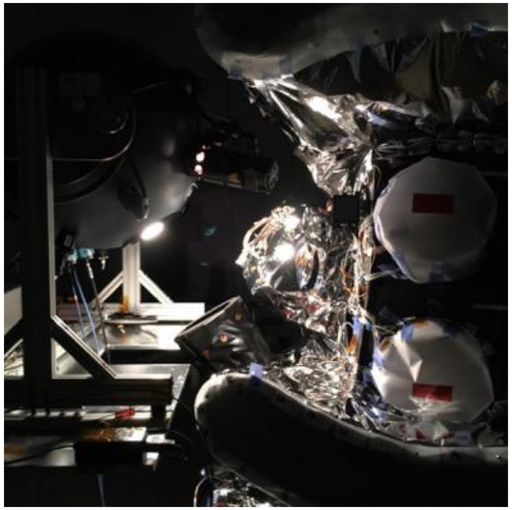


Radiometric response in the Earth view

$$R_{Viscal} = \frac{1}{W_{source}} \frac{g_{view}}{g_{viscal}}$$

Geometry of the source relative to the VISCAL diffuser

Radiometric response in the VISCAL view



Accounts for correlation of View and VISCAL radiometric response

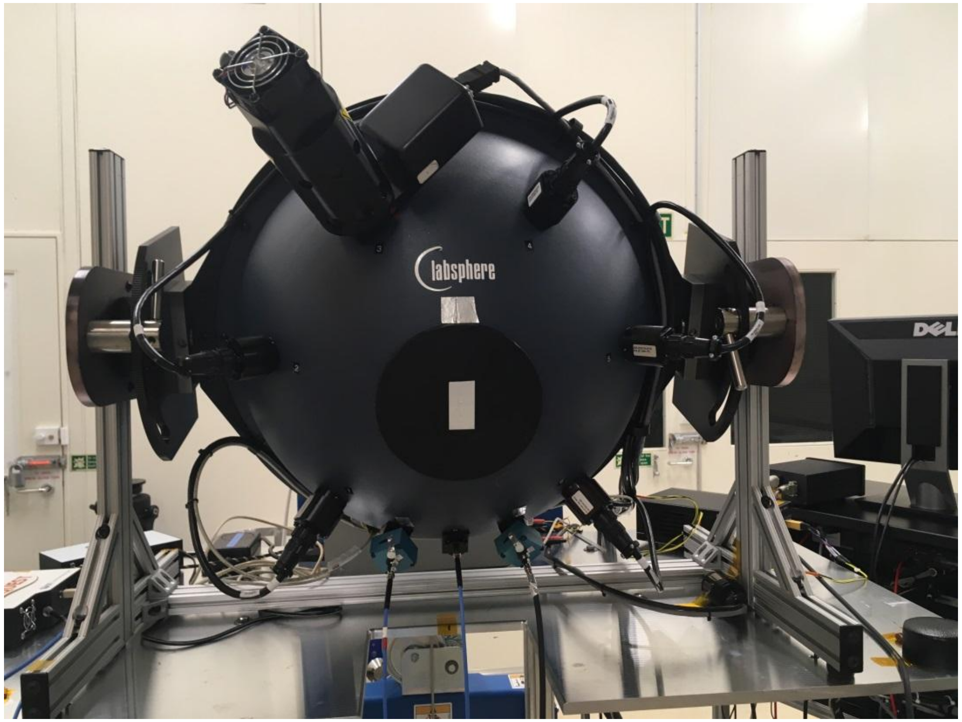
$$\left(\frac{uR_{VISCAL}}{R_{VISCAL}}\right)^2 = \left(\frac{uW_{source}}{W_{source}}\right)^2 + \left(\frac{ug_{view}}{g_{view}}\right)^2 + \left(\frac{ug_{viscal}}{g_{viscal}}\right)^2 - 2\frac{u(g_{viscal}, g_{view})}{g_{viscal}\, g_{view}}$$

Geometry of the source in relation to the VISCAL diffuser

Uncertainty in the radiometric gains in Earth and in VISCAL views

Source Setup

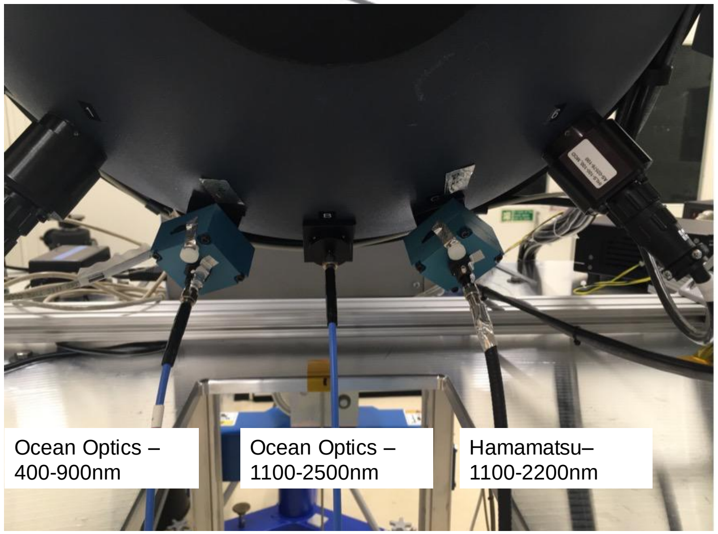
- Integrating sphere used for calibration of SLSTR
- 6 lamps, one (lamp 3) has a variable aperture. 0%=open, 100%=closed. Percentage is not proportional to open area.
- Lamp settings controlled and data recorded using labview interface on a PC



Source Setup

- Three spectrometers mounted on the sphere to monitor source output and traceability to NPL calibration
  - 2 SWIR
  - 1 for VIS-NIR

- Lamp settings controlled and data recorded using labview interface on a PC



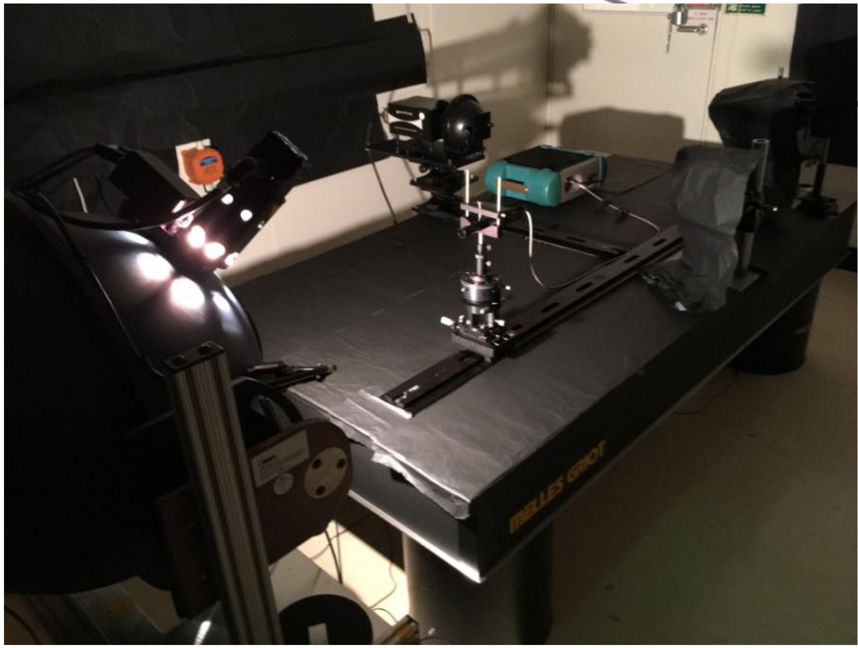
NPL-RAL-TAS Sphere Intercomparisons

An exercise was initiated to compare spectral radiances of integrating sphere sources used for SLSTR (RAL Space) and OLCI (Thales Alenia Space, France) calibrations.

NPL have performed measurements using spectroradiometers and reference source at host institution.

Measurements performed at RAL in December during SLSTR calibration campaign. Data being processed.

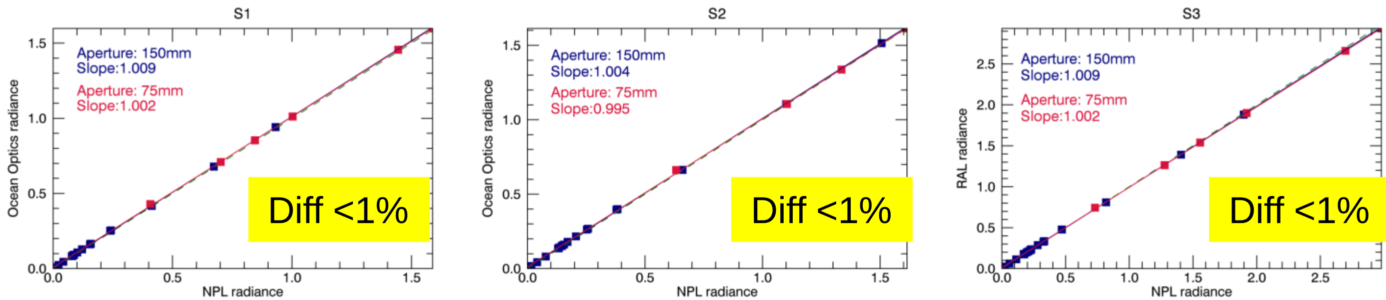
Measurements for OLCI performed in April



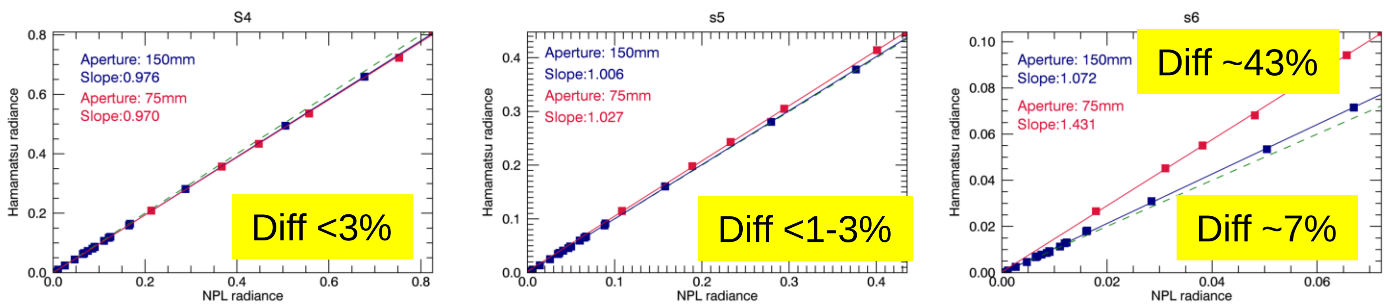
NPL's ASL spectrometer and source viewing RAL integrating sphere source.

Comparisons – RAL vs NPL measurements

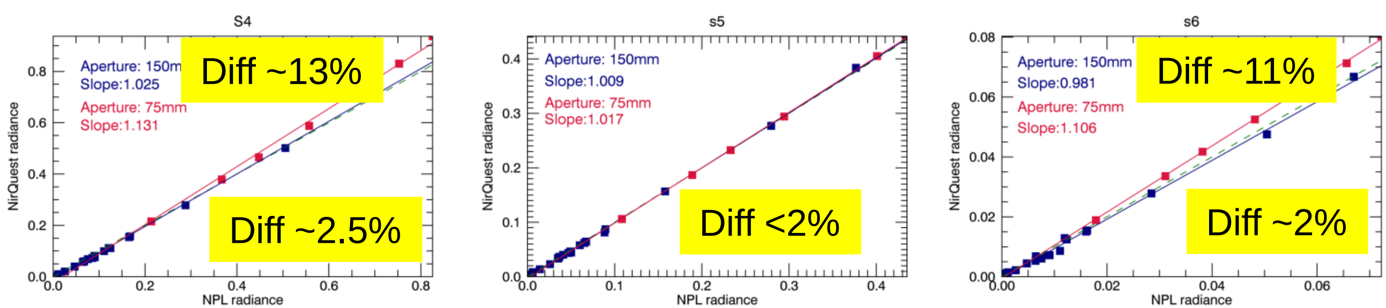
VIS-NIR (S1-S3)
Ocean Optics



SWIR (S4-S5)
Hamamatsu



SWIR (S4-S5)
Ocean Optics

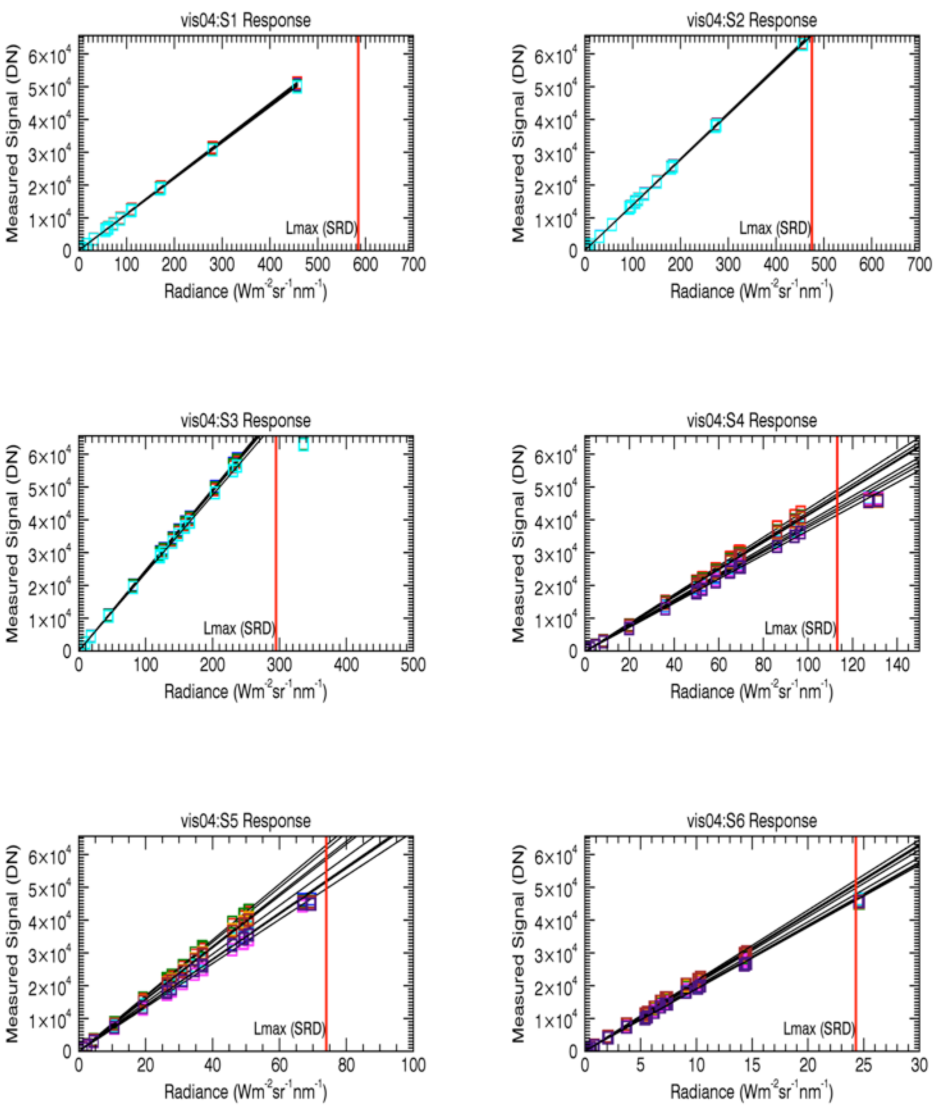


Good agreement at S1-S3, S5. Discrepancies at S4, S6

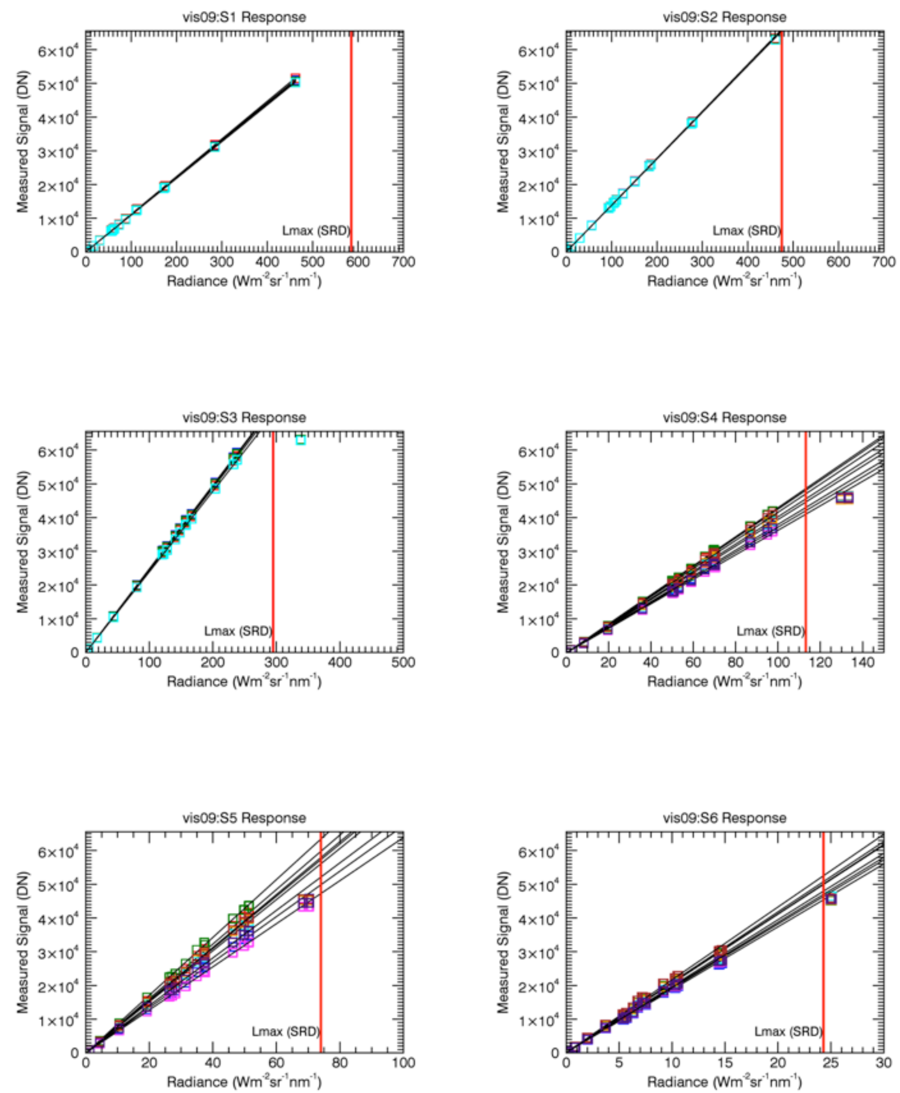
Radiometric Response in Earth View

RAL Space

Response Nadir View

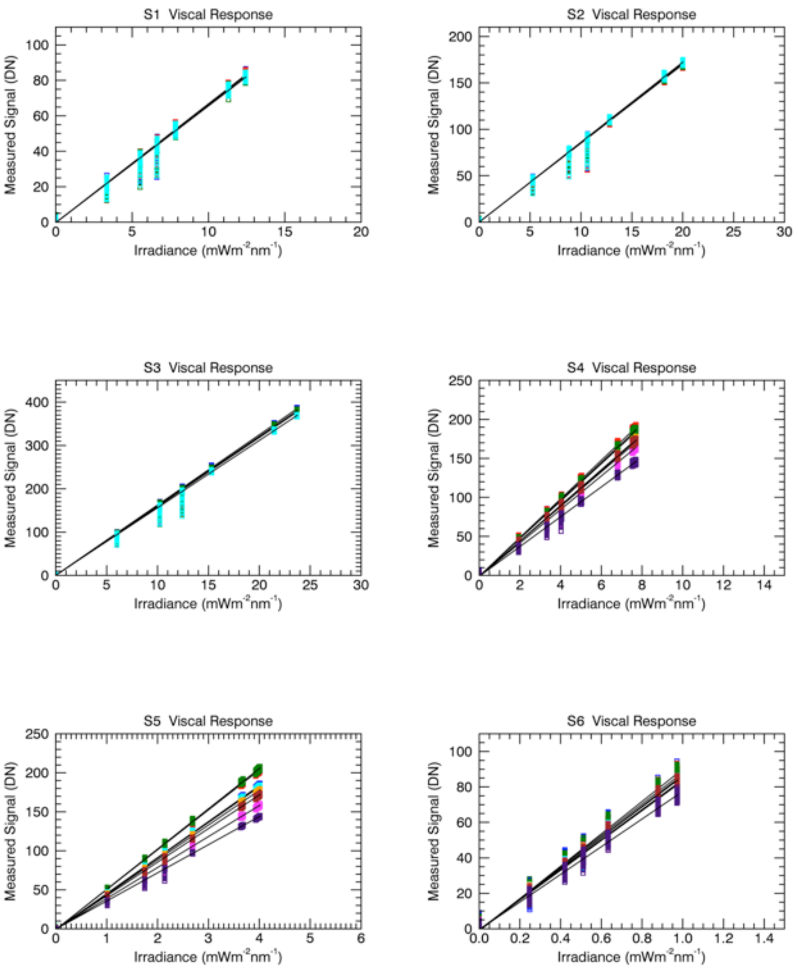


Response Oblique View

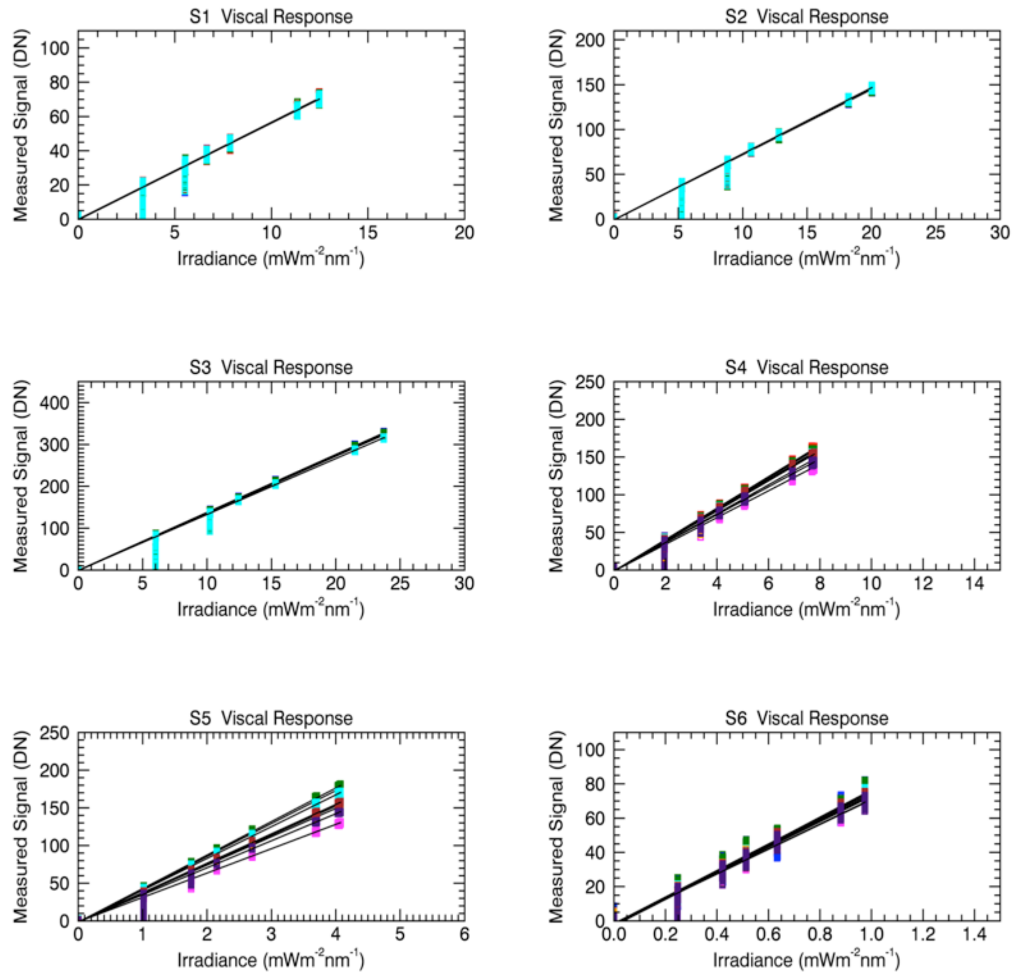


Response at VISCAL

Nadir



Oblique



AATSR R_{cal}

Parameter	Val	Uncert		
Am2	3408	97	mm^2	Based on analysis
A_{AATSR}	9503	157	mm^2	Design Value
Am2/AATSR*Cos(45)	0.254	0.008		

	555nm		659nm		870nm		1600nm		Ref.
	Val	Uncert	Val	Uncert	Val	Uncert	Val	Uncert	
FM Opal 0/45° Radiance Factor (%)	96.0	0.8	96.1	0.8	95.0	2.0	90.0	2.2	NPL Certificate QO03/6/94/084
FM UV Window Transmittance (%)	92.2	1.0	92.5	1.0	92.7	1.0	92.7	1.0	PO-TN-RAL-AT-0163
FM Mirror M1 Reflectance (%)	84.9	1.0	84.2	1.0	82.9	1.0	95.0	1.0	PO-TN-RAL-AT-0164
FM Mirror M2 Reflectance (%)	86.4	1.0	85.7	1.0	84.0	1.0	95.7	1.0	PO-TN-RAL-AT-0164
Rcal	**0.1646**	**0.0063**	**0.1627**	**0.0062**	**0.1555**	**0.0066**	**0.1923**	**0.0083**	
Uncert (% k=2)		**3.8%**		**3.8%**		**4.2%**		**4.3%**	

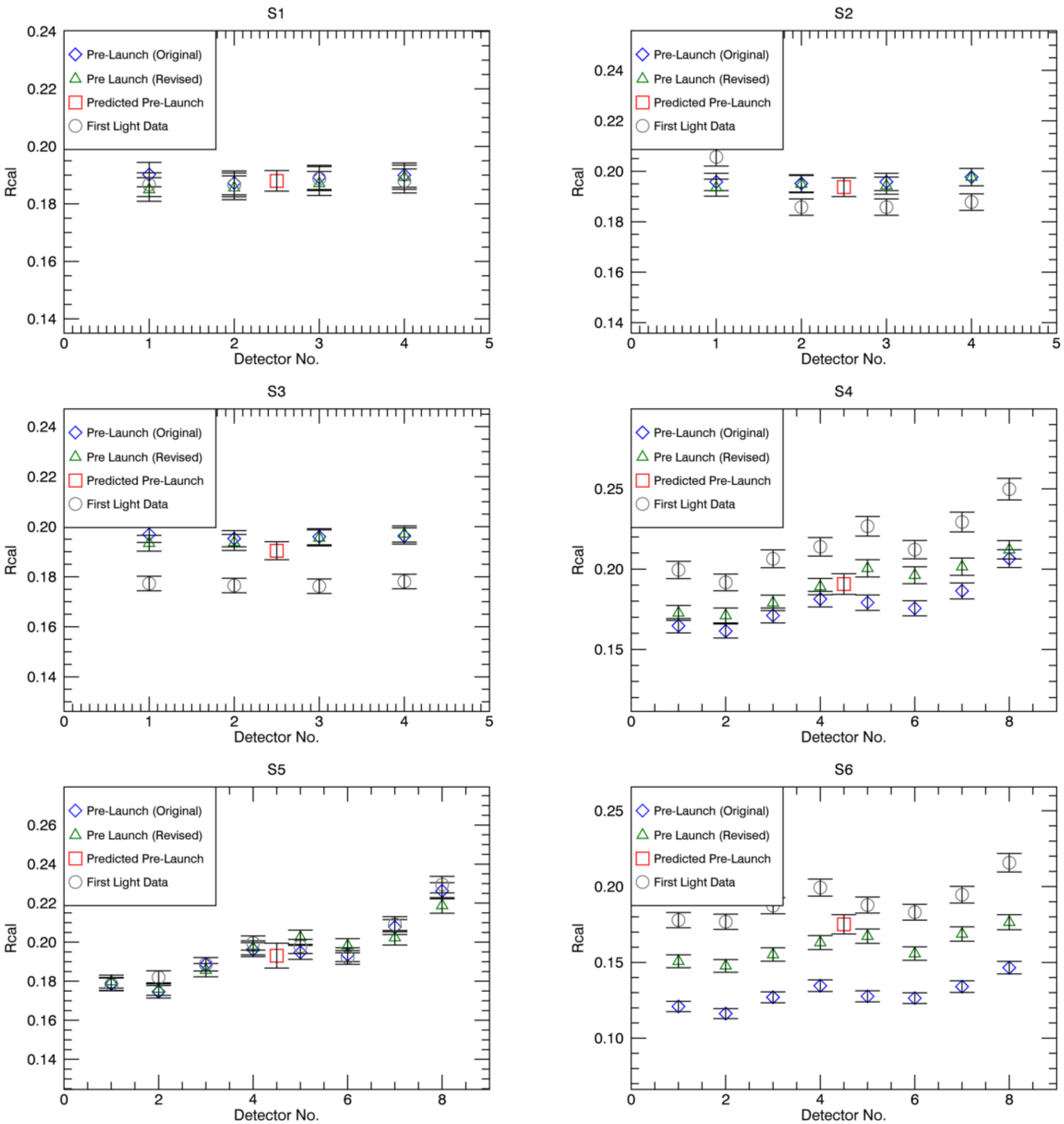
From Instrument Calibration

	555nm		659nm		870nm		1600nm	
	Val	Uncert	Val	Uncert	Val	Uncert	Val	Uncert
Rcal	**0.1646**	**0.0040**	**0.1648**	**0.0054**	**0.1548**	**0.0034**	**0.1928**	**0.0064**
Uncert (% k=2)		**2.40%**		**3.30%**		**2.20%**		**3.30%**
Diff (Abs)	-3.91E-05		2.15E-03		-7.06E-04		4.61E-04	
Diff (Rel)	-0.024%		1.319%		-0.454%		0.240%	

In Flight (Beginning of Life)

	555nm		659nm		870nm		1600nm		
	Val	Uncert	Val	Uncert	Val	Uncert	Val	Uncert	
AATSR-MERIS	3.34%	1%	3.10%	1%	2.99%	1%	N/A		Smith and Cox 2013
AATSR-MODIS	3.84%	3%	3.34%	2%	3.69%	2%	1.14%	1%	
Rcal adjusted to ref	**0.1591**	**0.0045**	**0.1597**	**0.0032**	**0.1502**	**0.0030**	**0.1901**	**0.0019**	
Uncert (% k=2)		**2.8%**		**2.0%**		**2.0%**		**1.0%**	

SLSTR-A R_{cal} (Nadir)



Differences have been observed between different methods of evaluating VISCAL reflectance factors in SWIR channels.

- Detector-Detector differences - Image stripes
- Differences in absolute factors – Especially S6

BOL on-orbit measurement of VISCAL signals appear to be more in-line with vicarious calibration + destriping correction.

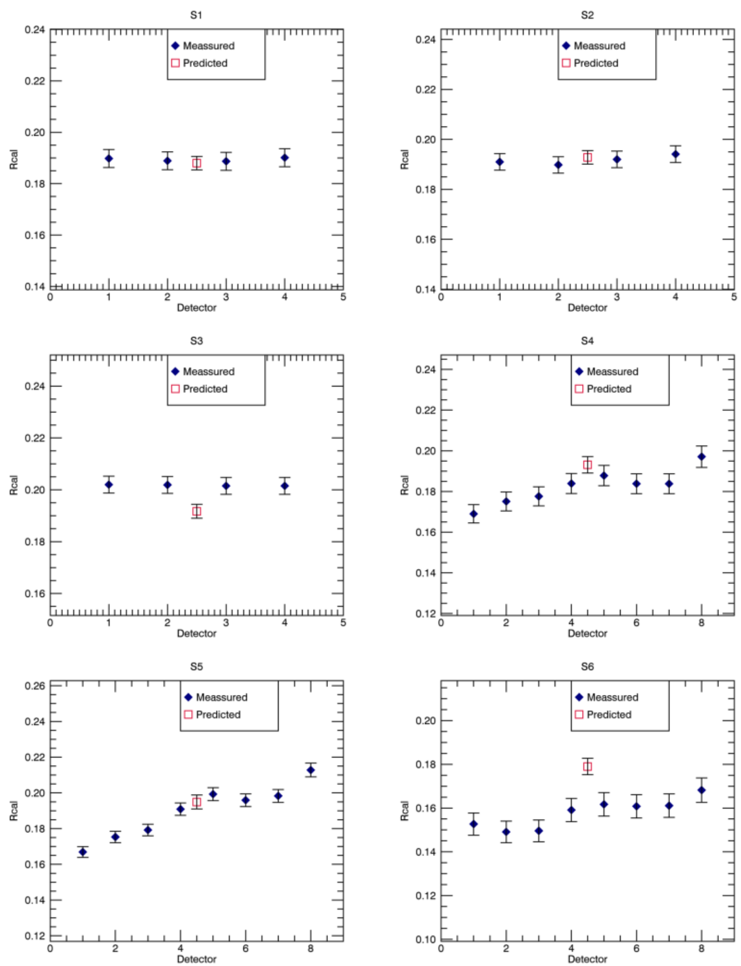
S1 and S5 Results show good consistency with different methods!

SLSTR-B R_{cal}

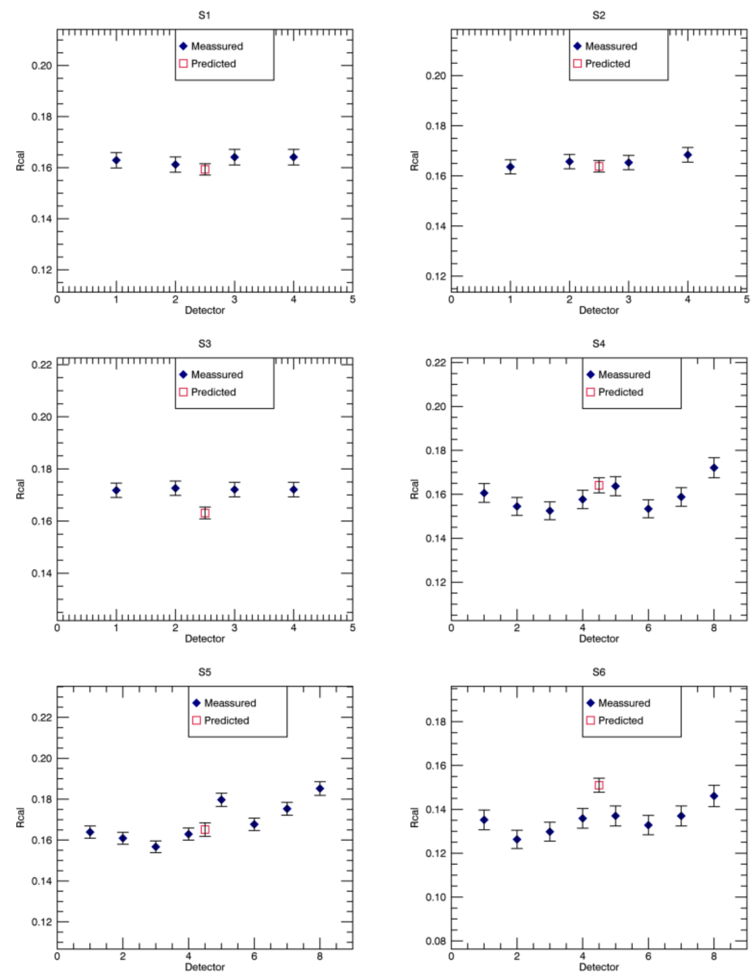
Predicted

Measured

Nadir



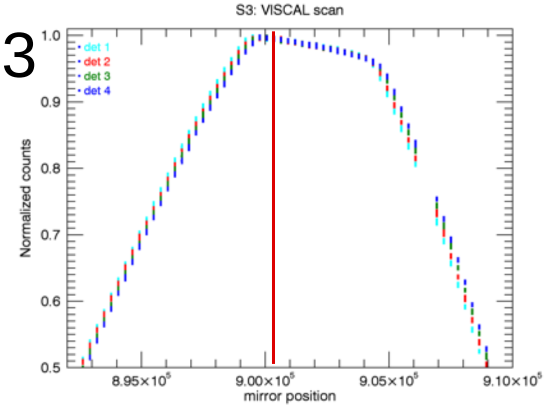
Oblique



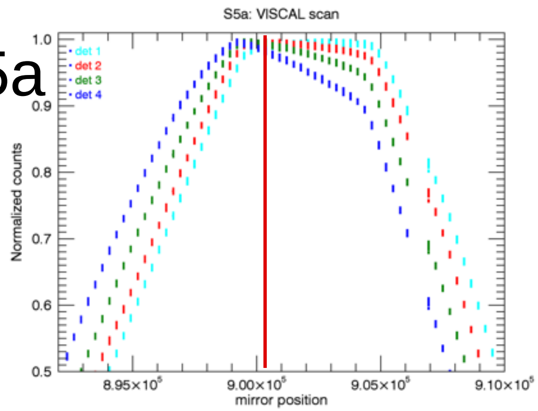
Note – Separate values for each detector + view

VISCAL Pixel Range and Uniformity

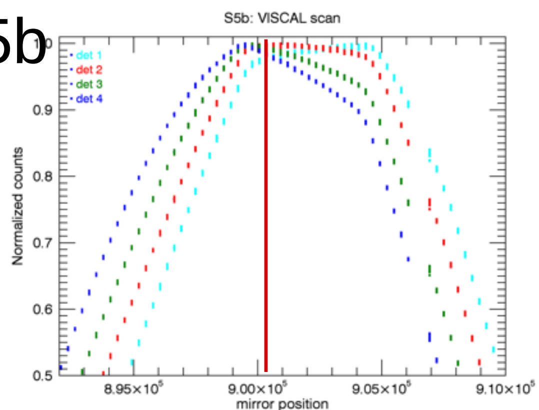
S3



S5a



S5b



We performed a set of measurements where the source illuminated the diffused and measured the signal response for different scanner positions.

Results determined the range of pixels to use on-orbit.

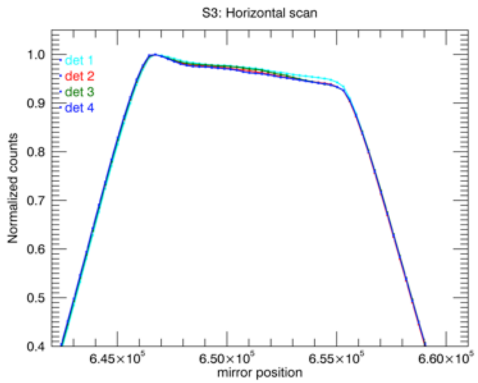
Showed a significant non-uniformity in the measured responses.

- For SWIR channels different for each detector
- Greater than expected variation in diffuser BRDF

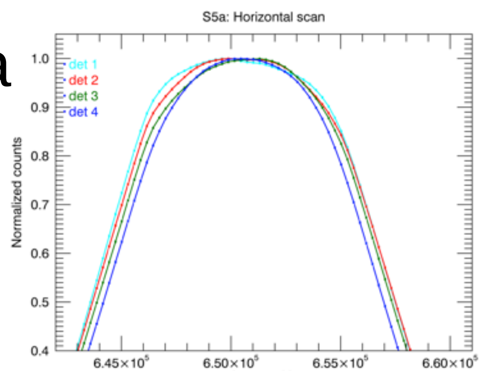
Why?

Pupil Uniformity – Along Scan

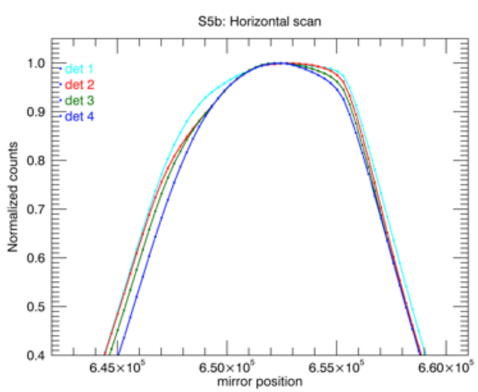
S3



S5a



S5b



To investigate cause of non uniformity we performed some additional measurements at centre of earth view.

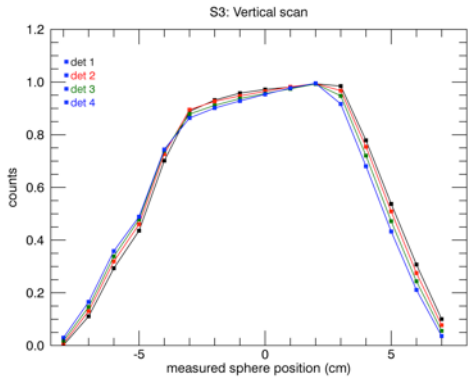
We illuminate the earth view with a 50mm diameter source (i.e. underfilling the pupil) and measure the instrument response as a function of scanner position (along scan direction)

Results show all VIS channels appear to fill main aperture uniformly.

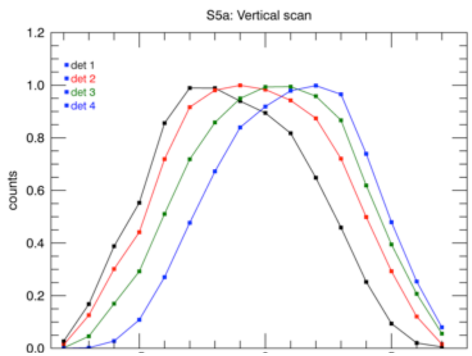
Differences seen in SWIR channel A and B stripes. Less uniform response

Pupil Uniformity – Along Track

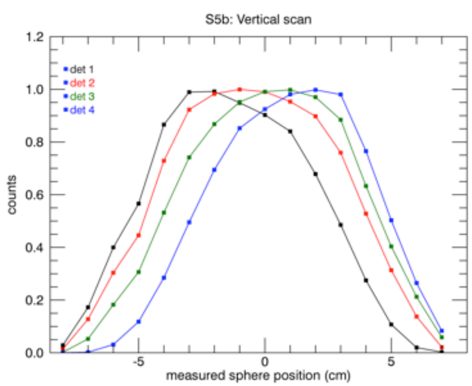
S3



S5a



S5b



We then repeated the measurements, this time moving source in vertical direction (along track direction)

Results show all VIS channels appear to fill main aperture uniformly.

Noticeable differences seen in each SWIR detector.

Conclusion:
Main telescope aperture is not the primary pupil for the SWIR channels

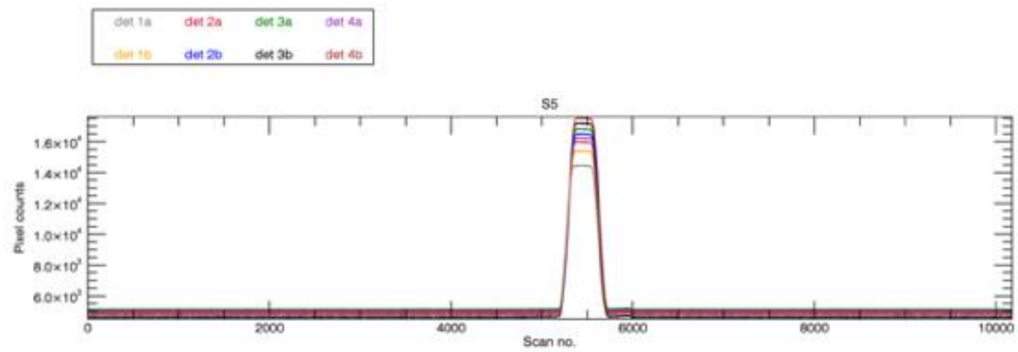
Provides root cause for variations in measured instrument response and Rcal

On-Orbit Monitoring

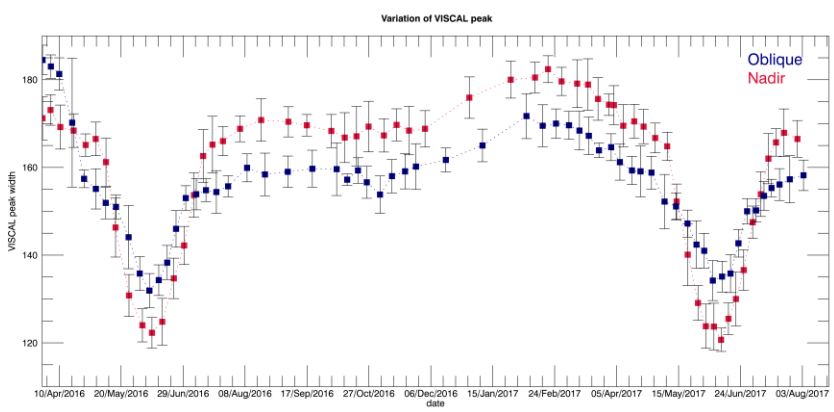
On-Orbit Performance

VISCAL is illuminated by the sun once per orbit

No dedicated calibration mode needed



Analysis shows seasonal variation of illumination period – consistent with solar azimuth.

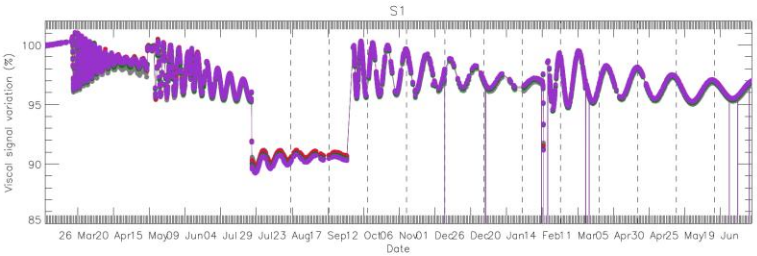


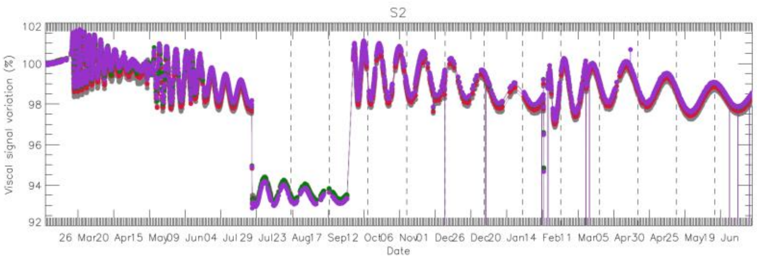
Data processing ensures only period at full illumination is used.

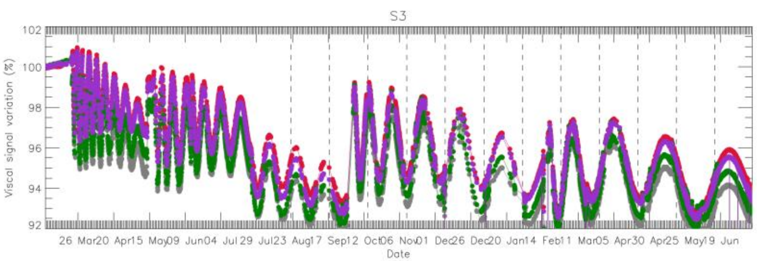
Variation in radiometric gains- SLSTR-A

RAL Space

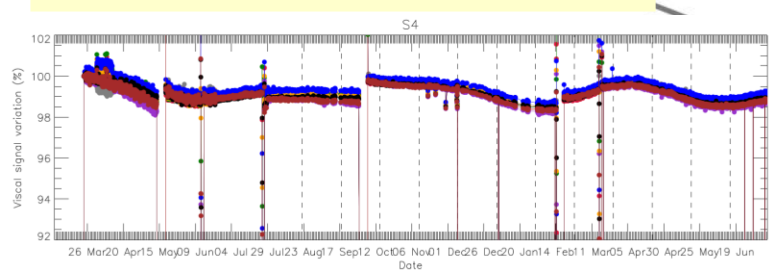
VIS/NIR Channels (Nadir)

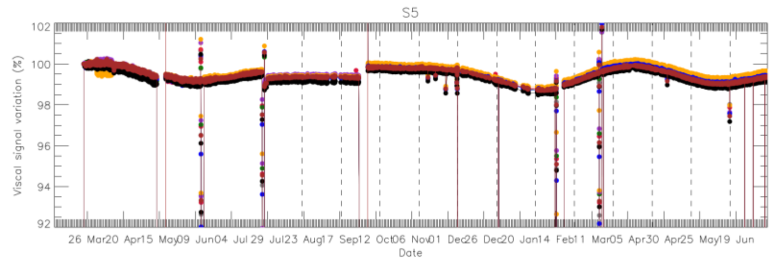


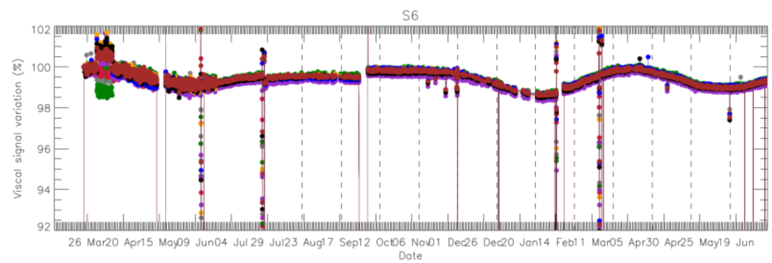




SWIR Channels (Nadir)







Signal oscillations in VIS/NIR channels due to build up of water ice on IR FPA optics – common to both nadir and oblique views (also seen on AATSR/ATSR-2). Use of gains derived from VISCAL signals should remove these short term variations.

Vicarious Calibration

Vicarious Calibration Approach

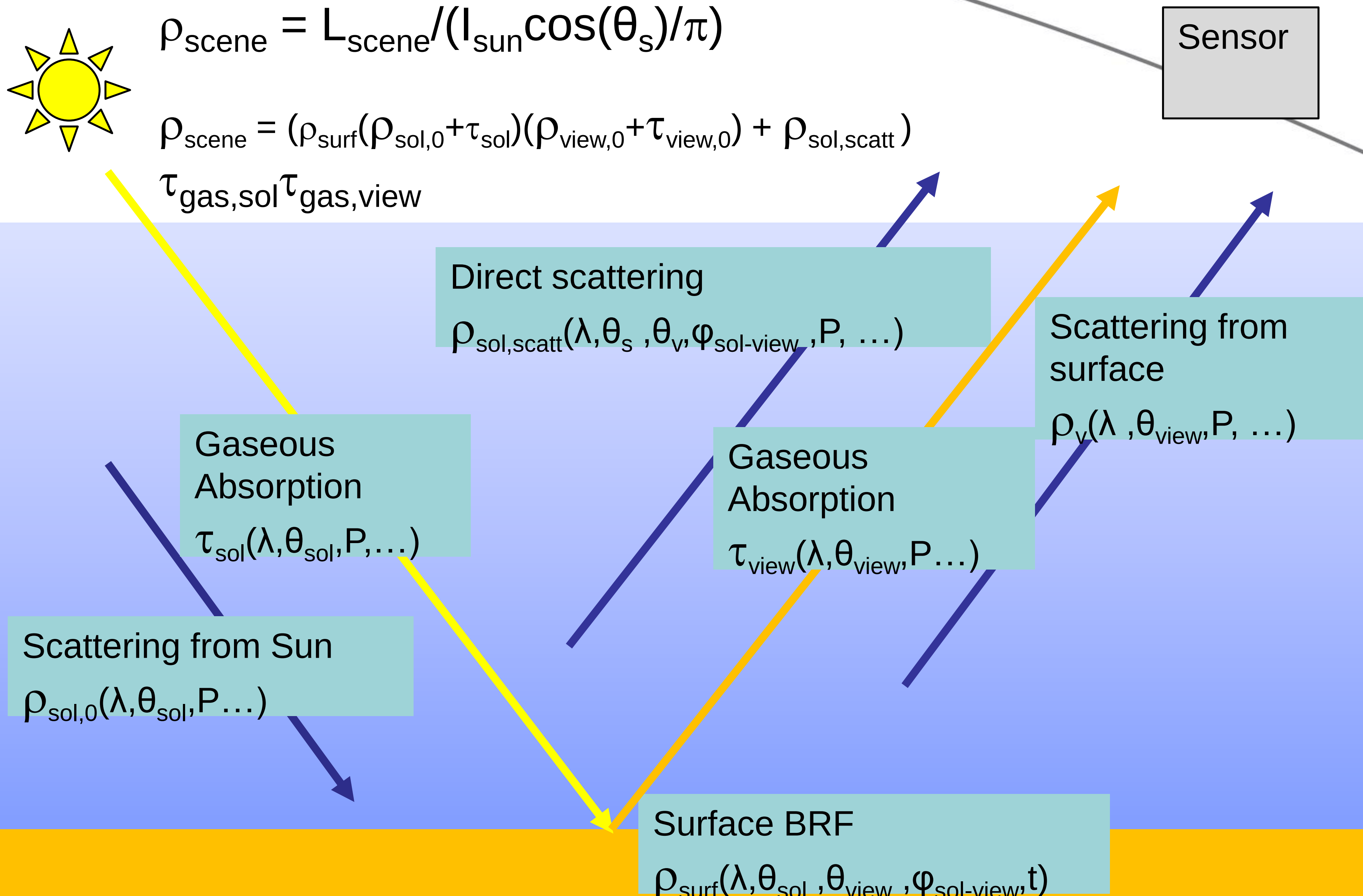
- Analysis using stable desert and ice targets as used for ATSR series, MERIS, MODIS etc…
- To avoid having to download large volumes of data, L1 images over desert, ice, sunglint have been processed using S3ETRAC tool and TOA reflectances + ancillary information are saved to Netcdf files.
  - Approach was developed and used successfully for AATSR
- Extractions allow comparisons with other sensors
  - Directly as in the case of SLSTR and OLCI/AATSR and MERIS
  - Indirectly where satellites are not time coincident using matching geometry
    - E.g. AATSR/MERIS vs MODIS
    - E.g. AATSR vs ATSR-2 vs ATSR-1

Vicarious calibration model over sites

$$\rho_{scene} = L_{scene}/(I_{sun}\cos(\theta_s)/\pi)$$

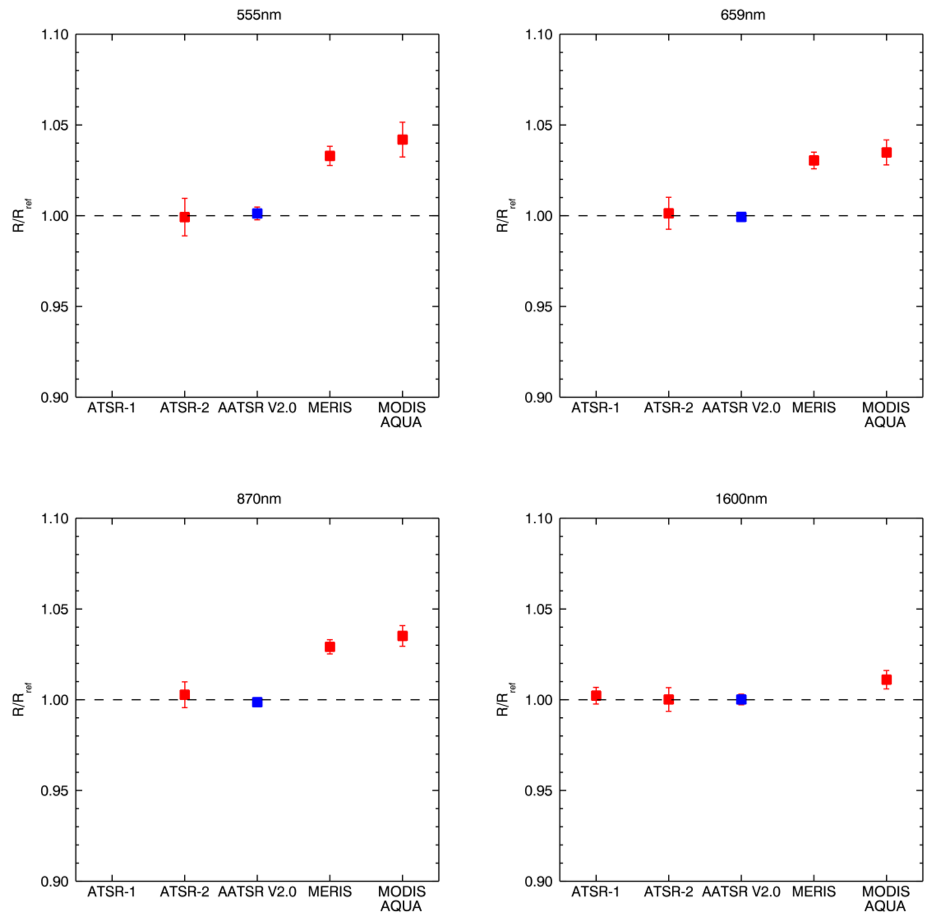
$$\rho_{scene} = (\rho_{surf}(\rho_{sol,0}+\tau_{sol})(\rho_{view,0}+\tau_{view,0}) + \rho_{sol,scatt})$$

$$\tau_{gas,sol}\tau_{gas,view}$$



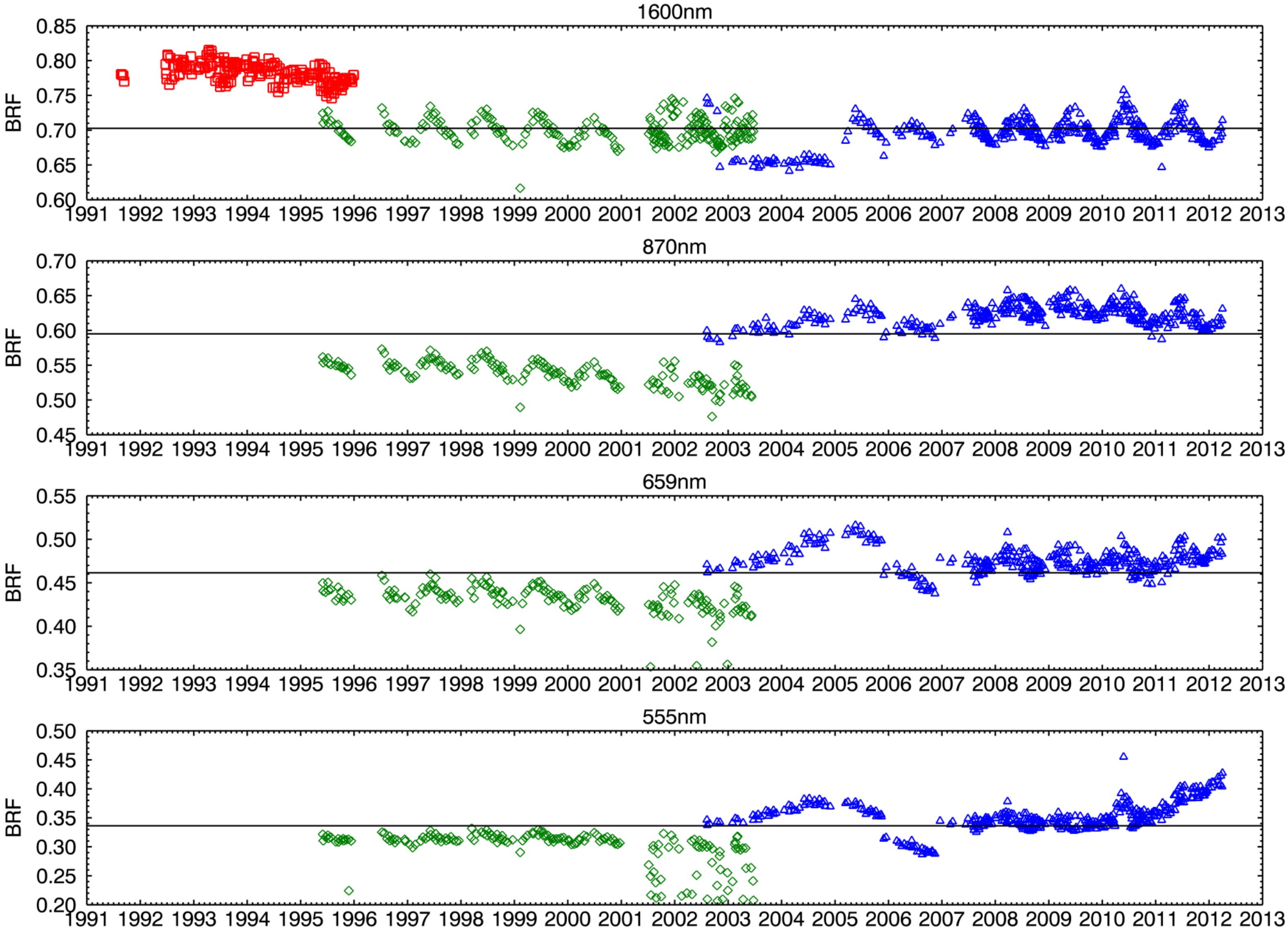
Summary of (A)ATSR Comparisons

- Globally reprocessed (A)ATSR calibration is self consistent at 1% level.
- Long term stability of calibration at 1% level
- AATSR V2.1 shows some improvement over outgassing periods
- Comparisons with MERIS & MODIS-A show 3% difference

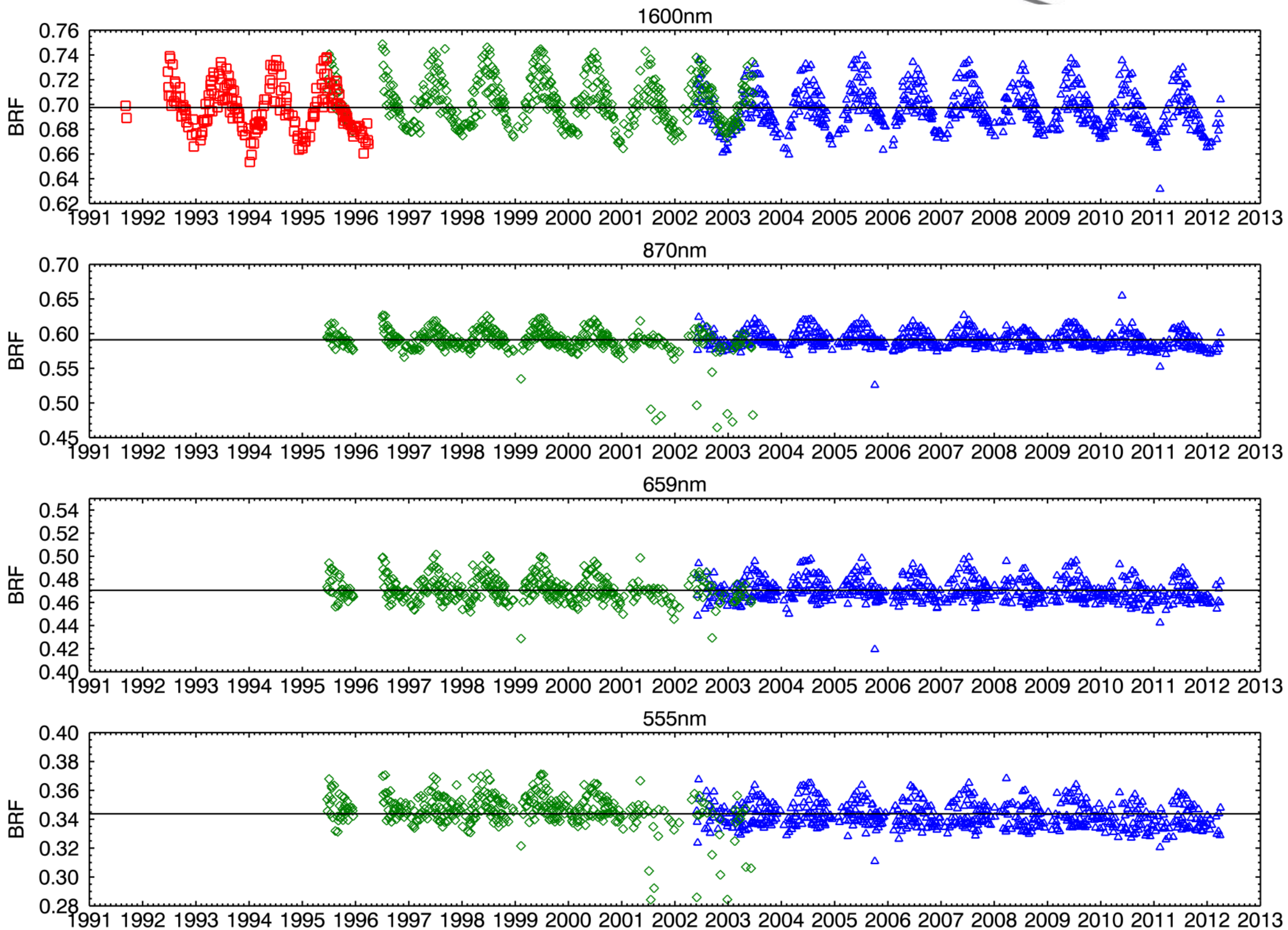


ATSR Series - Libya-4 BRF – V2.0

RAL Space

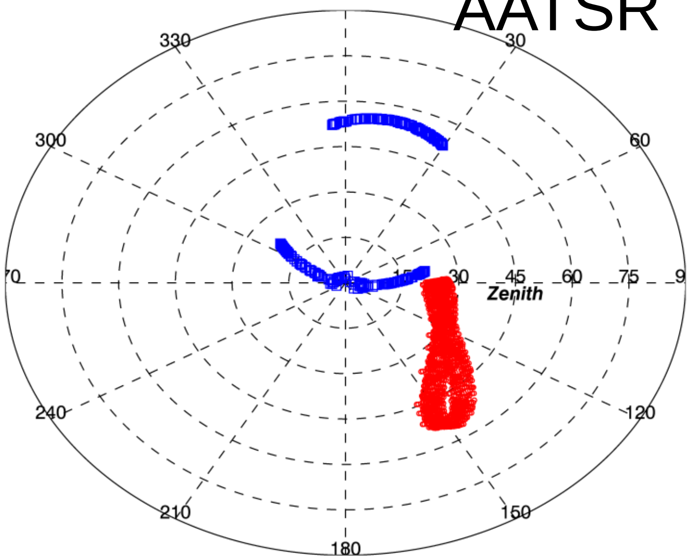


ATSR Series - Libya-4 BRF – V3 Data

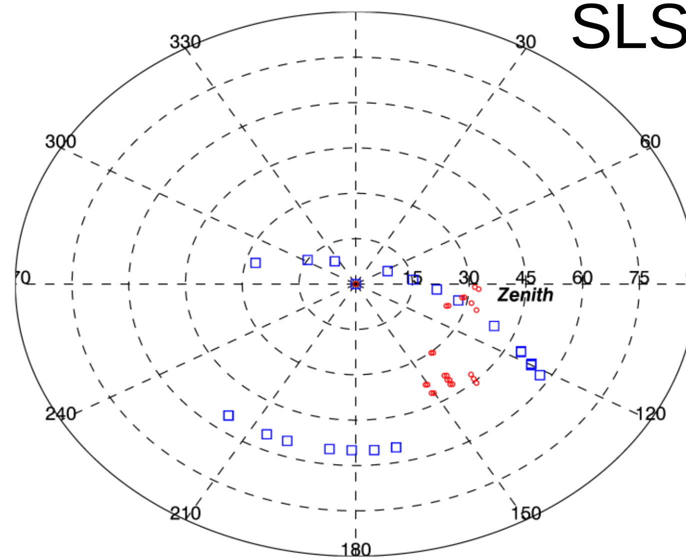


Geometric Comparisons

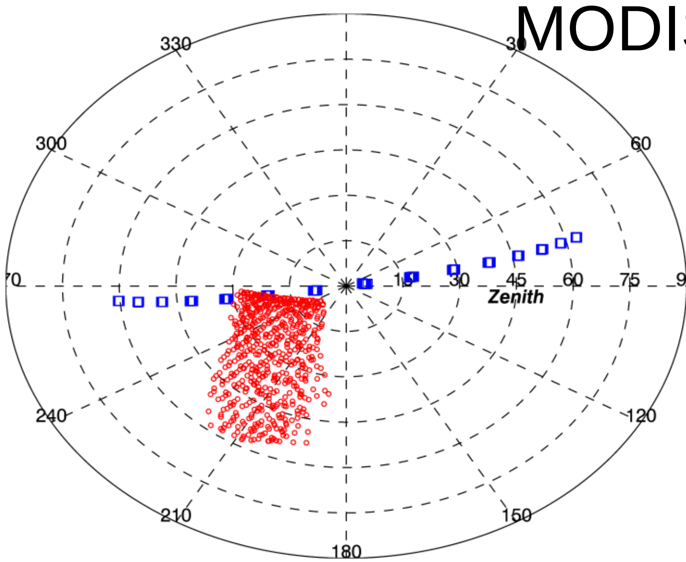
AATSR



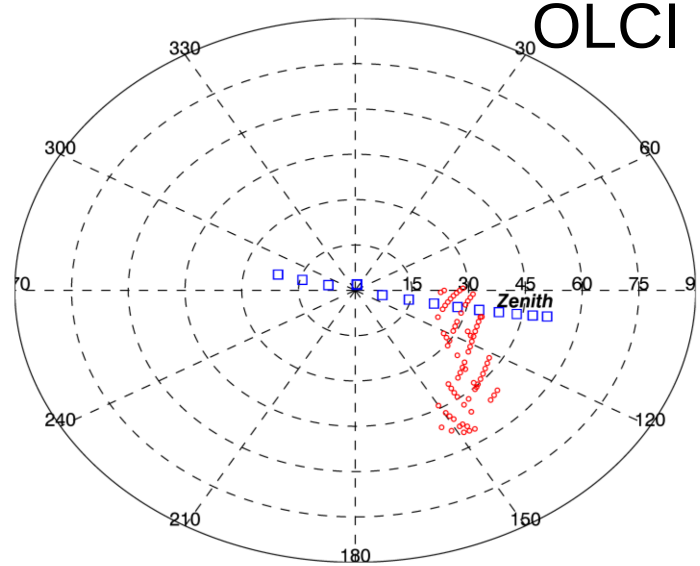
SLSTR



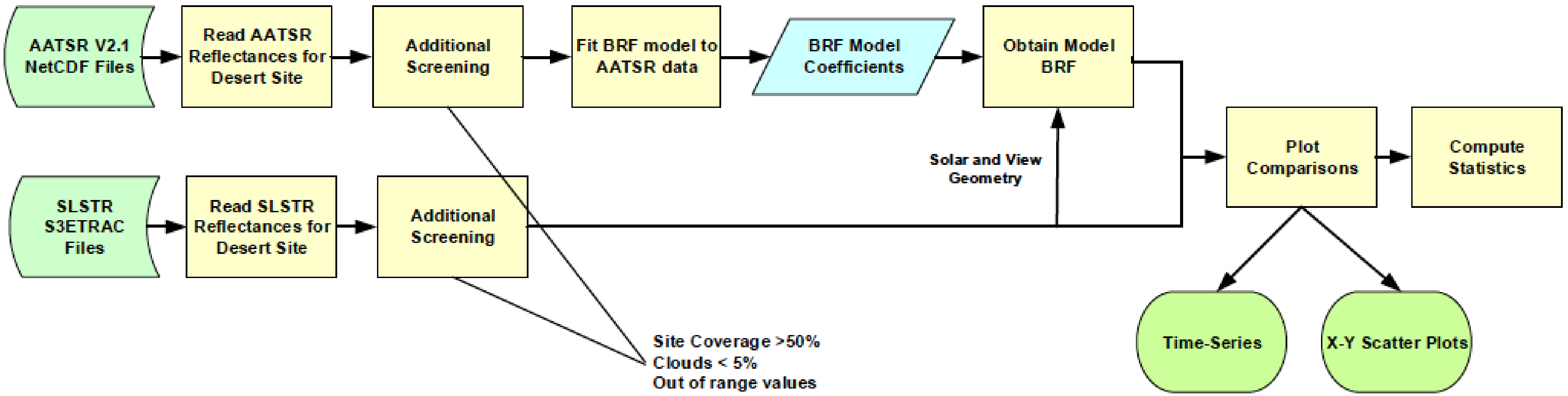
MODIS-A



OLCI



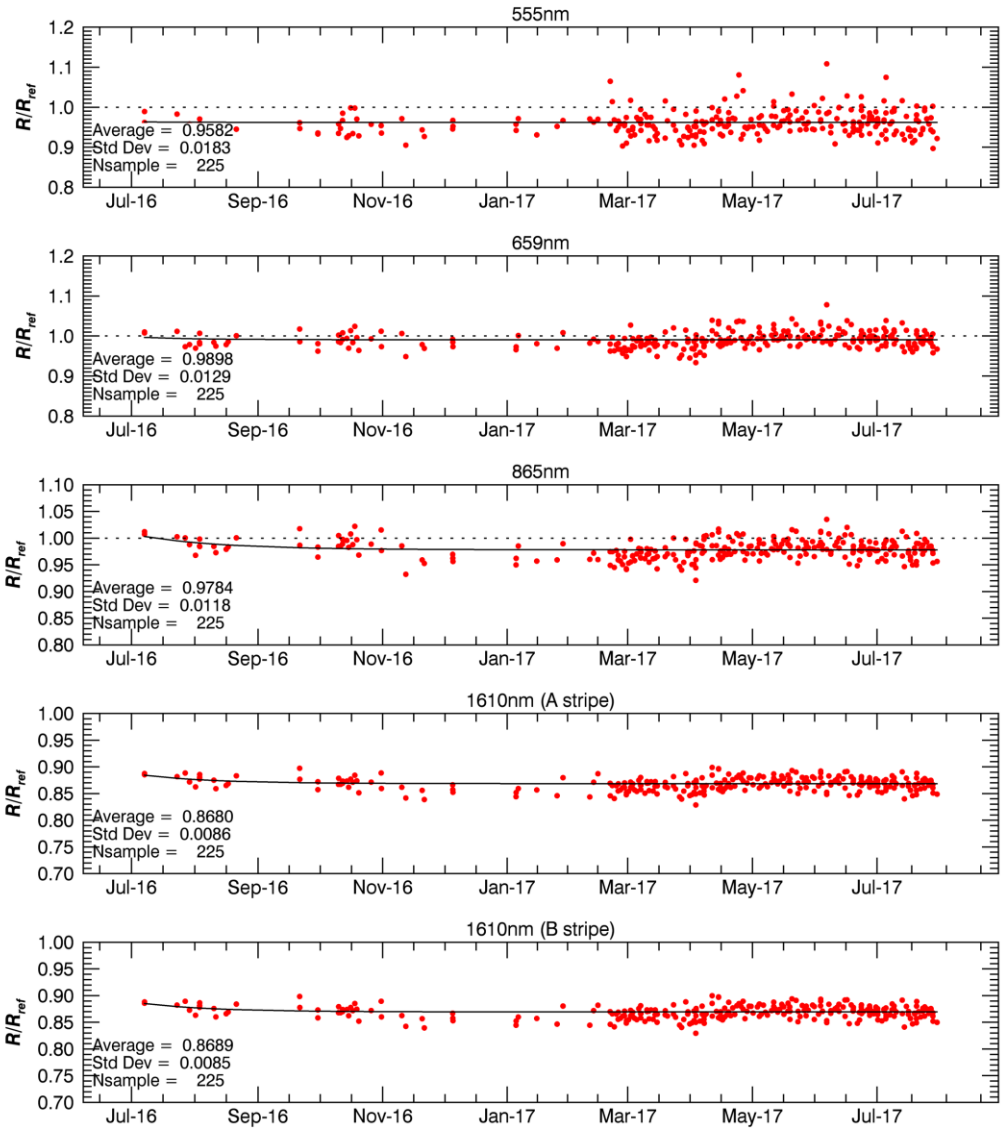
SLSTR vs AATSR BRF



Atmospheric corrections are not performed in the first instance since it is assumed that AATSR and SLSTR spectral responses are well matched

Any short term variations in atmospheric conditions should average out with time

SLSTR vs AATSR (Nadir View)



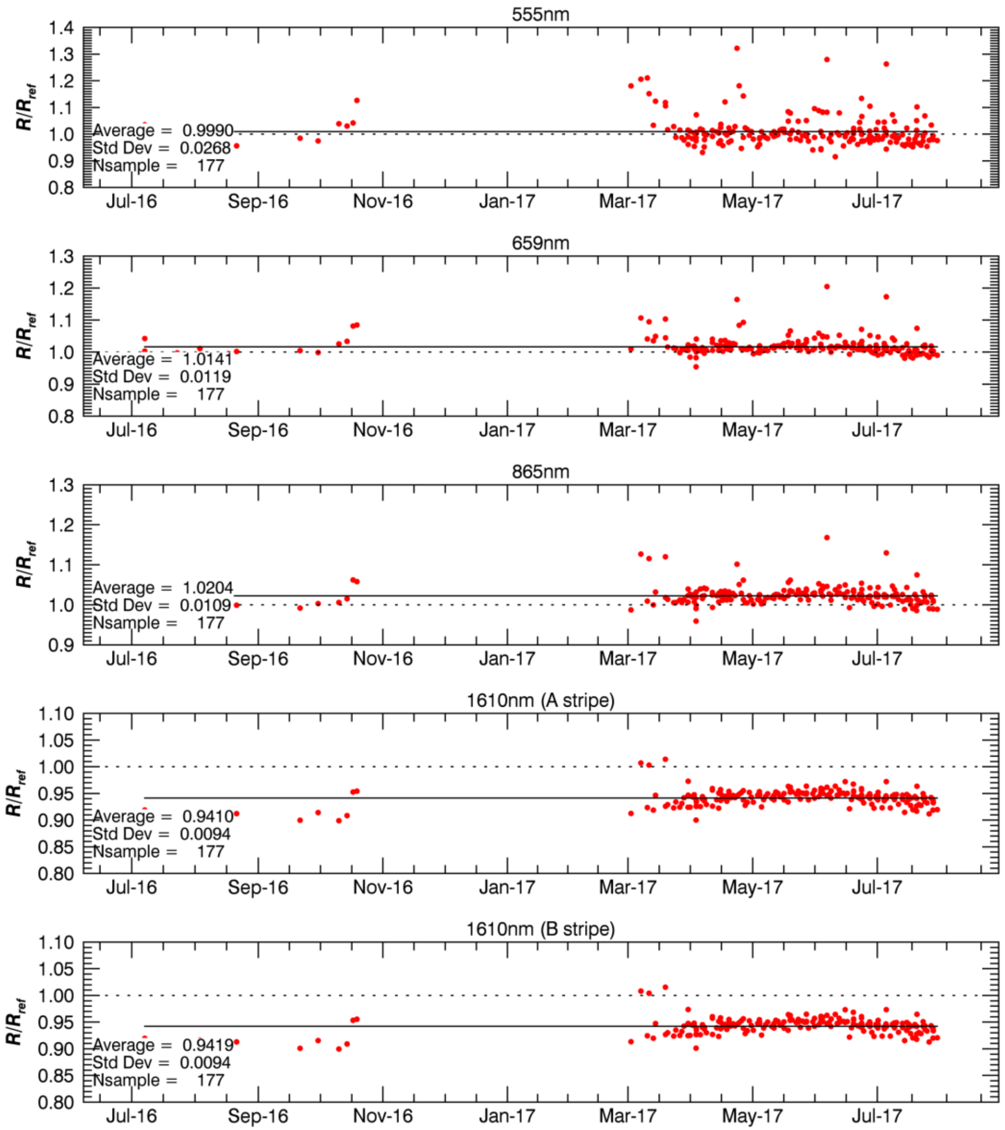
Combined results for all desert sites processed to date

Match-ups constrained to VZA <25 degrees

Drift follows exponential decay model to first order

SWIR A and B stripes show excellent agreement – mean difference < 0.1% ☺

SLSTR vs AATSR (Oblique View)



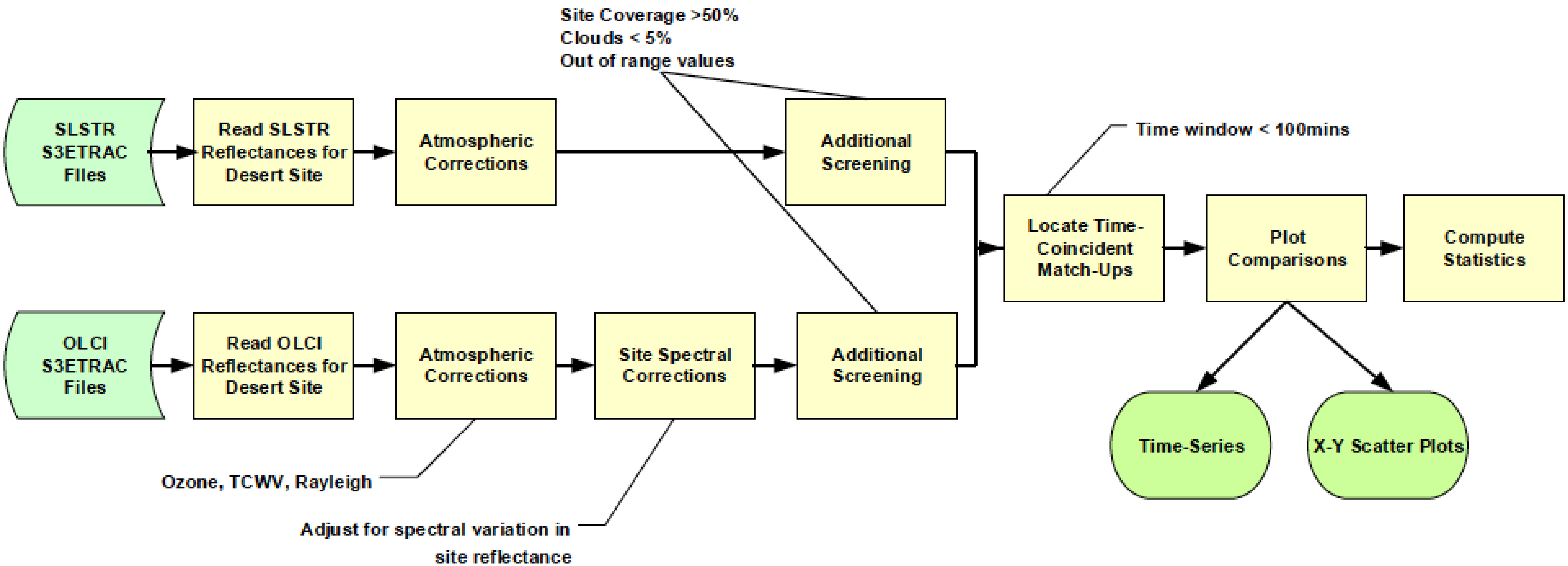
Combined results for all desert sites processed to date

Match-ups constrained to observations where nadir VZA <25 degrees

SWIR A and B stripes show excellent agreement – mean difference < 0.1%

Results suggest oblique view SWIR calibration is better than nadir !

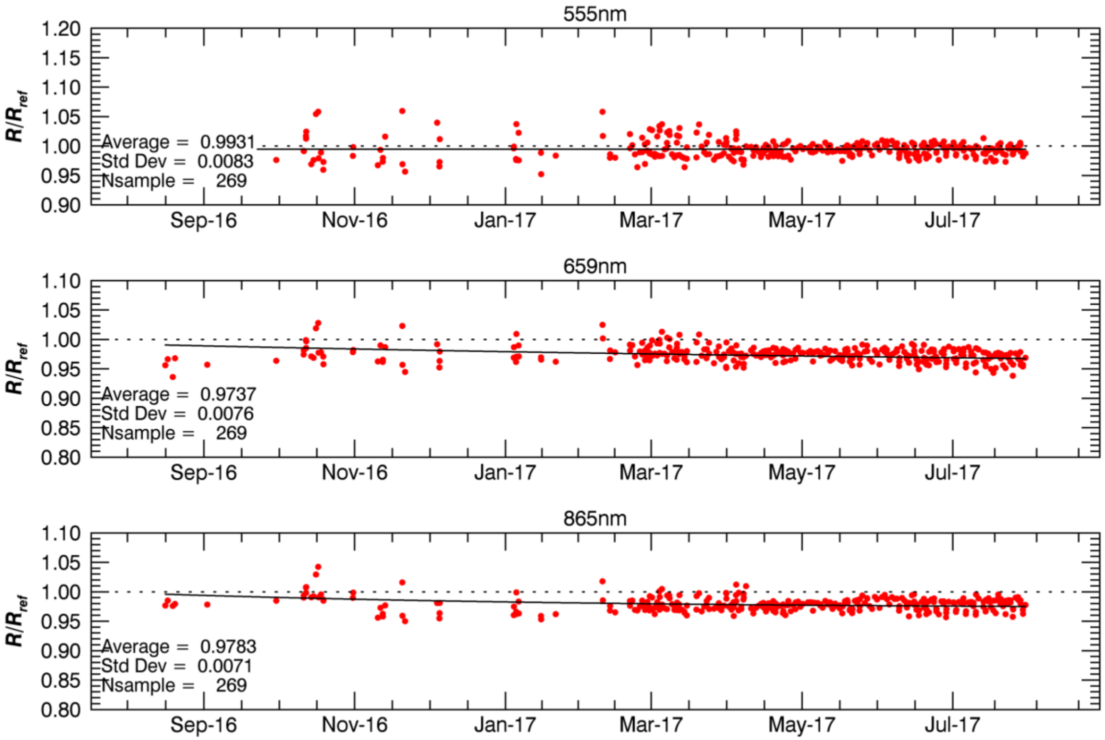
SLSTR vs OLCI



Geometric correction is not performed since measurements are time coincident and near matching geometry

Corrections for spectral variations, atmosphere + site spectral profile are needed

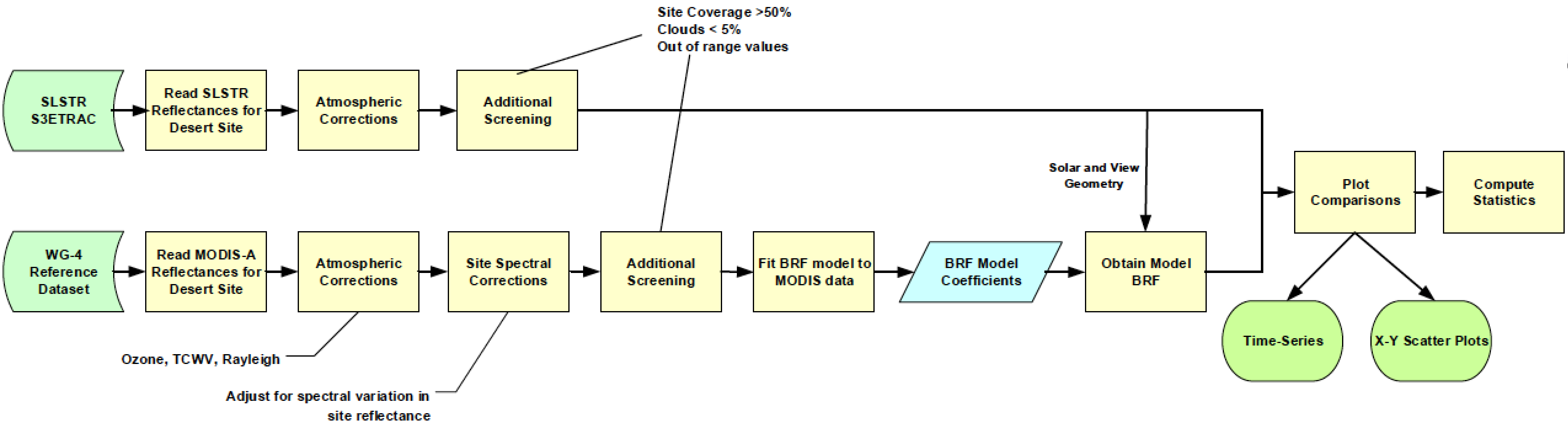
SLSTR vs OLCI



Combined results for all desert sites processed to date

Match-ups constrained to observations where nadir VZA <25 degrees

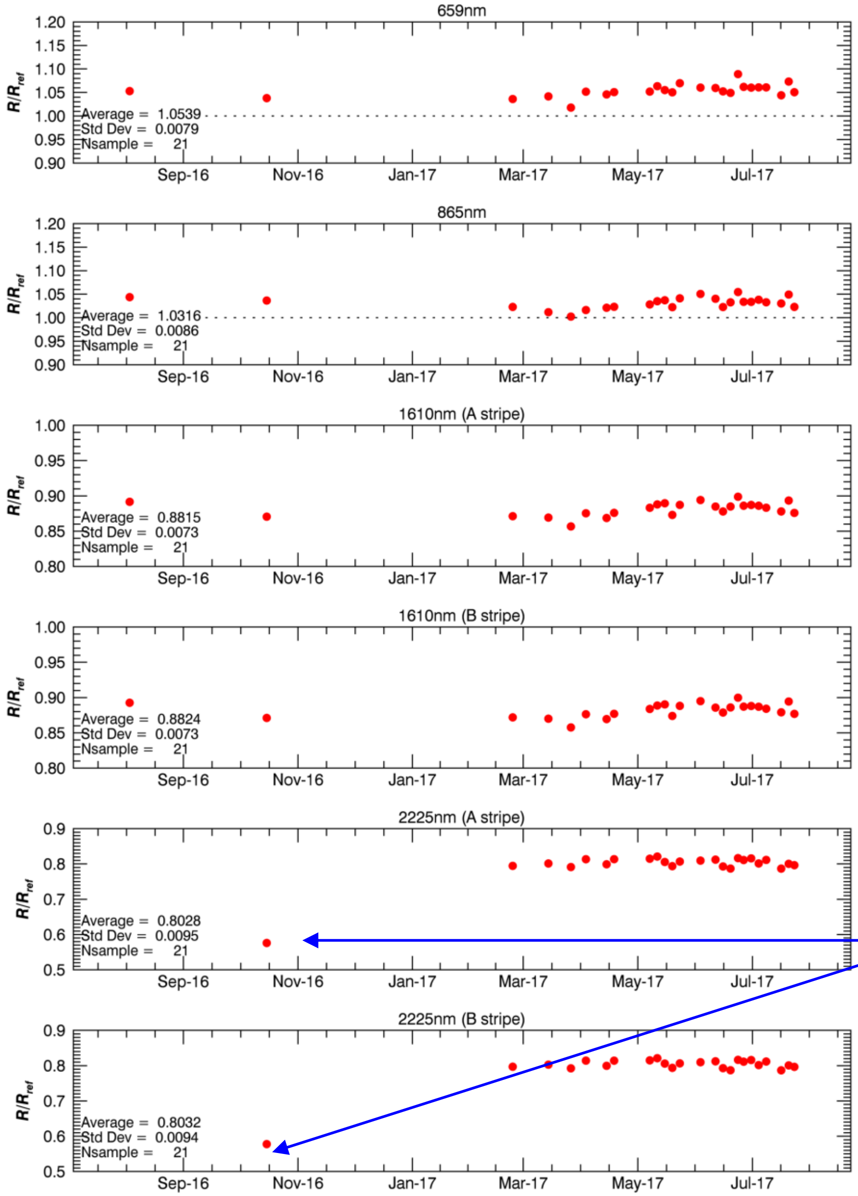
SLSTR vs MODIS Aqua



Geometric corrections are needed to account for different overpass times

Corrections for spectral variations, atmosphere + site spectral profile are needed

SLSTR vs MODIS-Aqua



Data for Libya-4 only from CEOS WG-4 dataset

Match-ups constrained to observations where nadir VZA <25 degrees

Results consistent with comparisons with AATSR

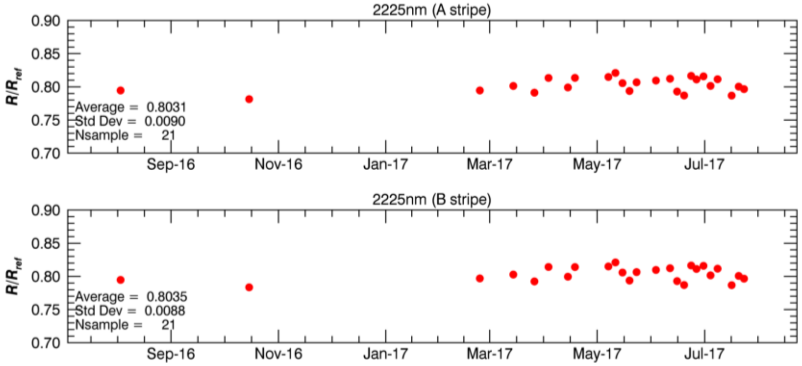
Note S6 jump in calibration – corresponds to update in CCDB

S6 Calibration Factors

Detector	Channel	Report Issue 2.0	CCDB 09/09/2016	On-Orbit (BOL)	Reprocessed pre-launch
S6.8	S6a 1	0.1218	0.1640	0.1779	0.1507
S6.7	S6a 2	0.1201	0.1576	0.1768	0.1477
S6.6	S6a 3	0.1253	0.1723	0.1874	0.1552
S6.5	S6a 4	0.1314	0.1826	0.1993	0.1631
S6.4	S6b 1	0.1330	0.1731	0.1878	0.1673
S6.3	S6b 2	0.1253	0.1715	0.1831	0.1558
S6.2	S6b 3	0.1356	0.1818	0.1946	0.1687
S6.1	S6b 4	0.1402	0.1987	0.2157	0.1765
		Ratio new:old	1.3571	1.0865	

SLSTR vs MODIS-Aqua
S6 with calibration adjustments

CCDB Update – Dec 2016

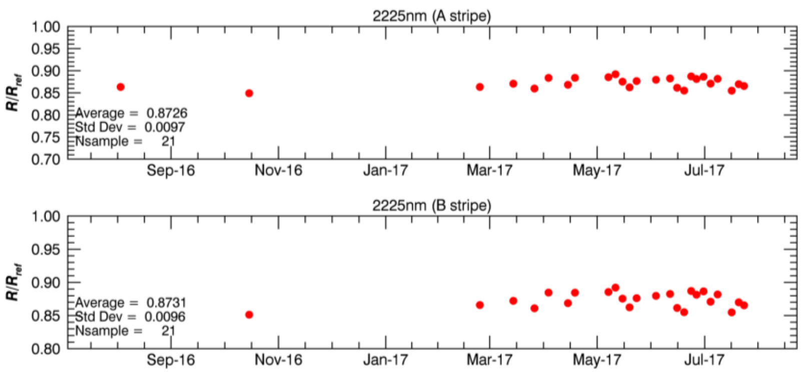


S6 now shows consistent trend for all measurements

~20% difference wrt. MODIS

A and B stripes agreement to <0.1%

Using first light measurements



~13% difference wrt. MODIS

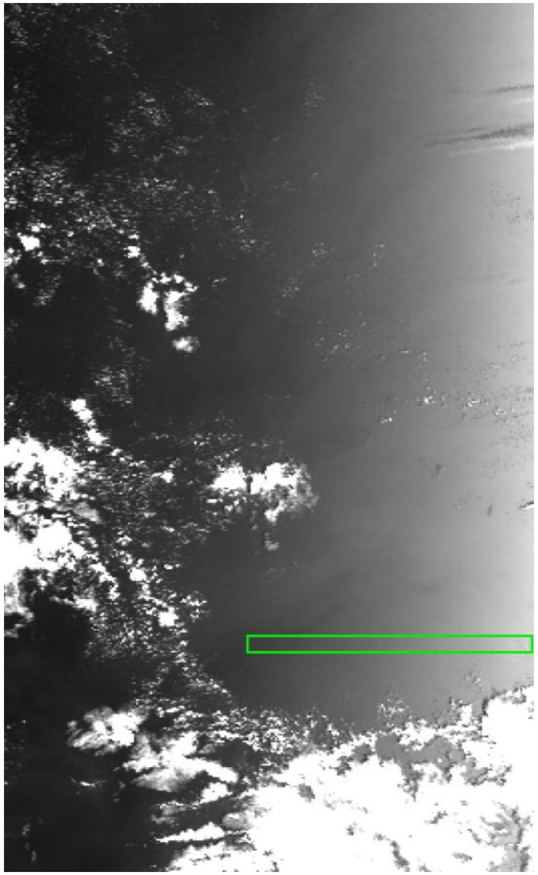
S6 now similar to S5

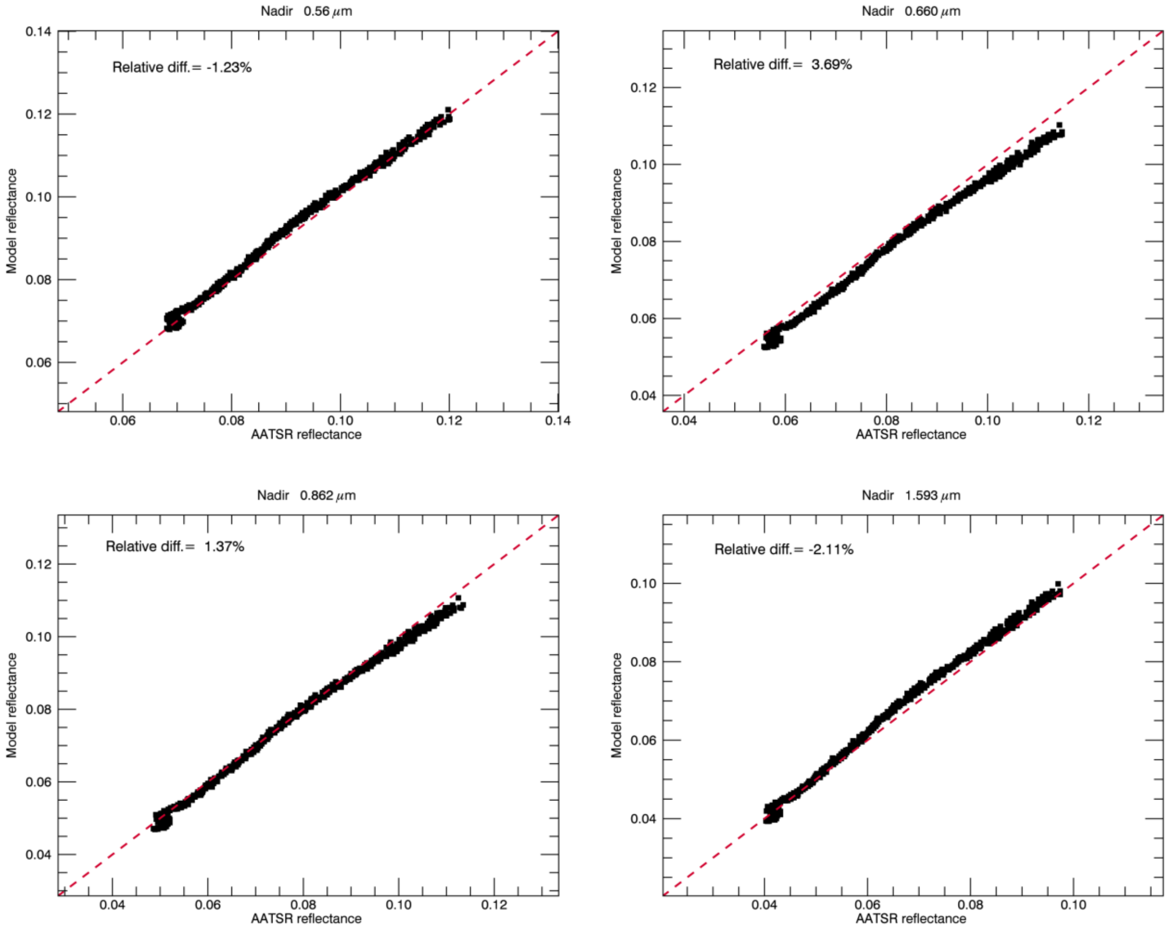
Sun-Glint Calibration Model

RAL Space

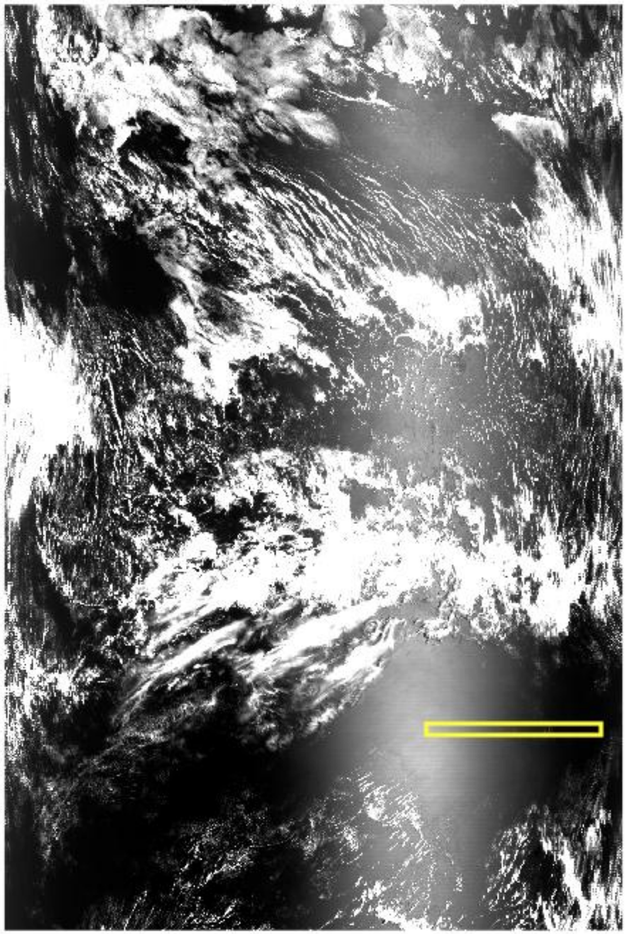
- The Sun-glint model is based on Cox and Munk (1954) and accounts for:
  - Surface reflectance (white-cap, wind-roughened surface)
  - Rayleigh scattering
  - Atmosphere transmittance
- For AATSR and MODIS we have used ECMWF data for wind speed and Aerosol values from Aeronet
- All the inputs needed are in the SLSTR Level-1 data products, **except aerosol optical depth**!
- So for SLSTR we need to determine the visibility, aerosol size distribution, and wind velocity by constraining the model to S1, S2 and S3
  - We assume that the relative calibration error is <3% (based on desert analysis)
- This is done for each image!

Sun-Glint Model vs. AATSR South Pacific 04/01/2010

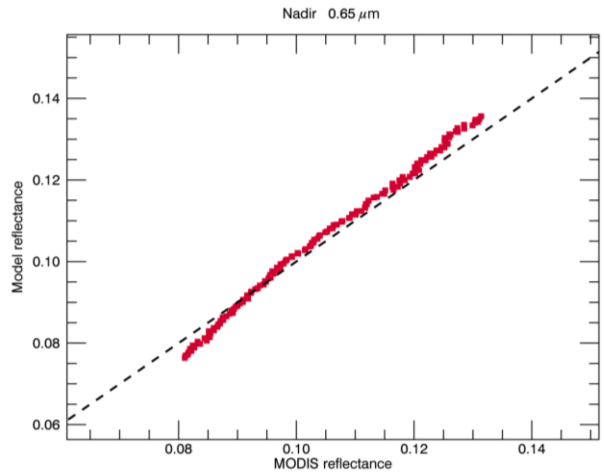




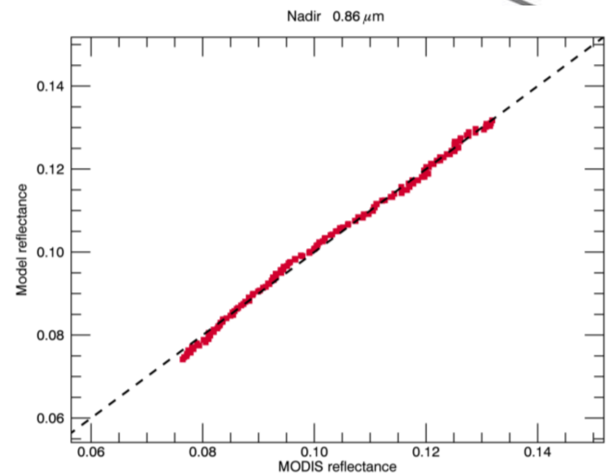
Sunglint Model vs. MODIS South Pacific 01/04/2017



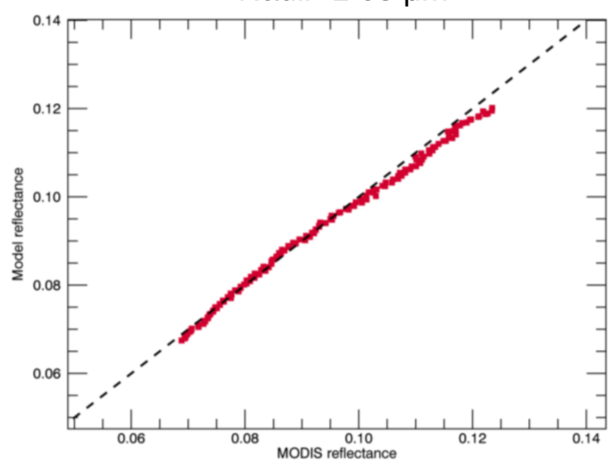
Nadir 0.65 µm



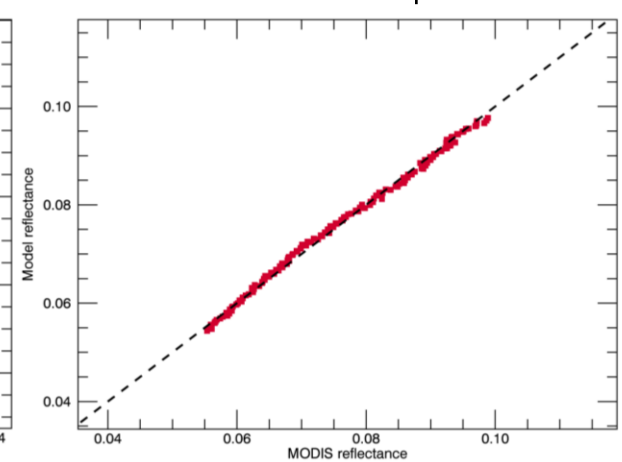
Nadir 0.86 µm



Nadir 1.63 µm



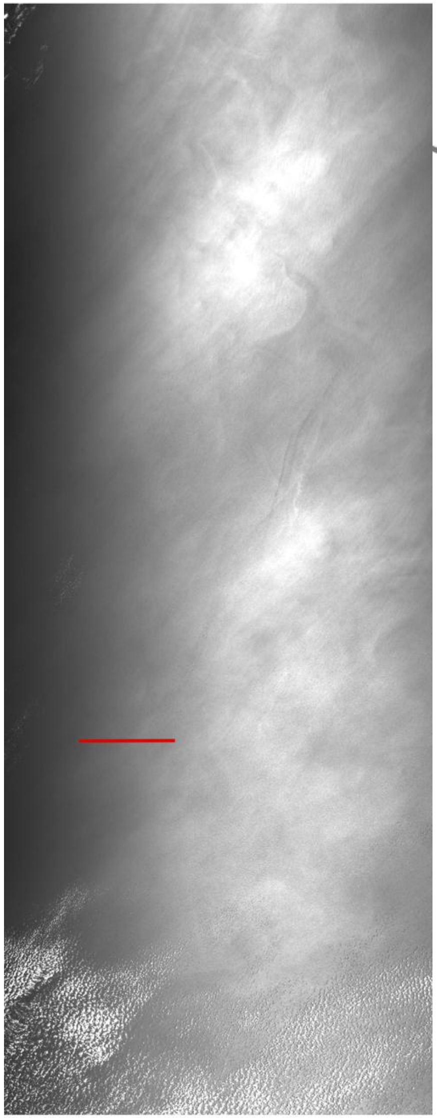
Nadir 2.11 µm



SLSTR vs Sunglint Model North Pacific 22/04/2017

Image from: https://coda.eumetsat.int/#/home

Product Name: S3A_SL_1_RBT____20170422T185118_20170422T185418_ 20170422T205046_0179_017_013_2520_MAR_O_NR_002.SEN3



The best solution for this image is for the following conditions:

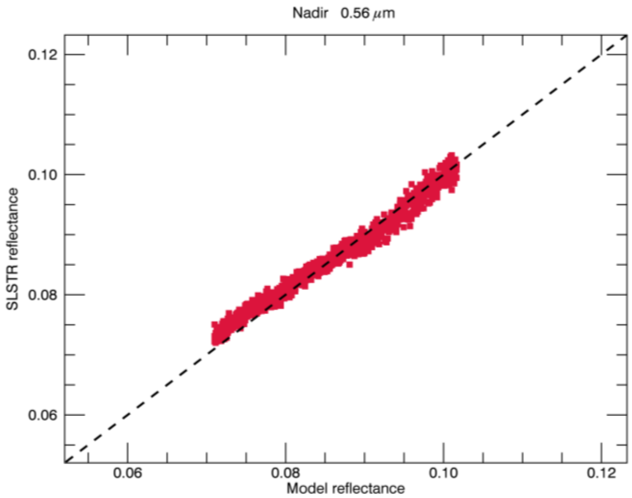
τ_{aer} (0.55 μm)= 0.099

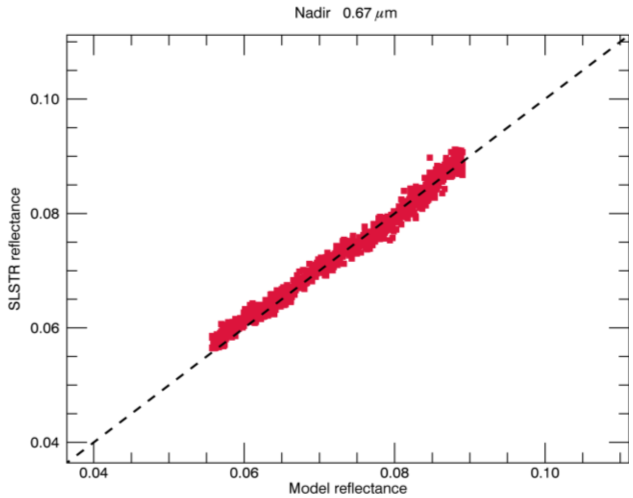
wind_x= -2.5 m/s (30% lower than wind_x provided in Level-1)

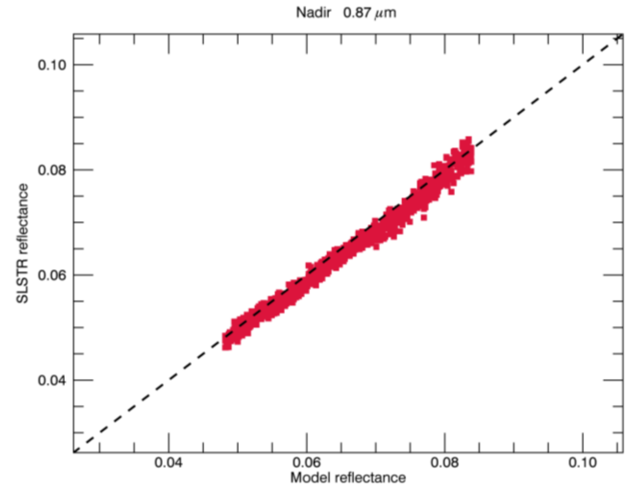
wind_y= -6.6 m/s (as provided in the Level-1 image)

Sunglint coordinates: lat= 22.63 deg., long= -128.36 deg.

SLSTR data vs. model







Ratio - meas/model:

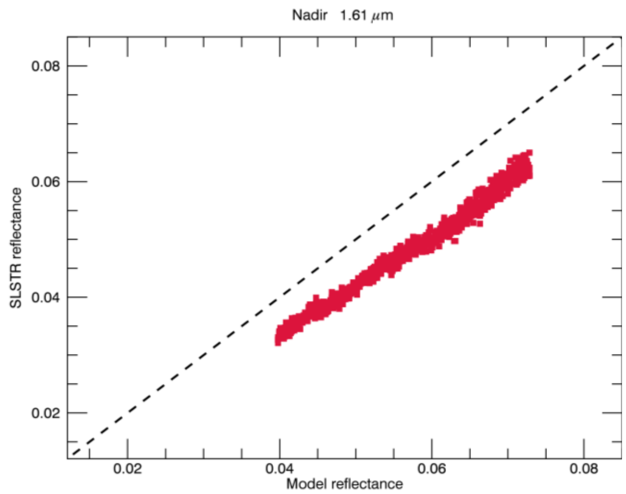
S1: 0.9840 (0.021) *

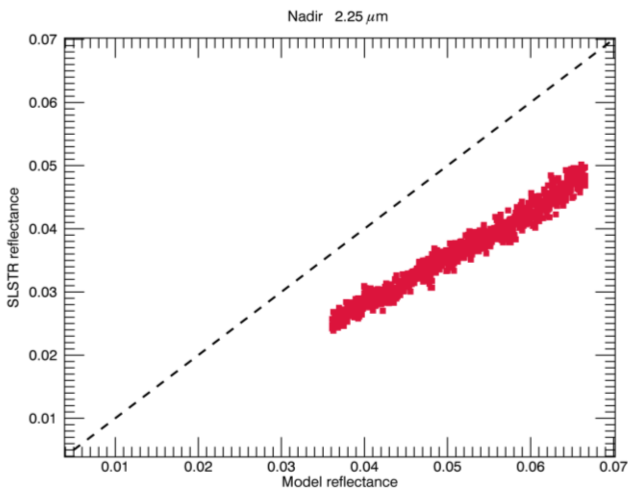
S2: 0.9830 (0.012) *

S3: 0.9980 (0.007)*

S5: 0.8560 (0.028)

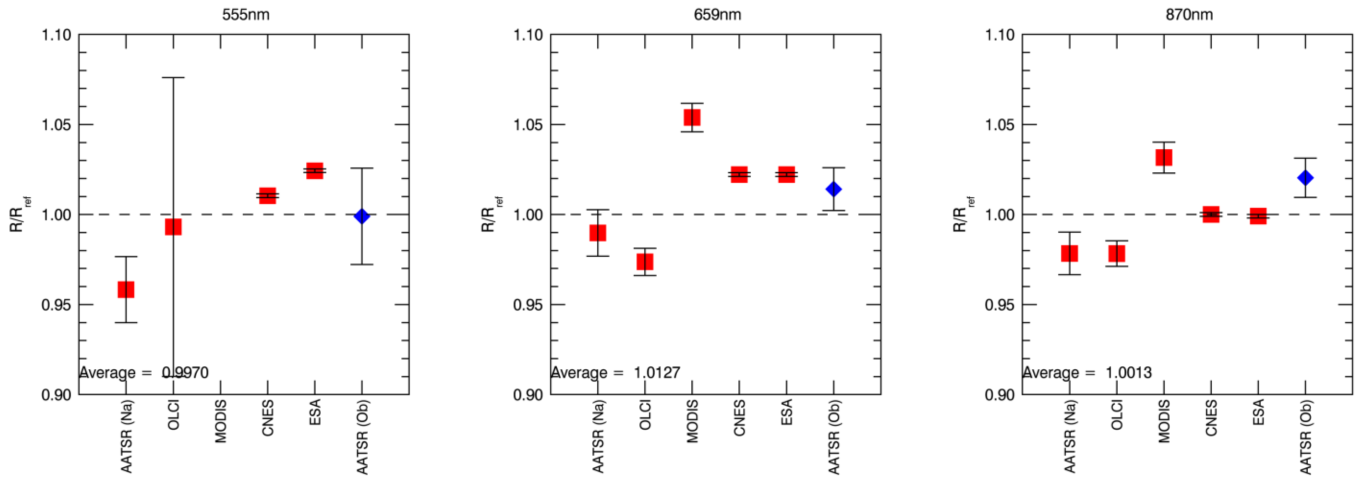
S6: 0.6950 (0.039)



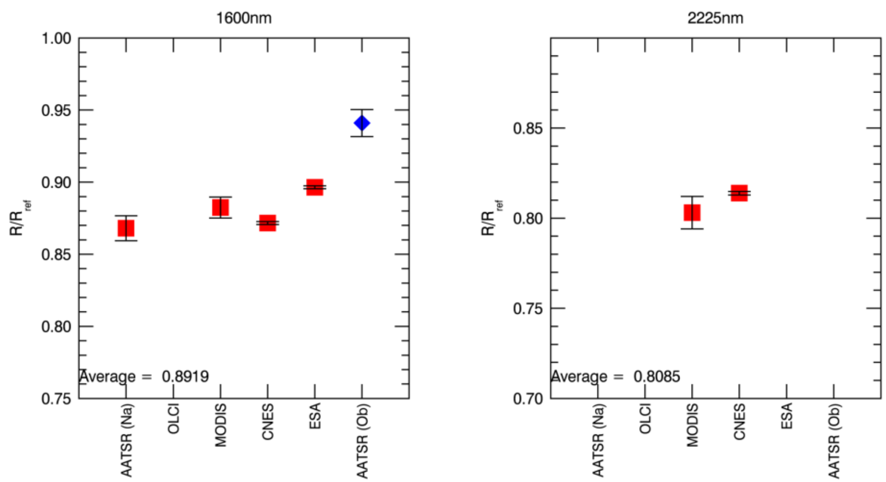


* Note model constrained to S1, S2, S3

VIS/SWIR Calibration Summary



Charts shows measured reflectances relative to reference



Data for S6 have been adjusted for update of CCDB

CNES and ESA (M. Bouvet) data from S3A IOCR in July 2016

Conclusions

- Pre-Launch calibration gives reflectance factors under ideal conditions.
  - For SLSTR we have found pixel-pixel differences due to instrument artefacts – gives rise to image ‘striping if not corrected’
  - Cross calibration of source necessary for all lamp combinations
- On orbit monitoring shows need for regular calibration monitoring for all channels and both views
  - Note early design phases proposed no VISCAL for SLSTR (or descoped version for nadir only).
- Vicarious calibration essential to determine any ground-on-orbit differences
  - Good agreement with OLCI for corresponding bands
  - Significant differences at SWIR channels – not fully explained yet
  - Data for early mission needed to complete time series
  - Uncertainty budgets to be compiled