CLARREO Inter-Calibration Studies Using SCIAMACHY and PARASOL Data

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Presentation Outline

- CLARREO inter-calibration goal.
- CLARREO: high resolution spectrometer with polarimetric ability on board.
- CLARREO inter-calibration approach.
- SCIAMACHY and PARASOL data.
- Definition of simulation parameters: sampling, offset, gain, RSR, matching noise.
- New simulation results:
  - broadband instrument (CERES)
  - narrowband instrument (MODIS)
- DOP (linear) from PARASOL.
- Summary.

CLARREO Inter-Calibration Goal

- **To be able to detect the anthropogenic radiative forcing of ~ 0.6 Wm^{-2} $decade^{-1}$**
  (IPCC Forth Assessment Report, 2007)
  50% change = 0.3 $Wm^{-2}decade^{-1}$ globally.

- **Relative to 50 Wm^{-2} (global average SW cloud radiative forcing) = 0.6%.**

- **Reducing uncertainty to 25% would require stability of 0.3% $decade^{-1}$ for SW broadband *(Loeb et al., 2007)*.**

- **<u>CLARREO Goal:</u> At least 0.2% (2σ) relative accuracy for SW broadband.**

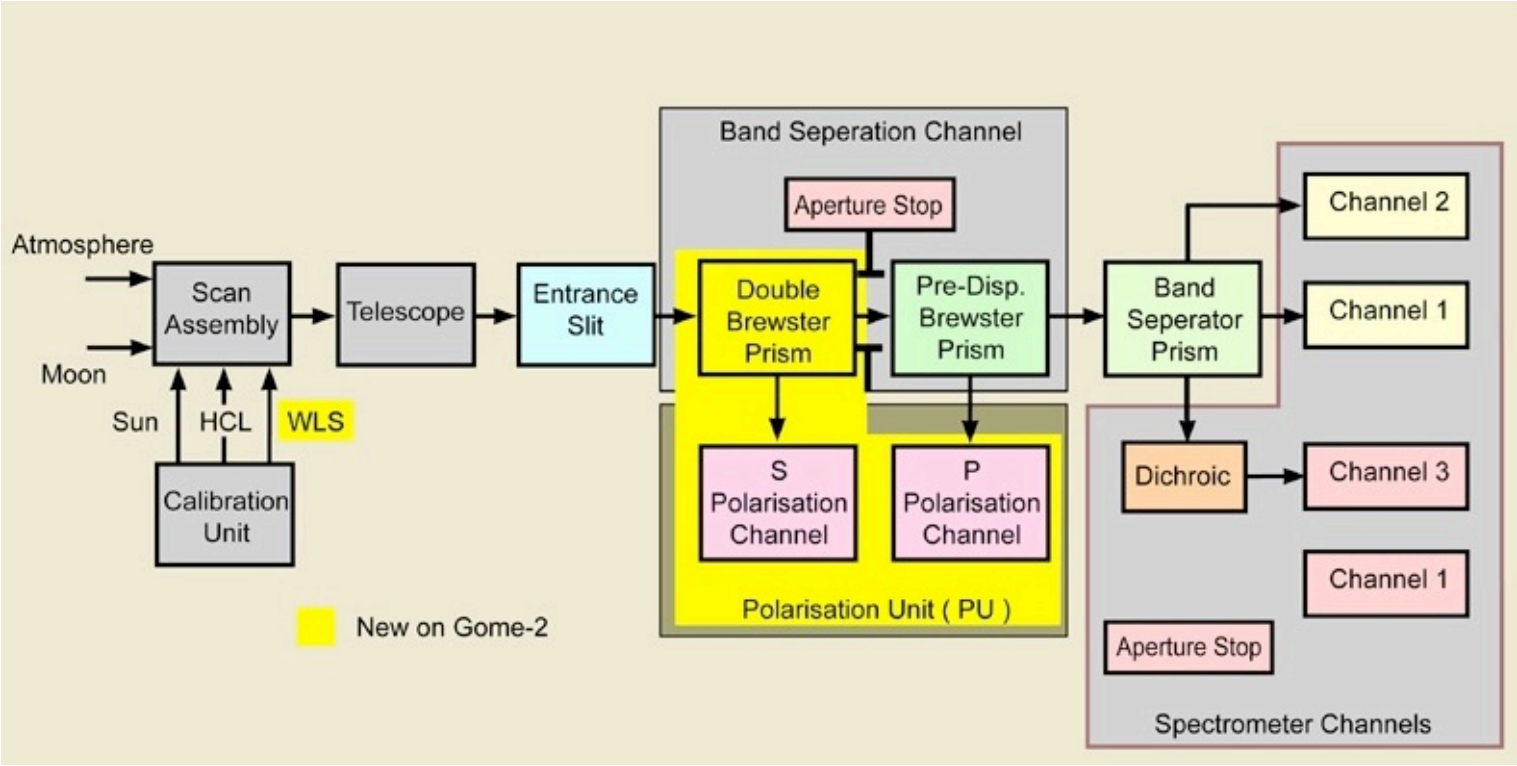
High Resolution Spectrometers with Polarimetry on Board

- **GOME-1 on ERS-2 (1995 – 2003 limited data, trace gases):**
  - Scanning. Spatial resolution from 40 km^2 to 40 x 320 km^2. Global coverage every 3 days.
  - Spectral range 240 – 790 nm with resolution 0.2 – 0.4 nm.
  - Correction for polarization from simultaneous measurements of Stokes *Q* and *U* in 3 bands.

- **SCIAMACHY on ENVISAT (2002 – Present, trace gases):**
  - Scanning. Spatial resolution from 30 x 60 km^2 to 30 x 240 km^2. Global coverage every 3 days.
  - Spectral range 240 – 1750 nm with resolution 0.2 - 1.5 nm.
  - Correction for polarization from simultaneous measurements of Stokes *Q* in 8 bands and *U* in one band.

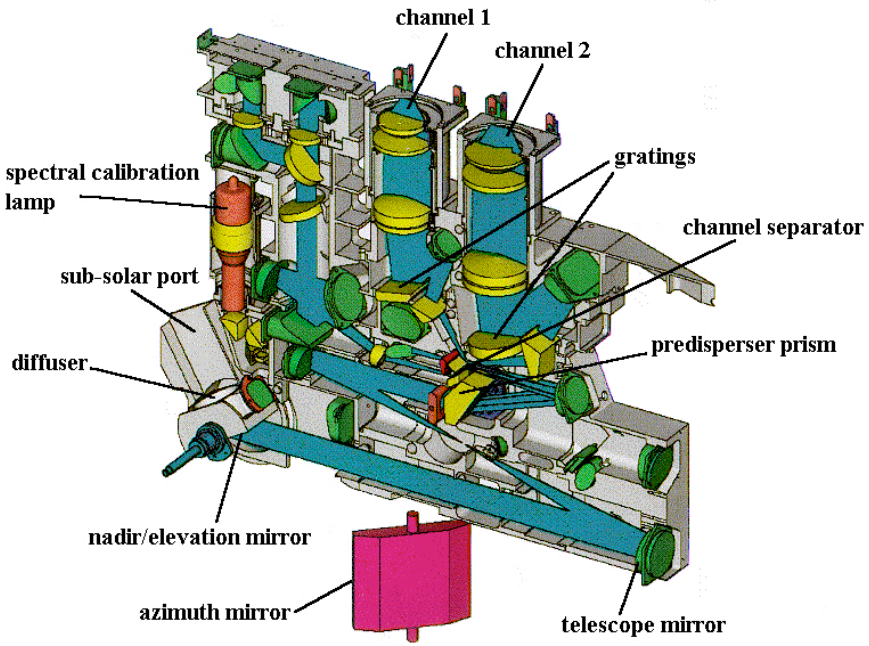
- **GOME-2 on MetOp (2006 – Present, trace gases):**
  - Scanning. Spatial resolution 40 km^2 for *I*, and 40 x 5 km^2 for polarization measurements. Global coverage every 3 days.
  - Spectral range 240 – 790 nm with spectral resolution 0.2 – 0.4 nm.
  - Simultaneous polarization measurements in 12 bands in spectral range from 312 to 790 nm with resolution from 2.8 nm to 40 nm, used for polarization correction and aerosol / clouds retrievals.

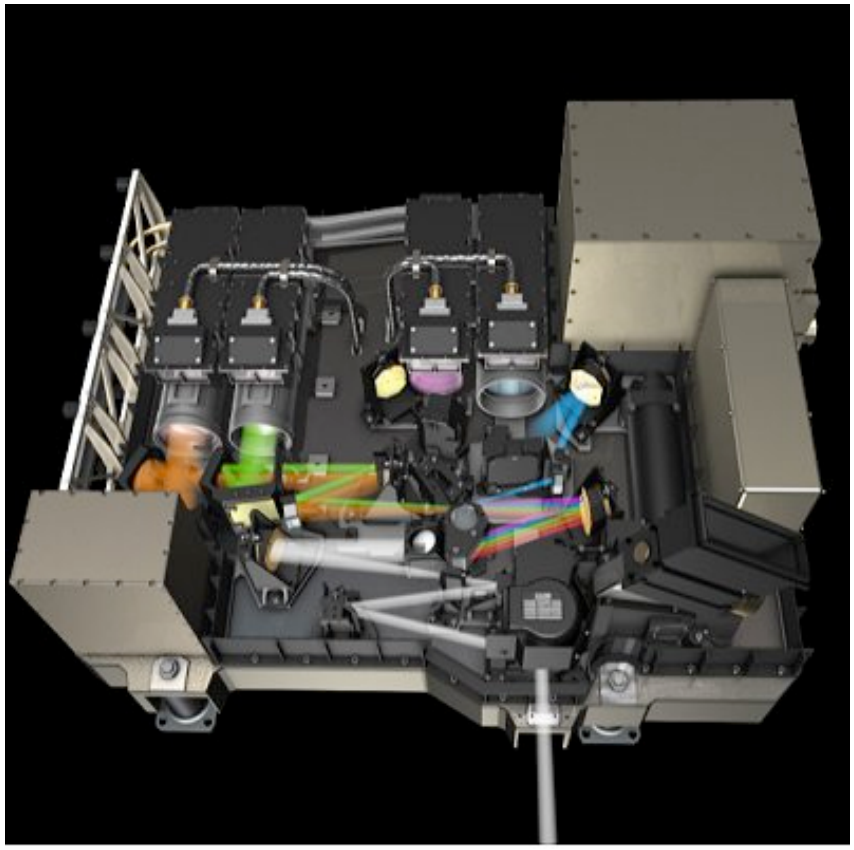
GOME-2 Instrument Design



- **The diagram is taken from ESA MetOp official web site.**

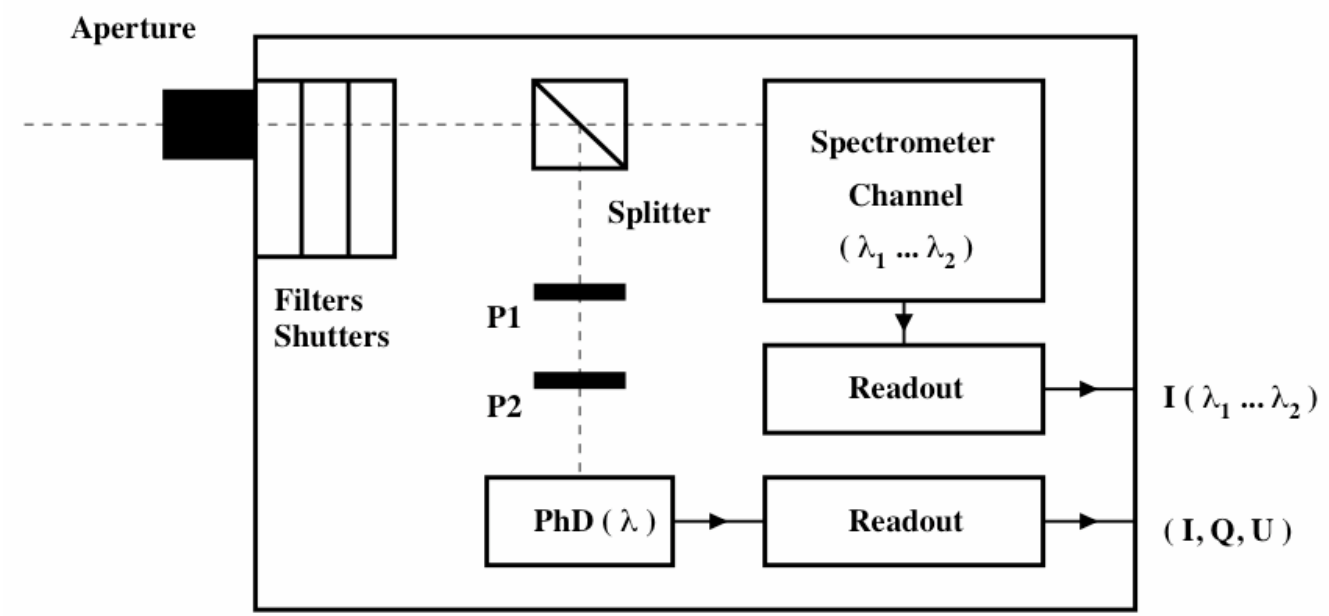
SCIAMACHY / GOME-2 Instruments





- **The pictures are taken from ESA official web site.**
- **<u>SCIAMACHY and GOME</u> experience:** ***Lichtenberg et al. (ACPD 2005), Schutgens and Stammes (JGR 2003), Schutgens et al. (JGR 2004), Tilstra and Stammes (ACP 2005).***

Possible Design of CLARREO Solar Channel

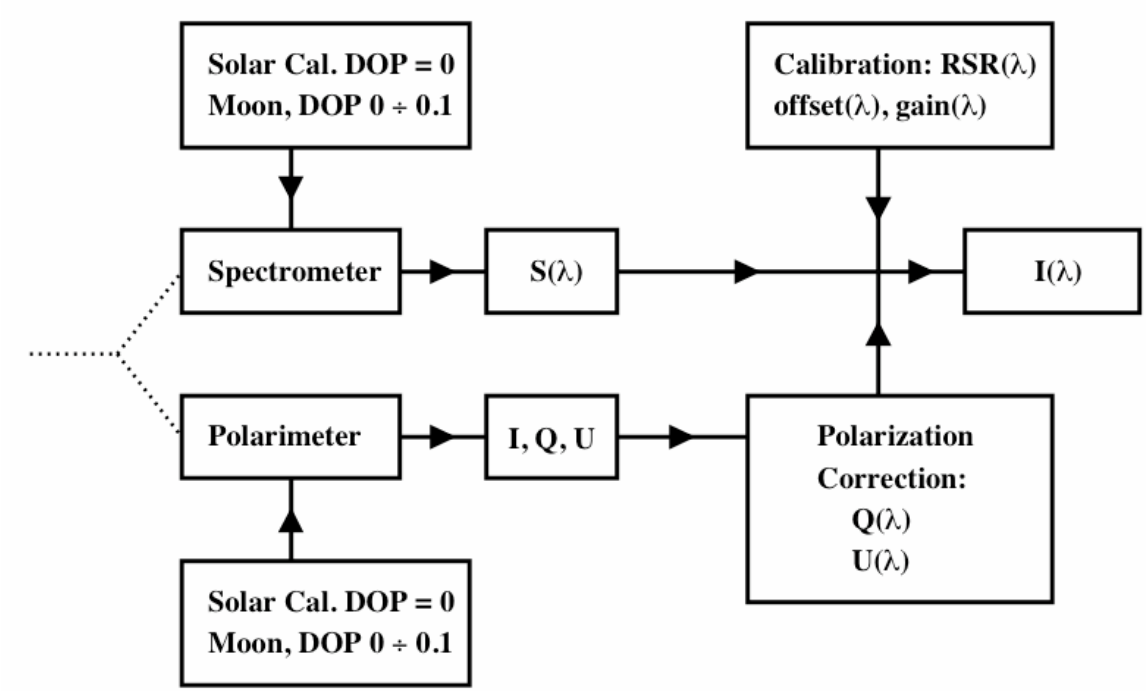


- **Spectrometer with 0.2% (1σ) accuracy (LASP IIP): $I(\lambda_1 - \lambda_2)$, designed with minimal sensitivity to degree of polarization (DOP): 0.2 % ?**

- **Simultaneous polarization measuremens with accuracy ≤ 1%: (I_λ, Q_λ, U_λ). Accuracy improvement with solar / lunar calibrations ?**

- **Sufficient number of polarization channels ? For 300 nm – 800 nm spectral range optimal *N* = 4 ? *(GOME-1, Schutgens and Stammes JGR 2003)***

Data Flow in CLARREO Solar Channel



- **Pre-launch:** **Characterization of CLARREO (every channel) sensitivity to polarization as explicit function of Stokes parameters: *I, Q, U* .**

- **On orbit:** **Correction of CLARREO raw signal for polarization using simultaneous measurements of the Stokes parameters (interpolation of Stokes parameters over spectral range).**

CLARREO Inter-Calibration Task

- **Formulation:**
  Inter-calibration process is multi-dimensional minimization of the difference between a sensor and CLARREO (true SI-traceable) signals performed for all available sampling with dimensionality equal to the number of *UNCERTAIN* parameters in sensor response function (offset, gain, RSR, cross-talk, polarization, etc.).

- **Concept of SI-Traceability:**
  Comparison to directly *MEASURED* SI-traceable quantities such as spectral radiance, units: $N\gamma\ m^{-2}\ s^{-1}\ sr^{-1}\ nm^{-1}$.

- **Sensitivity to Polarization:**
  - **For a polarimeter inter-calibration is performed in dimension space of Stokes parameters.**
  - **For a sensor without polarimeter on board inter-calibration is performed in dimensions of scene type (surface type, cloud types, etc.) and viewing geometry.**

CLARREO Inter-Calibration Task (continue)

- **CERES:** Broadband and not sensitive to polarization. All matched CLARREO/CERES data can be used together to inter-calibrate response function of the instrument.
  Imposed requirement: Broad spectral range.

- **PARASOL:** Measures *I* in 9 bands; *I*, *Q* and *U* in 3 bands. CLARREO calibration can be transferred to corresponding Stokes vector.
  Imposed requirements: Polarimetry, spatial and spectral resolution.

- **MODIS:** Sensitive to DOP on 1 - 2% level depending on band and viewing geometry (ground). On orbit ? Even DOP sensitivity is response of optic system, it results as an additional term to the gain, depending on scene type and viewing geometry.
  Inter-calibration steps for each MODIS band:

1) Stratify CLARREO/MODIS matched sampling in scene type (surface type, cloud types, etc.) and viewing geometry.
2) Use data with small DOP, and inter-calibrate offset and gain, check for RSR central wavelength shifts (expected to be small and well known).
3) Derive gain correction attributed to polarization sensitivity for all data configurations keeping offset, gain and RSR and from (2).
   Imposed requirements: large matched sampling, polarimetry, spatial and spectral resolution.

Suggestions from past work

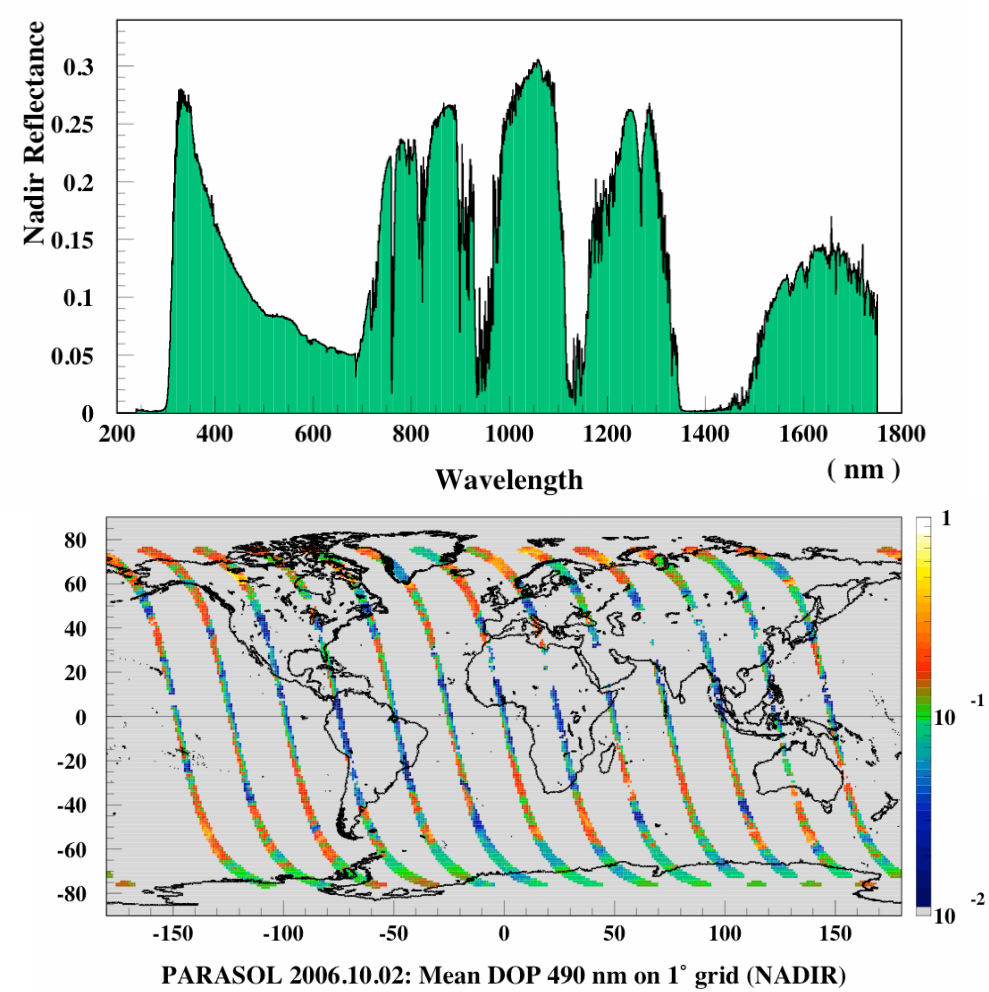
- CLARREO cross-orbit matched sampling for polar SSO is poor in tropics and mid-latitudes. For inter-calibration task CLARREO in precessing orbit would provide more sampling in tropics (this is contrary to the climate benchmark task):
  - Clear sky scenes (ocean, vegetation) are required to unscramble RSR functions for both broadband and narrowband radiometers.
  - Good sampling for clear sky scenes is required for inter-calibration with polarization measurements involved.

- CLARREO with pointing feature would increase matched samples times 40 for reduction of matching noise and ability to stratify data for obtaining polarization corrections (it is also required for calibration events).

- Noise from CLARREO time/space/angle matching to another instrument measurements is acceptable on 1% level for inter-calibration of offset and gain with 0.02% errors on condition of CLARREO having pointing ability.

Simulation Approach:

use advantages of existing spectral radiometric and polarization measurements



Advantages:

- **SCIAMACHY** data allow to use a realistic ensemble of scene types in CLARREO sampling and provide spectra with known radiometric errors (2 - 6%).
- **PARASOL** data allow to estimate expected levels of polarization at TOA and its distributions.

Plots:

- **Top:** SCIAMACHY average nadir reflectance spectra for clear-sky evergreen forests.
- **Bottom:** PARASOL mean DOP from 490 nm band for nadir-only (VZA < 10°) measurements.

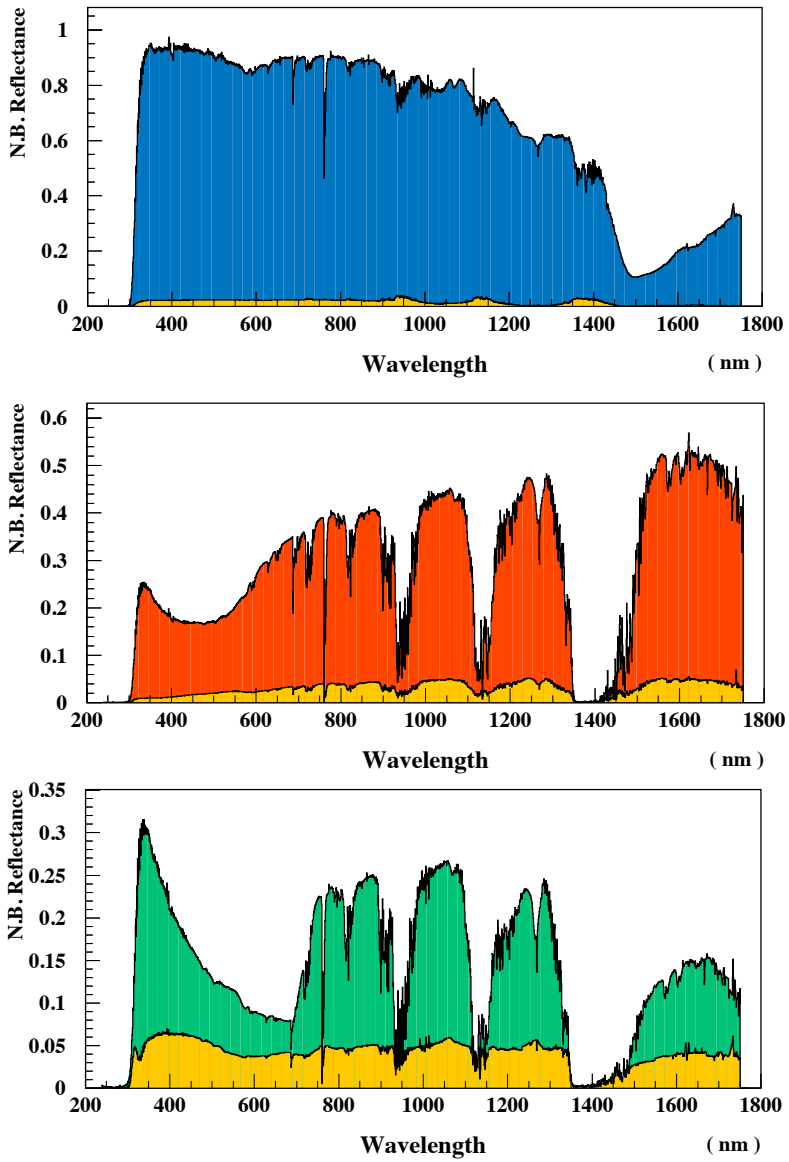
SCIAMACHY Data & Scene ID

- **ENVISAT SSP 10 am orbit (July 2002 – Present), 800 km altitude.**
- **Level-1B spectral radiance data product, latest available calibration, seasonal months for 2003 – 2007 time period.**
- **Footprint 30 km × 240 km (T_{int} = 1 s), swath 950 km in 5 integrations.**
- **Global coverage in 3 days.**
- **Continuous spectral range from 240 to 1750 nm wavelength is used.**
- **MODIS-based cloud parameters from CERES/Terra SSF matched to SCIAMACHY footprints.**

Channel	Spectral range (nm)	Spectral Resolution (nm)	Spectral Stability (nm)	Reflectance Errors (%)
1	240 - 314	0.24	0.003	3
2	309 - 404	0.26	0.003	2
3	392 - 605	0.44	0.004	3
4	598 – 790	0.48	0.005	2
5	776 - 1056	0.54	0.005	6
6	991 - 1750	1.48	0.015	4
7	1940 - 2040	0.22	0.003	Problems
8	2260 - 2384	0.26	0.003	Problems

Variability of Reflectance Spectra within a Scene Type

(SCIAMACHY 2004.07 data)



Plots:

- **Top:** SCIAMACHY average and STD nadir reflectance spectra for DCC.
- **Mid:** SCIAMACHY average and STD nadir reflectance spectra for tropical clear-sky desert.
- **Bottom:** SCIAMACHY average and STD nadir reflectance spectra for tropical clear-sky evergreen forest.

Comment:

- Spectral continuum of Intensity changes very abruptly with small variation in a scene type.

Definition of Simulation Parameters

- **Offset** – constant term of difference between sensor and CLARREO radiance, independent on wavelength, radiance units.
- **Gain** – linear term of difference, relative to CLARREO gain which is unity.
- **Nominal RSR** – sensor RSR as it is known.
- **Simulated RSR** – sensor RSR with degradation for broadband and CW shift for narrowband.
- **Noise** – combined random noise from time, space and angles mismatching, Gaussian distribution.
- **Sampling** – simulated CLARREO sampling for nadir-only and pointing capability matching (future studies should include estimates for data stratification in scene type and viewing geometry).

Definition of simulated Signals

- **CLARREO signal:** SCIAMACHY spectral radiances integrated over nominal RSR (CERES, MODIS), gain = 1.0, offset = 0.0 $Wm^{-2}sr^{-1}$.

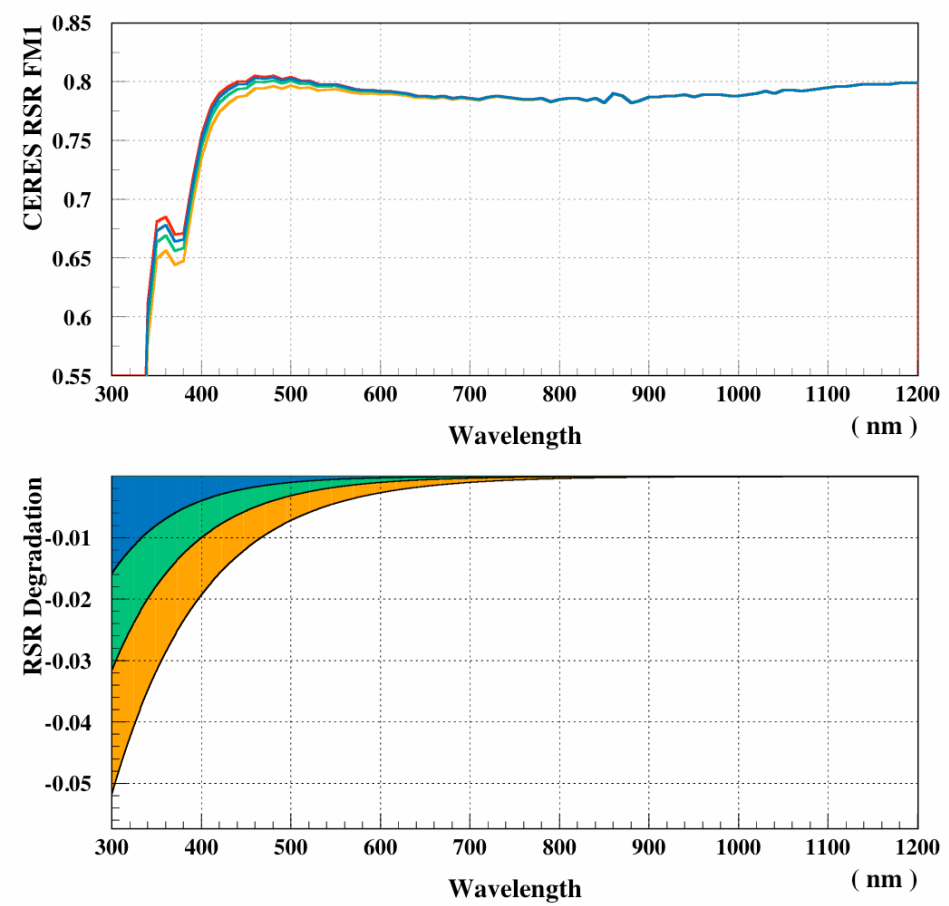
  Note: SCIAMACHY spectral radiances are corrected for polarization effects.

- **Instrument (CERES, MODIS) signals:**

  1) SCIAMACHY data integrated over nominal RSR (good), gain and offset differences with CLARREO.
  2) SCIAMACHY data integrated over simulated RSR (degradation & shifts), NO gain or offset differences with CLARREO.
  3) SCIAMACHY data integrated over simulated RSR (degradation & shifts), gain and offset differences with CLARREO.

CERES RSR Degradation Test

(SCIAMACHY data used)



Plots:

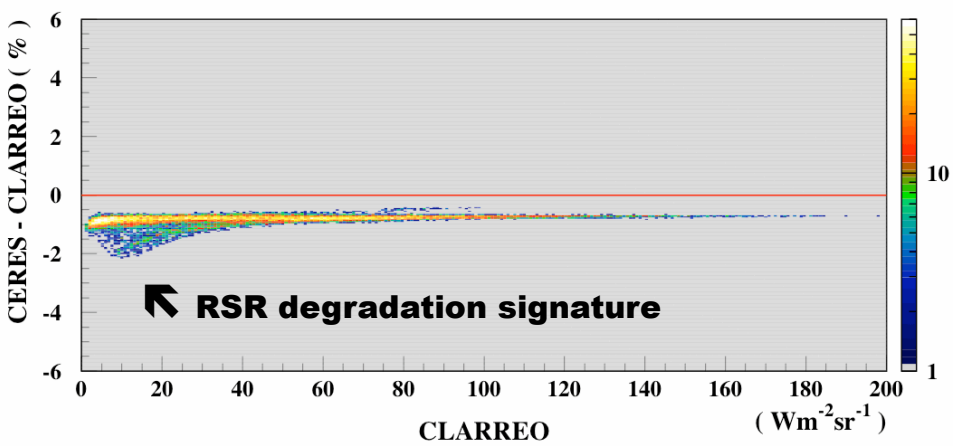
- **Top:** CERES FM1 pre-launch RSR and 3 cases of degraded RSR.
- **Bottom:** Amount of degradation

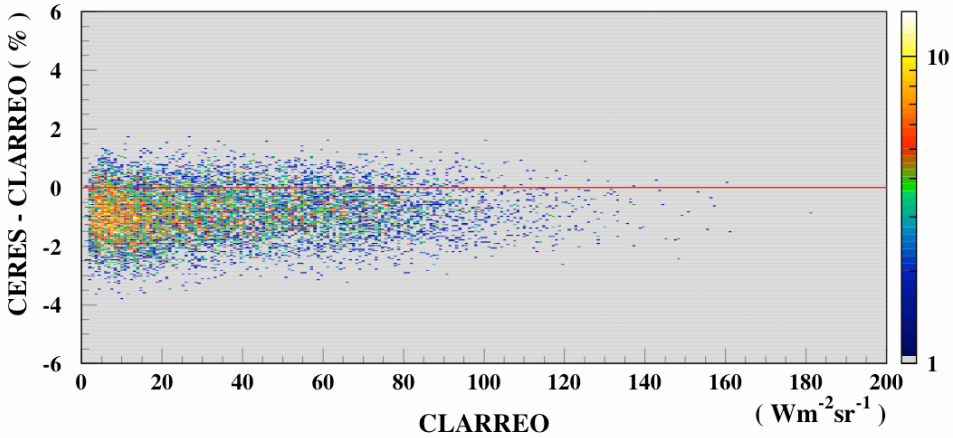
$$D(\lambda) = 1 - \exp(-\alpha\lambda)$$

α = 13.8155 (D=0.999 @ λ=0.5 μm)
α = 11.5129 (D=0.999 @ λ=0.6 μm)
α = 9.8155 (D=0.999 @ λ=0.7 μm)

CERES RSR Degradation Test

(No Offset or Gain difference, all-sky sampling)





CERES RSR Degradation:

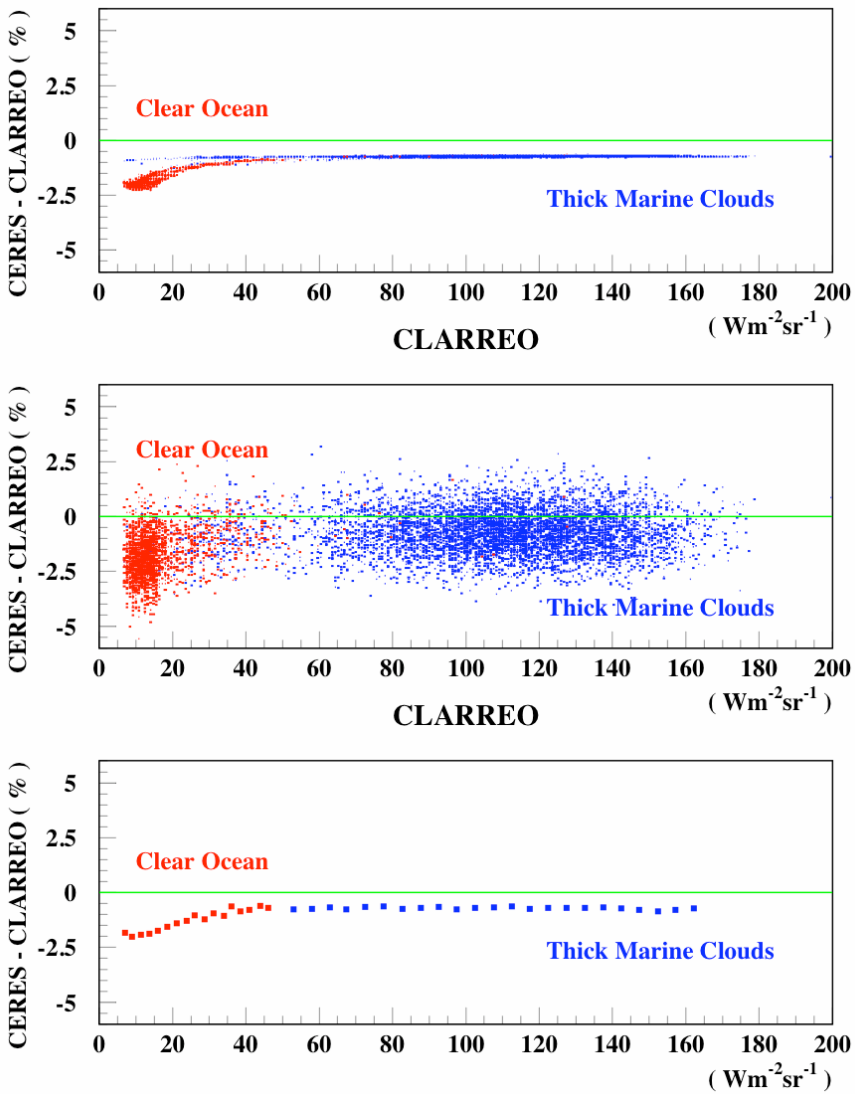
α = 9.8155 (D=0.999 @ λ=0.7 μm)

Plots:

- **<u>Top:</u> Relative difference between CLARREO and CERES versus CLARREO signals (all-sky).**
- **<u>Bottom:</u> Relative difference between CLARREO and CERES versus CLARREO signals with 1% matching noise (all-sky).**
- **For cloudy scenes effect of negative gain of about 0.7%.**
- **For clear-sky ocean and vegetation scenes effect of negative gain + offset.**

CERES RSR Degradation Test

(No Offset or Gain difference, clear ocean and marine clouds scenes)



CERES RSR Degradation:
α = 9.8155 (D=0.999 @ λ=0.7 μm)

Plots:

- **Top:** Relative difference between CLARREO and CERES versus CLARREO signals.
- **Bottom:** Relative difference between CLARREO and CERES versus CLARREO signals with 1% matching noise.

OFFSET + GAIN + NOISE :		
Scene	OFFSET ($Wm^{-2}sr^{-1}$)	GAIN (%)
CLRO	-0.183 ± 0.028	-0.31 ± 0.18
MCLD	0.021 ± 0.108	-0.73 ± 0.10

* **CLRO:** Offset error (2σ) = **0.21%**

* **MCLD:** Offset error (2σ) = **0.10%**

CLARREO/CERES Inter-Calibration

Step 1: Generate a series of reasonable RSR candidates for CERES degradation in orbit.

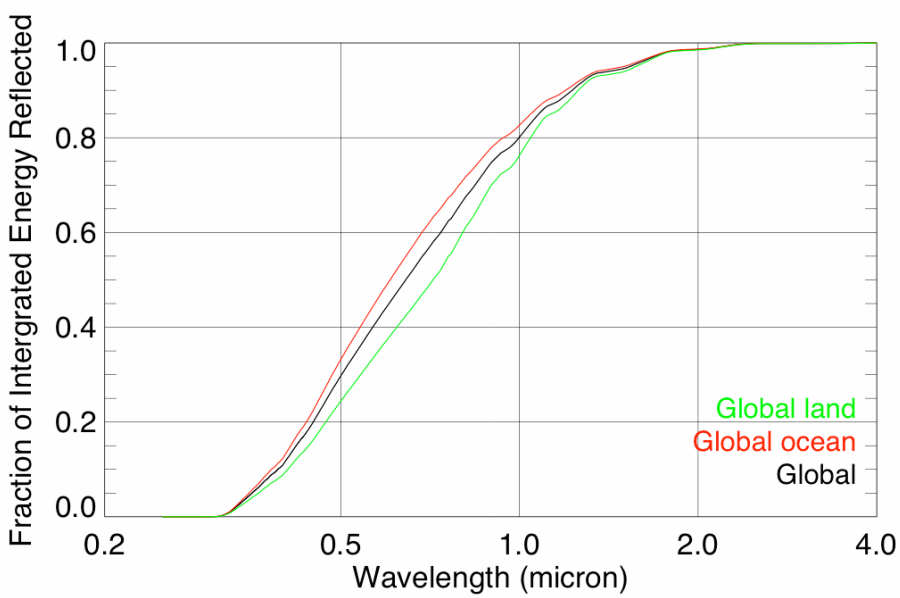
Step 2: Select clear-sky ocean and thick clouds scenes from CLARREO/CERES matched sampling. Perform noise reduction by averaging.

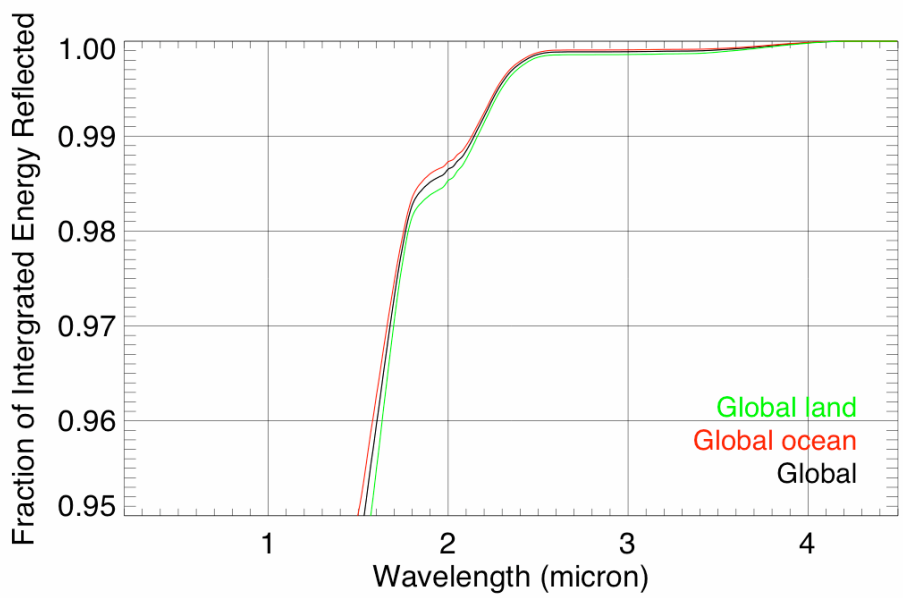
Step 3: Select the best CERES RSR for which offset and gain are ***the same*** for both scene types.

Step 4: Remaining offset and gain difference with CLARREO is attributed to the rest of CERES instrument response function.

Reflected Energy Fraction

(MODTRAN calculations by Zhonghai Jin, all sky)

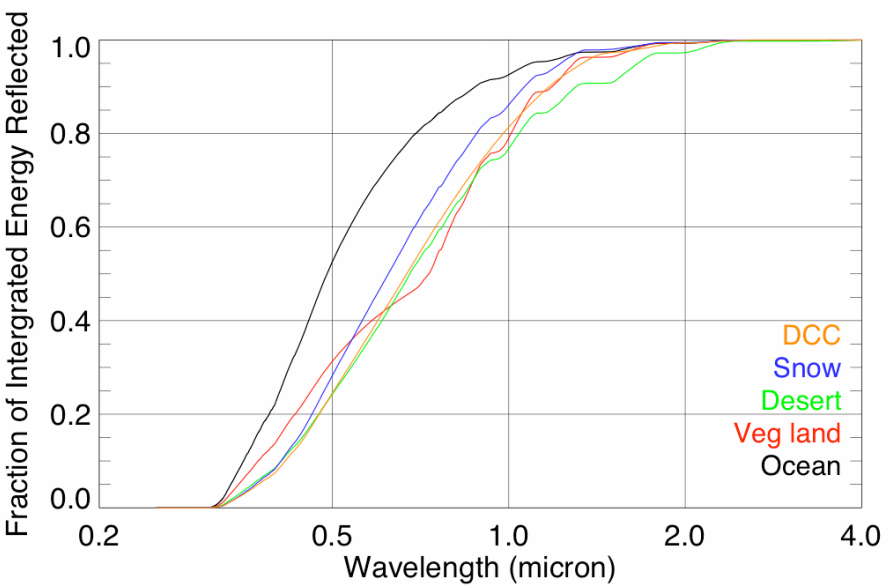


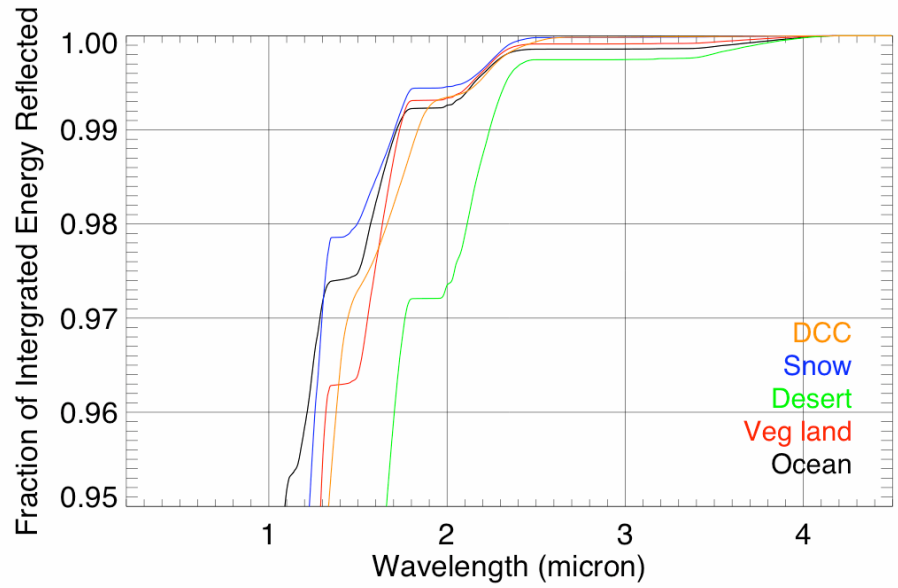


- **For all-sky cases average fraction of energy lost beyond 2.5 μm wavelength is about 0.2%.**

Reflected Energy Fraction

(MODTRAN calculations by Zhonghai Jin, scene types)

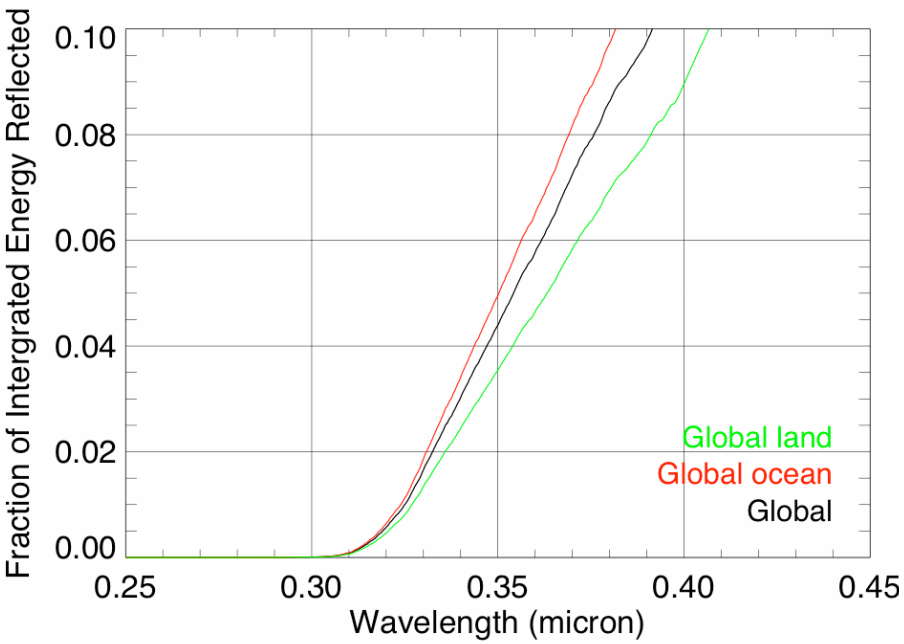


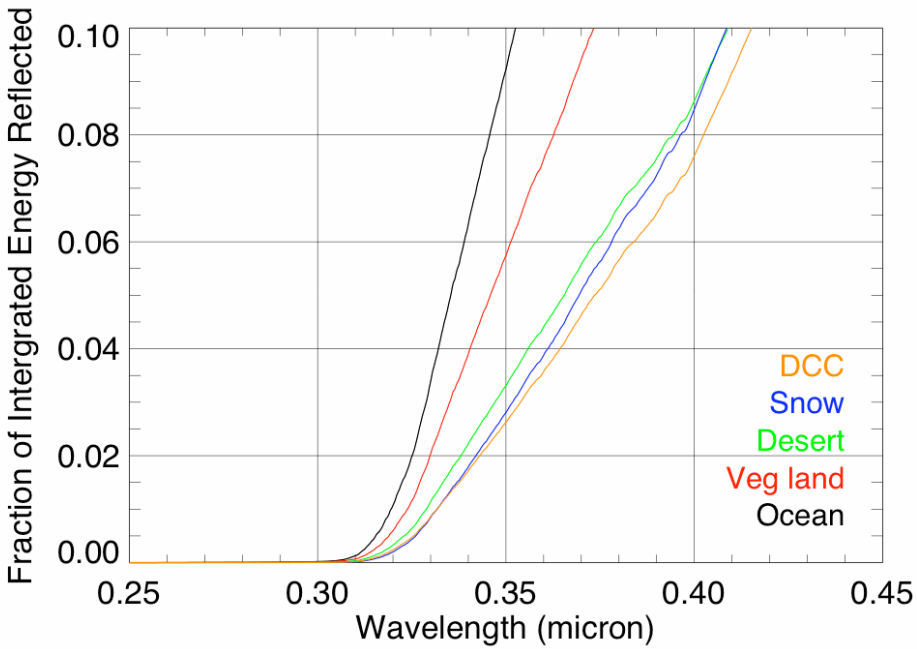


- **For clear-sky cases average fraction of energy lost beyond 2.5 μm wavelength is about 0.2% except for desert surfaces (about 0.3%).**
- **<u>Discussion:</u> Do RT calculations for spectral range beyond 2.5 μm meet CLARREO requirements ?**

Reflected Energy Fraction

(MODTRAN calculations by Zhonghai Jin, UV range)



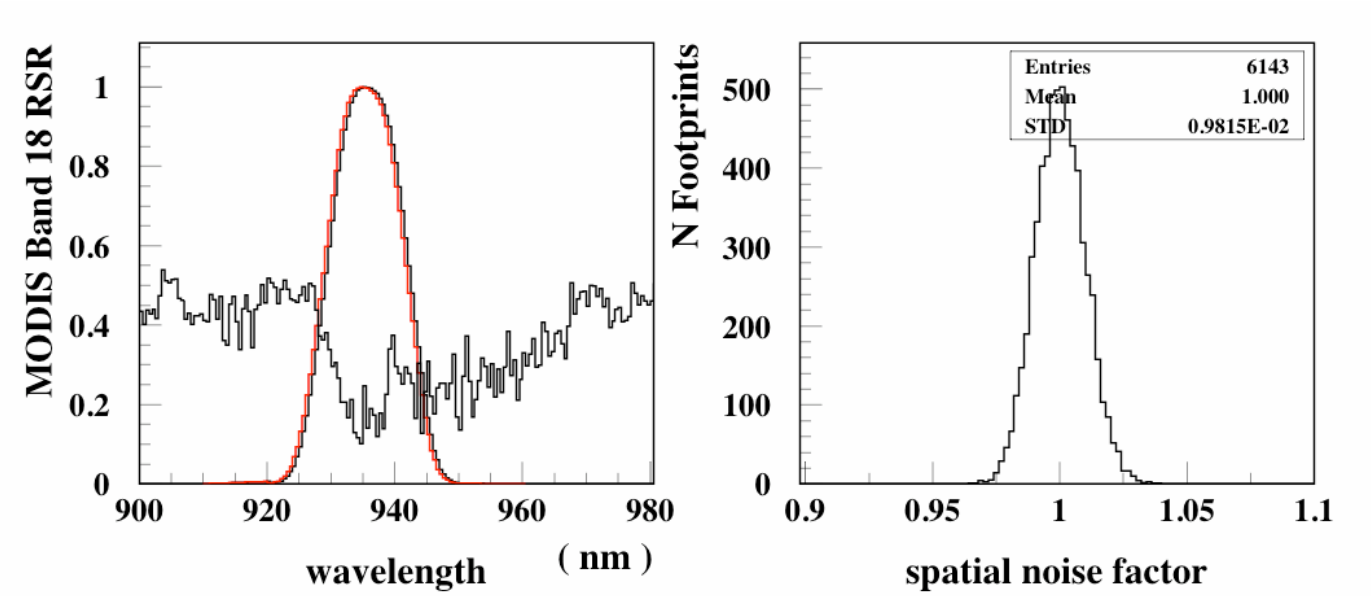


- **For clear-sky fraction of energy lost below 0.35 µm wavelength is about 10% for ocean and 6% for vegetation.**
- **Significant cost increase for spectral coverage below 0.35 µm (instrument design, LASP ?).**
- **Discussion: CLARREO spectral limit in UV ?**

CLARREO/MODIS Inter-Calibration

MODIS Band 18, SCIAMACHY data used.

Step 2: for small DOP matched data.



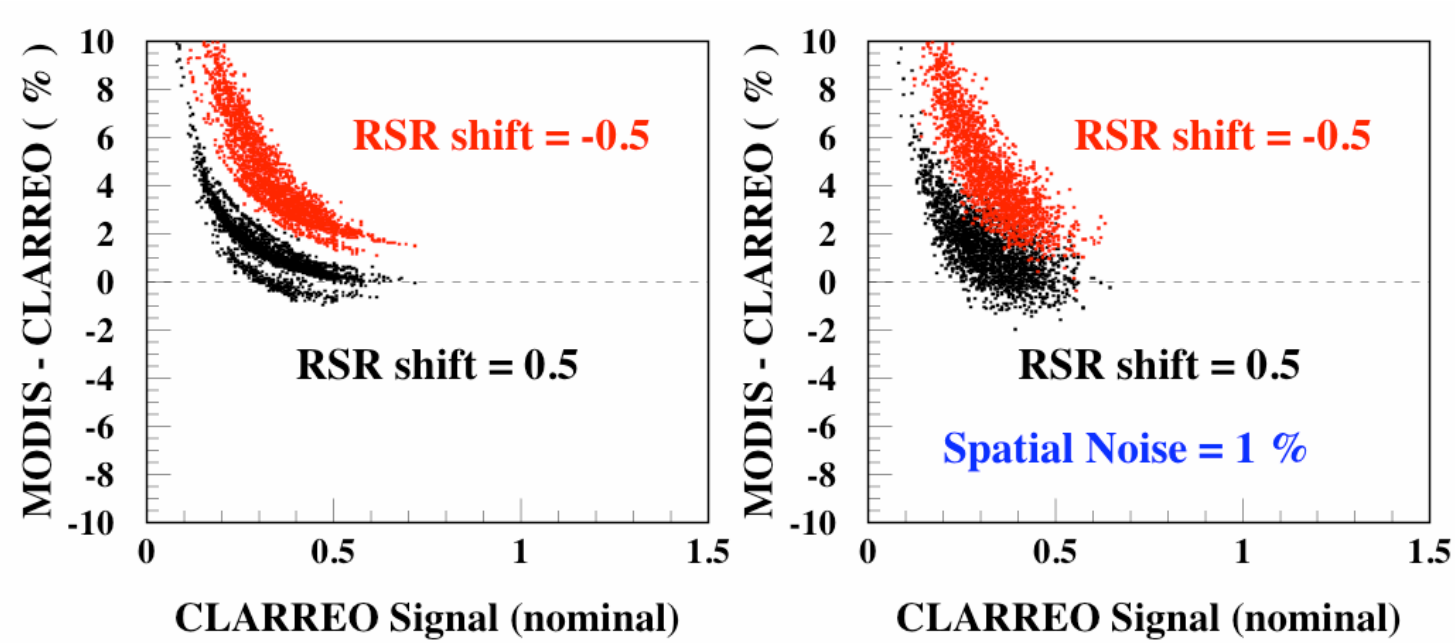
Plots:

- **Left:** MODIS band 18 original (black) and shifted -0.5 nm RSR (red). Nadir radiance spectra for marine stratus clouds is shown as histogram.
- **Right:** Matching noise of 1% (Gaussian) is used in simulation.

* MODIS/Terra Maximum CW shift in orbit = 0.5 nm.
* MODIS/Aqua Maximum CW shift in orbit = 0.3 nm.

CLARREO/MODIS Inter-Calibration

Matching noise = 1%, Differences in Offset = 0.1 $Wm^{-2}sr^{-1}band^{-1}$, Gain = 1%, RSR CW Shifts = ±0.5 nm

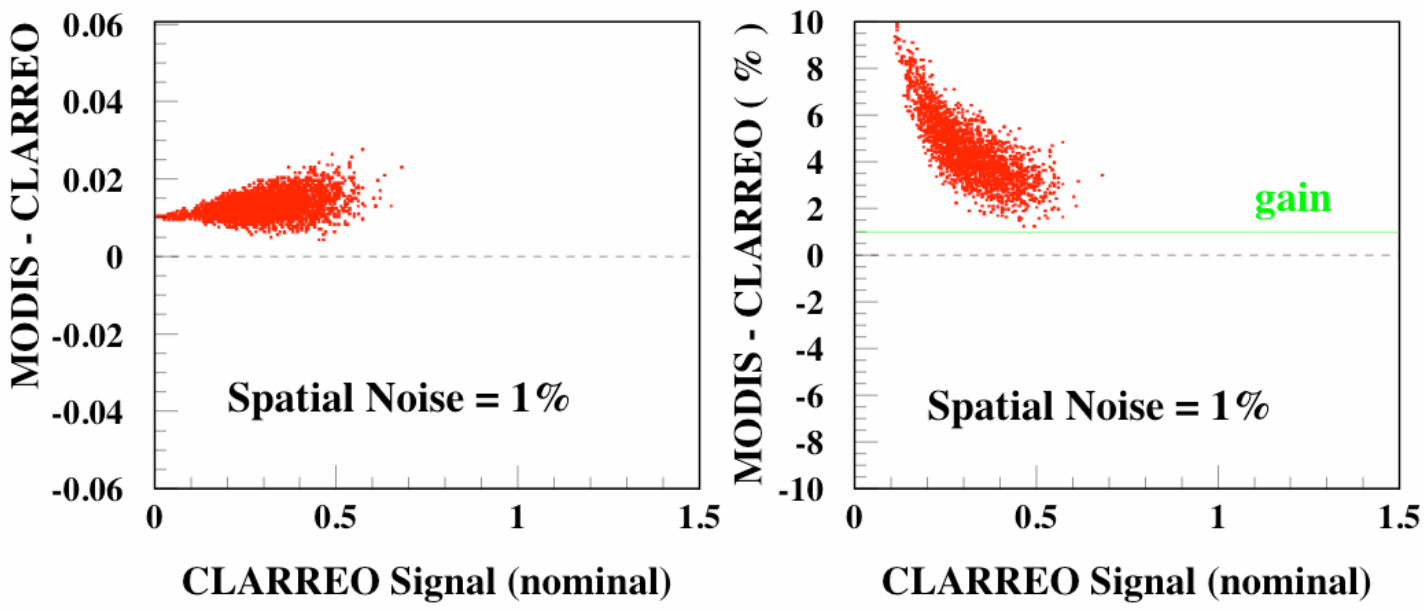


Plots:

- **Both: Relative MODIS and CLARREO signal difference versus CLARREO signal.**
- **Question: realistic offset for this band ?**

CLARREO/MODIS Inter-Calibration

Linear case with 1% matching noise:
difference in Offset = 0.01 $Wm^{-2}sr^{-1}band^{-1}$ and Gain = 1%



OFFSET + GAIN + NOISE :		
Sampling (Nfov)	OFFSET ($Wm^{-2}sr^{-1}$)	GAIN (%)
100	0.97e-02 ± 2.27e-03	1.31 ± 0.89
6000	1.00e-02 ± 2.39e-04	1.03 ± 0.07

* **Offset error (2σ) = 0.76% for 100 FOV, 0.08% for 6000 FOV.**

CLARREO/MODIS Inter-Calibration for Band 18

Step 1: Impose low level of DOP condition on the CLARREO/MODIS matched sampling.

Step 2: Select high and low clouds scenes from the matched sampling. Perform noise reduction by averaging.

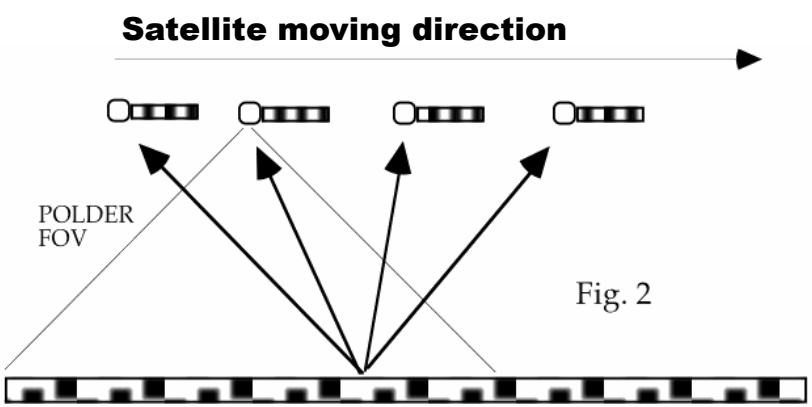
Step 3: Perform RSR CW shift tests until offset and gain are ***the same*** for both scene types.

Step 4: Remaining offset and gain difference with CLARREO is attributed to response of the rest MODIS instruments.

Step 5: Use the rest of the data to derive gain correction for sensitivity to DOP.

PARASOL Data & Scene ID

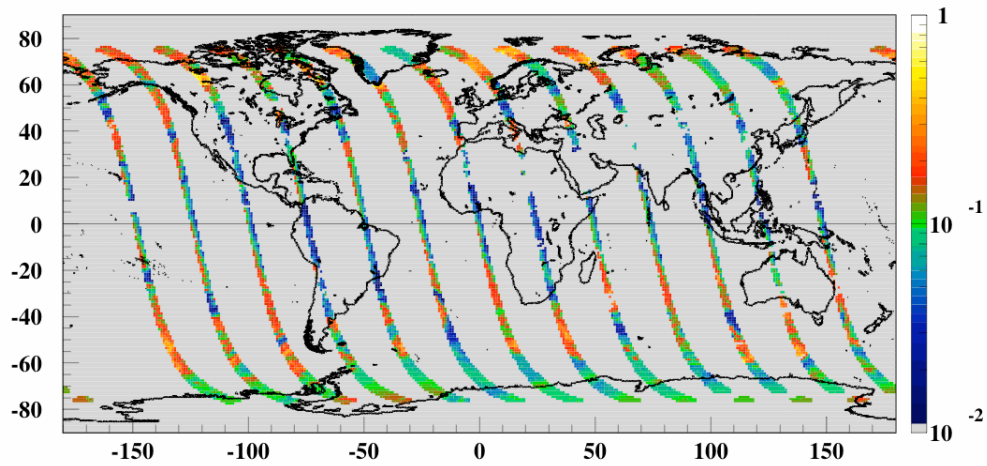
- **PARASOL, SSP 1:30 pm orbit, A-train, 705 km altitude.**
- **Level-1 data product: normalized radiances (9 bands) and Stokes parameters (*Q* and *U* in 3 bands). One day per month for year of 2006.**
- **Pixel size is about 6 km^2 at nadir, up to 15 views per pixel.**
- **Global coverage in about 2 days, 1600 km swath cross-track.**
- **Scene ID: MODIS-based cloud parameters used from CERES/Aqua SSF.**



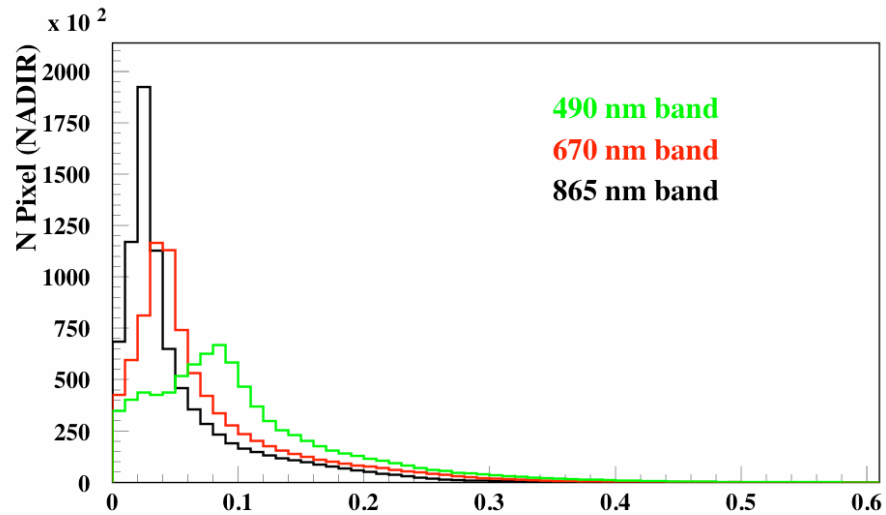
PARASOL/POLDER viewing geometry

Band	Central Wavelength (nm)	Bandwidth FWHM (nm)	Stokes Parameters
1	443	13.5	Stray Light
2	490	16.5	I, Q, U
3	565	15.5	I
4	670	15.0	I, Q, U
5	763	11.0	I
6	765	38.0	I
7	865	33.5	I, Q, U
8	910	21.0	I
9	1020	17.0	I

DOP Values and Distributions
(PARASOL 2006.10.02 data)



PARASOL 2006.10.02: Mean DOP 490 nm on 1° grid (NADIR)

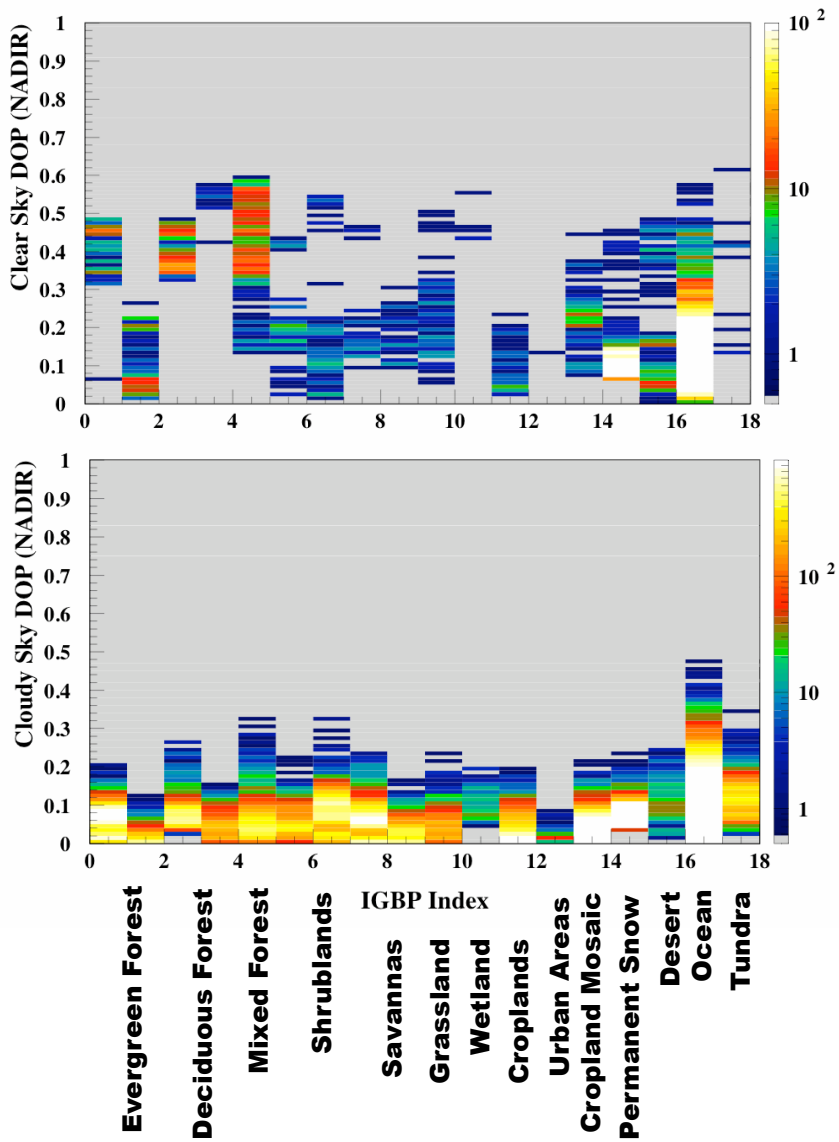


Plots:

- **Top:** PARASOL average DOP from 490 nm band on 1° grid. Nadir views only (VZA < 10°).
- **Bottom:** PARASOL all-sky DOP distributions from 490, 670 and 865 nm bands. Nadir views only (VZA < 10°).

DOP Distributions versus IGBP Index

(PARASOL 2006.10.02 data)



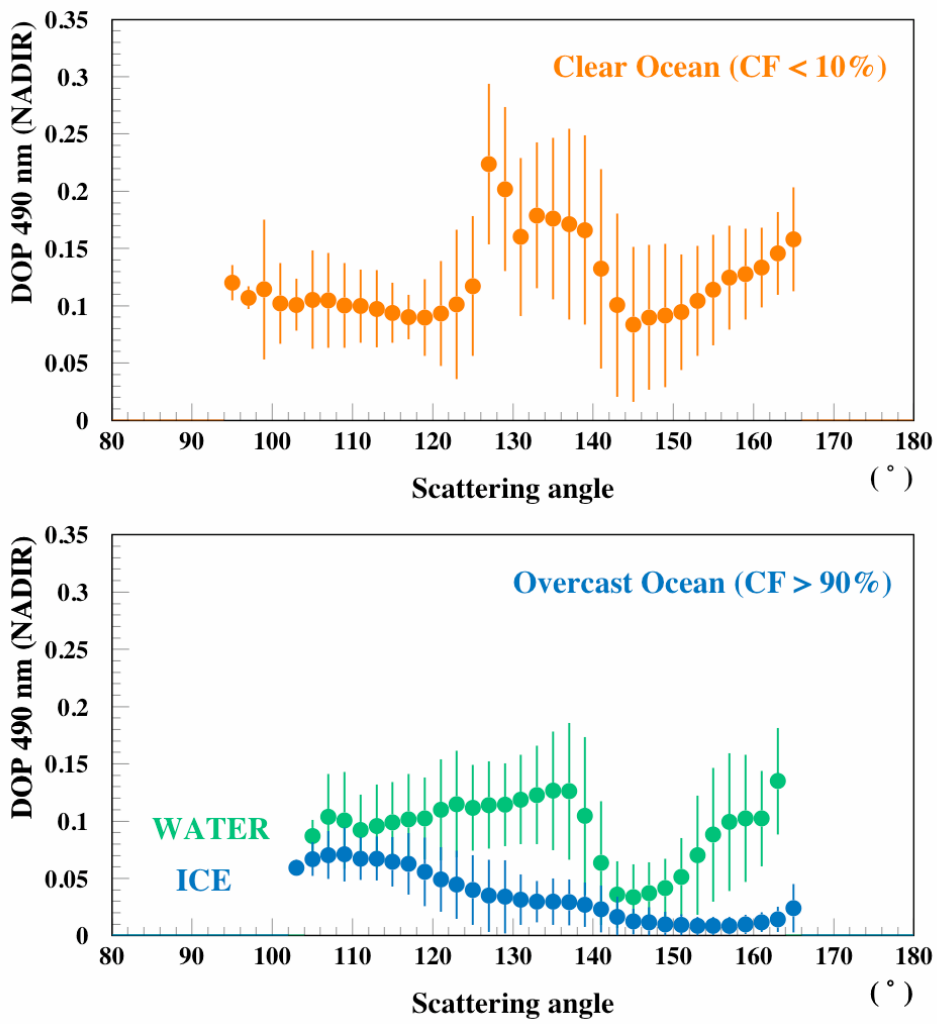
Plots:

- **Top:** PARASOL DOP from 490 nm band versus IGBP surface index for clear-sky conditions (CF < 10%). Nadir views only (VZA < 10°).
- **Bottom:** PARASOL DOP from 490 nm band versus IGBP surface index for cloudy conditions (CF > 10%). Nadir views only (VZA < 10°).

* Color scale is Number of Pixels.

DOP (mean and STD) versus Scattering Angle

(PARASOL 2006.10.02 data, ocean)



Plots:

- **<u>Top:</u> PARASOL DOP from 490 nm band (mean and STD) versus scattering angle for clear-sky ocean pixels (CF < 10%). Nadir views only (VZA < 10°).**
- **<u>Bottom:</u> PARASOL DOP from 490 nm band (mean and STD) versus scattering angle for overcast ocean pixels (CF > 90%) for ice (blue) and water (green) clouds. Nadir views only (VZA < 10°).**

Discussion on MODIS / PARASOL data matching

What do MODIS/Aqua and PARASOL Level-1 coincident data allow us to test ?

- **MODIS/Aqua radiances and PARASOL Stokes *Q* and *U* can be used to estimate MODIS dependence on DOP in orbit (look at trends of radiance dependence on DOP for various scene types and view geometries).**

- **Comparison of MODIS radiances (487, 666/677 and 866 nm bands) with PARASOL (490, 670 and 865 nm bands).**
  - **Uncertainty from CW difference (simulation with RT or from SCIAMACHY data) ?**
  - **PARASOL radiometric errors ?**

- **Help from MODIS team ? We can provide PARASOL daily pixel grid with normalized radiances, DOP and rough scene ID parameters for 12 days in 2006.**

Summary

- **For CLARREO realized as high resolution and high accuracy spectrometer with polarimetric ability on board the inter-calibration should be feasible on close-to-the-goal error level for broad- and narrow-band instruments.**

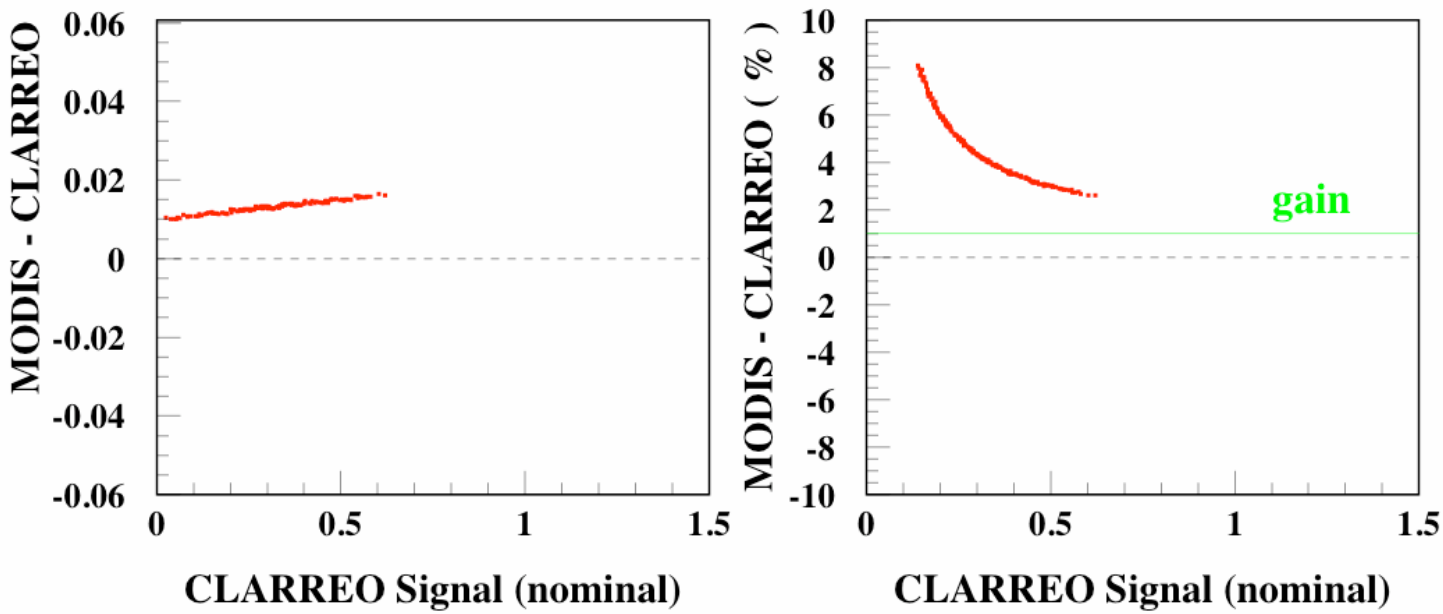
- **Suggested requirements for CLARREO as inter-calibration observatory in solar:**

  - **Precessing orbit to obtain more sampling in tropics.**
  - **Pointing ability to maximize sampling size.**
  - **Low level of matching noise (1% nominal).**
  - **Spectral range from 0.3X (?) to 2.5 μm.**
  - **High spatial resolution (1 km^2 ?).**
  - **High spectral resolution (from 1 nm ... ?)**
  - **Simultaneous measurements of Stokes *I*, *Q*, and *U* to account for sensitivity to polarization of CLARREO spectrometer and inter-calibrated sensor.**

Backup Slides

CLARREO/MODIS Inter-Calibration

Difference in Offset = 0.01 $Wm^{-2}sr^{-1}band^{-1}$ and Gain = 1%

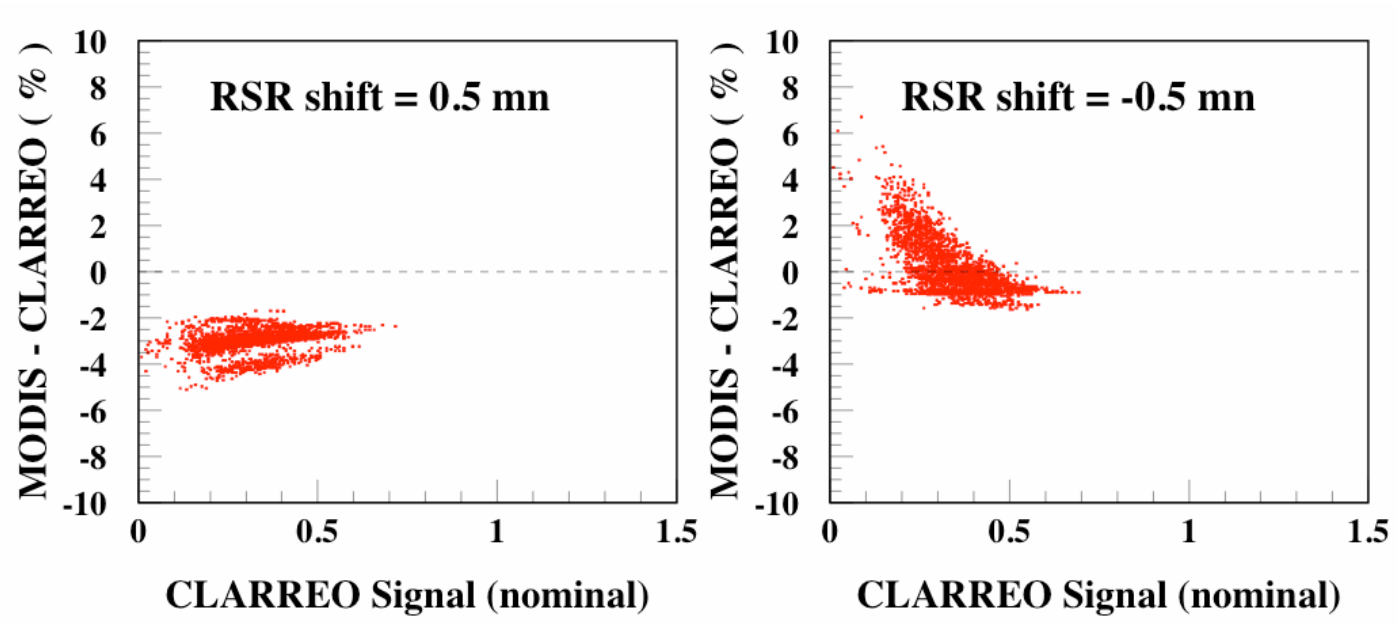


Plots:

- **Left: MODIS and CLARREO signal difference versus CLARREO signal in $Wm^{-2}sr^{-2}band^{-1}$.**
- **Right: Relative MODIS and CLARREO signal difference versus CLARREO signal.**

CLARREO/MODIS Inter-Calibration

RSR CW Shifts only: 0.5 nm



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- **Left: MODIS and CLARREO signal difference versus CLARREO signal in $Wm^{-2}sr^{-2}band^{-1}$.**
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