CLARREO: Reference Inter-Calibration on Orbit with Reflected Solar Spectrometer

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Presentation outline

◆ **CLARREO RSS Inter-calibration approach, mission requirements, and *on-orbit matched-data sampling*.**

◆ **CLARREO RSS inter-calibration *approach to sensor's sensitivity to polarization*, estimates for resulting radiometric uncertainty.**

CLARREO Reflected Solar Spectrometer (RSS)
Science Implementation Strategy

1) **CLARREO will create benchmark climate data records using two complementary approaches:**

   (a) *Direct benchmark observations by CLARREO RSS*: spectral fingerprinting techniques.
   (b) *Enabling Climate Benchmark* using CLARREO for reference inter-calibration of *existing operational sensors*.

2) **CLARREO Reference Inter-calibration (RI) will be used to determine and correct operational sensors for:**
   - Effective sensor offset and gain.
   - Spectral response function change on orbit.
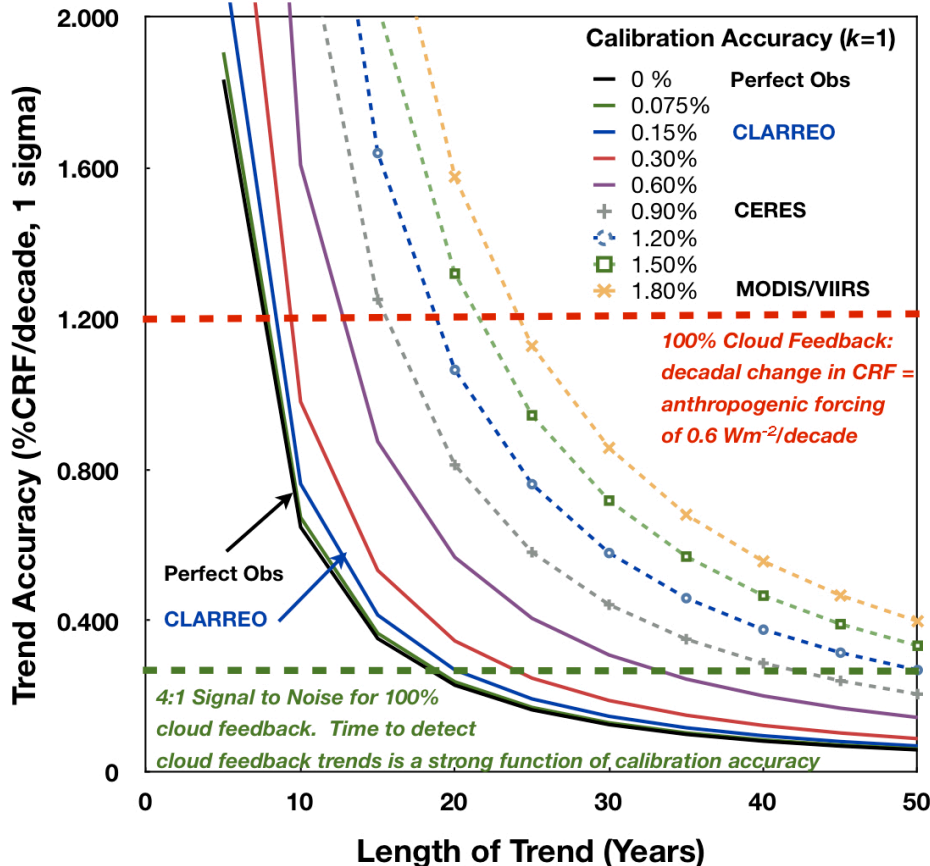   - Sensitivity to Polarization.
   - Non-linearity.

3) **CLARREO RSS RI goal: uncertainty contribution ≤ 0.15% (k=1) over autocorrelation time period ≤ 0.8 year** *(Wielicki et al., BAMS 2013)*

CLARREO RSS Mission Requirements

(1) CLARREO RS accuracy 0.15% (k=1) for measuring reflected radiation.

B. Wielicki et al. (BAMS, 2013)

Trend Accuracy & Calibration Accuracy: Reflected Solar

Calibration Accuracy (k=1)

— 0 %	**Perfect Obs**	
— 0.075%		
— 0.15%	**CLARREO**	
— 0.30%		
— 0.60%		
+ 0.90%	**CERES**	
1.20%		
□ 1.50%		
✳ 1.80%	**MODIS/VIIRS**	

100% Cloud Feedback: decadal change in CRF = anthropogenic forcing of 0.6 Wm^{-2}/decade

Perfect Obs

CLARREO

4:1 Signal to Noise for 100% cloud feedback. Time to detect cloud feedback trends is a strong function of calibration accuracy

Axis labels: **Trend Accuracy (%CRF/decade, 1 sigma)** vs **Length of Trend (Years)**

(2) High Priority RI Targets:

- **Sensors:** CERES & VIIRS/JPSS, AVHRR/Metop, Landsats, ESA Sentinels (optical), GEO imagers (all)
- **Surface:** Dome C, Desert sites.
- **Space:** Lunar spectral reflectance

(3) Uncertainty contribution from RI method: ≤ 0.15% (k=1) over climate autocorrelation time period 0.8 year.

RI error is considered to be random (data matching noise).

CLARREO RSS Reference Inter-calibration Objectives

RI Method: Sensor measurements compared to high accuracy reference on orbit (CLARREO RSS observations). The method is *statistical* , approach is different from sensor to sensor depending on its calibration model.

Requirement: *On-orbit* matched data sampling is required to reduce random noise from data matching by averaging. Data matching in Time & Viewing geometry in orbit.

Note: Requirements are set for limiting instantaneous data matching noise to 1% (k=1).

1) CLARREO RSS Inter-Calibration Objectives: Broadband Radiometers (CERES)

Parameter	Time scale	Variable	RI Error, k=1 (%)	N Samples
Effective Offset	monthly	Scan angle	≤ 0.45	2.5×10^3
Effective Gain	monthly	Scan angle	≤ 0.45	2.5×10^3
RSR Degradation	seasonally	Scene Type	≤ 0.25	30×10^3
Non-Linearity	Validation Annually, RI Error 0.15% (k=1)			
Sensitivity to Polarization	Not Sensitive, Validation Annually, RI Error 0.15% (k=1)			

2) CLARREO RSS Inter-Calibration Objectives: Imaging Radiometers (VIIRS)

| Parameter	Time scale	Variable	RI Error, k=1 (%)	
Effective Offset	monthly	Scan angle, DOP, HAM	≤ 0.45	7×10^3
Effective Gain	monthly	Scan angle, DOP, HAM	≤ 0.45	7×10^3
Sensitivity to Polarization	seasonally	Scan Angle(7), DOP, χ (9), HAM	≤ 0.25	1.2×10^6
RSR Center Wavelength Shift	Validation Annually, RI Error 0.15% (k=1)			
Non-Linearity	Validation Annually, RI Error 0.15% (k=1)			

CLARREO RSS Requirement - 2D Pointing Ability

Studies by CLARREO Engineering Team, K. Thome, and C. Lukashin

Requirement:
Ability to provide RI coincident data, matched in both RAZ and VZA angles.

Requirement implies at **least 2D pointing** ability in orbit.

**Yaw & Roll pointing:** roll +/- 55°, and yaw +/- 84° range.

Zenith

Wake

Ram

Reflected Solar
±125° with respect to nadir

Nadir
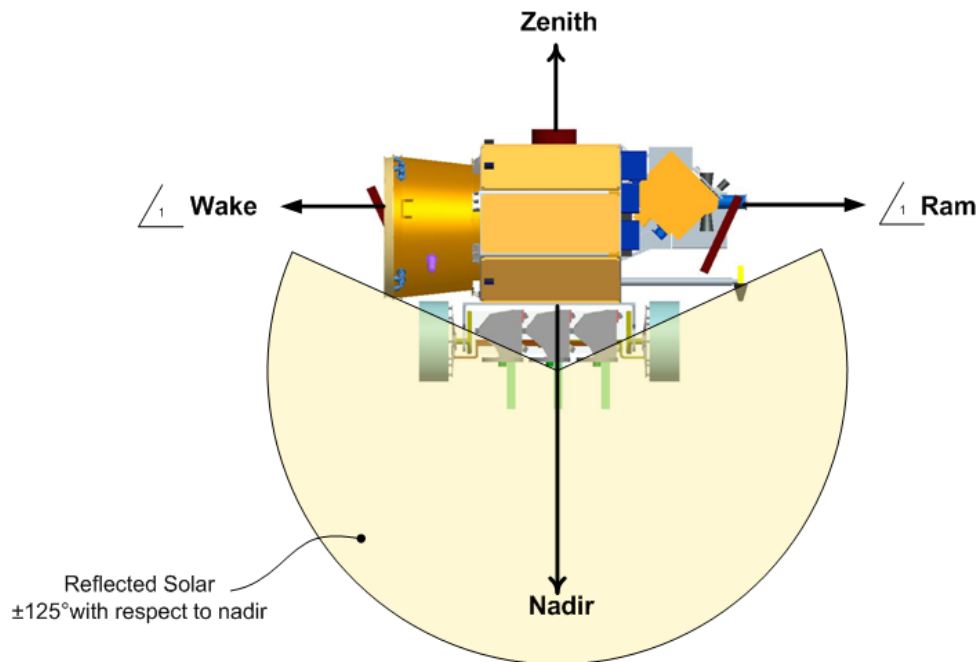
Comments:

- **Yaw & Roll** pointing option
  is preferred from RI point of view:
  RAZ is matched accurately,
  matching with GEO imagers
  is more effective.

- Hyperspectral image has
  directional definition of swath:
  RAZ (or Yaw).

CLARREO RSS On-Orbit Pointing Operations

CLARREO RSS 2D pointing option:

1) Yaw (azimuth angle) match = constant (matching within 0.4º).
2) Continuous Gimbal Roll (scan angle) match → a function of time.

Note: yaw could also be varied continuously
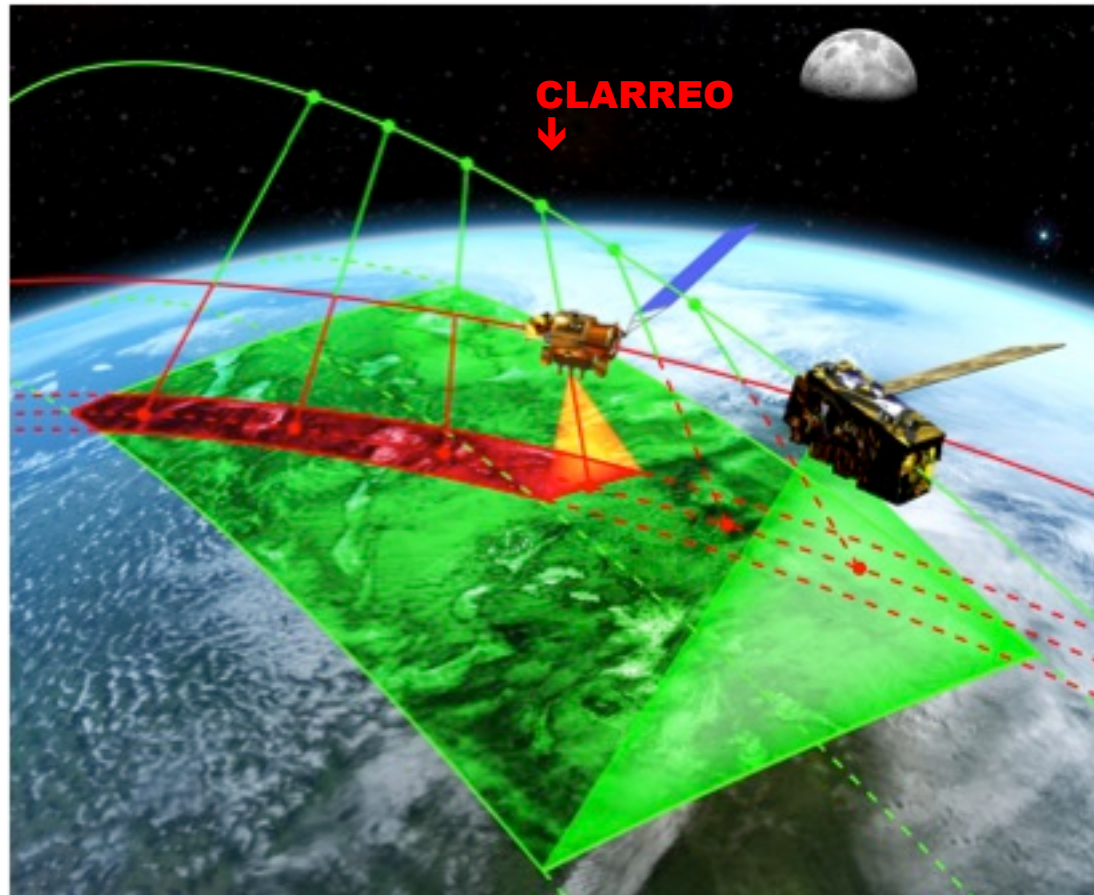
CLARREO

← JPSS

CLARREO RSS in Polar 90º Orbit – Orbital Modeling

Inter-calibration with sensors on the JPSS

Figure: CLARREO RSS *boresight locations*, which matched JPSS cross-track data over one year time period.
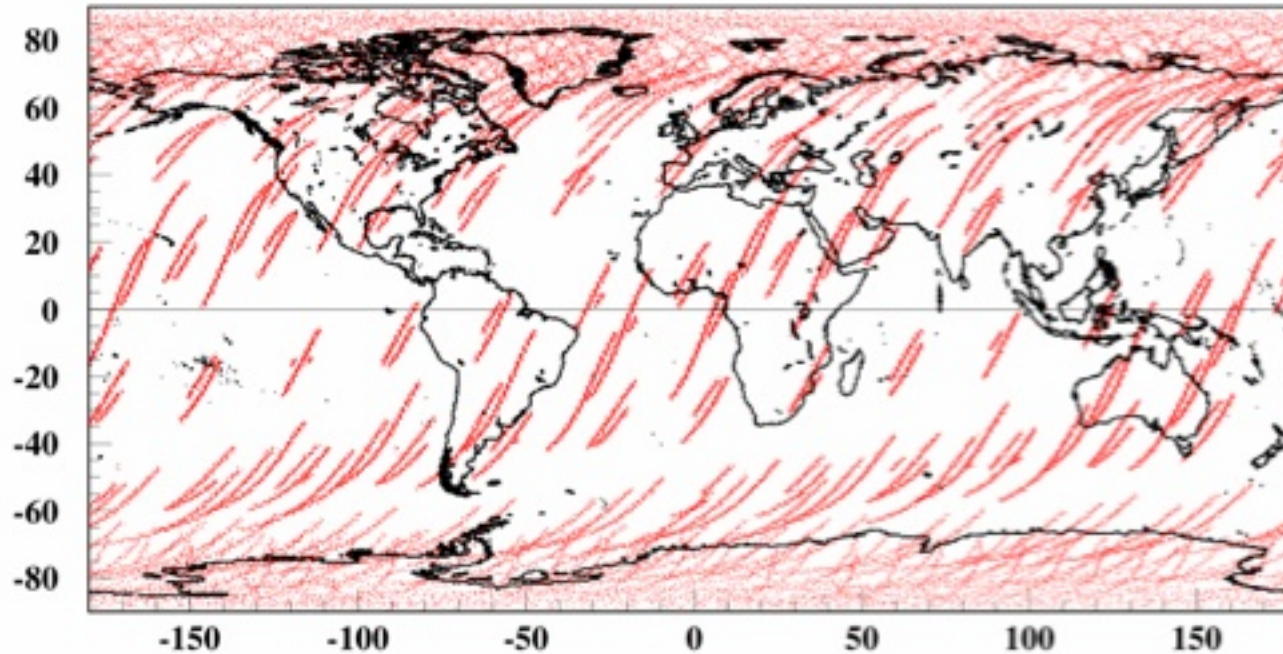
Goal:
- **Time/space/angle matching to obtain ensemble of samples with data matching noise ≤ 1%**
  Wielicki et al., IGARSS 2008

Matching requirements:
- **Within +/- 5 min of the JPSS passing.**
- **VZA match within 1.4° (CLARREO RSS 100 km swath).**
- **SZA < 75º.**
- **At least 10 km effective width of CLARREO swath.**

Sampling Estimates and Restrictions

◆ **Sampling for VIIRS/AVHRR is nadir equivalent 10×10 km area in angular space, 1º CLARREO elevation angle. To estimate number of samples with independent spatial noise 1 km shift (0.1º in elevation angle) is required from one sample to the next in both spatial directions (along and perpendicular to the ground track). With CLARREO spatial resolution of 0.5×0.5 km the 1 km shift ensures that only 2 boundary pixels are common.**

- **This approach to CLARREO/VIIRS RI sampling does not allow the inter-calibration on detector-by-detector basis. Relative calibration of VIIRS detectors to each other requires the use of VIIRS data alone, and would be performed using common histogram equalization, or overlapping field-of-view methods.**

◆ **For CERES sampling is estimated taking into account CERES FOV size of 25 km at nadir (from JPSS orbit, 2.5º in CLARREO elevation angle), and data acquisition rate 330/180 =** *1.8 footprints per degree of scan angle every 3.3 seconds.*

General Restrictions:

- SZA < 75º;
- CLARREO RSS effective swath > 10 km (VIIRS), and > 25 km (CERES).
- VZA difference < 1.4º.

CLARREO RSS / Target Sensor - RI Sampling

Summary: Monthly (top) and seasonal (bottom) RI sampling (RAAN = 0°)
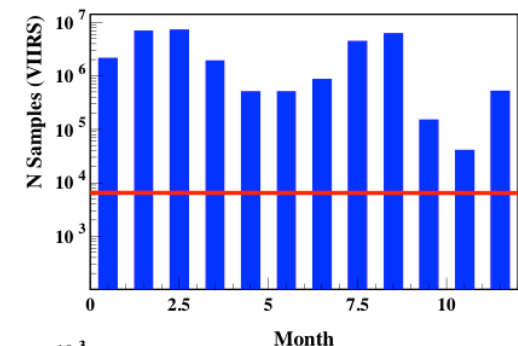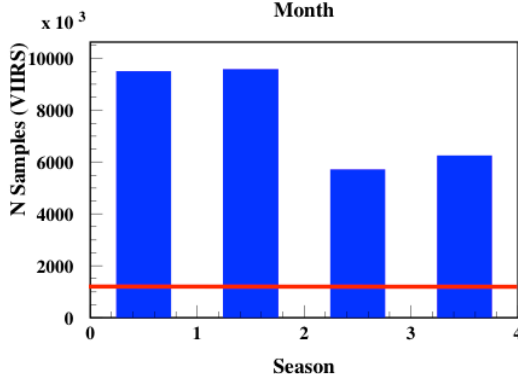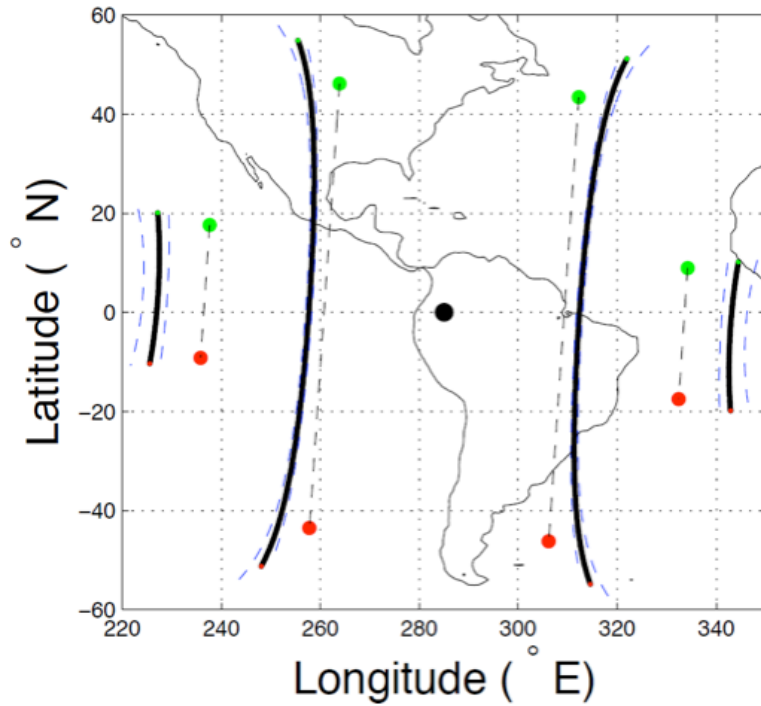
VIIRS   CERES
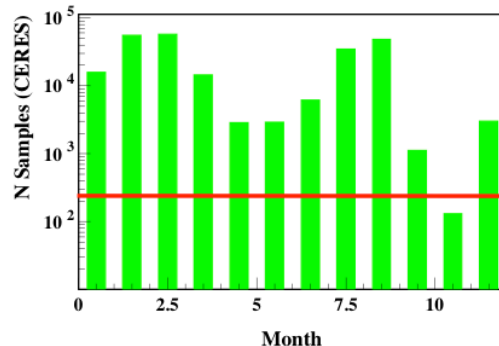
Red Lines: Required number of samples for RI monthly error contribution 0.45% (k=1)
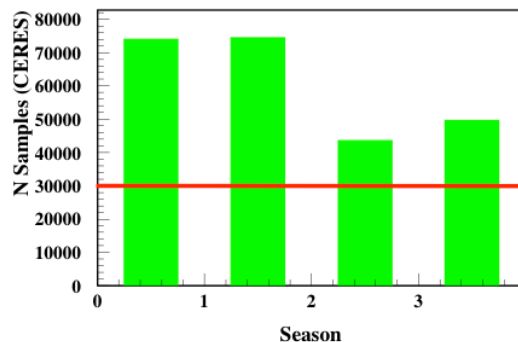
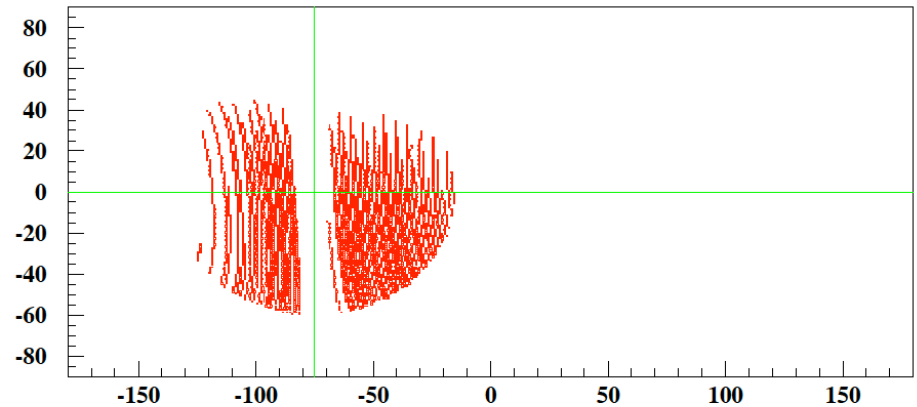**Red Lines:** Required number of samples for RI seasonal error contribution 0.25% (k=1)

CLARREO RSS / GEO Imager – Inter-calibration Sampling

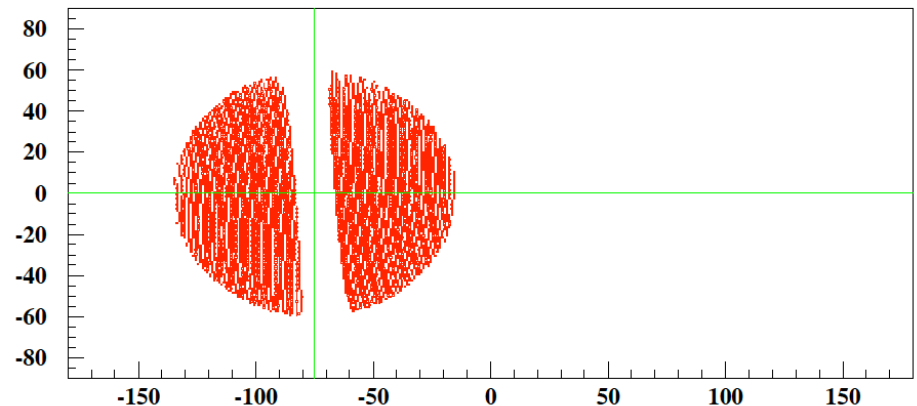**Summary: Daily (left) and monthly (right) RI sampling (CLARREO orbit RAAN = 0º)**

GEO: GOES-East (longitude = 75º W)

Note on time matching: future GEO imagers will have shorter duty cycle (about 10 min).

CLARREO GEO-75W Intercal Sampling: January

CLARREO GEO-75W Intercal Sampling: February
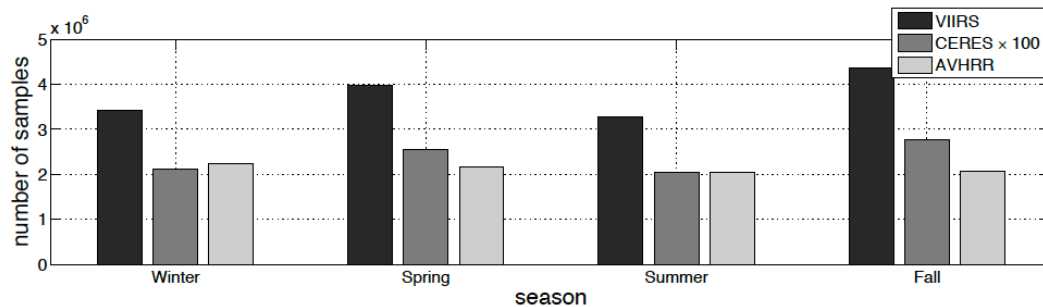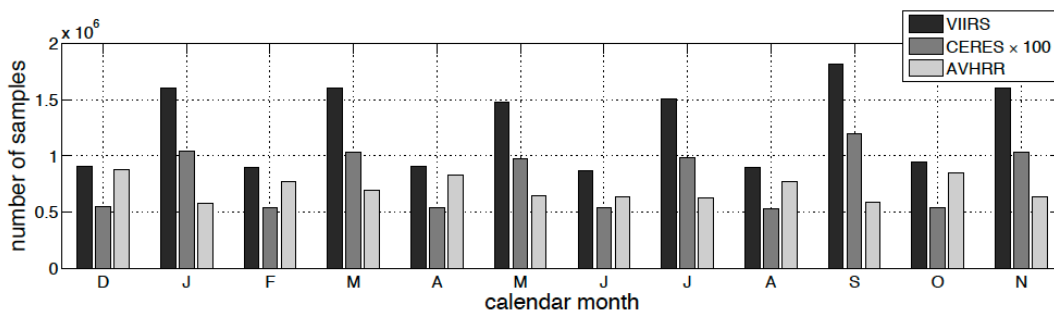
CLARREO RSS on ISS / Target Sensor - RI Sampling

Summary: Monthly and seasonal RI sampling (CLARREO on ISS)

Estimated inter-calibration sampling for VIIRS and CERES on the JPSS, AVHRR on the MetOP.
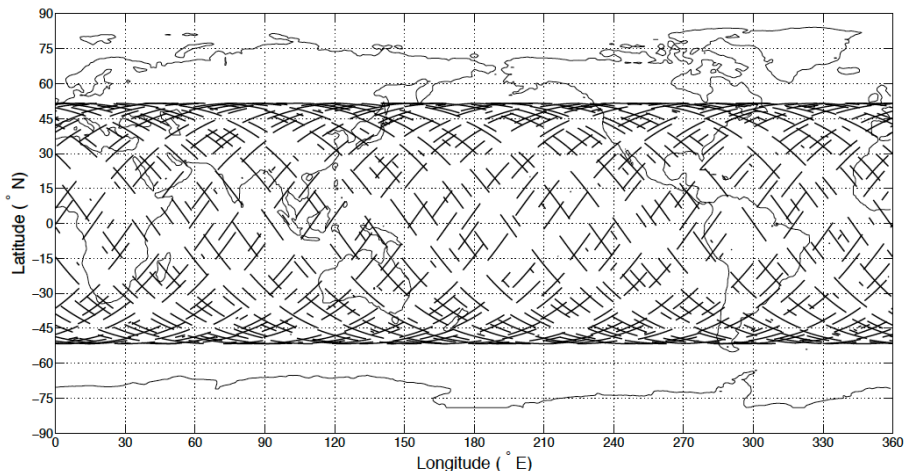
CLARREO RSS boresight locations matching JPSS cross-track data over one year time period.

Note: This is concept from GSFC and LaRC teams (2012). No obscuration from ISS.

Summary on CLARREO RSS Inter-Calibration Sampling

(1) CLARREO RSS instrument radiometric accuracy at 0.15% (k=1).

(2) CLARREO RSS 2-D data matching on-orbit (azimuth and elevation):
 constant in azimuth and varying in elevation within matching tent.

(3) All reference inter-calibration goals are feasible from sampling point of view CLARREO RSS instrument in polar 90° inclination orbit or the ISS orbit provides adequate sampling monthly, seasonally and annually for inter-calibration of sensors on the JPSS, MetOP, and in GEO satellites.

References:

C.M. Roithmayr, and P.W. Speth, Chap. 13, "Analysis of Opportunities for Intercalibration between Two Spacecraft," Advances in Engineering Research, Vol. 1, edited by V. M. Petrova, Nova Science Publishers, Hauppauge, NY, 2012, pp. 409 - 436.

C.M. Roithmayr, C. Lukashin, P.W. Speth, K. Thome, B.A. Wielicki, D.F. Young, "CLARREO Approach for On-Orbit Reference Inter-Calibration of Reflected Solar Radiance Sensors," submitted to IEEE Tran. Geo. Rem. Sensing, February, 2013.

C.M. Roithmayr, C. Lukashin, P.W. Speth, K. Thome, D.F. Young, B.A. Wielicki, "Opportunities to Intercalibrate Radiometric Sensors from International Space Station," in preparation for submission to JTECH, March, 2013.

CLARREO RSS Approach to Account for Imager Sensitivity to Polarization on Orbit
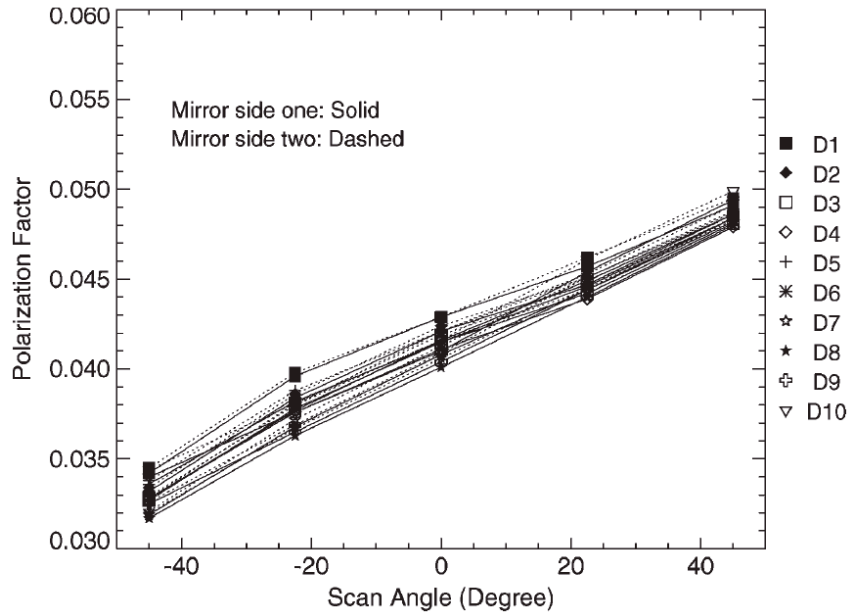
(a) Polarization factors for Aqua Band 8.
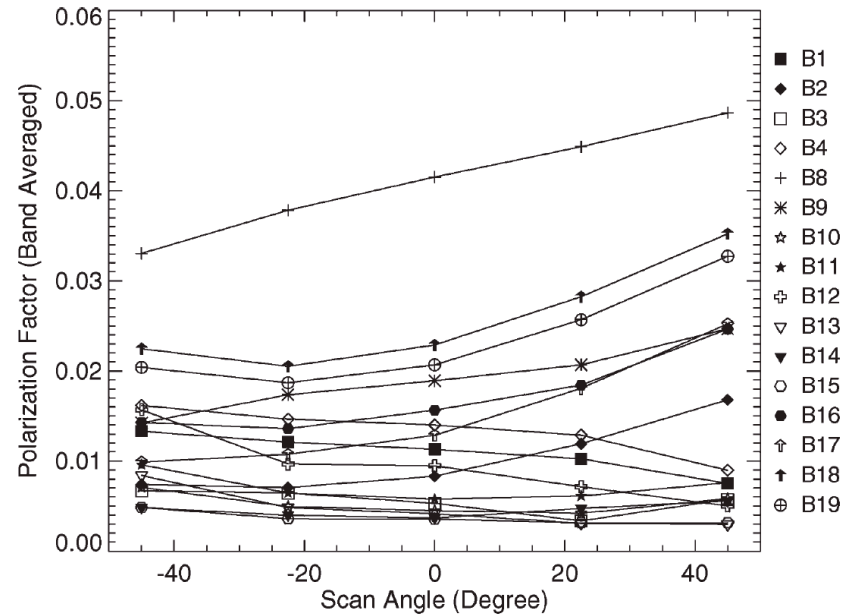
(b) Detector-averaged polarization factors for Aqua.

Sun and Xiong: "MODIS Polarization-Sensitivity Analysis",
IEEE Trans. on Geo. and Rem. Sensing, v. 45, n. 9, 2007.

Objective: Take into account MODIS/Terra/Aqua & VIIRS/JPSS sensitivity to polarization in orbit by providing Polarization information on as function of viewing geometry and scene type.

Impact: Accuracy of Level-1B data (intercal), Ocean Color and Level-2 Aerosol data products.

Imager Calibration Model (MODIS as an example)

MODIS calibration model, reflectance factor *(Xiong et al., 2003, 2006)*

$$\rho_{EV} \cos\left(\theta_{EV}\right) = m_1 dn_{EV} d_{ES}^2 \left(1 + k_{inst}\Delta T\right)/RVS_{EV}$$

θ_{EV} - solar zenith angle
m_1 - factor from solar calibration (Solar Diffuser and its Monitor)
dn_{EV} - detector response to earth radiance
d_{ES} - sun-to-earth distance
k_{inst} - temperature correction coefficient
ΔT - temperature difference from reference value
RVS_{EV} – Response Versus Scan angle (gain dependence)

Simplified RI Imager calibration model with polarization factor in:

$$\rho^{sensor} = \frac{\rho_0}{(1 + mP)}$$

Consistent with Sun and Xiong 2007.

m - sensitivity to polarization, it is function of θ and χ
$\rho_0 = \rho_{EV}$ (not-polarized reflectance)

CLARREO RSS RI: Polarization Parameters

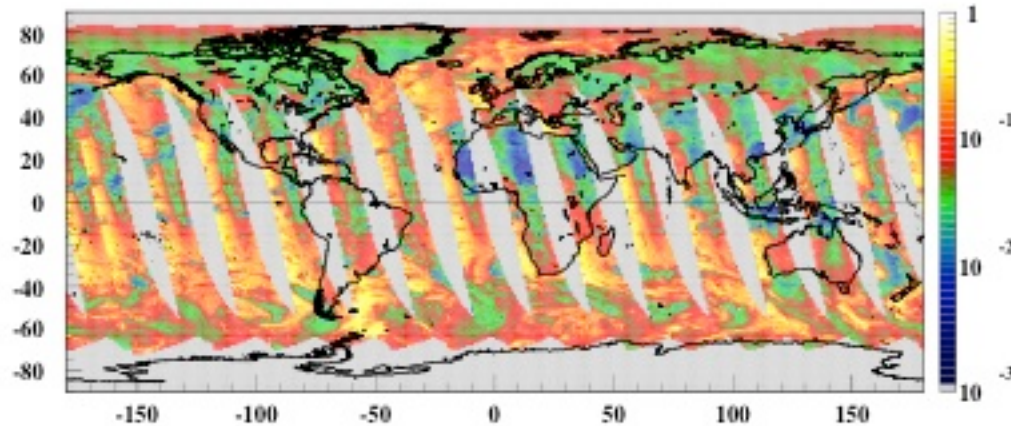**Degree of linear polarization (*P* or DOP):**

$$P = \frac{L_p}{L} = \frac{\sqrt{Q^2 + U^2}}{L} = \frac{\rho_p}{\rho} \; .$$

Polarization angle, defined relative to viewing plane
(PARASOL definition, range from -45° to 135°):

$$\chi = \begin{cases} tan^{-1}\left(U/Q\right)/2 \\ tan^{-1}\left(U/Q\right)/2 + \pi/2 \end{cases} \quad \text{if } Q < 0.$$

Note: The χ should be 90° for scattering in principle plane

Polarization Data from PARASOL (2006.04.01)

a) 2006.04.01: Degree of polarization at $\lambda = 670$ nm

PARASOL data:
Simulated cross-track sampling,
$1^o \times 1^o$ lon/lat grid,
670 nm wavelength.

DOP is color scale.

$\lambda = 490$ nm
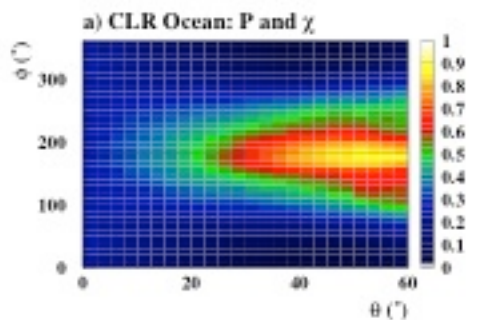$\lambda = 670$ nm
$\lambda = 865$ nm

b)
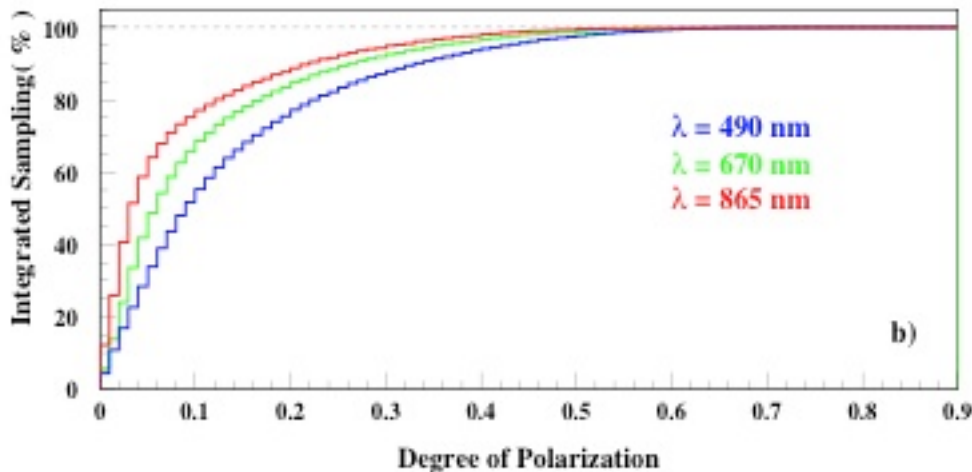
Cumulative sampling for
PARASOL Polarization bands

Examples of Empirical PDMs (12 days of PARASOL data)
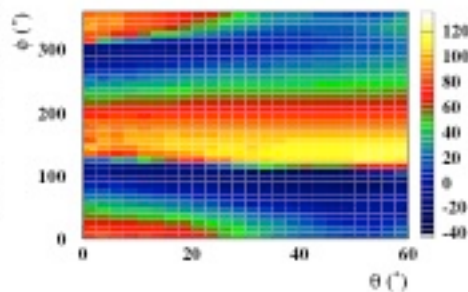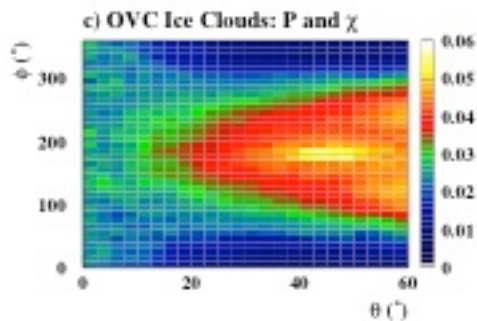
40° < SZA < 50°, 670 nm wavelength.

DOP:

Polarization angle:
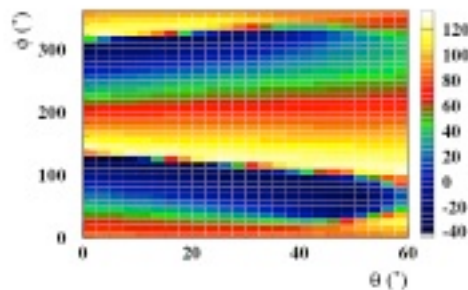
a) Clear-sky ocean:
   WS < 2.5 m/s
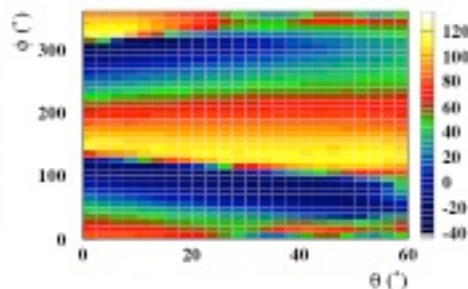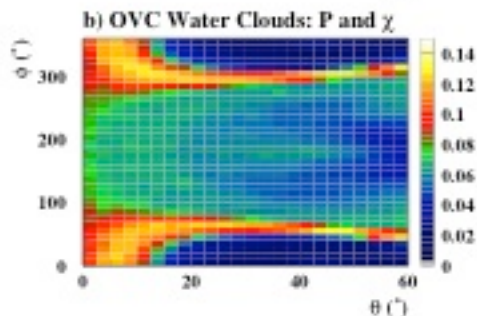
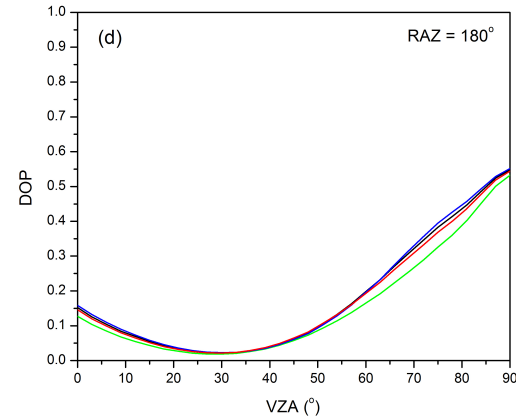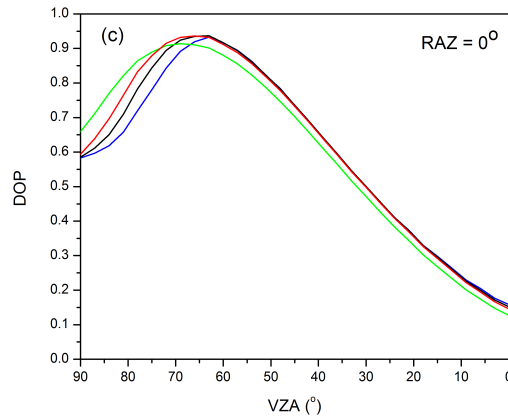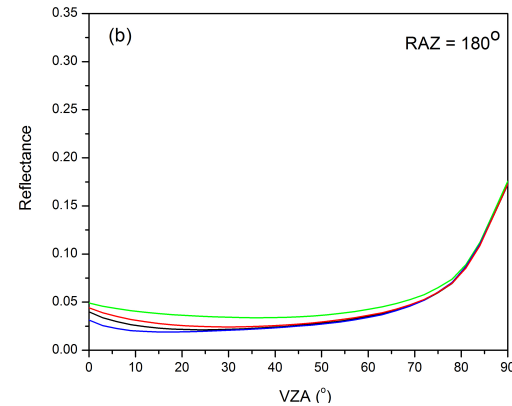b) Overcast water clouds over ocean:
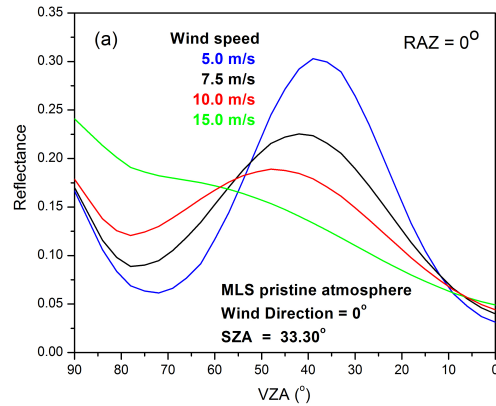   5 < OD < 10

c) Overcast ice clouds over ocean:
   5 < OD < 10

Note: DOP patterns are strongly dependant on scene type, but the Polarization angle is very similar.

Examples of Theoretical PDMs (clear-sky ocean)

Calculations by Wenbo Sun

The total reflectance and DOP at the principal plane calculated with the ADRTM at a wavelength of 670 nm. Pristine clear atmosphere with the mid-latitude summer atmospheric profile is assumed. The solar zenith angle is 33.3º. Wind direction is at 0º. Wind speeds are 5.0 m/s, 7.5 m/s, 10.0 m/s, and 15.0 m/s, respectively.

CLARREO/Imager Inter-Calibration: Resulting Radiometric Uncertainty

For fixed θ and χ values, assuming no correlation, reflectance variance:

$$\left(\sigma^{sensor}\right)^2 = \left(1 + mP\right)^2 \sigma_0^2 + \left(m\rho_0\right)^2 \sigma_p^2 + \left(P\rho_0\right)^2 \sigma_m^2$$

Then, relative radiometric uncertainty:

$$\frac{\sigma^{sensor}}{\rho^{sensor}} = \sqrt{\left(\frac{\sigma_0}{\rho_0}\right)^2 + \frac{P^2\sigma_m^2 + m^2\sigma_p^2}{\left(1 + mP\right)^2}}$$

First term is uncertainty for non polarized reflectance. Second term is from polarization effects.

$$\frac{\sigma_0}{\rho_0} = \sqrt{\left(\frac{\sigma^{clarreo}}{\rho_0}\right)^2 + \left(\frac{\sigma_{intercal}}{\rho_0}\right)^2 + \left(\frac{\sigma^{sensor}}{\rho_0}\right)^2}$$

The first term is combined accuracy of CLARREO, RI random error, and remaining Imager uncertainty (e.g. month-to-month stability).

Numerical Estimates of Inter-Calibrated Imager Uncertainty:

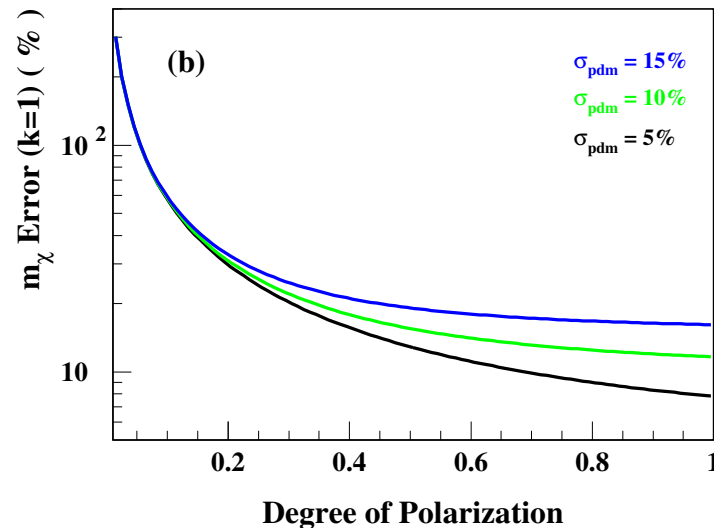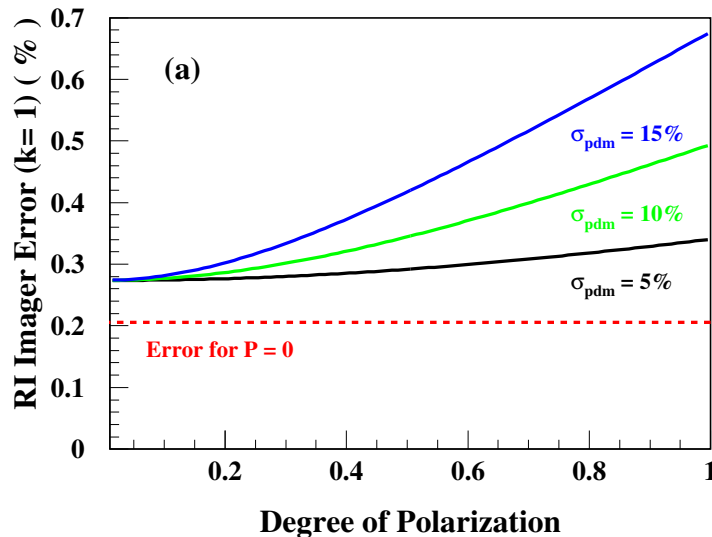## Single measurement of *m* on orbit

Inputs for calculation:

m = 3% (k=1)

σ_{pdm} = 5%, 10%, 15% (k=1) ← **Uncertainty in Polarization**

σ_{g0} = 0.10% (k=1)

σ_{gp} = 0.15% (k=1)

$\sigma_{clarreo}$ = 0.15% (k=1)

$\sigma_{residue}$ = 0.10% (k=1)

Summary on CLARREO RSS Polarization Approach

(1) CLARREO RSS instrument radiometric accuracy at 0.15% (k=1).

(2) CLARREO RSS 2-D data matching on-orbit (azimuth and elevation): constant in azimuth and varying in elevation within matching tent.

(3) Polarization Distribution Models are required for inter-calibrating sensor's sensitivity to polarization, and further its stand-alone operation. A global all-sky set of models should be built for DOP and polarization angle χ .

References:

C. Lukashin, B.A. Wielicki, D.F. Young, K. Thome, Z. Jin, and W. Sun, "Uncertainty Estimates for Imager Reference Inter-Calibration With CLARREO Reflected Solar Spectrometer", IEEE TGRS, Special Issue on Instrument Inter-calibration, DOI: 10.1109/TGRS.2012.2233480, 2012.

Wenbo Sun, B.A. Wielicki, D. F. Young, and C. Lukashin, "Modeling polarized solar radiation from ocean-atmosphere system for CLARREO inter-calibration applications," in preparation for submission to Journal of Geophysical Research, 2013.

C. Lukashin, Z. Jin, D.G. Macdonnell, K. Thome, W. Sun, B.A. Wielicki, D.F. Young , "Requirement for Instrument Sensitivity to Polarization for Climate Observing System in Reflected Solar," in preparation for submission to Journal of Geophysical Research, 2013.